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REVIEWS ***IN*** ***CHEMICAL*** ***ENGINEERING***

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MAGNETIC FIELD ASSISTED FLUIDIZATION – A UNIFIED APPROACH

Part 6. Topics of Gas-Liquid-Solid Fluidized Bed Hydrodynamics

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SUMMARY

Part 6 of the series *Magnetic Field Assisted Fluidization- a Unified Approach* is devoted to gas-liquid-solid fluidized beds. The article is a systematic analysis of this branch of magnetically controlled fluidization that is, in fact, the first review since the brief comments of Liu et al. (1991). Unified approach developed in the previous parts of the series does permit establishment of a clear point of view on the current state and definition of future problems. A special issue in this review is the classification of magnetically assisted three-phase fluidization. Nowadays, this classification

scheme is unique and allows to analyze the up-to-date status of magnetically assisted three-phase fluidized bed and to figure potential research branches both in deep process studies and development of new devices.

The analysis spans bubble columns with magnetization FIRST and LAST mode of operations, magnetically assisted slurry bubble columns, trickle beds based on magnetically stabilized (or frozen) beds and magnetically assisted airlifts with controllable liquid circulation. All these issues make Part 6 a comprehensive review thoroughly investigating one undeveloped, but with a great potential, branch of magnetic field assisted fluidization.

PREFACE- Preliminary Thoughts

Dear reader, Part 6 of the series Magnetic Field Assisted Fluidization (MFAF) was completed during the last two years (2006-2007) and collated results from investigations performed in many countries and published mainly in English and Chinese. The G-L-S fluidization began with the pioneering works of Hu and Wu (1987, 1988) 20 years ago. Magnetically controlled G-L-S fluidization is attractive technique for biotechnological and chemical mass transfer operations since magnetic particles can be easily removed from the process fluids and enable bed gas holdup control that directly affects the mass transfer efficiency.

The present article addresses basic hydrodynamic characteristics of gas-liquid-solid fluidized beds assisted by external magnetic fields such as critical velocities, pressure drop, phase holdups, etc. The unified approach in data analysis, established in Hristov (2002), is developed here thus allowing easy parallelism in bed behaviour description and analysis of phenomena. Particular sections explain the contemporary problems that should be solved. Generally, the article could be considered as a study on magnetically assisted G-L-S beds based on published results and performed from a unified point of view since systematic analysis has not been published so far.

1. INTRODUCTION

Part 6 of the ongoing MFAF series collates and investigates results relevant to hydrodynamic performance of gas-liquid-solids systems subjected

to external magnetic fields. Unlike the gas-solid and liquid-solid counterparts these fluidized systems are relatively new. Most of them deal with simple technological operations and the goals are in very narrow areas: to perform a particular mass transfer operation holding particles in the working volume by help of external magnetic field. This impedes the formation of a common source of knowledge since in many cases basic hydrodynamic information (the background of any mass transfer operation) is basically missing. Despite this, the work done here had as examples the previous reviews, devoted to gas-solid and liquid-solid beds and preferred as models of analysis performed with huge published data. That is, the style accepted in the previous reviews helps us to remove more data than those reported by the original works and to develop discussions that are more general then the particular topics of this review.

The review addresses commonly used characteristics in the fluidization such as pressure drop, phase diagrams, bed expansion, minimum fluidization velocity, phase holdups, etc. The main idea was to create a review with a structure similar to that done for gas-solid and liquid-solid beds allowing easy comparison and differentiation in bed behaviour under different experimental conditions imposed mainly by the gas-liquid flow mode and magnetization conditions. Commonly, unlike magnetically controlled gas-solid beds where bubbles cease is of primary importance, the three-phase fluidization calls for bubble size control via manipulation of the solid phase behaviour and adjustment of gas and liquid superficial velocities (Fan, 1989). The main idea from a chemical engineering standpoint is quite simple: to achieve high gas-liquid interface area through bubble breakup. Besides, manipulation of fluid flows (gas and liquid) looks for a desired flow regime such *dispersed bubble flow* (see further in the text) or at least *churn flow* mode. This is an essential formulation of the main idea how to apply external magnetic fields to fluidized magnetic solids, either on preliminary fluidized particles (Magnetization LAST) or on fixed beds (Magnetization FIRST) enabling creation of a "stabilized bed" regime. Mass transfer operations impose additional requirements such as low axial dispersion, almost plug-flow regime, etc. Such characteristics are not commented here since the present author's point of view is to discuss them alongside mass transfer operations - the forthcoming Part 7 is devoted to this important but yet not analyzed problem.

The present analysis begins with a general analysis of fluidization units, magnetic systems and particles used in various studies. This allows to create a general point of view concerning main tendencies in design of both magnetic systems and particles for G-L-S MFAF. Further, the major part of the review is devoted to bubble columns (BC). In contrast to original works a separation into sub-groups such as *Bubble columns with dense beds*, *Slurry bubble columns* and *Trickle beds* is done that enables easy analyses of data and creates links to non-magnetic counterparts. Magnetically assisted airlifts form a separate branch of G-L-S MFAF as it is illustrated by the classification drawn in the present review and commented next.

As usual, in this review series bed hydrodynamics is discussed with the two principle modes of magnetization, i.e. **FIRST** and **LAST**. Additionally two principle approaches to manipulate the flow modes, i.e. **Gas-Scan** and **Liquid-Scan** modes are conceived. This approach does permit to develop a classification scheme, based on that originated by Fan (1989), and initially conceived by Hristov and Hadzisavvas (1997). This classification fills the knowledge gap in the existing published works addressing systematization, namely: absence of any functional links between the magnetization modes, gas and liquid flow organization, solids phase behaviour, etc. Besides, this classification draws branches in G-L-S MFAF non-explored yet and forms a basis that can be expanded with new trends in the future.

This brief presentation draws the structure of the review but more detailed information is available in its particular sections. Hereafter, previous parts of the review series (Hristov, 2002, 2003a, b, 2004, 2006) will be referred as Part 1, Part 2, Part 3, Part 4 and Part 5 respectively for seek of simplicity. Part 6 is an independent study but some basic knowledge to understand the comments is required and in this context the previous reviews are essential sources of information to readers not experienced in MFAF.

1.1. Briefs on magnetically assisted Bubble columns and Airlifts

Fluidization of ferromagnetic particles in the presence of an external magnetic field was conventionally carried out with the fluidizing agent being liquid or gas in axial (Hristov, 2002, 2006) but in the last decade of the 20th century the attention was focused on the behaviour of magnetically stabilized three-phase (gas-liquid-solid) beds. Liu et al. (1991) gave a comprehensive review of the fluidization in a magnetic field including the studies of three-

phase fluidized bed published up to 1990. The present series of review papers (Hristov, 2002; 2003a, b; 2004; 2005) on magnetic field assisted fluidization has started a unified approach in the fluidized bed analysis and systematic interpretation.

The main area of applications of three-phase fluidized beds with magnetic solid phase is in biotechnology (Hristov and Ivanova, 1999). The first application of the possibility to control the solid phase movement as well as the gas holdup in a bubble column was reported by Hu and Wu (1987, 1988). After 1991 the efforts were directed to hydrodynamics (Kwauk et al., 1992; Thompson Worden, 1991, 1997; Chen and Leu, 1998a, 2001, 2002; Hristov and Hadzisavvas, 1997) studies of axial dispersion coefficients of the liquid phase (Kwauk et al., 1992; Thompson Worden, 1991, 1997; Chen and Leu, 1998b; Sajc et al., 1994), gas-liquid mass transfer (Kwauk et al., 1992; Thompson Worden, 1997; Chen and Leu, 1998a, 2001), gas-hold-up and interfacial area (Kwauk et al., 1992; Thompson Worden, 1997; Chen and Leu, 1998a,b; 2001, 2002; Sajc et al, 1995, 1996) and magnetically controlled bioreactors with immobilized enzymes and cells (Hristov and Ivanova, 1999; Ivanova et al, 1996; Al-Qodah, 2000c).

Most of the above commented studies were carried out in axial magnetic fields, while the use of transverse fields was rare (Hu and Wu, 1987, 1988; Ivanova et al., 1996; Hristov, 1998a; Hristov and Hadzisavvas, 1997; Al-Qodah, 2000c). Furthermore, the studies considered a co-current gas-liquid fluidization in accordance with the taxonomy of Epstein (1981) or with the E-I-a-1 mode according to Fan's classification (Fan, 1989) - see **Classification** next. The mode of operation with respect to the magnetic field application is Magnetization LAST (Siegel, 1987; Hristov, 1998b), i.e. the field acts on a preliminarily fluidized bed. Only two studies (Ivanova et al., 1996; Hristov and Hadzisavvas, 1997) applied the opposite mode (Magnetization FIRST) till 1996. The literature data till 1996 was collected by Hristov and Hadzisavvas (1997) and a classification scheme based on Fan's classification was conceived.

All the comments above address bubble columns while magnetically controlled airlifts belong to a relatively new trend in MFAF. In the airlift reactor the liquid velocity depends both on the gas velocity and the hydraulic resistance of the downcomer (Chisti, 1989). The interrelation between both velocities in the airlift loop (hereafter airlifts with external loops will be considered) is complex and the operating conditions affect the fluidization

regimes and the stability of fluidization (Verlaan, 1981; Douek et al., 1995). Recently Hristov (1998a), Al-Qodah et al. (Al-Qodah, 2000a, b, c; Al-Qodah and Al-Hassan, 2000) and Hristov (2005a, b) have reported results on airlifts utilizing transverse magnetic fields. These studies address mainly the magnetic field effect on the gas-holdup and the liquid circulation velocity. Moreover, Al-Qodah (2000a) and Al-Qodah and Al-Hassan (2000) demonstrated the magnetic field effect on the gas-to-liquid mass transfer in a way similar to that reported by Thompson and Worden (1997) in an axial field.

The variety of situations with magnetically assisted three-phase fluidized beds and the results published call for a systematization allowing easy comparison of existing information and more methodical future studies. Systematization is based on the Fan's classification (Fan, 1989) of non-magnetic G-L-S fluidized beds (see Fig.1) allowing easily to realize new issues imposed by magnetic field application is developed next.

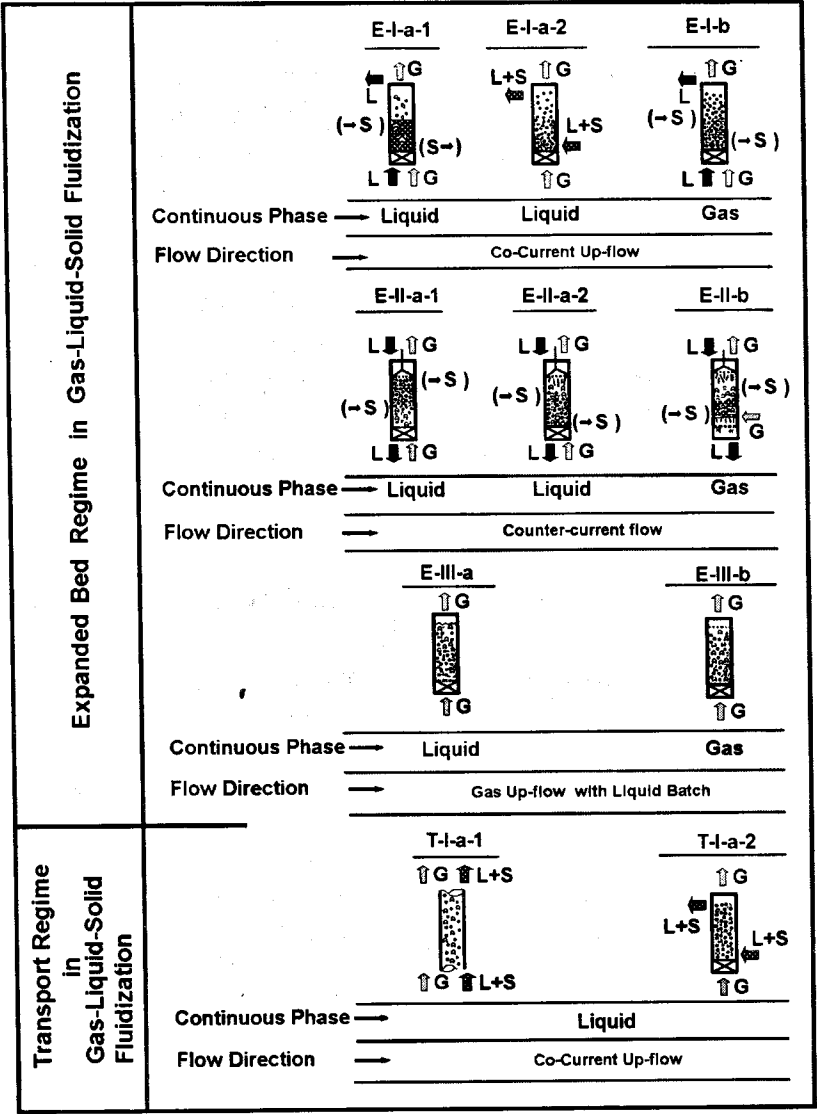


Fig. 1: Fan’s classification concerning expanded bed regimes of bubbles columns and transport flow regimes. Adapted after Fan (1989) and restricted to cases allowing magnetic field assistance.

1.2. Classification

The classification scheme conceived by Hristov and Hadzisavvas and

developed recently (Hristov, 2005a) (see Fig.2) allows clarifying the basic operation modes of bubble columns controlled by external magnetic fields. Further, it is an instructive chart providing present day information (till the end of 2007) in the area of magnetically G-L-S beds and builds a scheme allowing a more unified presentation of the regimes employed as well as to link these devices to the well known non-magnetic devices. The classification structure calls some basic terms to be elucidated, among them:

- The magnetic field and the fluidizing flow *can be applied independently on the particle bed* that leads to the well-known Magnetization **FIRST** and Magnetization **LAST** operating modes (Siegel, 1987; Hristov, 1998b). The two-phase (gas-liquid) fluidizing flow consists of two independent streams that may be applied in a different order to the particle bed in spite of the action of the external magnetic field. The scheme indicates that two modes of fluid flow application are possible:
- **Liquid-scan mode (LSM)** concerning a variation of the liquid velocity at a constant gas flow;
- **Gas-scan mode (GSM)**. This mode is well known from the classic three-phase fluidization where the studies are always performed at a fixed liquid velocity and a varying gas flow rate.

Liquid-scan and **Gas-scan** are additional terms allowing to realize how the experimental results are obtained and how the shifts in regimes are done. They explain variety of results obtained in most cases without clear strategies and addressing problems and bed characteristics without interrelations of phenomena behind them. In absence of a field as well as with Magnetization **LAST** mode there are no differences between **Liquid-scan** and **Gas-scan** modes. However, the application of Magnetization **FIRST** mode needs a clear definition of bed stabilization or fluidization developed by gas at a fixed liquid rate and *vice versa* (see further in the review).

This classification scheme and its pertinent terminology are followed in the analysis that henceforward follows.

1.3. Review Outlines:

Based on the drawn classification scheme the review addresses consequently topics of magnetically assisted G-L-S fluidized beds, among them:

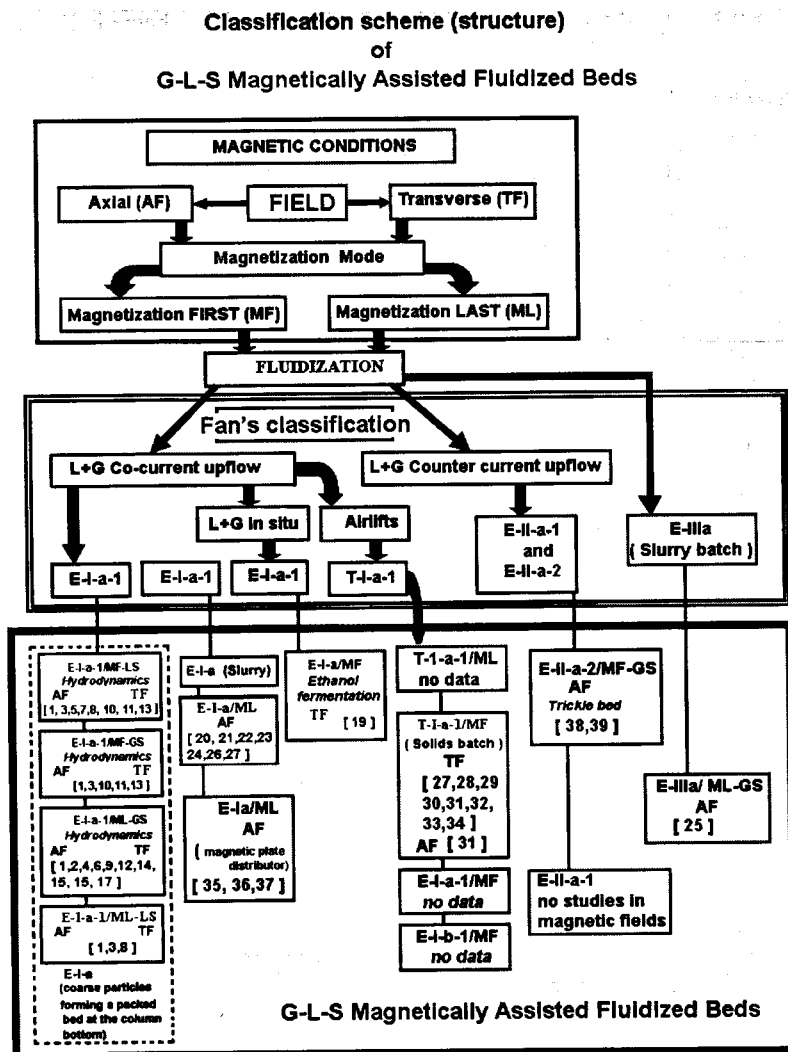


Fig. 2: Classification structure of magnetically assisted G-L-S fluidization.
Note : The origin was published by Hristov and Hadzisavvas (1997). An update was published by Hristov (2005a). The present scheme draws the nowadays situation and provide references published by the end of 2007 (see Table 1).

Table 1 - List of references relevant to the classification scheme in Fig. 2

Reference in Fig. 1	Reference in the present work	Fluidization System	Comments (modes)
1	Penchev et al. (1991)	BC-co-current	L-scan, G-scan FIRST, LAST
2	Hu & Wu (1987)	BC-co-current	G-scan , LAST
3	Hristov & Hadzisavvas (1997)	BC-co-current	L-scan, G-scan, FIRST
4	Hu & Wu (1987)	BC-co-current	LAST, G-scan
5	Kwauk et al. (1992)	BC-co-current	FIRST, L-Scan
6	Thompson & Worden (1997)	BC-co-current	G-scan LAST
7	Thompson & Worden (1991)	BC-co-current	FIRST, L-scan
8	Lu et al.	BC Slurry Co-current	FIRST, LAST, L-Scan
9	Sajc et al. (1994)	BC-co-current	LAST, G-Scan
10	Sajc et al. (1995)	BC-co-current	FIRST, L-Scan, G-Scan
11	Sajc et al. (1996)	BC-co-current	FIRST, L-Scan, G-Scan
12	Sonolika et al. (1999)	BC-co-current	G-scan , LAST
13	Pesic (1997)	BC-co-current	FIRST, L-Scan, G-Scan
14	Chen & Leu (1998a)	BC-co-current	G-scan , LAST
15	Chen & Leu (1998b)	BC-co-current	G-scan , LAST
16	Chen & Leu (2001)	BC-co-current	G-scan , LAST
17	Chen & Leu (2002)	BC-co-current	G-scan , LAST
18	Ivanova et al. (1996)	BC Liquid batch Gas in Situ	FIRST, L-scan
19	Meng et al. (2003)	BC Slurry, Co- current	LAST, L-scan
20	Li et al.(2006)	BC Slurry, Co- current	FIRST, L-Scan, G-scan
21	Mu & Min. (1996)	BC Slurry, Co- current	FIRST L-Scan

22	Mu et al. (1997)	BC Slurry, Co-current	FIRST, L-Scan
23	Mu et al. (2007)	BC Slurry, Co-current	LAST, L-scan
24	Sonolika et al. (1999)	BC Slurry Co-current	
25	Sonolika & Raja Rao (1996)	BC Slurry – L-batch	G-scan, LAST
26	Zong (2007)	BC Slurry, Co-current	FIRST, LAST, L-scan
27	Hristov (1998a)	Airlift –external loop	FIRST, G-scan
28	Al-Qodah & Al-Hassan (2000)	Airlift –external loop	
29	Al-Qodah (2000a)	Airlift –external loop	
30	Al-Qodah (2000b)	Airlift –external loop	
31	Raja Rao et al (1997)	Airlift -draft tube	
32	Hristov (2005a)	Airlift –external loop	FIRST, G-scan
33	Hristov (2005b)	Airlift –external loop	FIRST, G-scan
34	Al-Qodah & Lafi (2001)	Airlift –external loop	FIRST, G-scan
35	Ouyang et al. (1990)	BC Slurry with MDP	LAST, G-scan
36	Weng et al. (1990)	BC Slurry with MDP	LAST, G-scan
37	Weng et al. (1992)	BC Slurry with MDP	LAST, G-scan
38	Gui & Zhang (2006)	Counter-current Trickle bed	LAST, G-scan
39	Li et al. (2007)	Counter-current Trickle bed	FIRST,L-scan, G-scan

- **Overview of experimental conditions** among them: fluidization vessels, magnetic systems, solids, liquids and gas used, flow distributor design, measuring techniques and methodologies employed, basic operating modes addressing mainly the flow organization, etc.
- **Bubble Columns (BC) with coarse particles** allowing formation of fixed beds and operating with both Magnetization FIRST and LAST modes.
- **Slurry Bubble Columns (SBC) with fine particles** in both liquid batch and liquid up-flow modes.
- **Magnetically assisted airlifts**

2. OVERVIEW OF EXPERIMENTAL CONDITIONS AND ISSUES THEREOF

2.1. Fluidization units - columns and distributor designs

Generally the fluidization units used in studies of magnetically assisted G-L-S beds do not differ from those used in non-magnetic experiments. Practically all vessels, known so far, are cylindrical in shape and operate as simple bubble columns (Hu and Wu, 1987, 1988; Penchev et. al., 1991; Sajc et al, 1996; Chen and Leu, 2001, 2002), airlifts (Raja Rao and Sonolihar, 1996; Hristov, 1998a; Al-Qodah, 2000a; Hristov, 2005a), multistage G-L-S reactors (Wu et. al., 1988; Weng et al. 1992), trickle bed columns (Gui and Zhang, 2006; Li et al., 2007), etc.

Three-phase beds with upward gas-liquid flow impose special requirement to the distributor plates. It is well known that two-phase magnetically assisted beds require smooth flow conditions to create good conditions for bed stabilization (Siegel, 1987, Part 5). Figure 3 shows schematically some designs of gas-liquid distributing systems. The common approach in column design is to put the gas distributor above a distributor plate supporting the solids that is in general used to be fluidized by liquid only. In most of them the gas is introduced above the liquid input directly into the solids bulk. From the point of view of Magnetization LAST mode where no bed stabilization is required these are simple designs working quite well. However, in case of Magnetization FIRST mode another approach is needed, that is the G-L flow has to enter premixed at the bottom of the initially fixed bed. In this context, Hristov (1998, 2006a, b) and Hristov and

Hadzisavvas (1987) used a bottom bed of heavy particles that cannot be fluidized. The gas and liquid flow are introduced in a classical manner, that is the liquid at the bottom and the gas above it, but the supporting bed plays two roles: 1) produces almost homogeneous G-L flow, i.e. it works as a static mixer; 2) supports the magnetic bed under fluidization. More detailed description is given in Hristov (2005a) and 6. **Magnetically assisted airlifts**

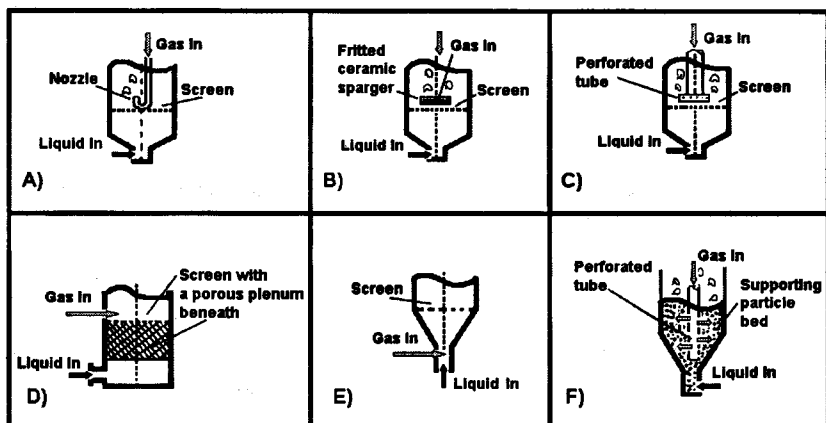


Fig. 3 Examples of gas-liquid distributor designs used in magnetically three-phase fluidization

Schematically

- a) Sada (1983)
- b) Sada (1983)
- c) Penchev et al. (1991)
- d) Hu and Wu (1987) – hydrodynamic experiments
- e) Hu and Wu (1987) phenol degradation
- f) Hristov (1998a, 2005a,b)

2.2. Magnetic Systems

Magnetic systems used to assist G-L-Fluidization do not differ so much from those employed in gas and liquid fluidization (Part 1 and Part 5). Besides, most of them are used for liquid fluidizations (see Part 5) as preliminary studies of bed behaviour. Figure 4 shows some typical configurations (*column-magnetic system*) used in G-L-S MFAF. Generally, axial magnetic systems based on short coils and solenoids dominate in the

studied performed. This a routine approach in MFAF with roots in the early studies on gas and liquid fluidized beds (see Part 1 and Part 5). Transverse fields are rare and based on parallel pole magnetic systems (Kwauk et al., 1992, Al-Qodah, 2000a) and saddle coils (Penchev et al., 1991; Hristov, 1998a, b; Hristov, 2005a, b). For laboratory level studies the axial magnetic systems have adequate sizes and may serve for variety of experiments. However, increase in fluidization unit scale toward pilot-plant and industrial level (Zong, 2007) results in huge systems with inefficiently used space. Further, G-L-S fluidization units such as bubble columns and airlifts are tall pieces of equipment that directly impose elevated magnetic systems. In this context, axial field based magnetic systems need large number of coils, while those employing transverse field have only one adequate solution known so far, which is *saddle coils*. In this context, iron-yoke based (parallel poles) electromagnets are by far inadequate and inapplicable due to enormous quantity of metal needed and low efficiency of the working volume with strong lateral field gradients. The correct magnetic system design is beyond the topic of the present review but some brief comments are given in the corresponding sections and in **5.3 Rationales of bubble column operation and design**. In general these problems will be discussed in Part 10 of the present review series.

2.3. Solids, liquids and gases

Three-phase systems (Solids, liquids and gases) used in experiments are quite simple and based mainly on water, air and iron particles. Further in this article detailed tables summarize experimental conditions of studies under review. In spite of that and for a glance at the systems reviewed some data are summarized in Table 2. Practically, iron, nickel and magnetite are the principle solids used. To some extent, compounds based on Ca-alginate (Sajc et al. 1995, 1996) doped with magnetite and magnetic cores covered by non-magnetic layers such as activated carbon and zeolite (Penchev et al., 1991; Al-Qodah, 2002a) are employed. In some studies (on bubble dynamics and gas holdup) surfactants similar to those in classical hydrodynamics experiments with bubble columns (Fan, 1989) are used.

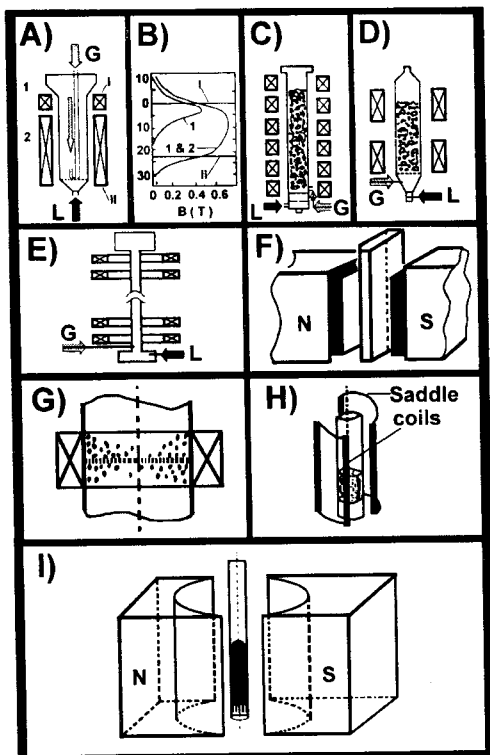


Fig. 4 Typical configurations *column- magnetic system*

- a) Sada et al, (1983): Two solenoids of different lengths. I- top section of the magnetic system; II- bottom section of the magnetic system; 1- top solenoid; 2- bottom solenoid
- b) Sada et al, (1983) - field distribution
- c) Hu and Wu (1987, 1988)- hydrodynamic experiments. Short coils based system.
- d) Hu and Wu (1987, 1988)-Helmholtz pair in phenol degradation experiments
- e) Kwauk et al (1992)- hydrodynamic experiments
- f) Kwauk et al (1992)- bubble size control , Iron-yoke based electromagnet with parallel poles
- g) Weng et al. (1992) – magnetic distributor plate (MDP)
- h) Saddles coils for transverse field generation (Penchev et al., 1991; Ivanova et al., 1996; Hristov and Hadzisavvas, 1997; Hristov, 2005a,b)
- i) Iron-yoke based electromagnet with circular poles.. Al-Qodah (all the studies of this author)

Table 2

Examples of experimental G-L-S systems used in various studies.

Reference	Type	G-L-S system
Penchev et al. (1991)	BC-co-current	Air + water + iron coated by active carbon
Chen & Leu (1998a)	BC-co-current	Air + water + nickel particles
Hristov & Hadzisavvas (1997)	BC-co-current	Air + water + ammonia catalyst
Hu & Wu (1987)	BC-co-current	Air + water + Polyacrylamide gel beads doped by magnetite
Kwauk et al. (1992)	BC-co-current	Air + water + Ca-alginate beads doped by magnetite
Thompson & Worden (1997)	BC-co-current	Air + water + Ca-alginate beads doped by magnetite
Lu et al.	Slurry-co-current	Air + water + iron powder
Sajc et al. (1994, 1995, 1996)	BC-co-current	Air + water + Ca-alginate beads doped by magnetite
Pesic (1997)	BC-co-current	Air + water + Ca-alginate beads doped by magnetite
Chen & Leu (1998a, b, 2001, 2002)	BC-co-current	Air + water + nickel particles
Ivanova et al. (1996)	BC Liquid batch -gas in Situ	Air + water/glucose + iron coated by active carbon and immobilized cells
Mu & Min. (1996, 1997)	BC Slurry, Co-current	Air + water + iron powder
Sonolika et al. (1999)	BC Slurry, Co-current	Air + water+ magnetite
Sonolika & Raja Rao (1996)	BC Slurry, Liquid-batch	Air + water+ magnetite
Hristov (1998a)	Airlift –external loop	Air + water + metallurgical dross
Al-Qodah & Al-Hassan (2000)	Airlift –external loop	Air + water + iron coated by active carbon
Al-Qodah (2000a, b)	Airlift –external loop	Air + water + iron coated by active carbon
Hristov (2005a, b)	Airlift –external loop	Air + water + metallurgical dross

Weng et al. (1990, 1992)	BC Slurry with MDP	Air + water + Ca-alginate beads doped by magnetite
Gui & Zhang (2006)	Counter-current Trickle bed	Air + water + iron
Li et al. (2007)	Counter-current Trickle bed	Air + sodium sulphite aqueous solution + CMC + SRNA-4 Nickel alloy catalyst

2.4. Operating modes

The classification scheme drawn at the beginning undoubtedly defines the operating modes either with respect to magnetization or the gas-liquid fluid flow organization. Expanded bed regimes (**E mode** in accordance with the classification of Fan) are the most attractive ones for magnetic field applications since basically in such beds there are enough magnetic bodies (particles) capable of interacting magnetically and affecting the surrounding gas-liquid flow (mainly the bubbles). Both co-current and counter-current flow modes are of interest as basic routes to perform gas-liquid contacts in mass transfer units. The transport regime (**T mode** - Fan, 1999) is performed by magnetically controlled airlifts with capability to control remotely not only the phase holdups in the risers but the liquid circulation velocity as well.

For the sake of clarity of analyses carried out in the present review two additional terms *Gas-Scan* and *Liquid-Scan* modes are introduced. They address better explanations of experimental conditions and methods of collecting experimental data. For instance, bubble columns with magnetization FIRST or LAST modes operate mainly with *Gas-Scan mode* with *bed pre-conditioning* through liquid flow variations since the gas-liquid mass transfer is the principle process performed in these units. In contrast, in bubble columns for bio-processes the *Liquid-Scan* mode is almost a standard approach to get data and establish suitable flow regimes since the most important process is the liquid-solids mass transfer. Additionally, airlifts of any kind work principally with the *Gas-scan* mode only due to inherent liquid flow dependences on gas flow in the riser. We hope these initial thoughts and definitions will help further analyses and enable a more organized presentation of the contemporary G-L-S magnetically assisted fluidization research.

2.5. Measuring techniques and methods – a brief review

Measurements help us to get data and interpret physical process of interest. With respect to G-L-S systems, in bubble columns and airlifts predominantly subjected to external magnetic fields, we need information about either the overall gas holdups or their local distributions (axial and radial). To some extent, considering mainly the mass transfer column performance, the interface surface area has to be measured since this parameter directly contributes to the volumetric mass transfer coefficient. The interface contact area is discussed in this article in cases with deficiency of data relevant to gas hold-up. In general, all measurements and techniques briefly reviewed here refer to hydrodynamic parameters of G-L-S flows but they form the background of mass transfer operations performed in those systems. For seek of simplicity of the discussion some techniques used will be briefly reviewed in view of measurements of basic process parameters.

2.5.1. Overall phase holdups.

Pressure gradient method. The pressure drop is strongly related to the individual phase holdup. In fluidized beds with low solids entrainment rates the average solids holdup can be expressed in terms of total mass of solids (W_s), solids density (ρ_s), column cross-section area (A_c) and effective bed height (h_b), namely (Fan, 1989)

$$\bar{\varepsilon}_S = 1 - \bar{\varepsilon} = \frac{W_s}{\rho_s A_c h_b} \quad (1)$$

where $\bar{\varepsilon}$ is the overall bed porosity.

A necessary condition of the phase volume fraction, or the individual phase holdup is

$$\varepsilon_G + \varepsilon_L + \varepsilon_S = 1 \quad (2)$$

where ε_G and ε_L are the gas and liquid holdups respectively.

On steady-state conditions with low or moderate liquid and gas flows, the total vertical (static) pressure gradient is

$$-\frac{dP}{dz} = (\varepsilon_s \rho_s + \varepsilon_L \rho_L + \varepsilon_G \rho_G) g \quad (3a)$$

with neglected wall friction and gas and liquid flow acceleration terms.

Since the contribution of the gas phase is generally negligible with respect to the other terms, Eq. (3a) can be simplified to

$$-\frac{dP}{dz} = (\varepsilon_S \rho_S + \varepsilon_L \rho_L) g \quad (3b)$$

Equation (3b) permits individual phase holdups to be evaluated. The solids holdup ε_S can be easily obtained from Eq. (1) with measured effective bed height h_b . The liquid holdup ε_L can be calculated from the total pressure drop gradient equation (3b). The overall gas holdup is calculated by difference based on Eq. (2). An advantage of the pressure gradient method is that the bed height can be determined from the intersection of the profiles of the bulk fluidized bed (G-L-S section) and the free board (G-L section above the bed) regions.

In magnetically assisted G-L-S beds the pressure gradient technique is adequately applicable to the free board regimes with Magnetization FIRST mode (Hristov and Hadzisavvas, 1997) and the entire bed with magnetization LAST mode (Hu and Wu, 1987; Penchev et al., 1991; Kwauk et al., 1992; Pesic, 1997; Weng et al., 1992). Recall, the magnetic field with magnetization FIRST mode creates a fixed bed that does not hold Eq. (3a), so correct application of the pressure gradient methods is possible with Magnetization LAST mode since the particles are suspended and Eq. (3a) is obeyed. The intersection of the profiles of the bulk fluidized (or stabilized) bed and the free board section was successfully applied by Hristov and Hadzisavvas (1997) with Magnetization FIRST mode and Al-Qodah and Al-Hassan (2000) for detection of the bed height.

Quick Valve technique is a technique allowing the overall phase holdups to be measured in a test section by simultaneously closing valves at the inlet and outlet of the fluidized bed (Fan, 1989). In the context of magnetically assisted beds this technique is most adequate to Magnetization LAST mode where all the phases are in motion. That is, the flow shutting off does not destroy any structure unlike the Magnetization FIRST mode where closing of gas or liquid flow might destroy the stabilized bed height if the system is not completely fluidized. In this context, Sajc et al., 1995, 1996; Al-Qodah and Al-Hassan, 2000; Sonolilar et al., 1999; Chen and Leu, 1998a,b and 2002; Thompson and Worden, 1997) successfully used the method and the results are commented further in the text.

Electrical resistivity method is applicable mainly to the local liquid holdup (see below) measurements requiring a quantitative description of the effective electric conductivity of the mixture and the volume fraction of both the continuous and dispersed phase. In magnetically assisted G-L-S fluidized beds this method is applied mainly to liquid and solids local holdup and to some extent to bubble size measurements.

Weight method based on Eq. (1) was applied to evaluate the solids phase holdup by Penchev et al., 1991; Al-Qodah and Al-Hassan (2000) and Pesic (1997) with Magnetization LAST mode; in homogenous fields the bed weight is not affected by magnetic body forces.

2.5.2. Local phase holdups

Two basic methods are used for evaluation of local holdups of the liquid and solid phase independently: 1) Measurement of the *electric impedance of conductivity double probe* as it was performed by Hu and Wu (1987), Al-Qodah and Al Hassan (2000), Sonolika et al.(1999), and Weng et al. (1992) for local gas-holdup measurements. 2) Optical fiber probe that unlike the electro conductivity method is not restricted to use with conductive liquids only. This technique was successfully used for local solids holdup in two studies: Hu and Wu (1987) and Weng et al. (1992).

Optical fiber probe method was successfully employed for local gas holdup data measured by two studies: Chen and Leu (2002), Thompson and Worden (1997). Besides, these reports provide adequate theoretical backgrounds and technical descriptions of the devices used in the experiments.

2.5.3. Bubble size and rise velocity

Electric conductivity method with two electrodes located at the column axis is commonly employed to measure the bubble size (vertical chord length) and bubble velocity. The method was successfully applied by Sajc et al. (1995, 1996) and Pesic (1997). Optical method based on bubble projection area by light beam and photocell matrix was developed by Kwauk (1992). All the results are collected and reviewed in **3.3 Bubbles in Magnetically Assisted Bubble Columns**

2.5.4. Flow regimes

Three flow regimes based on the bubble flow behaviour in three-phase

fluidized beds can be identified (Fan, 1989): the *coalesced bubble*, *dispersed bubble*, and the *slugging regime*. In the coalesced bubble regime, the bubbles tend to coalesce and both the bubble size and velocity become large. Coalesced bubbles rise near the column center with high velocity and stir the bed violently. This regime is typical of low liquid and high gas velocity. In the *dispersed bubble* regime there is no bubble coalescence, the bubbles are small and uniform in size. It is typical of high liquid flow velocities and low and intermediate gas velocities. According to Fan (1989) in small columns ($< 15\text{ cm}$) the gas bubbles can easily grow in size at high gas velocities and create slugs approaching the column diameter. The flow maps are usually plots $U_L = f(U_G)$. Particle properties also affect the dominating flow regime at given liquid and gas velocities. With low particle terminal velocities the increase in particle size adds to the transition velocity (Fan, 1989). To this end, remember that the magnetic flocculation enlarges the fluidized solids. At high pressure or with surfactants the bubbles can be very small ($< 1\text{ mm}$) yielding a dispersed flow regime. In this context, effects of particles greater than the bubble diameter become unimportant.

These classical comments have to be taken into account when reading articles on magnetically assisted G-L-S fluidized beds. The reader has to be imaginative to relate the bed descriptions to that of the non-magnetic three-phase fluidization. Since the field affects the solids phase behaviour creating large aggregates from small particles we should bear in mind the classical (non-magnetic) information concerning the solids size effect on bubble diameter and flow regimes. Nowadays the only work reporting flow maps and interpreting the regimes in the classical manner commented above is that of Chen and Leu (2002). All other studies on magnetically assisted G-L-S beds provide information about the solids behaviour rather than the gas-liquid flow regimes that hinders comparative analyses. To some extent, the present review does tentative links between both descriptions (see Magnetization LAST with Bubble Columns) but this calls for further systematic studies.

These briefs provide only the background required to understand the results commented further in the text and give some initial remarks on the adequacy of measuring techniques and methods employed. Additional comments are available in the corresponding sections of this review but readers interested in deep analyses and further implementation of presented (or novel) measuring techniques have to browse thoroughly books and journal articles.

3. BUBBLE COLUMNS

3.1. Magnetization FIRST Mode

3.1.1. Foreword concerning the G-L flow modes

Magnetization FIRST, as it was many times commented in the reviews, assumes fluid flow through an initially fixed (settled) and magnetized particle bed; i.e. the field is turned on before the fluidization. An attractive feature of two-phase systems (G-S and L-S) is the magnetically stabilized bed regime (MSB) with fixed structure (at constant fluid flow rate) and fluid-driven deformation (Part1, Part 5). With G-L-S magnetically assisted fluidization co-current two-phase flow passes upward through a particle bed that offers different expansion behaviours and regimes. In this context, with a column with co-current upward G-L flow, both the gas and the liquid flow are independent that in classical bubble columns creates different flow regimes. Commonly in laboratory experiments, that do not differ too much from their industrial counterparts the gas flow is the main operating stream yielding a variety of gas-liquid flow regimes (Fan, 1989): *dispersed bubble*, *coalesced bubble*, *churn-flow*, *slug flow*, etc. A particle bed might be fluidized either by liquid at fixed gas flow or by gas at fixed liquid velocity; the corresponding terms are (as it was mentioned at the beginning) *Liquid-Scan* mode and *Gas-Scan* mode respectively (coined by Hristov and Hadzisavvas, 1997). These terms allow easy to discriminate operating modes and resulting flow regimes either with Magnetization FIRST or Magnetization LAST modes. Hence, with these terms and the unified approach in hand we may begin with the oldest mode in MFAF, now under new and more complex circumstances that those at the beginning of this fluidization technique (see Part 1 and Part 5). Figure 5 shows schematically experimental set-up used with Magnetization FIRST mode. Additionally Table 3 summarizes data pertinent to studies of bubble columns performed with Magnetization FIRST mode

3.1.2. Phase Diagrams, Pressure drop and bed expansion

The regime map designed with the classical approach (Part1 and Part 5) means $U - H$ diagram, that with G-L-S magnetic beds has two versions, namely: $U_L = f(H)|_{U_G=const.}$ (*Liquid-Scan*) and $U_G = f(H)|_{U_L=const.}$ (*Gas-Scan*). The only available in literature phase diagrams of magnetically assisted beds (Fig. 6a, b) are developed with both *Gas-Scan* and *Liquid-Scan*

Table 3.
Experimental conditions in studies performed with magnetically assisted bubble columns- **FIRST magnetization mode**

Reference	Column	Magnetic field	Gas	Liquid	Solids	Operating mode	Measurements (Technique)	Problems studied
Penchev et al. (1991)	Plexiglas column 140 mm ID 1770 mm- in height	Transverse (DC) generated by saddle coils 200 mm ID 1400 mm in height $H_{\max} = 43 \text{ kA/m}$	Air	Water	Fe_3O_4 particles coated by non-magnetic materials	Co-current <i>Gas-Scan mode</i>	Pressure drop method	Phase diagrams, Gas holdup Bed expansion Minimum fluidization velocity
Sajc et al. (1995, 1996)	Plexiglas column 110 mm ID 500 mm in height	Axial (DC) generated by a long solenoid 330 mm high 120 mm ID $H_{\max} = 4 \text{ kA/m}$	Air	Water	Composite Ca-alginate/ Magnetite Spheres 1000 μm $\rho_s = 1930 \text{ kg/m}^3$	Co-current Liquid Scan mode Gas-Scan mode	Conductivity probe	Phase diagrams, Gas holdup Bed expansion Minimum fluidization velocity
Thompson and Worden (1991)	Glass column 50 mm ID 1400 mm in height	Axial (DC) Created by a solenoid 80 mm ID 600 mm in height	Air	Reverse osmosis water at 25°C	4mm Ca-alginate beads doped by magnetite - 50% (wt.) $\rho_s = 1700 \text{ kg/m}^3$	Co-current <i>Liquid-Scan mode (1991)</i> <i>Gas-Scan mode (1997)</i>	Quick closing valve Conductivity probe	(1991) Phase diagrams (1997) Overall gas holdup Overall liquid holdup Local holdup with respect to gas and liquid Solid phase behaviour

Table 3 (continued)

Hristov and Hadziavvas (1997)	Plexiglas Column 100 mm ID 2000 mm in height	Transverse (DC) generated by saddle coils 200 mm ID 1400 mm in height $H_{max} = 43 \text{ kA/m}$	Air	Water	Ammonia catalyst H. Topsoe KM-1 315 – 400 μm 800 – 1000 μm $\rho_s = 5100 \text{ kg/m}^3$	Co-current Liquid Scan mode Gas-Scan mode	Pressure drop	Phase diagrams, Gas holdup Bed expansion Minimum fluidization velocity
Pesic (1997)						Co-current Liquid Scan mode Gas-Scan mode	Conductivity probe	Bed expansion Minimum fluidization velocity Pressure drop
Sonolokar et al. (1999)	Glass column 55 mm ID 750 mm height	Axial (DC) generated by a long solenoid, 105 mm ID in $H_{max} = 500 \text{ Oe}$	Air	Water At approx. 30°C	Magnetite Fractions: 357 μm and 645 μm	Co-current Gas-Scan mode	Quick closing valve	Overall Gas hold-up Effect of magnetization mode

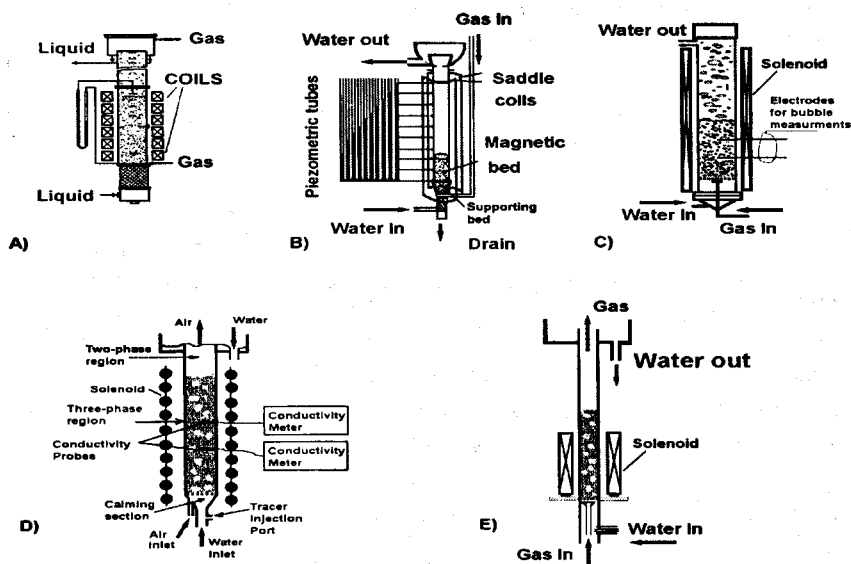


Fig. 5 Experimental set-up used with Magnetization FIRST mode

- a) Hu and Wu (1987, 1988)
- b) Penchev et al. (1991); Hristov and Hadzisavvas (1997)
- c) Sajc et al. (1995, 1996)
- d) Thompson and Worden (1991, 1997)
- e) Sonolika et al. (1999)

and fields with different orientations. Sajc et al. (1995, 1996) employing **Liquid-Scan** approach defines three principle regimes of an axial field assisted bed; i.e. *packed bed*, *Magnetically Stabilized Fluidized Bed (MSFB)* and *partially stabilized bed (PS MSFB)*. The MSFB regime is the *stabilized regime* with fixed structure while **PS MSFB** is, in fact, already *fluidized bed with chains* and small (negligible) bubbles. Similarly, but with transverse fields and **Gas-Scan** method, and employing the terminology of Kwauk et al. (1992), Hristov and Hadzisavvas (1987) termed the regimes **MSB** and **S-regime (Smooth fluidization)** respectively. With increase in gas velocity, the **S-regime** passes into **T-regime (Turbulent fluidization)** with large bubbles affecting the particle chains that are actually *random motion* and *chain regime* respectively. For clarity of explanation, hereafter we will use **Random motion** (particulate fluidization) *regime*, **Chain regime**, **Stabilized (MSB) regime** and **fixed bed** as terms.

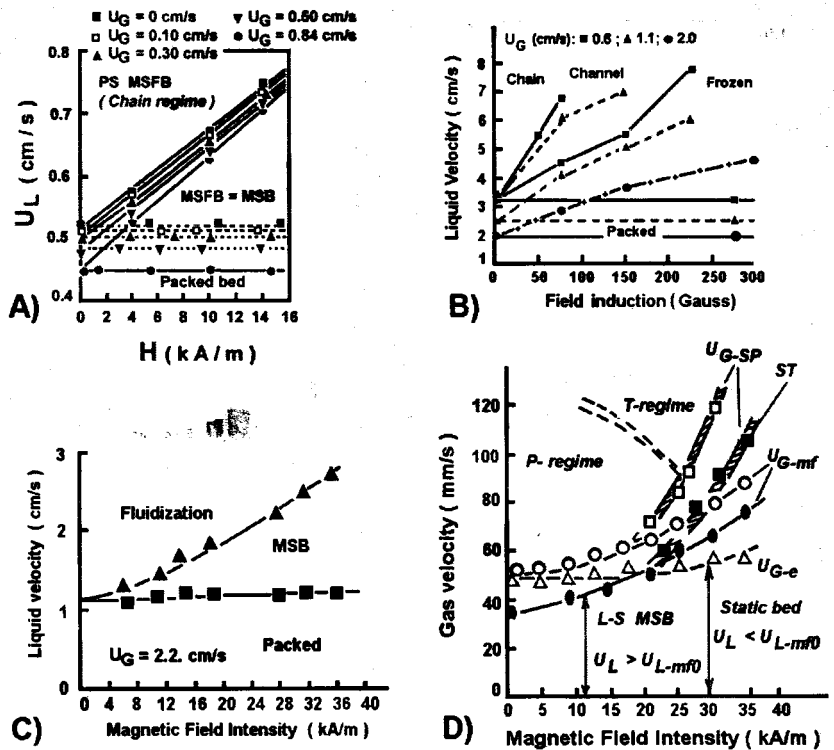


Fig. 6 Phase diagrams with Magnetization FIRST mode

- axial field assisted bed. *Liquid -Scan* mode. After Sajc et al. (1996).
- axial field assisted bed. *Liquid -Scan* mode. Thompson and Worden. (1991).

Note: 1 Gauss is a field induction corresponding to field intensity of about $1\text{Oe} \approx 79.56\text{ A/m}$ in air (this is taken into account in the calculations performed in the present work).

- Transverse Field assisted bed. *Liquid-Scan* mode. After Penchev et al. (1991)
- Transverse Field assisted bed. *Gas-Scan mode*. After Hristov and Hadzisavvas (1997).

Detailed information about the experimental conditions is available in Table 3.

The phase diagrams in Fig.6 clearly reveal that by varying either the gas flow (*Gas-Scan* - Fig. 6d) or the liquid velocity (*Liquid-Scan* - Fig. 6a,b) the critical points such as *minimum stabilization* and *minimum fluidization* depend on the bed *pre-fluidization* history. The latter simply implies that the bed could pass from *initial* into *stabilized bed* (MSB) either by gas or liquid flow that does not fluidize the bed but creates the *pre-fluidization conditions*. In the experiments of Sajc et al. (1996) the preliminary transition from a fixed bed into MSB state is caused by the gas flow, while the true fluidization is performed by the liquid. These transitions are clearly seen as almost parallel lines (see Fig. 6a, b) depending on the flow creating the bed *pre-fluidization conditioning*, i.e. the gas flow. Bear in mind, these experiments (Sajc, 1995, 1996, Pesic, 1997, Thompson and Worden, 1991) were oriented to biotechnological applications where the liquid is the principle flow, while the gas supplies only oxygen and stirs the suspension by bubbling. If the gas velocity with *Liquid-Scan* mode is not enough to shift the bed from *fixed* into *stabilized* one, the demarcation zone is represented by a single line (Fig. 6c) as in the experiments of Penchev et al. (1991).

In contrast, the *Gas-Scan* as the common operating mode in bubble columns (Fan, 1989; Krishna et al. 1999) was employed in the experiments of Hristov and Hadzisavvas (1997), Sonolika et al. (1999) and Al-Qodah (2000). Figure 6d reveals how the pre-conditioning shifts the demarcation lines between the regimes. Owing to the transfer field orientation (Hristov and Hadzisavvas, 1997) these lines are not parallel as those of axially assisted beds, but the gross physical behaviour is almost the same.

Transition in bed behaviour with increase in the principle fluidizing flow (*Gas-Scan* or *Liquid-Scan* mode) is accompanied by loss of pressure and bed expansion that are interrelated. With *Liquid-Scan* mode and axial fields the pressure drop curves (Fig.7a, b) look like those of two-phase (G-S or L-S) beds (Part 1 and Part 5). However, at fixed field intensity increase in gas velocity (pre-conditioning) reduces the pressure drop (Fig.7b) and yields deeper beds (Fig.8a). This is an expected result since bed expansion and changes of its internal structure depend on the total energy dissipated by the flow. Similarly, increase in interparticle forces as a result of increased field intensity, augments the pressure losses (see Fig.7a) and keeps the beds shorter (Fig.8b).

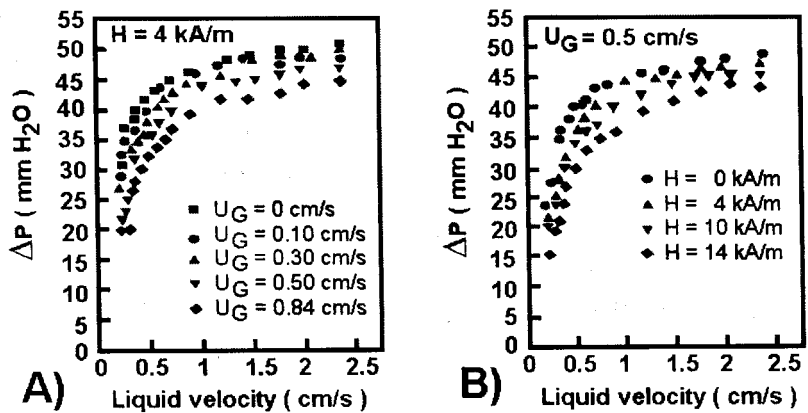


Fig. 7: Pressure drop across G-L-S magnetically assisted beds. Magnetization FIRST.

- Pressure drop with *Liquid-Scan* mode at fixed field intensity and $U_G = \text{var.}$. After Sajc et al. (1991) and Pesic (1997).
- Pressure drop with *Liquid-Scan* mode at different field intensities and $U_G = \text{const.}$. After Sajc et al. (1991) and Pesic (1997).

These bed expansion experiments, performed mainly in axial fields (Sajc et al., 1995, 1996; Pesic, 1997) and giving information about the regime influence on bed height are missing that hinders further analysis. In a graph of Hristov and Hadzisavvas (1997) obtained in a transverse field the required information is presented by dotted demarcation lines (see Fig.8c) denoting rapid bed expansion in MSB pre-conditioned either by liquid or gas. In fluidized states beyond the minimum fluidization points the bed depths approach plateaus. Bed height data are the primary source to calculate the overall bed porosity and phase holdup commented next and can be obtained either visually or by specific points of pressure profiles (Fig. 8d).

3.1.3. Bed porosity and Phase holdups

The porosity of expanding MSB provides information about the free volume available for the gas-liquid flow through it (see Fig. 9 and Fig. 10). In this context, the plots in Fig. 9 reveal that increase in field intensity reduce the slopes of the porosity profiles no matter what fluid-driven deformation (*Gas-Scan* or *Liquid-Scan* mode) creates the MSB regime. This is a general

tendency, already commented in case of liquid fluidized beds (Part 5), that allows to apply more uniform approach to data treatment as it is demonstrated further in this review. To this end, Pesic (1997) tried to apply the Richardson-Zaki scaling equation (RZE) to $\varepsilon = f(U_L)|_{U_G=const.}$ (*Liquid-Scan* mode) but the result was disappointing. The problem arising from these circumstances directly addresses scaling principles and velocity scales in RZE that are by far different from those in two-phase beds (gas or liquid fluidized). These briefs draw new ideas and need deeper analysis that is beyond the scope of the present section.

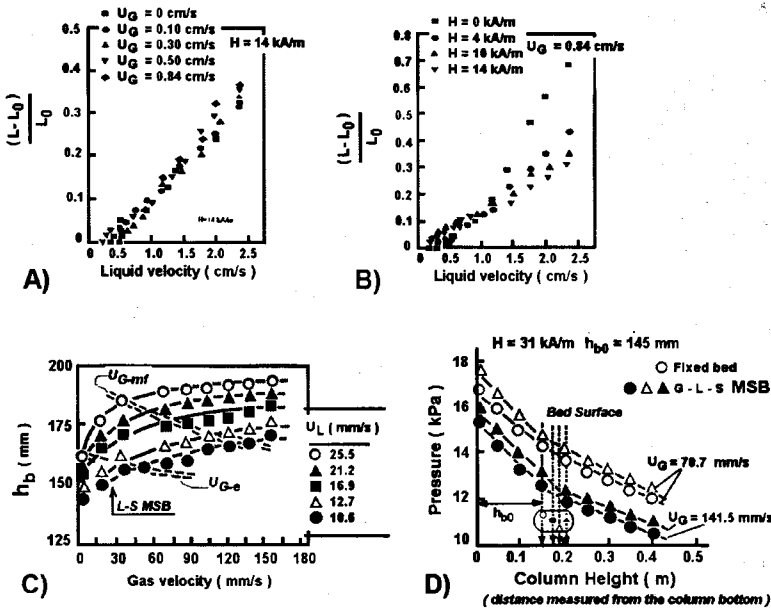


Fig. 8: Bed expansion of G-L-S magnetically assisted beds. Magnetization FIRST.

- Bed height with *Liquid-Scan* mode at fixed field intensity and $U_G = var.$ After Sajc et al. (1991).
- Bed height with *Liquid-Scan* mode at different field intensities and $U_G = const.$ After Sajc et al. (1991).
- Bed height with *Gas-Scan* mode and $U_L = var.$ From Hristov and Hadzisavvas (1997).
- Bed height detection with *Gas-Scan* mode and $U_L = var.$ via pressure drop profiles along the column. From Hristov and Hadzisavvas (1997).

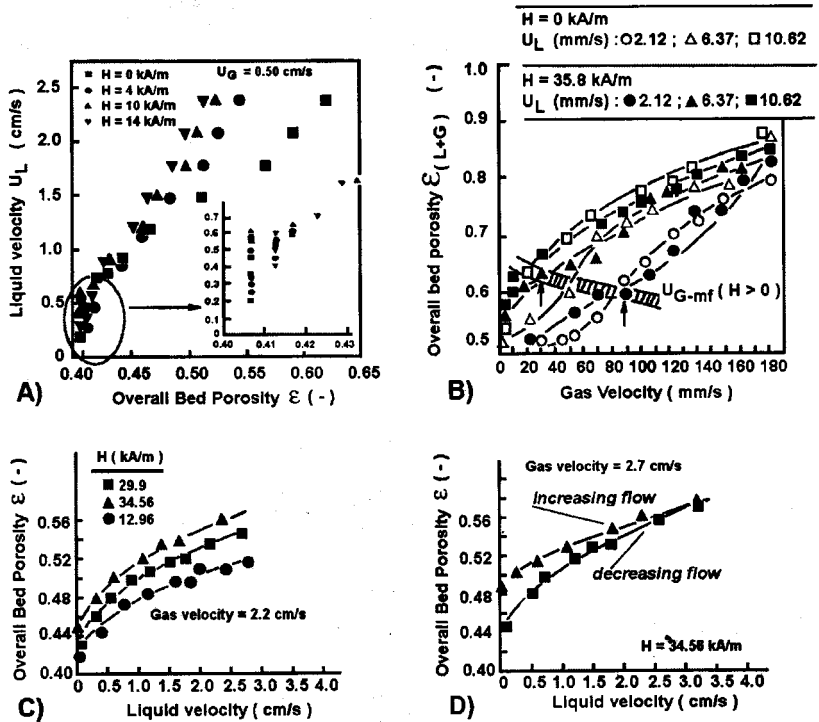


Fig. 9: Bed porosity- fluid flow profiles of magnetically assisted G-L-S beds- Magn. FIRST

- Overall porosity evolution with variations in liquid velocity (**Liquid-Scan**) at different field intensities. Axial field. From Pesic (1997).
- Overall (gas and liquid) porosity of magnetically assisted G-L-S beds. Transverse field and **Gas-Scan** mode. From Hristov and Hadzisavvas (1997).
- Overall (gas and liquid) porosity of magnetically assisted G-L-S beds. Transverse field and **Liquid Scan** mode. From Penchev et al. (1991).
- Bed porosity (overall) hysteresis with Liquid-Scan mode and transverse field stabilization. From Penchev et al. (1991).

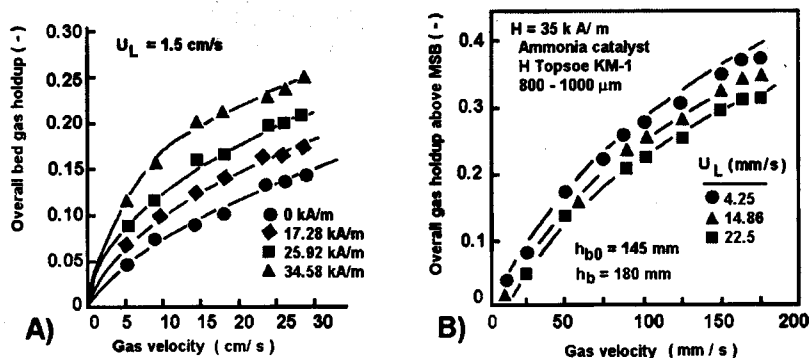


Fig. 10: Gas and Liquid holdups in magnetically assisted G-L-S beds. Magn. FIRST

- Gas holdup of magnetically assisted G-L-S beds in MSB regime. Transverse field and *Gas Scan* mode. From Penchev et al. (1991).
- Gas holdup of the two-phase (G-L) section above the magnetically stabilized top surface. From Hristov and Hadzisavvas (1997).

3.1.4. Minimum Fluidization

The minimum fluidization point in G-L-S beds is always considered with respect to the gas velocity effect on the minimum liquid fluidization velocity (Fan, 1989). This implies that this approach assumes the *Liquid-Scan* mode in accordance with the present terminology and the common plots of descending $U_{L-mf} = f(U_G)$ curves (see Fig. 11a). With magnetically assisted G-L-S beds the question is: how the field intensity affects the $U_{L-mf} = f(U_G)$ curves? The only published curves are shown in Fig. 11b,c both of them obtained in transverse fields (Penchev et al., 1991; Hristov and Hadzisavvas, 1997) but with different flow modes. Generally, increase in field intensity shifts up the *minimum liquid fluidization velocity* (Fig. 11b) albeit the gas velocity might increase; that is the main effect of augmented interparticle forces. The second chart (Fig. 11c) explains just the opposite *Gas-Scan* mode with *pre-fluidization conditioning*. The bottom half of the chart is the bed phase diagram in case of L-S fluidization only thus explaining the upper $U_{G-mf} = f(U_L)$ plots by simple elucidation of the bed *pre-fluidization history*.

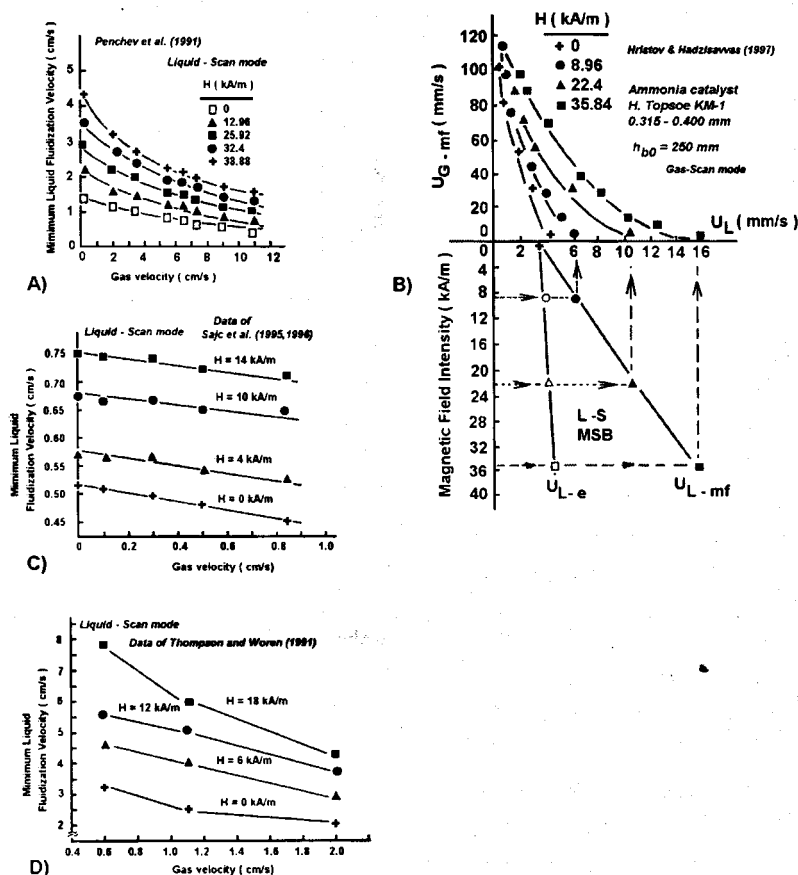


Fig. 11: Minimum fluidization velocities in Magn. FIRST assisted G-L-S beds with two different flow modes and field intensity effects.

- Minimum liquid fluidization velocity (**Liquid-Scan**) as a function of the gas superficial velocity at various field intensities. Transverse field. From Penchev et al. (1991).
- Minimum liquid fluidization velocity (**Gas-Scan**) as function of the gas superficial velocity at various field intensities. Transverse field From Hristov and Hadzisavvas. (1997). The bottom half of the figure is the L-S phase diagram elucidating the bed *pre-fluidization* history
- Minimum liquid fluidization velocity (**Liquid-Scan**) as a function of the gas superficial velocity at various field intensities. Reconstructed data of Sajc et al. (1995,1995) through digitalization of the phase diagram in Fig. 6a

- d) Minimum liquid fluidization velocity (**Liquid-Scan**) as a function of the gas superficial velocity at various field intensities. Reconstructed data of Thompson and Worden (1991) through digitalization of the phase diagram in Fig.6b and Figs. 4a, b, c in the original work.

The minimum fluidization point can be reached in two ways: 1) Low liquid velocity $U < U_L$ ($H = 0; U_G = 0$) that is not enough to deform the bed and to create MSB. The bed is deformed by the gas flow only and it consequently passes from a fixed bed into MSB that finally reaches its breakdown at U_{G-mf} . The plots in Fig. 11b reveal that the $U_{G-mf} = f(U_L)$ curves are steeper if the bed is not preliminarily in MSB created by the liquid flow. 2) High liquid velocity ($U_L > U_{L-mf0}$) enough to shift the bed from fixed into MSB regime yields smooth variations in U_{G-mf} with further increase in U_L since the principle work towards the fluidization is already done by the liquid flow. Hristov and Hadzisavvas (1997) approximated the $U_{G-mf} = f(U_L)$ plots with **Gas-Scan mode** as

$$\frac{U_{G-mf}}{U_{G-mf0}} = \exp \left[(-3.14 \pm 0.32) \left(\frac{U_L}{U_{L-mf0}} \right) + 0.041H \right] \quad (4)$$

where the field intensity H is in (kA/m) and with accuracy of 9.8%.

This relationship approximates the plots obtained in zero fields too. It is by far from generalization but this has been the only correlation published so far. The contribution of the magnetic term to the exponent of (4) is based on the fact that the plots $U_{G-mf} = f(U_L)$ at different field intensities are almost parallel and move up with increase in H . The advantage of (4) is its dimensionless form (the magnetic term is not dimensionless-see comments below) allowing the velocity scales U_{G-mf0} and U_{L-mf0} to be determined separately by two-phase fluidization experiments or relevant equations. The latter implies that bearing in mind the general forms of $U_{G-mf} = f(U_L)$ at $H = 0$ and $U_{G-mf} = f(H)$ at $U_L = 0$ commonly expressed as

$$\frac{U_{G-mf}}{U_{G-mf0}} = \exp \left(-a_L \frac{U_{L-mf}}{U_{L-mf0}} \right)_{H=0} \quad \text{and} \quad \frac{U_{G-mf}}{U_{G-mf0}} = \exp \left(b_H \frac{U_{L-mf}}{U_{L-mf0}} \right)_{U_L=0} \quad (5a,b)$$

with intercepts 1 at $H = 0$ and $U_L = 0$ since the minimum fluidization point is unaffected by these controlling parameters. Hence, combining (5a,b) we read

$$\frac{U_{G-mf}}{U_{G-mf0}} = \exp\left(-a_L \frac{U_{L-mf}}{U_{L-mf0}}\right) \exp(b_H H) \Rightarrow \exp\left(-a_L \frac{U_{L-mf}}{U_{L-mf0}} + b_H H\right) \quad (6a,b)$$

that is in fact, the approximation (4).

In order to give more data to the readers the plots of Penchev et al. (1991) shown in Fig.11a were approximated in the present work in a similar way that yielded for

$$\frac{U_{L-mf}}{U_{L-mf0}} = \exp\left(-a_G \frac{U_{G-mf}}{U_{G-mf0}} + b_G H\right) \Rightarrow \exp\left(-0.106 \frac{U_{G-mf}}{U_{G-mf0}} + 0.0269 H\right) \quad (7a,b)$$

with field intensity H in [kA/m] accuracy of about 6% ..

Similarly, the phase diagram of Sajc et al. (1995, 1996) was transformed into $U_{L-mf} = f(U_G) | H = \text{const.}$ plots in Fig.11c. A digitalization by *Scan It* (freeware) and non-linear data regression processing (*Origin, 6.0*) yielded a correlation, namely (*Liquid-Scan Mode*)

$$\frac{U_{L-mf}}{U_{L-mf0}} = \exp\left(-a_G \frac{U_{G-mf}}{U_{G-mf0}} + b_G H\right) \Rightarrow \exp\left(-0.524 \frac{U_{G-mf}}{U_{G-mf0}} + 0.0263 H\right) \quad (8)$$

with field intensity H in [kA/m] and with accuracy of 7 %. The value of U_{G-mf0} was calculated by equation (21)-p. 69 of Kunii and Levenspiel (1989) employing basic particle data provided in the original works of Sajc et al. (1995, 1996) since such particle characteristics are completely missing in the texts. In this context, the data of Thompson and Worden (1991) do not allow such regression analysis due to insufficient number of points (see Fig. 11d).

The expressions (6a) and (7a) contain dimensional terms representing the field intensity contribution. It is hard to express the field intensity effect in a dimensionless form, i.e. H/Ms , that makes the pre-factors b_H dimensionless

too, since commonly with composite materials like those used in the referred experiments data about the magnetic properties of particle materials (especially *Ms*) are completely missing. These are straightforward attempts to correlate experimental data without any implementation of physical meaning and model assumptions. Nevertheless they give the general trends and the main contribution of the field applied.

3.2. Magnetization LAST Mode

Magnetization LAST mode applied to developed G-L-S fluidized system has the only task to control the gas bubble behaviour through remote action on magnetizable solids. This results in particle flocculation into chains, intensive bubble break-up and control of both the gas holdup and interfacial area. In view of the fact that the system is controlled by three macroscopic variables, i.e. *Gas velocity*, *Liquid velocity* and *Field intensity* we have a variety of cases that have to be investigated. Commonly, the *Gas-Scan* mode is used since it is well known from the non-magnetic bubble columns (Fan, 1989) that the gas velocity controls the gas holdup. The latter could be controlled by liquid velocity (*Liquid-Scan*) and surface tension to some extent. These comments will be illustrated by results reviewed and analyzed below. Table 4 summarizes information about experiments performed so far with Magnetization FIRST mode. To this end, mainly axial fields are used and transverse counterpart to some extent. This characteristic feature imposed by preferred magnetic system design and process conditions will be commented in the course of the analysis of experimental results.

3.2.1. Phase diagrams and Bed collapse curves

Phase diagrams are basic graphical presentations of the complex phenomena occurring in magnetically assisted bubble column. The first work published by Hu and Wu (1987, 1988), performed in an axial field, reports three principle states: *particulate chains* and *condensed* but without a flow map. Phase diagrams corresponding to these definitions were published later, in a transverse field (Fig.12a) by Penchev et al., (1991). Further, Thompson and Worden (1997) and Chen and Leu (2001) published extensive studies on common problems but with two distinct phase diagrams commented next.

Thompson and Worden (1997) reported diagrams (Fig.12b, c) with field intensity as an independent variable and liquid velocity as a parameter. In the

Table 4
Experimental conditions in studies performed with magnetically assisted bubble columns- LAST magnetization mode

Reference	Column	Magnetic field	Gas	Liquid	Solids	Operating mode	Measurements (Technique)	Problems studied
Hu and Wu (1987)	Plexiglas Column 92 mm ID 2700 mm height	Axial (DC) generated by 6 short coils $B_{\max} = 42 \text{ mT}$	Air	Water	Composite beads of Polyacrylamide gel with 50% (wt) Mn-Zn ferrite. Cubic in shape with d_p (equivalent) = 3.6 mm $\rho_s = 1450 \text{ kg/m}^3$	Co-current Gas-Scan mode	Pressure drop method	Overall gas holdup Radial holdup profiles with respect to gas and solids
Penchev et al. (1991)	Plexiglas Column 140 mm ID 1770 mm in height	Transverse (DC) generated by saddle coils 200 mm ID 1400 mm in height $H_{\max} = 43 \text{ kA/m}$	Air	Water	Fe_3O_4 particles coated by non-magnetic materials	Co-current Gas-Scan mode	Pressure drop method	Phase diagrams, Gas holdup
Thompson and Worden (1991) (1997)	Glass column 50 mm ID 1400 mm in height	Axial (DC) Created by a solenoid 80 mm ID 600 mm in height	Air	Reverse osmosis water at 25°C	4 mm Ca-alginate beads doped by magnetite - 50% (wt.) $\rho_s = 1700 \text{ kg/m}^3$	Co-current Liquid-Scan mode (1991) Gas-Scan mode (1997)	Quick closing valve Conductivity probe	(1991) Phase diagrams (1997) Overall gas holdup Overall liquid holdup Local holdup with respect to gas and liquid Solid phase behaviour
Sonolokar et al. (1999)	Glass column 55 mm ID 750 mm in height	Axial (DC) generated by a long solenoid, 105 mm ID $H_{\max} = 500 \text{ Oe}$	Air	Water at approx. 30°C	Magnetite Fractions: 357 μm and 645 μm	Co-current Gas-Scan mode	Quick closing valve	Overall Gas hold-up Effect of magnetization mode
Chen and Leu (1998a) (1998b) (2001) (2002)	Plexiglas (1998a,b; 2001) 50 mm ID 500 mm in height (2002) 80 mm ID 500 mm in height	Axial (DC) Helmholtz pair 160 mm ID $H_{\max} = 24 \text{ kA/m}$	Air	Water	Spherically shaped Nickel powder d_p (av): 194 μm ; $\rho_s = 8900 \text{ kg/m}^3$ Iron shots (190 – 930 μm) Initial bed height = 70 mm		(2001) Quick closing valve (2002) Quick closing valve Optical probe	Flow maps (gas-liquid) Overall Gas hold-up Overall liquid holdup Local holdup with respect to gas and liquid

context of magnetic phase behaviour six flow regimes were reported (see Inset in Fig.12) that match in general the three principal states mentioned above. In contrast, Chen and Leu (2001, 2002) drew a map in a classical manner (Fan, 1989), i.e. $U_L - U_G$ diagrams but with field intensity as a controlling parameter affecting the regime shift. These maps refer to the gas phase regimes rather than the solids behaviour albeit they are interrelated. For people experienced in magnetic fluidization the map of Penchev et al. (1991) and those of Thompson and Worden (1997) are familiar but to those skilled in classical bubble column hydrodynamics the charts of Chen and Leu (2001, 2002) give more valuable information.

With these maps in hand we may analyze the gross bed performance and attempt the gas and the solids behaviours to be interrelated. The maps of Chen and Leu (2001, 2002) reveal that at low gas flow and moderate liquid velocities, when *dispersed bubbling* exists, increase in field intensity does not change the bubble flow behaviour but the lower boundary defined by the liquid could be decreased. Similarly, the boundary between *dispersed* and *coalesced* regime goes down to lower liquid velocities with increase in field intensity, while at the same time the upper gas flow boundary shifts to higher velocities. These boundaries depend simultaneously on solids size and field intensity (Fig.13a, b, c, d) that implies increase in aggregate size, intensive bubble break-up and suppressed coalescence as the field strength increases. In this context, the boundary between the *dispersed bubble* and *coalesced bubble* regimes was related by Chen and Leu (2002) to a critical field intensity H_c depending on the particle size (see Fig.14), namely

$$H_c = 193d_p^{-0.487} \quad (9)$$

This is an empirical dimensional equation which is by far from generalizations, but it teaches that decrease in particle diameter needs higher fields to create enough strong aggregates and *vice versa*. The fact is nice, but needs further investigations with deep physics and more data allowing reliable dimensionless correlations.

In general, the map of Chen and Leu (2001) refer to increase in bubble break-up due to increase in aggregate size, i.e. due to increase in field intensity. This, in fact, shifts the boundary of the undesirable slug flow regime toward higher gas velocities (with about 200 %) by increasing the field intensity up to 23 kA/m . These are expected results if the physics of the interaction between phases in the bed is known since these maps are only

macroscopic descriptions of microscopic phenomena taking place in the G-L-S system.

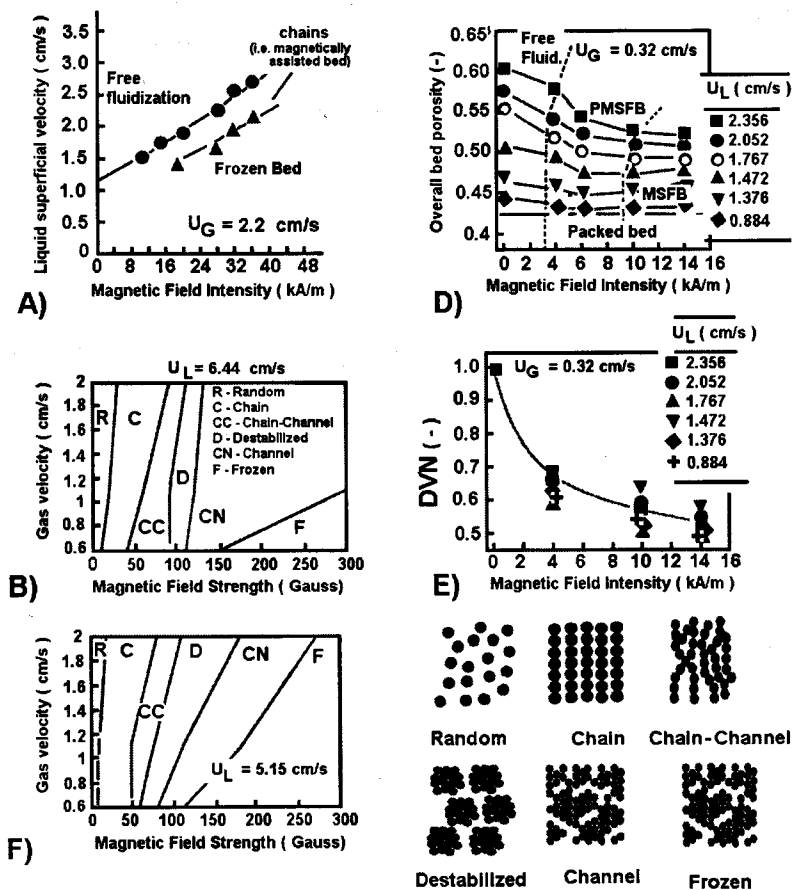


Fig. 12: Phase diagrams and bed collapse plots with Magnetization LAST modes addressing solid phase behaviour

- Phase diagram of Penchev et al. (1991).
- and c) Maps of Thompson and Worden (1997).
- Bed collapse curves of Pesic (1997) with denoted regimes pertinent to the solid phase behaviour.
- $DVN = f(H)$ approximation of experimental bed collapse curves of Pesic (1997).

Inset : Solid phase behaviour after Thompson and Worden (1997) – schematically .

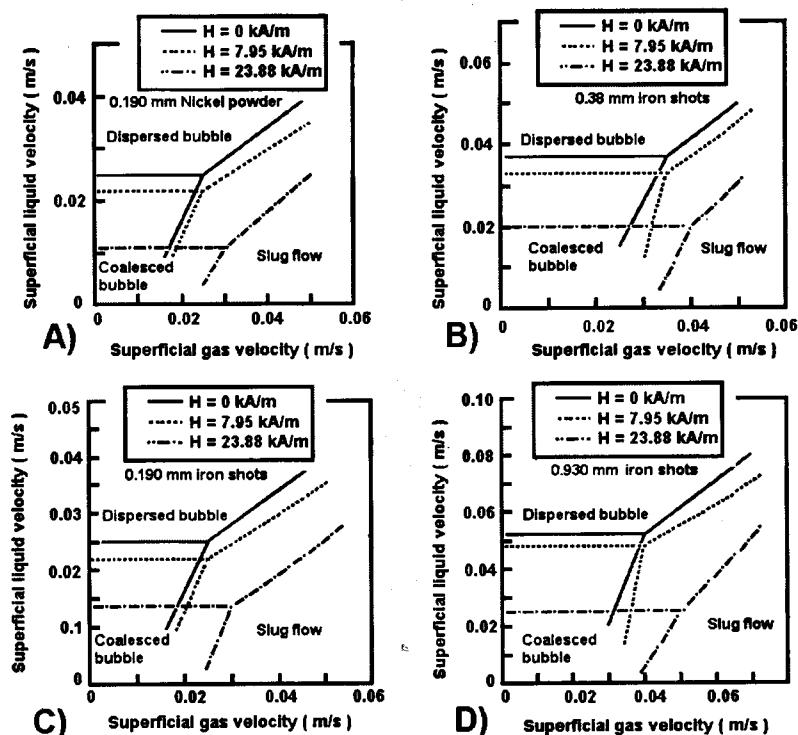


Fig. 13. Phase diagrams with Magnetization LAST modes addressing gas-liquid flow modes. After Chen and Leu (2001, 2003).

There is no direct link between the phase diagrams of Chen and Leu (2001, 2002) and those of Thompson and Worden (1997) since they describe gross behaviours of different phases. However, considering the above comments we might suggest that *random (particulate)* and *chain* regimes match *dispersed* and *coalesced bubble* ones. Increase in field intensity augments the aggregates and suppresses the slug formation that is *chain-channel* and *destabilized* regimes correspond to the new zone between the old and new margins of the slug flow moving to right in the map of Chen and Leu (2001). These are only suggestions resulting from comparison of published results but direct physical observations from this standpoint are not reported yet, so the problem remains open and calls for future detailed studies.

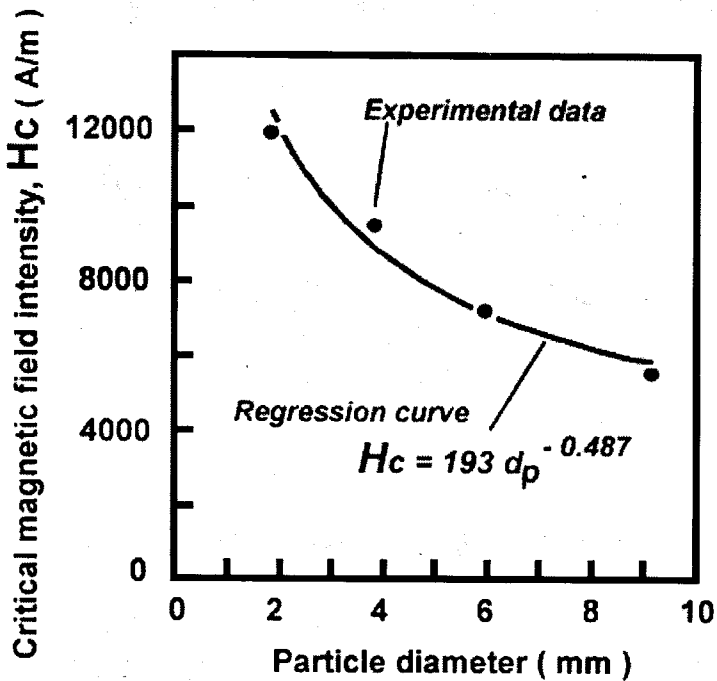


Fig. 14. Particle diameter effect on the critical field intensity corresponding to the boundary between the *dispersed bubble* and *coalesced bubble* regimes. After Chen and Leu (2002).

Bed collapse curves typical of G-S and L-S beds (see Part 1 and Part 5) are practically not published yet in accessible literature. This seems strange, but the published works deal mainly with gas holdup, interfacial area and mass transfer and do not care about the hydrodynamic backgrounds of processes performed. We have already commented such approaches in the previous review (Part 5) that generally hinders data analysis. Fortunately, a thorough search of articles on MFAF yielded a bed collapse plot reported by Pesic (1997) - see Fig.12d. Nowadays these are unique graphical results on G-L-S bed collapse with magnetization **FIRST** and **Liquid-Scan** mode. Pesic (1997) approximated the bed profiles similarly to the S-shaped curves of Kwauk et al. (1992) (see also Part 5) as a dimensionless voidage number (DVN) defined as

$$\frac{\varepsilon^H - \varepsilon_{mf}^H}{\varepsilon^0 - \varepsilon_{mf}^H} = \exp\left(-\frac{H}{H_0}\right)^S \quad (10a)$$

where H_0 is a characteristic field intensity (see Part 5 for details).

The form of DVN developed by Pesic (1997) is

$$DVN = \frac{\varepsilon^H - \varepsilon_{mf}^H}{\varepsilon^0 - \varepsilon_{mf}^H} = \exp(-aH)^S \quad (10b)$$

The voidage ε_{mf}^H in the definition of DVN corresponds to bed voidage at minimum fluidization condition and a given field intensity, ε^0 is the voidage of the non-magnetized three-phase bed, while ε^H is the actual bed voidage. The validity of this approximation is illustrated in Fig.12c. Pesic (1997) reports slight increase in the pre-factor a with decrease in the superficial gas velocity. To this end, missing of experimental data hinders further analyses and calls for studies in this direction.

3.2.2. Phase holdups - Overall Gas and Liquid holdups

Hu and Wu (1987, 1988) employed the simplest pressure drop method to estimate the overall gas holdup (see Fig. 15a) and modelled empirical relationship by the equation

$$\bar{\varepsilon}_G = 0.04U_G^{0.507}U_L^{0.01} \exp(0.00208) \quad (11)$$

with average relative error of 7.33% .

Similarly, employing the two principle methods, i.e. the valve technique and the optical probe method, Chen and Leu (2001, 2002) show that the overall gas holdup depends on three principle macroscopic process variables, namely:

- **Gas velocity** (with a little effect of the liquid flow) as it shown in Fig.15b,c
- **Magnetic field intensity** that yields almost linear increase in gas holdup (Fig. 15b) thus confirming the results of Hu and Wu (1987, 1988). In coalesced bubble regime the overall gas holdup is relatively independent of the field intensity since the bubble break-up is not significant.

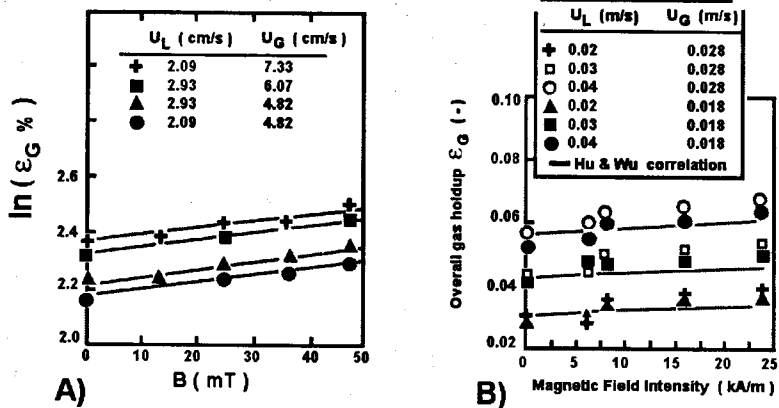


Fig. 15: Overall gas holdups in magnetically assisted co-current bubble columns Plot of Hu and Wu (1987) showing almost exponential effect of field intensity.

- Plot of Hu and Wu (1987) showing almost exponential effect of field intensity.
- Data of Chen and Leu (2001).

- Particle size**, which as a result of magnetic flocculation affects the resultant aggregate size and consequently the bubble break-up process see Figs.16a,b,c. According to Chen and Leu (2002) the field intensity effect is more pronounced with smaller particles (approx. $190\mu m$) as compared to larger solids ($930\mu m$) and those of $3.6mm$ in diameter employed by Hu and Wu (1987, 1988).

Thompson and Worden (1997) report results that in general confirm those of Chen and Leu (2001, 2002) but the field intensity effect is not so clear - see Figs.17a, b, c, d. In general, the measurements by the optical probe reveal that higher field intensities provide higher gas holdup but the demonstrated effects are weak. The probable reason for that is based on the fact that Thompson and Worden (1997) use $4mm$ Ca-alginate beads doped with magnetite; such beads *do not aggregate* under stronger fields due to their low magnetic susceptibility. In this context, the pure iron particles of Chen and Leu (2001, 2002) flocculate easily and the effect of bubble break-up by aggregates, which macroscopically is performed as magnetic field effect, is more pronounced. According to Thompson and Worden (1997) the gas fraction is most sensitive to field intensity at low field intensities where

chain, chain-channel and destabilized regimes can be created. At the highest fields, i.e. in the frozen (condensed) bed, the gas fraction is relatively independent. The effect is obvious, since the gas fraction is affected by the particle mobility, while at stronger fields the solids form a bed at the distributor plate playing a role of additional gas sparger. This effect is commented too in the section devoted to Slurry Bubble Columns operating in batch mode.

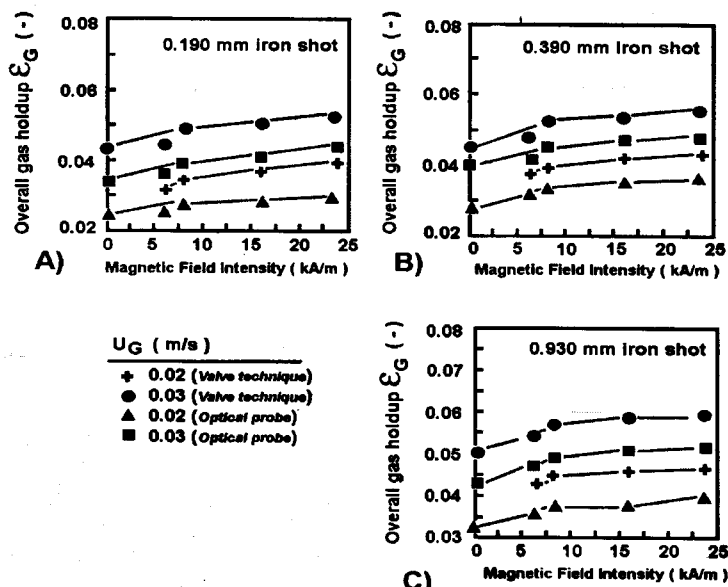


Fig. 16: Overall gas holdup as a function of field intensity and showing the particle size effect. –After Chen and Leu (2002).

Results and explanations similar to those of Thompson and Worden (1997) were reported by Sonolika et al. (1999). According to these authors, the system is more sensitive to the gas velocity at about $H = 100 \text{ Oe}$ - see Figs. 18a, b. No physical explanations exist in the original work, so it might be suggested that the behaviour is similar to that reported by Thompson and Worden (1997). Sonolika et al. (1999) compared the effect of the magnetization mode on the overall gas holdup trends with increase in field intensity (see Fig. 18b). The profiles almost match that is a reasonable result since beyond the minimum fluidization point (magnetization FIRST) and the minimum field intensity causing chain formation (magnetization LAST) the bed exhibits basically identical flow regimes. For instance, this analogy and

similarity was discussed in the case of gas fluidized beds (Part 1, Hristov, 1998b).

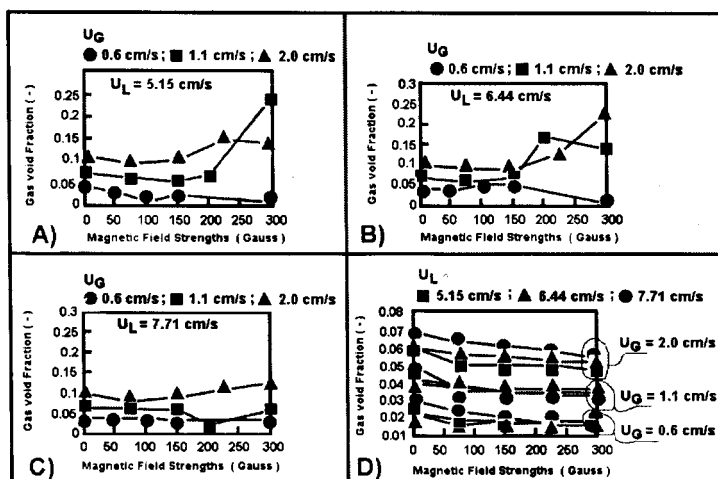


Fig.17: Data of Thompson and Worden (1997) concerning the overall gas holdups in magnetically assisted co-current bubble columns.

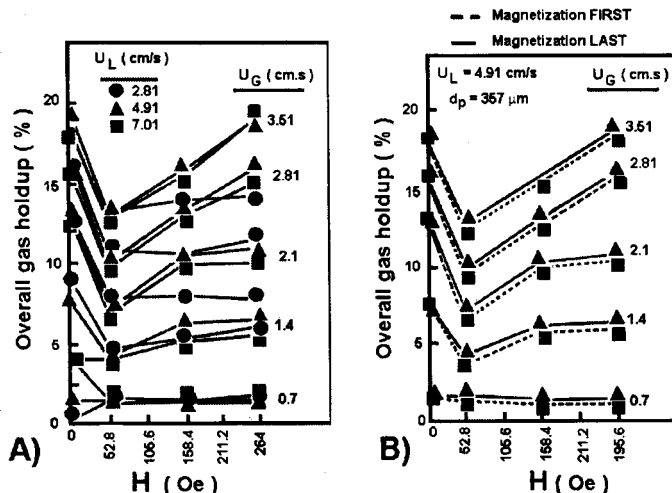


Fig. 18. Overall gas holdup as a function of field intensity measured by Sonolika et al. (1999)

- Field intensity effect on the gas overall holdup at different gas and liquid velocities.
- Effect of the magnetization mode on the gas holdup trend with increase in field intensity.

Thompson and Worden (1997) observed bed contraction (collapse) with increase in field intensity but results either graphical or numerical were not published. Further, they especially mentioned that their results contradict the findings of Hu and Wu (1987, 1988) denoting slightly increase in gas holdup as the field is increased. In this context, the authors reported that little bed contraction due to addition of gas phase like in non-magnetic beds (Fan, 1989) was observed outside the random regime since as the field intensity increases the induced magnetic forces (creating aggregates) predominate over the hydrodynamic (drag) forces dispersing the particles. Thompson and Worden (1997) suggested that the bed increasingly took on properties resembling a packed bed, rather than a fluidized bed. Higher fields causing bed contraction resulted in smaller bubbles with reduced rising velocities that yielded increased gas fraction. This suggestion is not supported by direct comparison with solid phase behaviour but provides a reasonable physical explanation. To this end, more visual observations directly related to the gas holdup and bed expansion (collapse) have to be performed.

The general trend in the overall gas holdup variations was approximated as

Chen and Leu (2001)

$$\bar{\varepsilon}_G = 0.75U_G^{0.78} \exp(8.12 \times 10^{-2} H) \quad (12)$$

based on 45 data points and with average relative error of 8.5%.

and

Chen and Leu (2002) see Fig. 19b

$$\bar{\varepsilon}_G = aU_G^b \exp(cH) \quad (13a)$$

with coefficients dependent on the particle size, namely

$$a = 0.123d_p^{-0.21}, \quad b = 0.226d_p^{-0.144}, \quad c = 1.11 \times 10^{-6} H \quad (13b)$$

The trends in gas hold-up evolution with increase in field intensity and gas velocity and those predicted by Eqs. (12, 13) and that of Begovich and Watson (1978), namely

$$\bar{\varepsilon}_G = (1.61 \pm 0.336) U_G^{(0.72 \pm 0.028)} d_p^{(0.368 \pm 0.0621)} D_c^{(-0.125 \pm 0.088)} \quad (14)$$

are illustrated by Figs.19a, b,c,d. To this end, Chen and Leu (2002) mentioned that the correlation of Begovich and Watson (1978) provide reasonable agreements with their data.

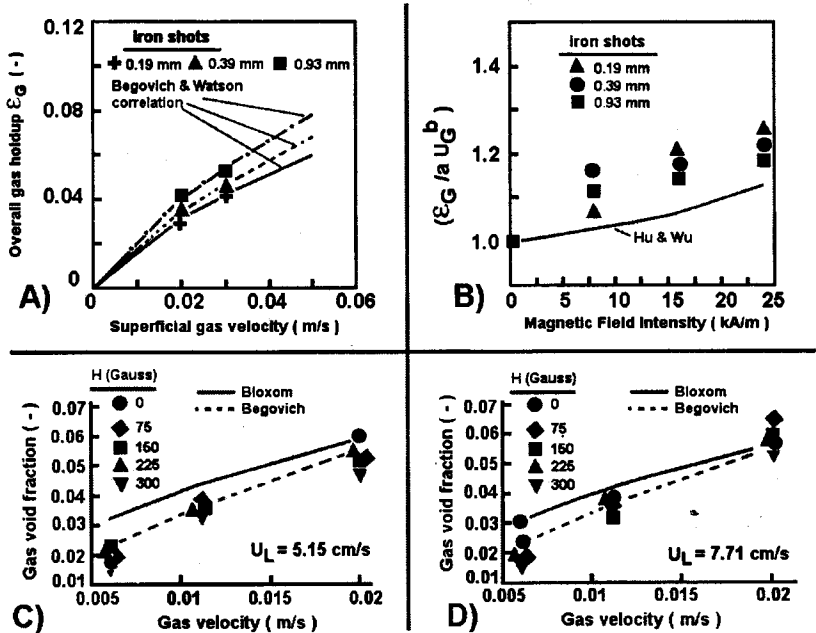


Fig. 19: Overall gas holdup as a function of particle size and magnetic field intensity. After

- Comparison of overall gas holdup as function of superficial gas velocity After Chen and Leu (2002).
- Comparison of magnetic field intensity effect on overall gas holdup. After Chen and Leu (2002).
- Comparison of gas fraction measured at different field intensities to literature data as function of gas and liquid velocity - After Thompson and Worden (1997).

Concerning the accuracy of the gas holdup measurement techniques, Thompson and Worden (1997) showed that both methods provide practically equal results for gas holdups lower than 10%. Increase in overall gas holdup yields underestimation of the valve technique with respect to the optical method- see Fig.20. Chen and Leu (2002) reported an agreement between the data obtained by the valve method and the optical technique; those from the valve technique are about 22% higher- see Figs. 16a,b,c, .

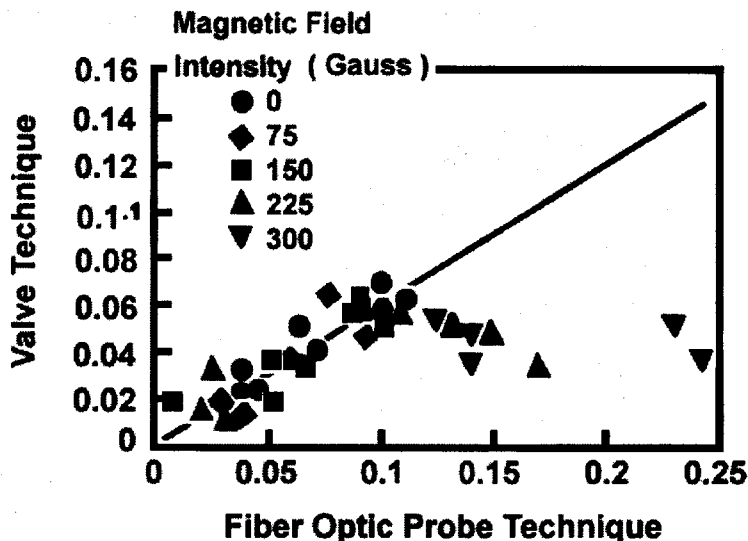


Fig. 20: Comparison of gas fraction measured by the valve technique to that measured by the fiber-optic probe. After Thompson and Worden (1997).

The overall *liquid holdup* was measured by Thompson and Worden (1997) and Chen and Leu (2001) only. In the context of bed contraction and field effects on the overall gas holdup in *dispersed bubble* regime (small bubbles in accordance with these authors) the field has more pronounced effect on the liquid holdup than the gas fraction, particularly at highest liquid velocity - see Figs.21a,b. These findings slightly contradict those of Chen and Leu (2002), albeit the trend with increase in H (see Fig. Fig.21c) but probably they could be explained by differences in solid phase behaviour as the field intensity increases. Chen and Leu (2001) correlated 45 data points and provided the relationship

$$\bar{\varepsilon}_L = 1.49 U_L^{0.228} \exp(-8.3 \times 10^{-6} H) \quad (15)$$

Unfortunately, no more published results are available for further analysis. We may suggest that answers to questions arising so far reviewing the overall phase holdups will be provided in the next section concerned with local values of phase fractions.

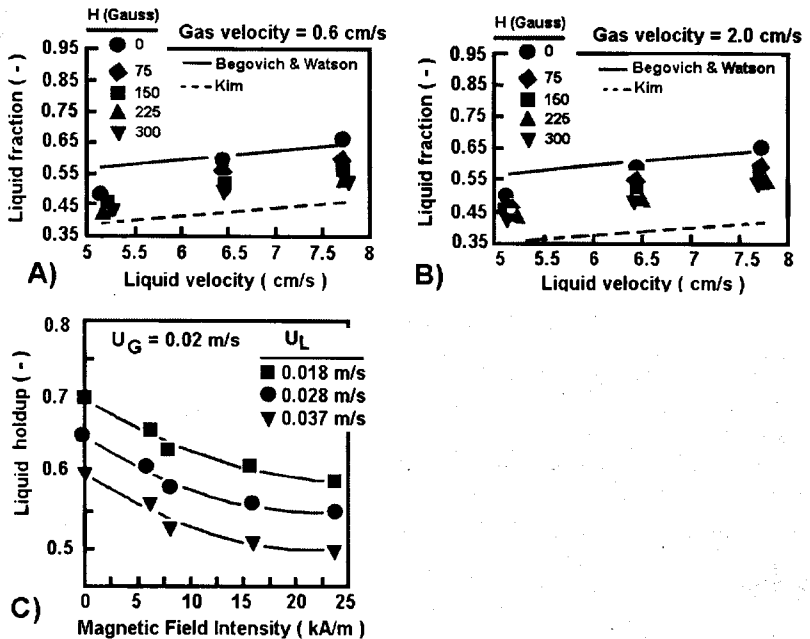


Fig. 21. Overall liquid holdup measured at different field intensities and gas velocities as a function of liquid velocity.

a,b) Comparison of liquid holdup measured at different field intensities as function of the liquid velocity. After Thompson and Worden (1987).

c) Liquid holdup as a function of magnetic field intensity. After Chen and Leu (2001).

Note: In the original work the liquid holdup is denoted as local rather than overall. Careful reading of the text revealed that the data are relevant to the overall liquid holdup even more the quick valve technique was used rather than local probe measurements.

3.2.3. Phase Holdups - Local values

Radial and axial phase distributions measured by different techniques provide substantial information about the field effect on particle behaviour and consequent bubble break-up. Hu and Wu (1987, 1988) reported almost parabolic gas holdup radial profile (measured by micro electro conducting probes) and non-homogeneous solids distribution across the column cross-section (measured by optical fiber probes). The plots in Fig.22a, b reveal flat (more homogenous) radial profiles as the field intensity increases. The

bubbles pass mainly along the column axis while the solids are groped close to the wall. The solids phase behaviour is a strong indicator of the radial field homogeneity. In the experiments of Hu and Wu (1987, 1988) the radial field inhomogeneity is about 10 %. Certainly this causes lateral magnetic forces increasing the particle concentration near the wall that consequently shifts the gas flow towards the column axis. Increase in field intensity augments the flocculation and causes bed contraction that in fact makes the solids distribution across the radius more homogeneous and the particles tend to behave almost as a packed bed or highly concentrated slurry. Recall that Thompson and Worden (1997) report increase in size of particle formations (aggregates and clusters of aggregates—see inset in Fig.12). Such structures (*destabilized, channel and frozen*) resemble porous media with G-L flows through them. To this end, denser particle packing, more homogenous flow phase distributions across the bed.

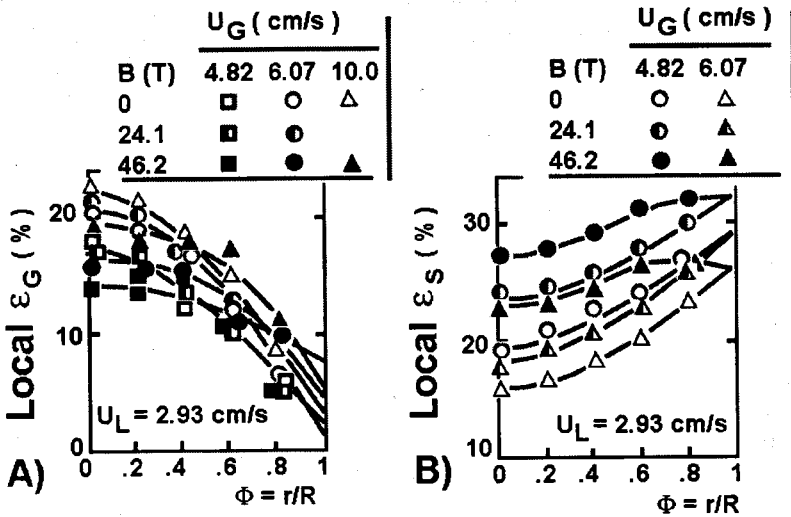


Fig.22: Radial phase holdup distributions with effects of magnetic field and U_G . From Hu and Wu (1987).

- a) Radial gas holdup profiles.
- b) Radial solids holdup profiles.

According to Hu and Wu (1987, 1988) the unevenness of radial phase holdup profiles is marked by increase in U_G . With zero and weak fields these distributions were expressed as parabolic equations, namely

$$\varepsilon_G = \varepsilon_{G0} - k_G \left(\frac{r}{R} \right)^{1.6} \quad (16a)$$

$$\varepsilon_S = \varepsilon_{S0} + k_s \left(\frac{r}{R} \right)^{1.6} \quad (16b)$$

where

$$k_G = 0.0122U_G^{1.32} \text{ and } k_s = 0.0542U_G^{0.356} \quad (16c)$$

A more detailed study on the local gas holdup considering the bubble flow regimes was performed by Chen and Leu (2002). In general, their measurements confirm the almost parabolic profiles of Hu and Wu (1987, 1988) but focus on two principle points:

- **Particle size effect** is performed by higher gas holdups at the column axis with increase in particle diameter (See Fig.23a,b), irrespective of the regime (*dispersed* or *coalesced*)
- **Field intensity effect** on the radial gas holdup profile depends on the bubble flow regime. In *coalesced bubble* regime and at low field intensities the profiles become sharper that confirm the observations of Hu and Wu (1987, 1988) - see Fig.23e,f. In *dispersed bubble* regime and at high fields the profiles become smoother. Chen and Leu (2002) mention that their profiles differ from those of Sonolika et al. (1999) showing different trend with increase in field intensity. However, see further in Slurry Bubble Column section, Sonolika et al. (1999) work with fine slurry ($d_p = 90 \mu m$) at low solids concentration while Chen and Leu (2002) employ a system of coarse particles. The radial gas holdup distributions of Chen and Leu (2002) are compared (see Fig.23c, d) to those from non-magnetic bubble columns (Lee and De Lasa, 1987; Yu and Kim, 1988).

3.2.4. Closing Comments on BC with Magnetization LAST mode

Results reviewed in this section reveal the field effect on the G-L flow affected by particle flocculation (mainly through bubble breakup) and the regime shifts there-of. The work of Chen and Leu (2002) may serve as a template for further studies on Magnetization LAST modes referring to gas-liquid flow regimes. Similarly, the results of results of Thompson and Worden (1997) show the solid phase behaviour in details. There are no direct

interrelations published so far, except some suggestions done in this review that refers to new experimental studies. Besides, the maps of Chen and Leu (2002) are only graphical illustrations but detailed knowledge of bed hydrodynamics requires quantitative relationships like those available for non-magnetic bubble columns (Fan, 1989). To this end, the correlation of the critical velocities denoting the shifts in the flow regimes is a problem that should be solved.

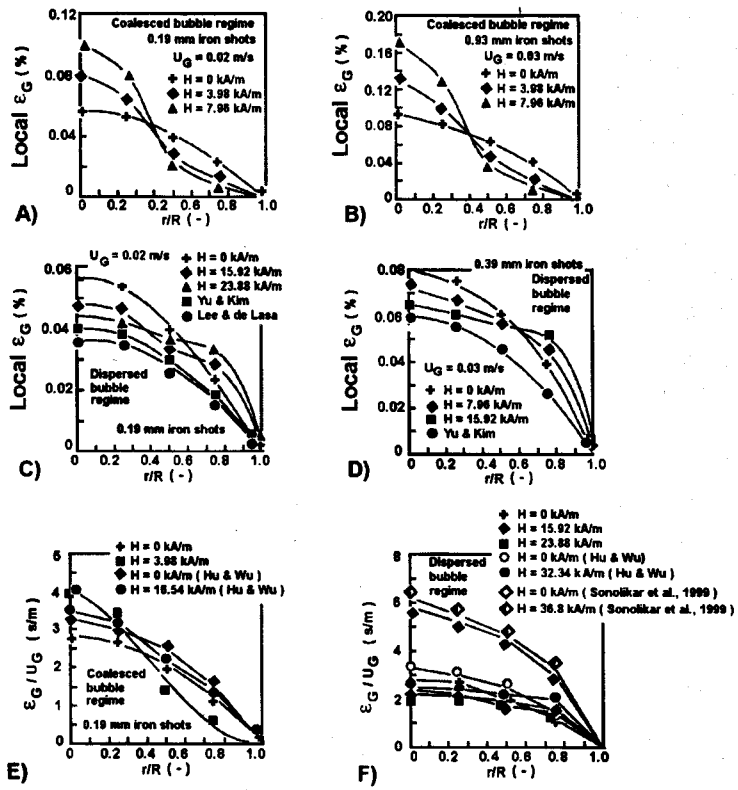


Fig. 23: Radial gas holdup distributions with particle size and field intensity effects in two bubble flow regimes. After Chen and Leu (2002).
a, b) Radial gas holdup distribution in the coalesced bubble regime.
c, d) Radial gas holdup distribution in the dispersed bubble regime.
e,) Comparison of the radial gas holdup distribution in the coalesced bubble regime.
f) Comparison of the radial gas holdup distribution in the dispersed bubble regime.

The ability to control the phase holdups remotely is a remarkable one but more quantitative knowledge based on basic assumptions and models thereof and experimental data are needed. We suggest the reviews and these closing briefs could motivate further studies of problems referred to.

3.3. Bubbles in co-current magnetic bubble columns

With strong magnetic fields applied to three-phase fluidized beds of ferromagnetic particles, almost all solids can be immobilized in a fixed bed (MSB or a condensed bed (CB)) depending on the magnetization approach employed. By varying the field intensity the bubbling could be controlled by magnetic action on the ferromagnetic particles, from free bubbling down to complete ceasing in MSB or CB. Obviously, particle immobilization in fixed beds splits the column into two parts: a *bottom particle bed* at the bottom with G-L flow through it and a *G-L bubbling section* above the bottom bed top surface. The latter is a conventional case in G-L-S magnetic beds and will be commented further with slurry bubble columns operating in batch mode. However, we are interested now in bubbles of completely developed G-L-S fluidized beds with magnetically controlled solid phase.

Reports concerning bubble size measurements in magnetically assisted G-L-S beds are rare in literature. Only two studies have been published so far. The first (Sajc, 1995, 1996) operates with axial fields created by a solenoid; both articles report identical results so we refer to them as one study. The second belongs to Kwauk et al. (1992) and addresses mainly bubble shape, bubble size and field intensity effect. In contrast to the work of Sajc et al. (1996, 1996) a transverse magnetic field created by electromagnet (horse-shoe design) with parallel poles was used. Despite the differences in the experimental conditions we will try to present shortly the information and to collate the data in a manner allowing their generalization.

Bubble size measurements performed by Sajc et al. (1995, 1996) are based on a system utilizing two conductivity probes located centrally in the bed at 3 cm distance (details about the experiments are available in Table 5). The mean bubble chord length was obtained by conductivity profiles using the method described by Cheremisinoff (1986). With this techniques and calculations based on the method of Matsuura and Fan (1984) the results shown in Fig.24 reveal that in absence of a field the bubble size is practically independent of gas velocity but decreases with increase in liquid velocity

(**Liquid-Scan** mode). Sajc et al. (1986) explain these results with more uniform liquid velocity profiles due to increase in the liquid flow rate, decrease in liquid residence time and low extent of coalescence. Further, bubbles measured in a packed bed (i.e. MSB and $U_L < 0.6 \text{ cm/s}$ - see Fig.6a) were higher than those in a fluidized bed. With field intensities higher than $H = 14 \text{ kA/m}$ substantial bubble size reduction was detected. In this context, increase in gas velocity at fixed field intensity and liquid velocity leads to increase in bubble size. On the other hand, since we have three macroscopic variables (H, U_G, U_L), variations (increase) in U_L , at fixed H and U_G , affect seriously the bubble size. In a fluidized bed with chains (called by Sajc et al. a "partially stabilized bed") with $U_L > 1.2 \text{ cm/s}$, $U_G = 0.50 \div 0.84 \text{ cm/s}$ and $H > 14 \text{ kA/m}$ no bubble size reduction was observed. The observation of Sajc et al. (1995, 1996) indicates smaller and faster bubbles in MSB and partially stabilized (chain) regime than those observed under equivalent flow conditions: the same U_L , U_G , and zero field intensity. Schematically the qualitative bed behaviour is illustrated by the inset in Fig. 24.

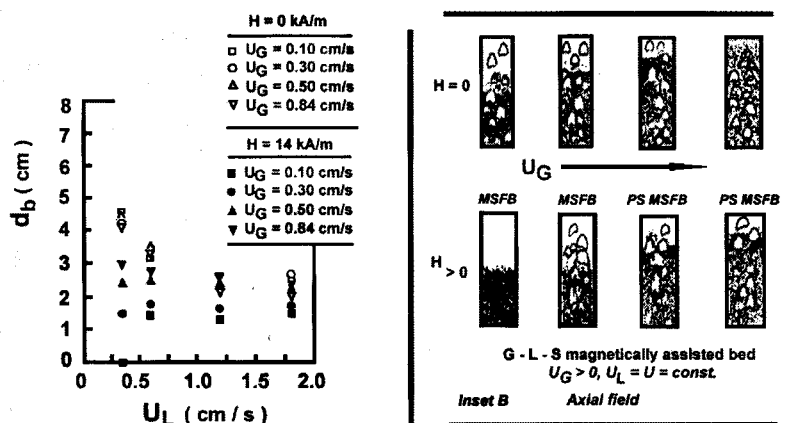


Fig. 24: Bubble size as function of gas, liquid velocity, and field intensity. Adapted from Sajc et al. (1996, 1996).

Inset : Bed behaviour- schematically. After Sajc et al. (1996).

Table 5
Experimental conditions in studies relevant to bubble properties measurements in three-phase MFAF

Ref.	Column	Magnetic field	Gas	Liquid	Solids	Operating mode	Magnetization mode	Measurement techniques
Sajc et al. (1995) (1996)	Plexiglas column	Axial (DC) generated by a long solenoid	Air	Water	Composite Ca-alginate/Magnetite	<i>Co-current</i>	Variation of field intensity at fixed gas velocity, i.e. Magn. FIRST	Two fast pressure drop transducers located at the column axis and
	110 mm ID 500 mm in height	330 mm high 120 mm ID $H_{\max} = 4 \text{ kA}$			Spheres 1000 μm $\rho_s = 1930 \text{ kg/l}$	Liquid Scan mode Gas-Scan mode		Two conductivity probes and saturated NaCl solution as a tracer
Kwauk et al. (1992)	2D Column	Transverse (DC)		Tap water with surfactants	Iron granules	<i>Co-current</i>	Magn. FIRST	Air injected by solenoid valve
	150x10 mm cross-section 1 m in height	See the picture $H_{\max} = 200$	Air		87 – 371 μm	Liquid Scan mode		Photocell matrix For shadow bubble detection

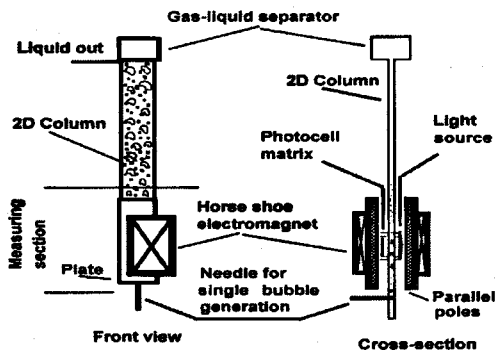


Fig. 25: Sketch of the experiments of Kwauk et al. (1992) on bubble size control in magnetically G-L-S beds.

Kwauk and co-workers (1992) used a 2D column of Wu et al. (1988) – see details in Table 5 and the sketch in Fig.25. Tap water with different amounts of surfactants was used to vary the liquid surface tension. Single bubbles were generated by a 3 mm nozzle closely above the liquid distributor. Bubbles were detected by a horizontal matrix of 29 photocells deployed equidistantly at 5 mm. A single movable upper probe was located at 18 mm above the matrix. The column was illuminated from the opposite side, so parallel light rays were directed through the bed towards the bubble detector. The signals from the photocells were processed by a computer.

A series of pictures (Fig.26) shows the field intensity effect on bubble behaviour. Without a field a large single bubble, about 9 mm in diameter, rises through the bed. With increase in field intensity within the range $0 < 80$ Oe the large bubbles break up into progressively decreasing in size smaller bubbles, while at stronger fields (see Fig.26d, e, f) practically there is no field impact either on the bubble size or the number of fragments. At $H > 160$ Oe the bed is condensed (i.e. Magnetization LAST mode is used) and the gas bypasses near the column walls.

Kwauk et al. (1992) developed a theory based on the fact that the magnetic tension in solid-liquid suspension (through which the gas bubbles rise) tries to compress the gas void that forces the particles to penetrate the bubbles and break them. The bubble top surface is subjected to simultaneous action of magnetic forces, penetrating particles, hydrodynamic forces and surface tension. The bubble roof was assumed as its weakest point that led to a formula of a maximum bubble size, namely

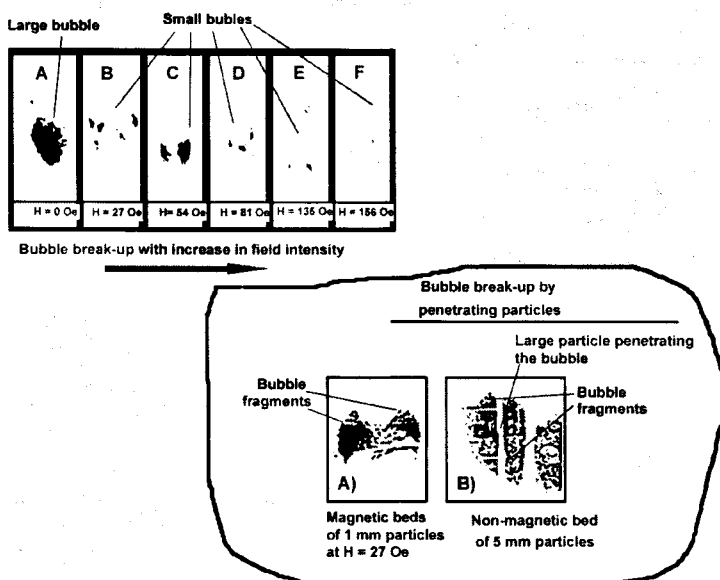


Fig. 26: Bubble behaviour with increasing field intensity. Adapted from Kwauk et al. (1992). The present author converted the original picture into (inverted) negative one. The black spots are the bubbles, while the white area is the bed.

Inset: Mechanism of bubble break up . Also negative picture of the original one for better illustration.

$$d_{bubble \text{ (max)}} = \frac{K_D d_p U_B + f(\theta) \pi d_p \sigma - (\pi/6) d_p^3 g \rho_s}{K_H H (H - H_d) - (\pi/8) g (\rho_s \varepsilon_s + \rho_L \varepsilon_L + \rho_G \varepsilon_G) d_p^2} \quad (17)$$

This equation and the relevant theory are commented further in 5.2. The theory seems general but the experiments performed to validate it utilized transverse fields only. There is no similar theory or experimental data for G-L-S beds in axial magnetic fields. In general, the bubble rise velocity depends on the liquid properties and the bubble size controlled by the field intensity (see Fig.27). With increase in field intensity the bubble rise velocity diminishes due to a reduction in the bubble diameter.

Kwauk et al. (1992) demonstrated the mechanism of bubble break up by particles penetrating the bubble roofs (see the inset in Fig. 26) compared to non-magnetic beds (Henriksen and Ostergaard, 1974). According to Kwauk et al. (1992) and the photos in Fig. 26 the particles break the bubble through

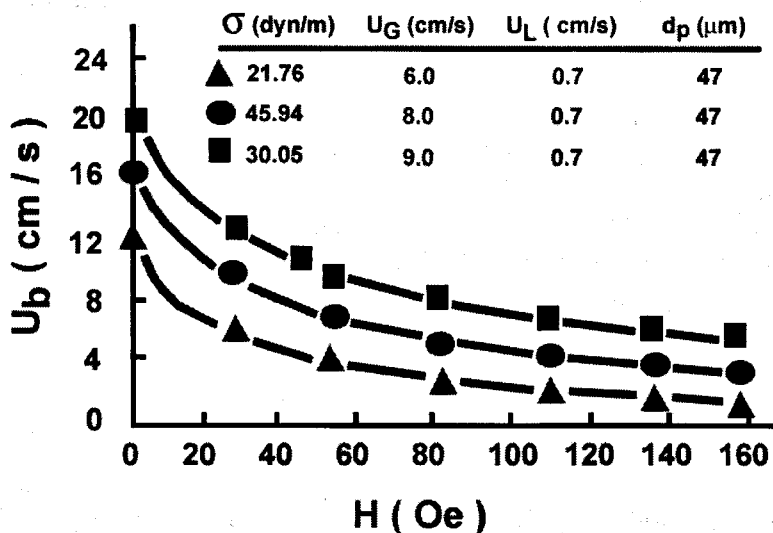


Fig. 27: Simultaneous effect of field intensity and liquid surface tension on bubble rise velocity. Adapted from Kwauk et al. (1992).

the roof. However, as mentioned by Kwauk et al. (1992) in non-magnetic beds bubble break-up calls for large particles, while in magnetically controlled fluidization small particles may break the bubbles effectively. The theory does not take into account the particle aggregation and considers the solid-liquid suspension as a system of homogeneously suspended particles penetrating the gas bubbles. This is by far away from reality since the increase of particles in size (magnetic flocculation) makes the suspensions inhomogeneous rather than similar to ferrofluids like in the Kwauk's theory. To this end, all results relevant to gas hold-up and interfacial area reveal strong field effect on bubble break up (increase in interfacial area mainly) in chain regimes rather than in particulate fluidization. Further, the inset in Fig. 26 reveals large particle formations breaking bubbles in both magnetic and non-magnetic a bed that confirms the above statement different from the explanations in the original work of Kwauk et al. (1992).

These results are small spots in the literature on magnetically controlled beds. They are pertinent to the efficiency of all mass transfer devices utilizing magnetically controlled G-L-S beds. Bubble size and behaviour are to a large extent important for correct performance of both the gas-liquid and the gas-solid mass transfer. Further detailed studies performed with more refined

techniques are needed parallel to macroscopic measurements of gas hold-up and interfacial area.

4. SLURRY BUBBLE COLUMNS (SBC)

4.1. Introductory thoughts

Slurry bubble reactors (SBR) are widely encountered in chemical processes characterized by continuous liquid phases with fine solids (catalysts) through which gas is dispersed and catalyst suspended. The solids may be also inert and their motion augments the gas-liquid mass transfer rate. Typical processes are: hydrogenation, oxidation, halogenation and polymerization reactions as well as biological wastewater treatment and fermentation.

Magnetic versions of SBCs emerged in the last 10 years (Sonolihar and Raja Rao, 1996; Mu and Min, 1996, 2007; Min et al., 1997; Lu et al., 1999; Sonolihar et al., 1999; Li et al., 2006; Zong, 2007). All these studies are represented briefly by the data summarized in Table 6. The main idea of magnetic SBC is to control magnetic solid phase movement by external fields that directly affect the gas-solid mass transfer. In general, the problem requiring magnetic field application is due to low solid-liquid slip velocity. According to Fan (Fan, 1989- pp.251-253) for SBC operating in both the expanded bed and the liquid batch regimes typically the particle terminal velocity U_t is less 5 cm/s. With liquid phases close to water (i.e. aqueous solutions of various substances) this implies solid fractions less 100 μm . The solid fractions used in the magnetic SBC go with this limit more or less. Besides, due to the low volumetric fraction of the solids (see Table 6) in SBC (Fan, 1989) the settled bed formed at the column bottom is negligible. This immediately defines, as a rational approach, the use of Magnetization LAST mode. Magnetization FIRST mode is used under some conditions but this is not the typical case of magnetic BSCs.

There are serious reasons to operate with Magnetization LAST mode, among them:

- First, the catalyst acts in the liquid phase that demands high interfacial area. Bubbles rising through the liquid coalesce that decreases the interfacial area and the overall mass transfer coefficient. Thus, bubble

Table 6a
Experimental conditions in studies performed with magnetically assisted slurry bubble columns

Reference	Column	Magnetic field	Gas	Liquid	Solids	Operating mode	Magnetization mode	Problems studied
Sonolkar and Raja Rao (1996)	90 mm ID 700 mm in height	Axial (DC) generated by a long solenoid $H_{\max} = 480 \text{ Oe}$	Air	Distilled water with $0.6 \text{ Kmole} / \text{m}^3$ sodium sulphite at $\text{pH} \approx 8.5$ At approx. 30°C	Magnetite Fractions: $90 \mu\text{m}$ $127.5 \mu\text{m}$ $180 \mu\text{m}$ Slurry Concentrations: $\%(\text{vol.}) : 2; 5; 10$	Liquid Batch Solids Batch	Variation of field intensity at fixed gas velocity, i.e. Magnetization LAST	Local Gas hold-up Interfacial gas-liquid contact area
Sonolkar et al. (1999)								
Lu et al. (1999)	Plexiglas Column 265 mm pre-distributor in height and 800 mm fluidization section 80 mm ID	Axial (DC) Generated by 8 Helmholtz coils Total height: 470 mm 40 mm distance between 2 coils Coil: 80 mm ID; 23 mm height $H_{\max} \approx 6 \text{ kA} / \text{m}$	Air Supplied by two types of spargers: Porous sintered sparger and Perforated tube	Water	Iron Fraction $< 75 \mu\text{m}$ $\rho_s = 7860 \text{ kg} / \text{m}^3$	Co-current Liquid Scan mode	Magnetization LAST Magnetization FIRST	Bed regimes Bed expansions Effect of the gas distributor design
Mu and Min (1996)		Axial (DC) Generated by a series of short coils $H_{\max} = 5324 \text{ A} / \text{m}$	Air		Mixture of Iron powder $100 - 150 \mu\text{m}$ and Ni-Re-P catalyst $150 - 200 \mu\text{m}$	Co-current Liquid Scan mode	Magnetization FIRST	Minimum fluidization velocity U_{mf-L} Pressure drop
Mu et al. (1997)								

Table 6b
Experimental conditions in studies performed with magnetically assisted slurry bubble columns - continued

Reference	Column	Magnetic field	Gas	Liquid	Solids	Operating mode	Magnetization mode	Problems studied
Li et al. (2006)	Plexiglas column 100 mm ID 1500 mm in height	Axial (DC) Generated by a series of short coils Each coil is 160 mm ID and 100 mm in height		Sodium sulphite (0.5 mol/l) aqueous solutions with CMC to control the viscosity within the range 1–5 mPa.s Surface tension: 54–72 mN/m	SRNA-4 amorphous Nickel alloy catalyst 80–120 μm 120–200 μm $\rho_s = 2500 \text{ kg/m}^3$	Co-current Gas Scan Liquid Scan	Magnetization FIRST	Gas holdup Interfacial area G-L mass transfer coefficient
Mu and Min (2007)		Axial (DC) Generated by a series of short coils 160 mm ID • No data about the magnetic systems	Hydrogen	Benzene 11.42–12.08, aromatic 62.95–67.24 $\rho_L = 700–800 \text{ kg/m}^3$	SRNA-1 amorphous Nickel alloy catalyst 60–90 μm spherical shape in the reactor the catalyst is mixed with iron powder at a ratio 2:1 (vol.)	Co-current	Variation of field intensity at fixed gas velocity, i.e. Magnetization LAST	Hydrodynamics Mass transfer
Zong (2007)	Plexiglas column 140 mm ID 2000 mm in height	Axial Various magnetic systems used	Air Hydrogen	Water	SRNA-4 amorphous Nickel alloy catalyst 30–70 μm 70–125 μm 125–180 μm 80–400 μm $\rho_s = 2500 \text{ kg/m}^3$	Co-current	Magnetization LAST Magnetization FIRST	Hydrodynamics Cold simulations of caprolactam hydrofining

breakers (**BB**) are needed. Increase in field intensity leads to particle aggregation and bubble break-up by them, i.e. the aggregation and bubbling can be controlled remotely that is impossible in non-magnetic BSC;

- Further, the bubble break-up process is accompanied by particle chain disruption (break-up) and aggregation (flocculation) again. The continuous aggregate break up (and formation) allows the catalyst surface contacting the liquid (or gaseous) phase to be renewed thus enhancing the mass transfer process.
- A secondary effect of particle aggregation is the increase in particle-fluid slip velocity that together with the *aggregate break-up / formation* process reduces the mass transfer resistance caused by stagnant liquid layers around single small particles.

Magnetically assisted BSC do all these processes possible and the next analysis addresses some hydrodynamic issues among them:

- Gas-holdup and interfacial area controlled by external magnetic fields,
- Pressure drop, phase diagrams, bed expansion, etc.

To this end, a common feature of the fields that assist magnetic BSC is the co-linearity with the column axis, i.e. axial fields are used only and the magnetic systems employed are based on long solenoids (Sonolikar and Raja Rao, 1996) and multi-coil magnetic systems (Mu and Min, 1996, 2007; Min et al., 1997; Lu et al., 1999; Li et al., 2006; Zong, 2007) – see Fig. 28.

4.2. Hydrodynamic issues

The data summarized in Table 6 reveal that most of the experiments were performed in a co-current mode with energy for fluidization introduced by the gaseous phase. In the experiments performed in China (Mu and Min, 1996, 2007; Min et al., 1997; Lu et al., 1999; Li et al., 2006; Zong, 2007) the **Liquid-Scan** mode is used also to establish the optimal operating conditions. In view of the fact that the work of Sonolikar and Raja Rao (1996) is unique with liquid batch mode it will be commented separately next.

4.2.1. Magnetic BSC in liquid batch mode

Sonolikar and Raja Rao (1996) address mainly the gas-liquid interfacial area (IA) so general hydrodynamic information is hard to be removed from

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4.2.1. Magnetic BSC in liquid batch mode

Sonolika and Raja Rao (1996) address mainly the gas-liquid interfacial area (IA) so general hydrodynamic information is hard to be removed from

the text. However, bearing in mind that the interfacial area is strongly related to gas holdup ε_G and the mean bubble diameter d_{b-avs} (avs means average in slurry), namely

$$a = 6 \frac{\varepsilon_G}{d_{b-avs}} \quad (18)$$

it is possible to get information related to the gas holdup (or the bubble size), to do data analysis and comments. We have to mention that average gas holdup was measured by Sonolika et al. (1999) with coarse particles (357 μm and 645 μm in size) that are by far away from the conditions considered for slurry columns. The classical quick closing valve technique was used.

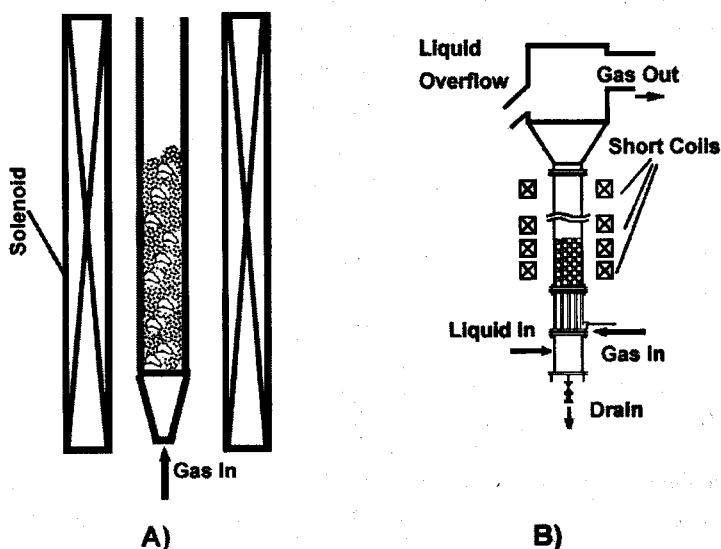


Fig. 28: Experimental set-ups of slurry bubble columns

- a) Sonolika and Raja Rao (1996)- designed by the present author due to absence of picture in the original work.
- b) Multi-coil systems of Mu and Min (1996, 2007), Mu et al. (1997), Lu et al. (1999); Li et al. (2006)

In accordance with the introductory comments about the field effect on the interfacial area through particle aggregation and bubble breaking the

results shown in Fig.29a reveal strong effect of the field intensity on the interfacial area (IA). Sonolika and Raja Rao (1996) comment that the gas holdup is mainly affected by the gas flow rate (Fig.29a, b, c) and no significant effect of the field can be detected. On the other hand, the bubble break-up by particle chains is the principle mechanism to control the interfacial area. Increase in solids concentration (Fig.28) augments IA too but beyond 2% (in magnetized or non-magnetic slurries) the effect is just the opposite. In this context, increase in particle diameter (Fig.29c, d) yields reduced interfacial areas.

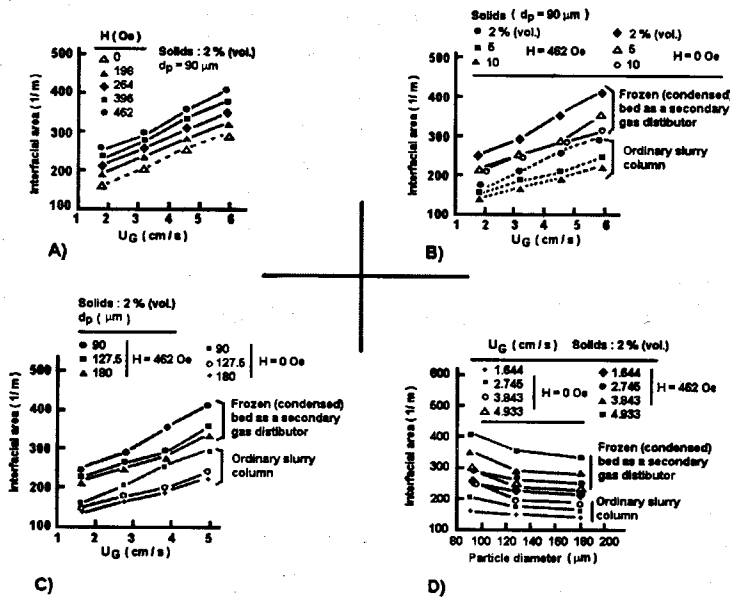


Fig. 29 Interfacial area as function of the gas velocity. Liquid batch mode, Fixed field intensity and Gas-Scan mode. After Sonolika and Raja Rao (1996)

- Interfacial area a vs. U_G at different field intensities and low solids concentration.
- Interfacial area a vs. U_G with additional effect of the solids concentration in two distinct cases: non-magnetic BSC and magnetized mode corresponding to frozen (condensed) bed formation- see the explanations in the text.

- c) Interfacial area a vs. U_G with additional effect of the particle diameter at low solids concentration. Larger particles easy form aggregates with low mobility so increase in particle diameter yields low interfacial area. The same effect is shown in Fig. c
- d) Interfacial area a vs. the particle diameter at low solids concentration with U_G with additional effect of U_G . The plots demonstrate the same effects as in Fig. A.

All these comments address experiments with fixed field intensities and variation in the gas velocity (**Gas-Scan** mode). In contrast, variations in field intensity at fixed gas velocity (**Magn. LAST** mode) result in three principle regimes: *random particle motion* (*particulate fluidization*), *chain regime* and *condensed bed*. These terms are well known (Hristov, 1998, Part 1 and Part 5) and for seek of clarity we will use these terms henceforward. The fluidization regimes could be established by different combination of the two macroscopic variables: *Field intensity* and the *gas flow rate*; in view of the fact that the aggregate motion and break-up as well as the bubble size and behaviour depend on the balance between the field and the hydrodynamic effects in the slurry.

Actually, Figs.29ab, c,d show interfacial areas as functions of the gas velocity in two distinct cases: *non-magnetic BSC* and *BC without particles but with a condensed bed at the supporting plate*. This distinction is absent in the original work of Sonolihar and Raja Rao (1996) but the text clearly states that at field intensity $H = 462 \text{ Oe}$ ($\approx 37000 \text{ A/m}$) all the solids are at the column bottom as a condensed bed, i.e. practically no particles in the bubbling liquid exist. Therefore, in absence of a field and low field intensities as well, the interfacial area is affected by the particles while at $H = 462 \text{ Oe}$ (and beyond) they have no effect on the bubble behaviour. The condensed bed plays a role of additional gas distributor. These regimes yield two separate groups of data points in the Fig. 29ab, c, d- *see the additional labels*. In general, condensed beds as distributors yield higher surface areas than those in non-magnetic slurries.

In the context of the above comments, the formation of condensed beds at the column bottom does not affect the radial gas holdup profile (see Fig.30a) but make the axial gas distribution more homogenous (Fig.30b). The local gas holdup was measured by the resistivity probe techniques of Yashunishi et

al. (1986).

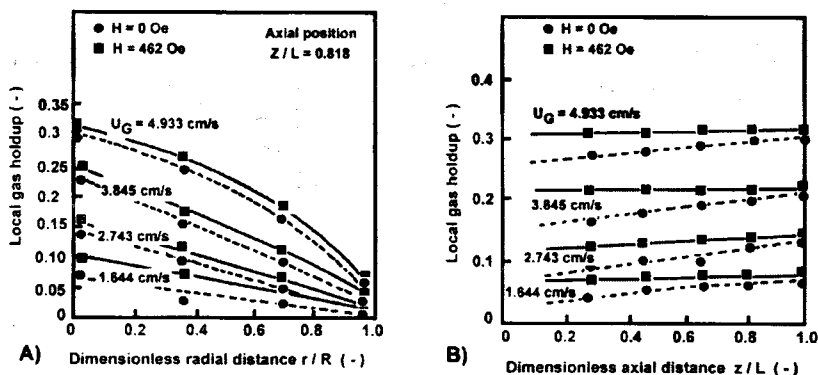


Fig. 30: Local gas holdup profiles. Adapted from Sonolika et al. (1999).

a) Radial profiles with various gas velocities at $z/L = 0.818$ (too far from the bottom)

b) Axial profiles with various gas velocities.

Note: Zero field condition means ordinary particulate fluidization. At $H = 462$ Oe all the particles are at the bottom (condensed bed) - see the text.

The field effects illustrated by Fig.31 and the text of Sonolika and Raja Rao (1996) identify the Magnetization LAST (see Part 1 and Part 5) as a magnetization method. According to these authors increase in chain size with increase in field intensity up to 200 Oe (≈ 15000 A/m) decelerates the solids in the slurry. Field strengths beyond this limit yield stable chains that cannot be distorted by the bubbles but the motions of the solids slow down. At field intensity about 400 Oe (≈ 30000 A/m) the particles form a *condensed bed*. In general, decrease in gas velocity or increase in solids concentration, with increase in field intensity, augments the aggregation process. The plots in Fig.31 show these effects but, as a general rule, the reason for the drop in the interfacial area is the reduced particle mobility. To this end, larger particles easily form aggregates with low mobility than the finer ones, so increase in particle diameter yields low interfacial area (see Fig.29d).

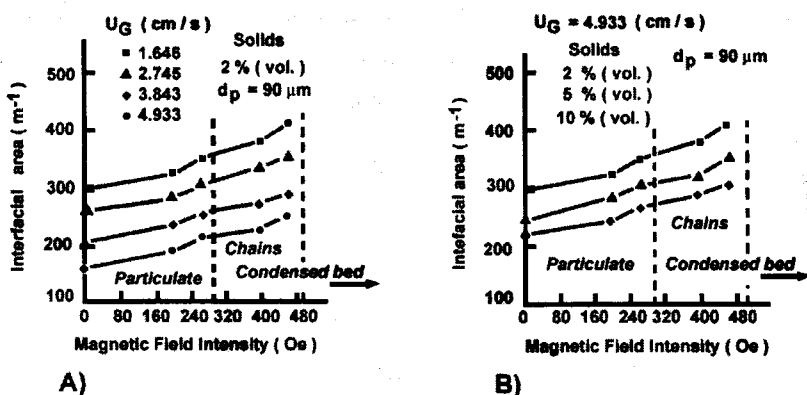


Fig. 31: Interfacial area as function of the field intensity. After Sonolika and Raja Rao (1996).

- Effect of gas velocity at low solids concentration and small particles in size.
- Effect of gas velocity at high gas velocity but with variations in the solids concentration. See explanations in the text.

Note: The vertical dotted lines and the labels denoting the regimes were added by the present author for seek of clarity of explanation.

4.2.2. Co-current gas-liquid flow

The gas-liquid co-current mode in bed expansion regime is mainly investigated by the team of SINOPEC (China) in the course of development of efficient operating conditions for amorphous nickel alloy-based catalyst SRNA. The studies passed through different steps from small laboratory units (Mu and Min, 1996) to large-scale industrial applications (Zong, 2007). The steps in the scale-up process will be discussed in the future Part 10 of the series. Now we address only hydrodynamic problems developed with laboratory and pilot-scale units.

An interesting step in all these studies is the employment of a mixture of SRNA with magnetite or iron powders that are inert with respect to the process. The use of magnetite (or iron) augments the magnetic properties of the mixture and enables to keep (hold) the entire solids in the working volume with minimum losses due to continuous liquid flow through the column. Besides, the addition of magnetite or iron make the slurry solid concentration greater than that in liquid batch SBC and the mixtures may form deep settled beds at the column bottom in absence of fluid flow. The

latter allows application of either of Magnetization LAST or Magnetization FIRST modes commented next separately.

4.2.3. Magnetization FIRST- Co-current upflow

The hydrodynamic behaviour with Magnetization FIRST mode does not differ, in general, from that observed with coarse particles in expanded mode (see Fig.32) either with *Liquid-Scan* or *Gas-Scan* approaches. The plots in Fig.33 show results obtained with *Liquid-Scan* Mode. In the context of the previous comments, the increase in iron content decreases the minimum field intensity required to control the particles in the column (see Fig.33d, i.e. to “condense” all the solids at the bottom).

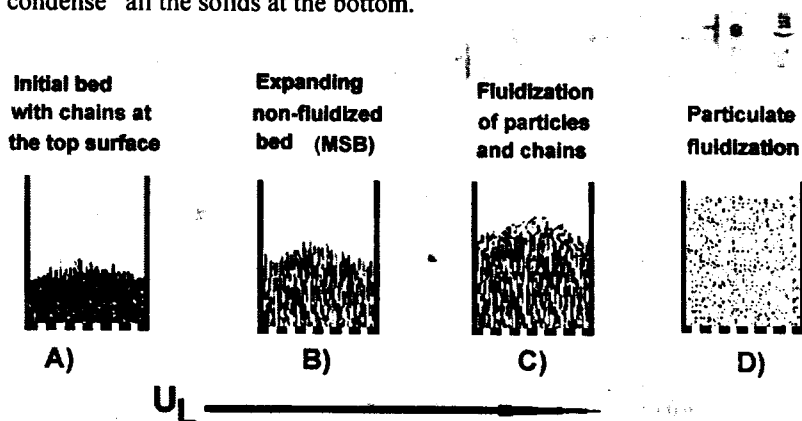


Fig. 32: Bed Behaviour with Magnetization FIRST and Liquid scan modes. After Mu and Min (1996).

The *Gas-Scan* experiments of Li et al. (2006) provide results similar to those obtained with coarse particle systems, as it is illustrated by Fig.34a,b,c. Generally, increase in gas velocity, field intensity (Fig.34) and liquid dynamic viscosity (Fig.34b) yield increase in the gas holdup and consequent augmentation of the gas-liquid mass transfer coefficient (Fig.34c,d).

An important detail in this study of Lu et al. (1999) is the effect of the gas distributor design (see inset in Fig.35). It was reported that fine bubbles produced by a sintered gas distributor (called “sandy distributor” in the original work) yield more uniform fluidization than a perforated tube leading to large bubbles and slugs. Because *Liquid-Scan* mode was used an effective bubble breakup by particles was observed at *high liquid velocities*. To this

end, at *low liquid velocities*, no particles escape from the bed and the bubbles run away mainly from the bed center (above the bed) and form slugs.

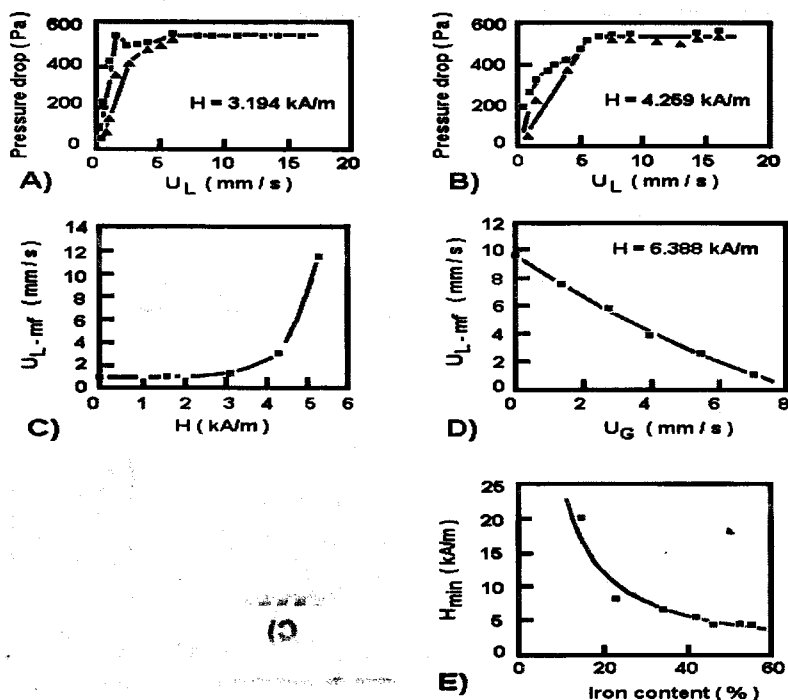


Fig. 33 Hydrodynamic characteristic of Slurry Bubble Columns with co-current flow: Magnetization FIRST and Liquid-Scan mode. After Mu and Min (1996)-

- a) , b) Pressure drop curves with liquid-Scan mode at two field intensities.
- b) Field intensity effect on minimum fluidization velocity (liquid).
- c) Gas velocity effect on the minimum liquid fluidization velocity .
- d) e) Effect of the iron particles content in the mixture on the field required to hold the particles in bed.

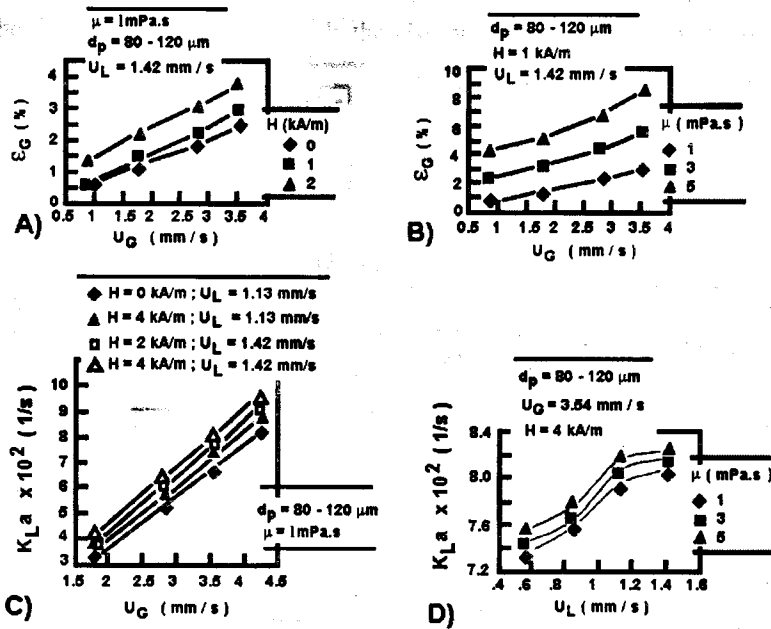


Fig. 34: Effect of operating conditions on the average gas holdup and gas-liquid mass transfer coefficient with Magnetization FIRST and Gas-Scan modes. After Li et al. (2006).

- Average gas holdup as a function of magnetic strength and gas velocity.
- Effect of liquid velocity on average gas holdup.
- Effect of superficial gas velocity on $K_L a$.
- Effect of liquid viscosity on $K_L a$.

In processes employing magnetic slurries the bed height, i.e. the depth of the G-L-S zone is a measurable parameter of the reactor. The observation of the bed expansion of Lu et al., designed as a phase diagram, is shown in Fig.35. The relative bed expansion based on 225 data points was correlated simply by

$$\bar{\epsilon}_G = 9.46 U_L^{0.2038} U_G^{0.06645} \exp(-0.003606 H) \quad (19)$$

with field intensity H in Oerstedts (Oe) ($1 Oe \approx 79.9 \text{ A/m}$) and missing information about the regimes spanned, i.e. velocity ranges of both U_L and U_G . Some experimental data are shown in Fig. 36.

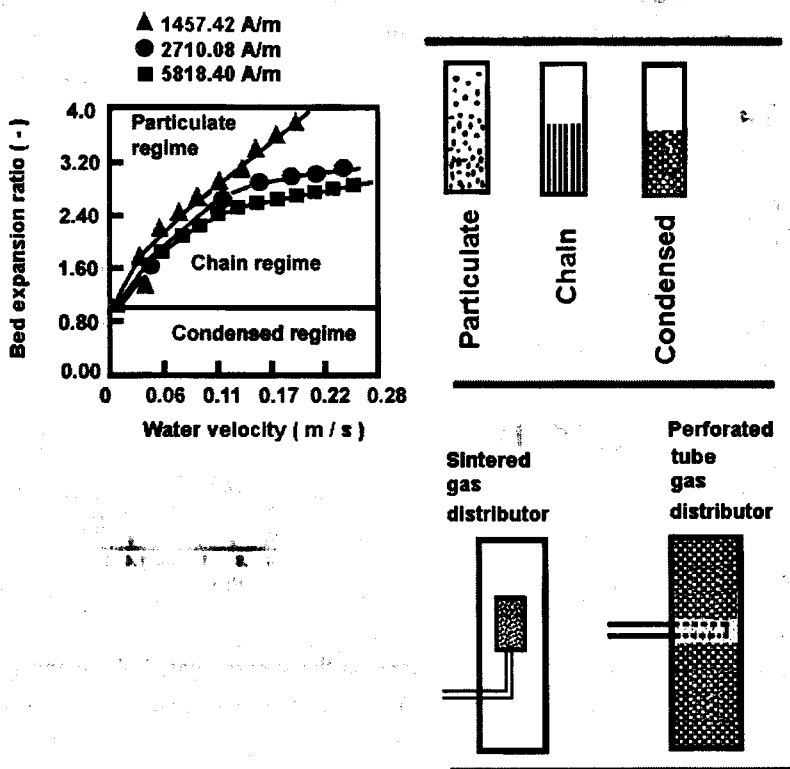


Fig. 35: Bed expansion diagram in case of co-current (Liquid Scan) flow and Magnetization FIRST mode. After Lu et al. (1999).

Inset: Gas distributor designs and schematic picture of gas mobility in the liquid.

4.2.4. Magnetization LAST : Co-current upflow

Mu et al. (1997) and Lu et al. (1999) especially address the bubble behaviour depending strongly on the field intensity. The picture in Fig. 37 illustrates observed bubble shapes with increase in field intensity. Non-magnetic (and low-field intensities) behaviour is similar to that of condensed beds (high-field intensity) with large bubbles and tendencies to form gas plug flow. These limiting regimes are characterized by inefficient effects of the solids on the bubble behaviour. This implies that at low field intensity the particle and the accidentally formed aggregates are too small to work as bubble beakers. The rising bubbles coalesce and with increase in gas velocity form large bubbles and slugs. High fields form condensed beds and bubbles escaping

their surfaces coalesce through the rise across the two-phase (liquid-gas) sections and form slugs.

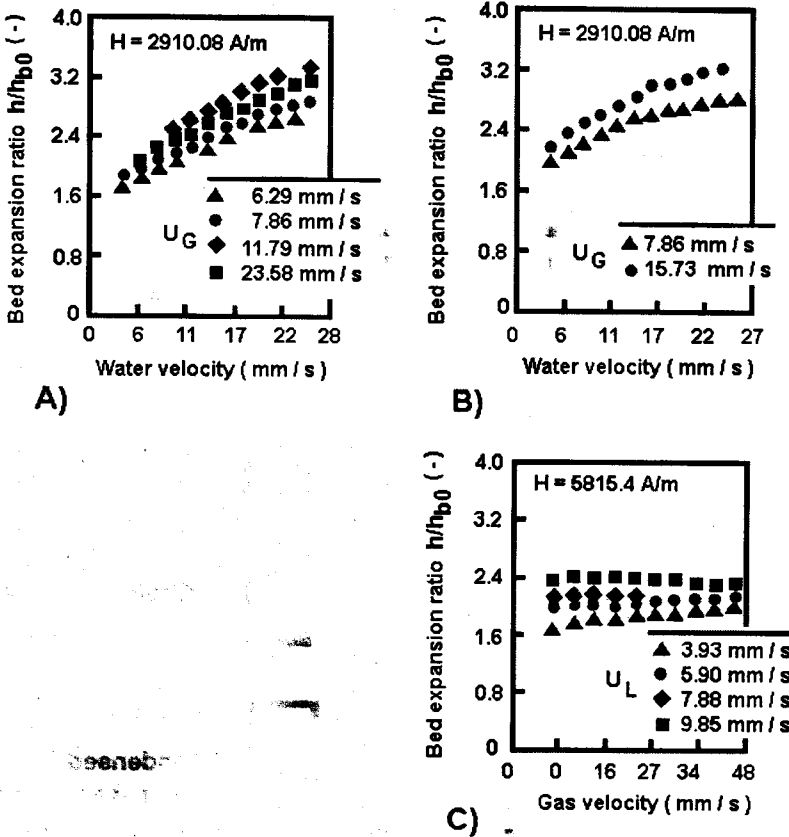


Fig. 36: Relative bed expansion in case of two types of gas distributors and Liquid-Scan or Gas-Scan co-current flows with Magnetization FIRST mode. After Lu et al. (1999).

- Relative bed expansion as a function of water velocity with “sandy” gas distributor at fixed gas flow rate (*Liquid-Scan* mode).
- Relative bed expansion as a function of water velocity with tube gas distributor at fixed gas flow rate (*Liquid-Scan* mode).
- Relative bed expansion as a function of gas velocity (*Gas-Scan* mode) with “sandy” gas distributor at fixed water velocity.

At moderate field intensities, that actually depends on the magnetic properties of the solid phase, the magnetic flocculation is strong enough and the aggregates are efficient tools in the bubble break-up process that immediately affects the gas holdup and mass transfer efficiency.

This short text collates all the published knowledge about Magnetization LAST mode and bubble slurry columns with co-current G-L flow. We might believe that further development of processes based on SRNA catalysts might be published and available for the readers in the future.

Field Intensity (Oe)	Bubbling in G-L system	Bubbling in magnetically assisted G-L-S system
33 - 100		 Particulate
133 - 230		 Chain
270 - 835		 Condensed

Fig. 37: Bed behaviour and bubble released above its surface. After Mu et al. (1997).

4.3. Closing comments about magnetically assisted slurry bubble columns

External magnetic fields are effective tools for remote control of G-L mass transfer through bubble break-up by flocculated magnetic particles. In this context, Magnetization LAST is more efficient with low-concentrated (< 10%) slurries than Magnetization FIRST mode. With addition of inner

magnetic material both magnetization modes could be applied successfully but bearing in mind the basic principle of G-L-S operations the efficient approach is Magnetization LAST.

The results published so far are scarce and unsystematic. The work done to collate this section and the analysis performed reveal that:

- No information exists about bubble behavior, local gas holdup, radial and longitudinal gas holdup profiles, etc.
- Axial magnetic field used with low-concentrated slurries leads to large waste of magnetic (electric) energy since short coils and solenoid assure homogenous fields over only 30 % of the column radius (see Part 1). The work of Zong (2007) provides data revealing that in spite of the increase in coil size the column diameter is restricted to 1/3 of the coil inner diameter
- Magnetically assisted SBCs are attractive devices calling for industrial applications since many existing (non-assisted by magnetic fields) units operates with magnetic catalysts such SRNA based on modified Raney-Nickel fine powders. The magnetic field assistance allows avoiding dangerous separation operations and contacting with air due to powder pyrophoric properties and high amount of hydrogen adsorbed at even used catalyst. The later implies that the field holds all particles in the working volume thus combining loading and separation operation in one volume (Krishna and Sie, 1994).

5. VERSIONS OF G-L-S MFAF

5.1. Trickle beds (Counter-current flow)

Magnetically assisted trickle beds (MATB) with co-current gas-liquid flow are new devices in focus of researchers in the last 2 years (Gui and Zhang, 2006; Li et al., 2007). These studies address directly overall mass transfer characteristic of the devices studied and information pertinent to bed hydrodynamics is scarce. Table 7 collates data about these experiments. Based on articles published so far we will comment the existing results end try to draw some ideas about future trends in this branch of MFAF. The experimental set-ups are sketched in Fig.38.

First of all, trickle bed operations need fixed particle structures (packing), so there are three potential regimes of MFAF assuring such conditions:

Table 7
Experimental conditions in studies performed with counter-current magnetically assisted trickle beds

Reference	Column	Magnetic field	Gas	Liquid	Solids	Operating mode	Magnetization mode	Problems studied
Gui and Zhang (2006)	Stainless steel column 100 mm ID 800 mm height	Axial (DC) Short solenoid: 300 mm ID 400 mm height $B_{\max} = 400 \text{ Gs}$	Flue gas With inlet temperature of about 250°C with SO_2 $2500 \text{ mg} / \text{m}^3$ Volumetric Flow rate $30 - 50 \text{ m}^3 / \text{h}$	Water-lime suspension with white lime: water ratio 1:20 Mole ratio Ca and S 1:38	Iron $220 - 450 \mu\text{m}$ $\rho_s = 7870 \text{ kg} / \text{m}^3$	Counter-current	Magnetization FIRST De-fluidized bed beds at various field intensities	Flue gas desulphurization
Li et al. (2007)	Plexiglas column 100 mm ID 1500 mm height	Axial (DC) Generated by a series of 7 short coils Each coil is 160 mm ID and 100 mm height	Air	Sodium sulphite (0.5 mol/l) aqueous solutions with CMC to control the viscosity within the range 1-5 mPa.s Surface tension: 54-72 mN/m	SRNA-4 amorphous Nickel alloy catalyst $120 - 200 \mu\text{m}$ $\rho_s = 2500 \text{ kg} / \text{m}^3$	Counter-current Gas Scan Liquid Scan	Magnetization FIRST like in Li et al (2006)	L-S mass transfer coefficient

- 1) Magnetically stabilized bed (MSB) with Magnetization FIRST mode with gas velocities beyond U_{mf0-G} but lower than the minimum fluidization point at which MSB breaks down;
- 2) Settled (de-fluidized) bed (SB) formed along the decreasing gas flow branch of the fluidization curve. Such beds have structures looser than those of the initial fixed bed and strongly dependent on the field intensity. The velocity range is limited from the above one by U_{mf0-G} (approximately).
- 3) Condensed (or frozen) beds (CB) formed at high field intensities with Magnetization LAST mode.

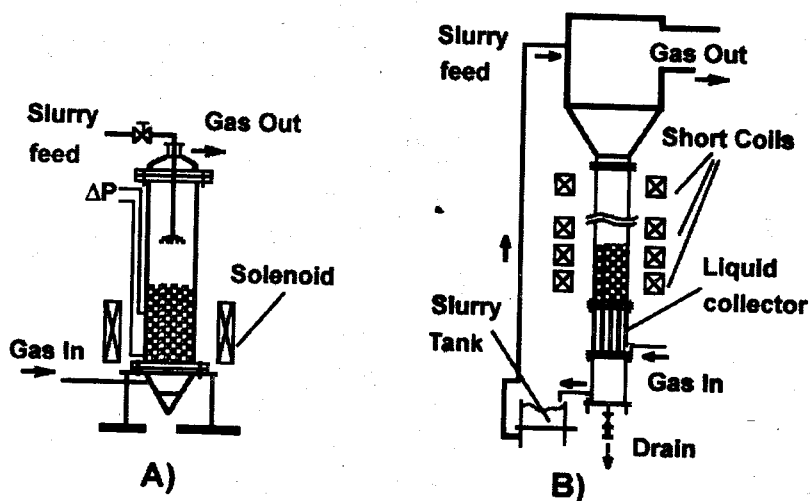


Fig. 38: Experimental set-ups used in trickle-bed experiments

a) Gui and Zang (2006)

b) Li et al. (2007)

Details in Table 7.

All these structures form themselves under concurrent orienting actions of magnetic field and fluid (gas) flow. Particles follow the field lines orientation and two of these beds, namely SB and CB have totally anisotropic structures while MSB's particle arrangements are between the initial (isotropic) structure and completely aligned particles.

In trickle beds (Carberry, 1976, p.592) the principle mass-transport resistances may exist in gas-film, trickling-liquid film, or within the porous

catalyst. As in the case of slurry reactions the gas-film resistance is usually negligible while the importance of liquid film and pore diffusion depend on the chemical reaction dynamism.

In view of these facts we have to decide which of the aforementioned packed bed regimes are suitable for trickle-bed operations with magnetic beds. Since the pore diffusion is pre-determined by the catalyst design the only task of magnetically assisted structures is to assure suitable development of liquid films over the particles and the particle aggregates as well. Intuitively, since no data from exact experiments exist, we might suggest that SB and CB assure loose structures with totally aligned particles with small channels between them. Unfortunately, these loose structure are very fragile, i.e. easily fluidizable, that limits from above both the gas flow rate and downward liquid flow. On the other hand, MSB structures are more stable mechanically than those of SB and CB due to incomplete particle arrangements along the field lines. Besides, MSB allows gas velocity range up to 4-5 times U_{mf0-G} (see Part 1). Obviously, the stability range should depend on the liquid flow and the liquid accumulated in the bed respectively.

These thoughts figure what we wish and how G-L-S magnetically assisted reactors have to be designed, but experimental data verifying these ideas are insufficient. Let us see what the present status in the field is. First, the experiments of Gui and Zhang (1996) only inform about the mass transfer efficiency in a hot desulphurization process. In general, these experiments were performed with Magnetization FIRST mode using SB fixed structure in an axial field. The data reveal increase in bed efficiency with variations in field intensity from 100 up to 200 Gs. Hence, with knowledge about the MFAF mechanics (see Part 1) this is a clear indication that development of loose structures with increase in field intensity enhances the gas-liquid mass transfer process. In this context, bear in mind that the depth of SB increases as the field intensity is increased (Part 1), Gui and Zang (2006) balanced the desulphurization efficiency and the operating costs (pumping power, electric power, etc.) that finally yielded an optimal operating condition at a field of 350 Gauss. In general, particle control in a magnetically assisted bed enhances the process from 29.56% in absence of particles, to 52.71% of an ordinary bed and beyond to 78.42% with magnetically assisted SB. The iron in the experiments of Gui and Zhang (2006) is a catalyst, so we may consider the entire process as L-S mass transfer enhancement since the particles react with liquid films over them.

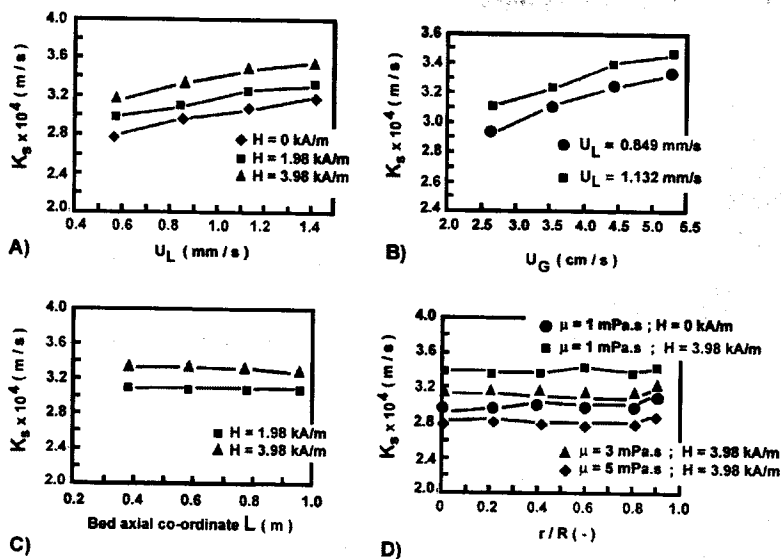


Fig. 39: Trickle-bed experimental data represented by the L-S mass transfer coefficient. Adapted from Li et al. (2007). Details in Table 7.

- Effects of liquid superficial velocity and magnetic field intensity on K_s with $U_G = 5.31$ cm/s.
- Effect of gas superficial velocity on K_s with $H = 3.98$ kA/m.
- Axial distribution of K_s with $U_L = 0.849$ mm/s and $U_G = 5.31$ cm/s.
- Radial distribution of K_s under the effect of different liquid viscosity and magnetic field intensity with $U_L = 0.849$ mm/s and $U_G = 5.31$ cm/s.

In the context of L-S mass transfer efficiency, the data of Li et al. (2007) reveal that increase in both the gas and liquid flow rates yields augmented L-S mass transfer coefficient (see Fig. 39). The particle alignment in homogenous structures imposed by the field homogeneity results in almost flat radial and axial profiles of K_s - see Fig. 39c, d.

It is hard to draw a general opinion about the present status of magnetically assisted trickle beds due to insufficient published data. However, it might suggest that the aforesaid thoughts could allow developing this new branch of MFAF.

5.2. Bubble columns with magnetic distributor plates (Co-current flow)

5.2.1. Foreword

All previously discussed bubble columns utilize magnetic systems covering almost entirely the fluidized beds. Alternatively, based on a short solenoid, a magnetic distributor plate (MDP) was developed by Ouyang et al. (Ouyang et al., 1990, 1992; Weng et al., 1990). The main idea comes from the magnetic distributor downcomers (MDD) discussed at large in Part 4 (Hristov, 2004). Schematically, MDP plays the role of a magnetically controlled plate at the bottom of a bubble column (see Fig. 40a, b) operating with a co-current mode (see the Fan's classification and that drawn here). The experimental conditions in these studies are summarized in Table 8. Two of the three available designs of MDD (collar, grate and adjacent type), i.e. the collar and grate one were investigated. Almost all published results address the collar type design (see Fig. 40a) placed above a pre-distributor of the gas made in a classical manner (perforated tube or porous plate: unfortunately no information is available in the works published).

The application of MDD with short solenoids means inherent radial and axial inhomogeneities of the fields generated by them. This immediately leads to non-homogeneous particle distribution with a solid phase concentration gradient oriented towards the column wall (i.e. the solenoid windings) as it is illustrated by Fig. 40b. Consequently, the pressure drop across the magnetic distributor is non-homogeneous in the radial directions and exhibits a minimum at the column axis of symmetry. Besides, the overall pressure drop depends non-linearly on gas and liquid flow rates with inexplicable maxima and minima (see Fig. 41). Both the inhomogeneous particle arrangement by the field lines and the radial dependence of the pressure drop affect the gas bubble generated –size, local concentration and rise velocity.

Table 8
Experimental conditions in studies performed with MDPs

Reference	Column	MDP	Gas	Liquid	Solids	Main problems studied
Ouyang et al. (1990)	No information provided but the results reveal it is the same as in Weng et al. (1992)	Grate type	Air and CO ₂	- Water - No information about the agent allowing variation in surface tension is available.	$< 1mm$ magnetic fields and $d_p > 3mm$ in absence of a field	Hydrodynamics Bubble size Gas holdup Liquid Mixing G-L-Mass Transfer
Weng et al. (1990)		Collar type	Air	Water	Magnetite/Ca-Alginate beads $d_{p(average)} = 210 \mu m$ $\rho_s = 1080 kg / m^3$	Hydrodynamics (Magn. LAST) Bubble size (visually-optical) fiber probe Gas holdup (electric conductivity method) Ethanol fermentation in 0.66 m (in height) pilot-scale three-stage bioreactor
Weng et al. (1992)	15 cm I.D. 100 mm in height	Collar type with iron mesh	Air	Molasses		

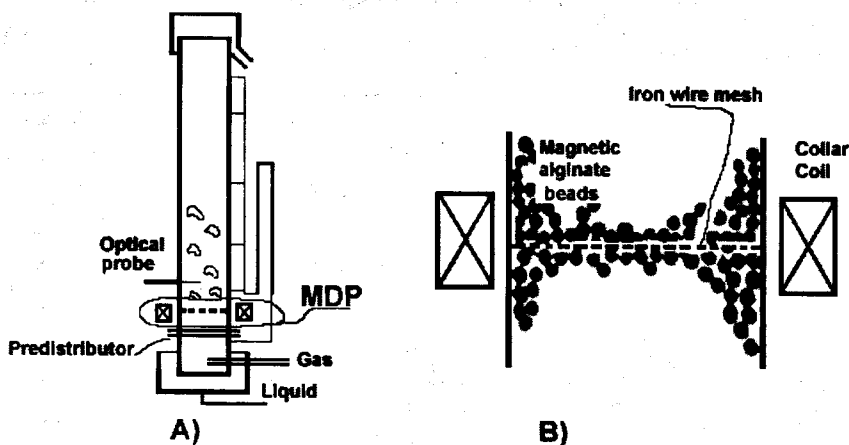


Fig. 40: Bubble column with magnetic distributor plate. After Weng et al. (1990, 1992).

- a) Bubble column-principle design (Weng et al., 1992).
- b) Magnetic Distributor plate (Weng et al., 1992).

Note: No additional details about the column design are available in the literature.

According to Weng et al. (1992) the gas passes essentially in plug flow and the average gas holdup increases with increase in the gas velocity. This result is obvious since at a short distance above the MDP the device becomes a conventional bubble column. The field (in fact the MDP design) affects the three-phase hydrodynamics in a short distance around the coil and the grid (an iron grid was used to hold the particles). Some topics of these studies will be commented next.

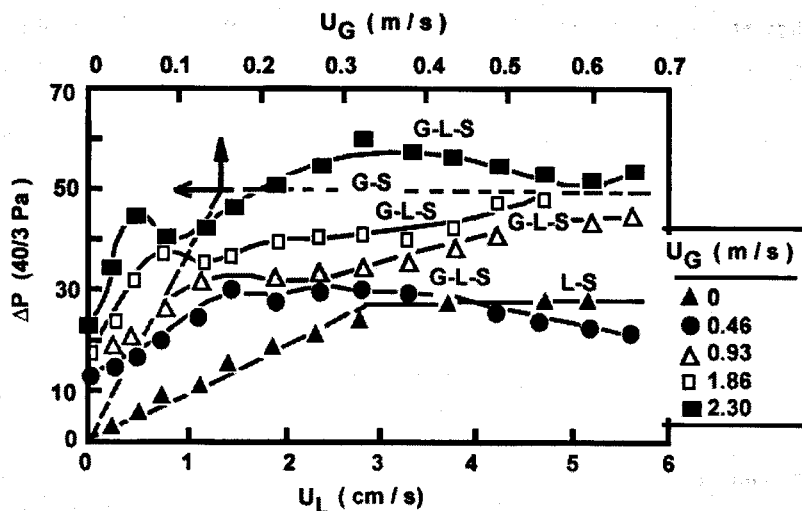


Fig. 41: Pressure drop across the G-L-S bed at different gas and liquid velocities. After Ouyang et al. (1990). The non-linear behaviour with respect to two-phase pressure drop curves (G-S and L-S) is obvious.

5.2.2. Phase holdups

Particle grouping into clumps near the column wall form a porous medium with holes (pores) finer than those formed by similar clumps at the MDP center. Since the initial bubble size depends on the nozzle size (diameter) the bubbles close to the wall are finer than those formed at the MDP center. Macroscopically this yields non-uniform distributions in the bubble diameter; bubble velocity and local gas holdup in the radial direction (see Fig. 42a, b). Increase in field intensity yields more uniform gas holdup distribution at field intensities up to 125 *Oe* but further increase in field strength causes non-uniformities in the radial gas distribution. The local gas holdup was modelled empirically by (Weng et al. 1990, 1992)

$$\varepsilon_{G(local)} = a_{MDP} \bar{\varepsilon}_g (1 - \Phi^2) \quad (20a)$$

The coefficient a_{MDP} depends on many process parameters, among them: bed diameter, liquid viscosity, field intensity, magnetic susceptibility of the

solids, etc. With constant bed diameter its dependence on the field intensity is approximated (Weng et al. 1992) as

$$a_{MDP} = 1.878 - 0.0036H \quad (20b)$$

The functional relationship $\varepsilon_{G(local)} = f(\Phi)$ is illustrated by Fig. 42c as a function of the dimensionless radial co-ordinate $\Phi = r/R$.

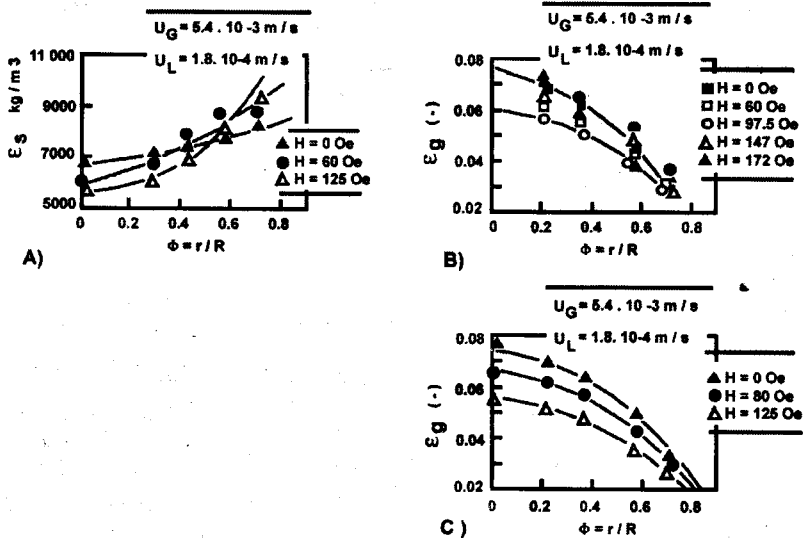


Fig. 42: Radial phase holdups as effect of the MDP design . After Weng et al. (1992)

- Field intensity effect on the solids holdup.
- Field intensity effect on the gas holdup .
- Field intensity effect on the gas holdup : experiments and approximations by Eqs. (20a,b)

The local pressure drop (relevant to the gas holdup) non-homogeneities yield liquid phase vortexing. Liquid vortexing is a result of large gas bubble rising along the column centerline and bubble coalescence, while near the wall (high pressure drop, dense particle packing and small bubble size) a homogenous bubbling (dispersed regime) takes place. In the region weakly

controlled by the field the vortex flows cause both liquid and solids backmixing.

5.2.3. Bubble characteristics and wake model of gas holdup

• Bubble size and rise velocity

Bubbles, as the main results of the proper work of the gas distributor, are at the same time the main tools for liquid mixing determining the gas-liquid mass transfer area. As mentioned above, due to radial field inhomogeneity a radial dependence of bubble size was observed. With $H < 125$ Oe the probability to form bubbles less than 2 mm increases as the field intensity is increased and can be approximated by Weng et al. (1990, 1992) as

$$\Gamma_{size} = 0.3056 + 0.00375H^{1.12} - 14.2U_G^{1.017} - 0.1754H^{1.12}U_G^{1.017} \quad (21)$$

The bubble rise velocity is related to the bubble size and in this context the low velocity bubble probability is

$$\Gamma_{low\ velocity} = 0.262 + 0.0115H^{0.92} - 22.76U_G^{1.008} - 1.006H^{0.92}U_G^{1.008} \quad (21a)$$

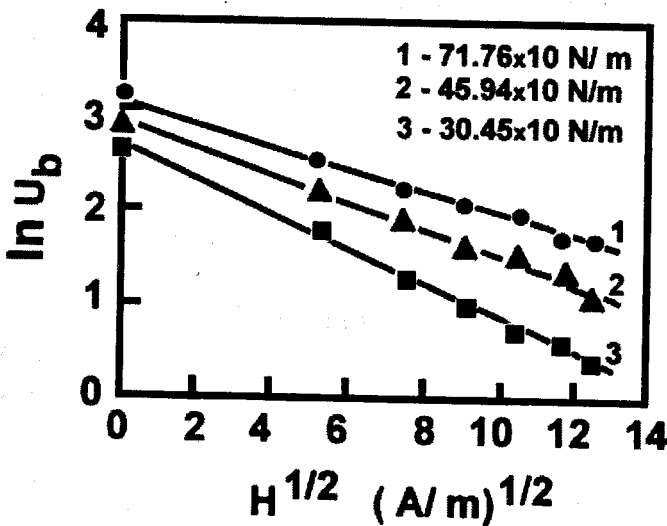


Fig. 43: Field intensity effect on the bubble rise velocity at different liquid surface tensions. After Ouyang et al. (1990).

Linear regression of experimental data, with reference to Kim et al. (1977), permits the bubble rise velocity to be expressed as (see Fig. 43)

$$U_b = (0.182\sigma + 10.02) \exp \left[\left(1.52.10\sigma - 2.18.10^{-2} \right) \sqrt{H} \right] \quad (22)$$

• **Bubble splitting mechanism**

The external magnetic field tends only to split bubbles into smaller ones, but not to eliminate them. In this context, a functional relationship between bubble diameter d_b and field intensity H is required, namely

$$f(d_{b(\max)}, H) = 0 \quad (23)$$

According to Ouyang et al. (1990) there exist three principle conditions:

$$\begin{array}{ll} d_b > d_{b(\max)} & \text{Bubbles will split} \\ d_b = d_{b(\max)} & \text{Bubbles remain stable} \\ d_b < d_{b(\max)} & \text{Bubbles will coalesce} \end{array} \quad (24)$$

A bubble could be splitup by cutting-in of particle wedge from the top. The force balance at the bubble top surface considers:

• **Magnetic force** $F_H = K_H H (H - H_d) d_b \quad (25a)$

$$K_H = \frac{2}{3} \pi k_H \mu R_L \quad (25b)$$

• **Surface tension** $F_\sigma = f(\theta) \pi d_p \sigma \quad (26)$

where $f(\theta)$ is a function of the contacting angle between the phases, usually taken as constant.

• **Gravity** $F_g = m_p g = \frac{\pi}{6} g \rho_s d_p^3 \quad (27)$

- **Pressure**

$$F_p = \frac{\pi}{8} \left[g (\rho_s \varepsilon_s + \rho_L \varepsilon_L + \rho_G \varepsilon_G) d_p d_b \right] \quad (28)$$

- **Drag**

$$F_d = K_D d_p U_b, \quad K_D = 3\pi k_D \eta_L \quad (29)$$

Then, the force balance of the particles resting on the top of the bubbles is

$$\sum F = F_M - F_\sigma - F_p - F_g - F_d \quad (30a)$$

and when

$$F > 0 \text{ the particles cut into the bubbles} \quad (30b)$$

$$F < 0 \text{ the particles do not cut into the bubbles} \quad (30c)$$

In accordance with this assumption the maximum bubbles diameter can be calculated from the condition $\sum F|_{db\ MAX} = 0$ that yields (Ouyang et al., 1990):

$$d_{b\ MAX} = \frac{K_D d_p U_b + f[\theta] \pi d_p \sigma - \frac{\pi}{6} g \rho_s d_p^3}{K_H H (H - H_d) - \frac{\pi}{8} g (\rho_s \varepsilon_s + \rho_L \varepsilon_L + \rho_G \varepsilon_G) d_p^3} \quad (31a)$$

where it is assumed that

$$H_d = k_1 U_G^{\alpha_1} U_L^{\beta_1} \quad (31b)$$

$$(\rho_s \varepsilon_s + \rho_L \varepsilon_L + \rho_G \varepsilon_G) = k_1 U_G^{\alpha_1} U_L^{\beta_1} \quad (31c)$$

with an empirical coefficient k_1 and exponents α_1 and β_1 (see Table 9)

A substitution of (31a) into (22) yields

$$d_{bMAX} = \frac{K_D d_p k_3 U_G^{\alpha_3} U_L^{\beta_3} (k_A \sigma + b_A) e^{(k_B + b_B) \sqrt{H}} - f(\theta) \pi d_p \sigma - \frac{\pi}{6} g \rho_S d_p^3}{K_H H \left(H - k_1 U_G^{\alpha_1} U_L^{\beta_1} \right) - \frac{\pi}{8} g k_2 U_G^{\alpha_2} U_L^{\beta_2} d_p^2} \quad (32)$$

The empirical coefficients are summarized in Table 9 and correspond to the plots in Fig. 44.

The visual observations (Ouyang et al., 1990) reveal that with a column and particles smaller than 1 mm the bubble diameter is about 9 mm in absence of a field ($H = 0$). With the range $0 < H < 80$ Oe the larger bubble begins to split into a multitude of smaller ones having almost equal sizes.

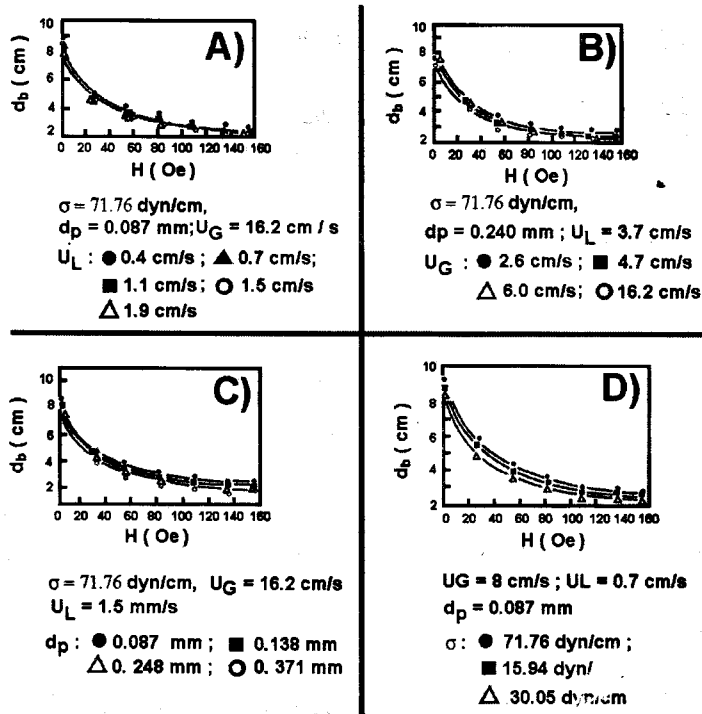


Fig. 44 Bubble diameter generated by MDP under various operating conditions. After Ouyang et al. (1990).

- Effect of varying liquid velocity
- Effect of varying gas velocity
- Effect of varying particle size
- Effect of varying surface tension

Table 9
Values of empirical coefficients in the bubble splitting model

$K_H = 2.54 \cdot 10^{-3}$	$f(\theta) = 4.25$	$K_D = -12.34$
$k_1 = 79.1$	$\alpha_1 = 0.532$	$\beta_1 = -0.0748$
$k_2 = 1.38$	$\alpha_2 = 0.424$	$\beta_2 = -0.0761$
$k_3 = 0.360$	$\alpha_3 = 0.470$	$\beta_3 = -0.0435$
$k_4 = 0.182$	$b_A = 10.02$	
$k_B = 1.52 \cdot 10^{-4}$	$b_B = -2.18 \cdot 10^{-2}$	

Note: All these coefficients have to be either dimensional or dimensionless. Unfortunately, the original source (Ouyang et al., 1990) does not provide the required information. The reader interested in details might evaluate the dimensions bearing in mind that all of them are in basic SI units.

• *Bubble Wake model*

The wake model of the bubble column with MDP under conditions imposed by low gas and liquid velocities is (Weng et al., 1992): i) The column is composed by a *bubble region*, *wake region* and *L-S fluidization zone*. ii) Variations in field intensity yield three fluidization regimes in the L-S fluidization zone: *particulate*, *chain* and *magnetically condensed*; that directly indicates Magnetization LAST mode. Besides, the wake region and the bubble move at the same velocity. Additionally, the RZE (Richardson-Zaki)-like power-law relationship (see (34) below) describes the L-S zone expansion. In accordance with the aforementioned assumptions we read

$$\bar{\varepsilon}_g + \bar{\varepsilon}_L + \bar{\varepsilon}_L = 1 \quad (33a)$$

$$\bar{\varepsilon}_L = \varepsilon_{fL} [1 - \bar{\varepsilon}_G - (1-x)k\bar{\varepsilon}_G] + (1-x)k\bar{\varepsilon}_G \quad (33b)$$

$$k = \left(0.61 + \frac{0.037}{\bar{\varepsilon}_G + 0.013} \right) (1 - \bar{\varepsilon}_G)^3 \quad (33c)$$

$$\frac{U_G}{\bar{\varepsilon}_G} - \frac{U_L}{\bar{\varepsilon}_L} = U_B + 2U_G \quad (33d)$$

where ε_{fL} is the liquid hold-up in the L-S fluidization zone. Further,

$x = \frac{\varepsilon_{WS}}{\varepsilon_{fS}}$ and $k = \frac{\varepsilon_W}{\varepsilon_G}$, where ε_{fS} is the solids hold-up in the L-S fluidization zone, ε_{WS} is the solids hold-up in the wake and ε_W is the wake volume (dimensionless) expressed through a porosity term.

Because the solids hold-up in the wake region is $\varepsilon_{WS} < \varepsilon_{fS}$ the assumption $x = 0$ takes place. Further, a modified Richardson-Zaki equation is established (Weng et al., 1992), namely

$$\frac{U_{fL}}{0.043 \exp(0.0621H)} = (\varepsilon_{fL})^{[3.84 \cdot \exp(0.327H)]} \quad (34)$$

Irrespective of the fact that it correlates experimental data, the relationship casts doubts about its physical consistency since *the fluid velocity scale is field-dependent*. Besides, in the context of the last discussion on the Richardson-Zaki scaling rules (Part 5), if the velocity scale increases with increase in the “external cause” (the field), this immediately yields augmentation in the R-Z exponent since these effects are inherent ones of the data fitting procedures. These computational effects are well demonstrated by (34) but this scaling approach is physically incorrect since *the velocity scale must be a field independent value*.

5.2.4. Fluidization of admixtures

Experiments with magnetic particles mixed with non-magnetic ones (Ouyang et al., 1990) with two types of particles distinguished with respect to the minimum fluidization (U_{mf-M} and U_{mf-N}) and terminal velocities (U_{t-M} , U_{t-N}) were performed, namely

- *Magnetic particles alone fluidized*

$$U_{mf-M} < U_0 < U_{t-M} \quad (35)$$

- *Fluidized admixture*

$$U_{mf-M} < U_0 < U_{t-M} \quad (36a)$$

$$U_{mf-N} < U_0 < U_{t-N} \quad (36b)$$

- *Magnetic particle unfluidized forming a packed bed (MDD)*

$$U_0 < U_{mf-M} \quad (37)$$

with fluidized non-magnetic solids

- Non-magnetic particles fluidized in the interstices of vertically aligned chains of unfluidized magnetic particles

$$U_0 < U_{mf-N} \quad (38a)$$

$$U_{mf-N} < U_0 < U_{t-N} \quad (38b)$$

The fluidization behaviour is schematically illustrated in Fig. 45a.

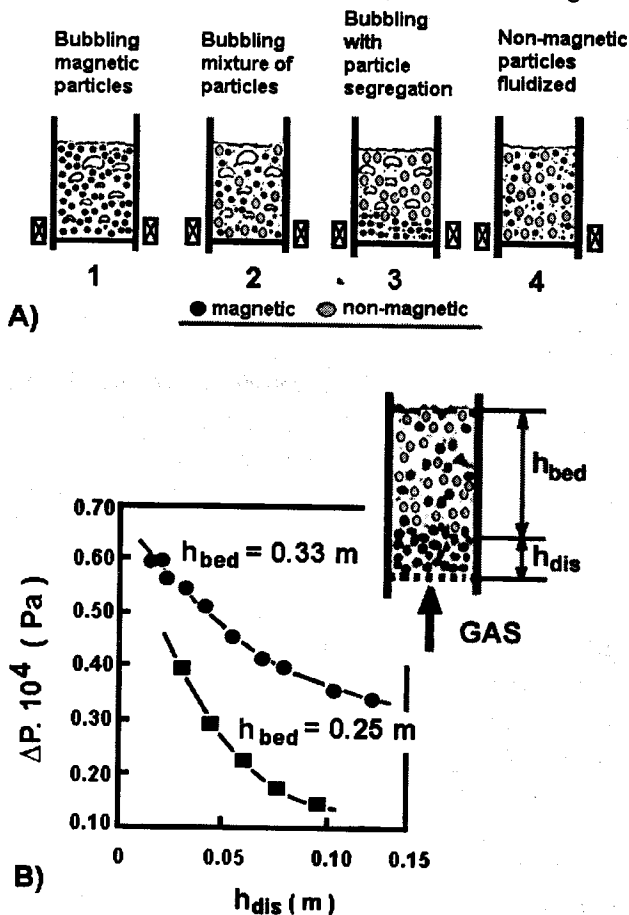


Fig. 45: MDP with admixture beds. After Ouyang et al. (1990).

- Fluidization behaviour
- Effect of unfluidized magnetic MDP on the fluidization quality represented by the overall pressure drop

Segregation criteria of the admixture under the experimental conditions of Ouyang et al. (1990) were chosen, namely

$$\text{Particles separated} \quad \frac{U_{mf-M}}{U_{mf-N}} > 2 \quad (39a)$$

$$\text{Particles mixed} \quad \frac{U_{mf-M}}{U_{mf-N}} < 2 \quad (39b)$$

$$\text{Magnetic particles mixed} \quad \frac{U_{mf-M}}{U_{mf-N}} < 1 \quad (39c)$$

In addition, the experiments (Ouyang et al., 1990) reveal that the height of the unfluidized magnetic MDD denoted as h_{dis} (distributor height) has a strong effect on the behaviour of non-magnetic particles fluidized above it (see Fig. 45b). There exists particle segregation along the bed height with nonmagnetic solids in the upper parts while the field collects the magnetic phase close to the bottom.

5.2.5. Multistage beds with MDP

Evidently the main idea of MDD is corrupted here since the field does not control the bubbles directly unlike the solid phase in the original devices (see part 4). However, the works of Ouyang et al. draw an idea addressing multistage magnetically controlled G-L-S beds (see Fig. 46). In fact, this is the idea of multistage magnetic distributor downcomers (Part 4) and, in general, the design of co-current plate based columns is widely encountered in the chemical and petrochemical industries. The main deficiency is the non-uniform field distribution imposed by the short solenoid design. The controlling parameters of the multistage beds are the fluid flow rate and the solids throughput (see for details Part 4), the bed height and the average solids retention time t_{s-ret} expressed as

$$t_{s-ret} = \frac{1}{4} \pi D_c^2 \rho_s (1 - \varepsilon_0) \frac{h_b}{G_{bed}} \quad (40)$$

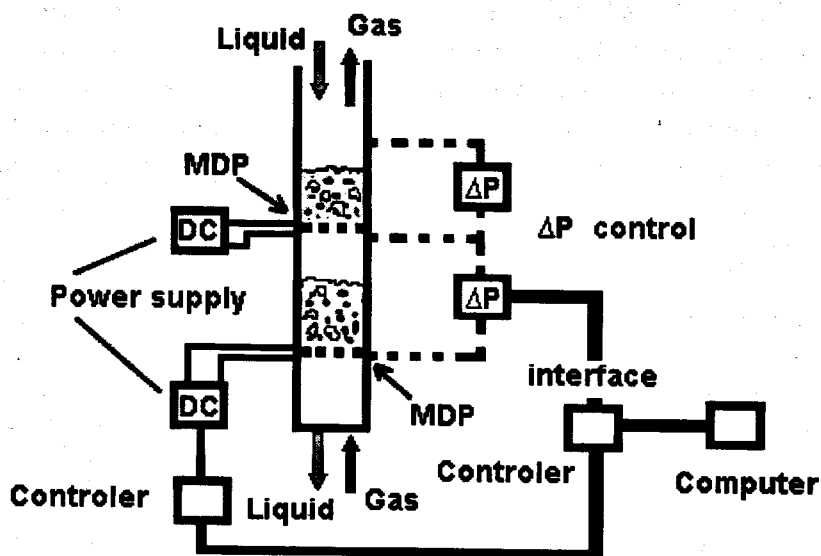


Fig. 46: Multistage magnetically controlled G-L-S beds with MDPs. After Ouyang et al. (1990).

5.2.6. Final Comments

Obviously, no matter of generalization could be found in these studies but they clearly demonstrate how the improper preliminary analysis (i.e. the preliminary mental experiments) and the lack of knowledge of the basic physics of magnetism and particle dynamics generate a practically useless device. Short solenoids have limited applications due to strong lateral inhomogeneities imposed on the particle arrangement that immediately limits the application to columns with diameters less than 100 mm either with single MDP or multistage devices.

The nice analysis of bubble splitting (Ouyang et al., 1990) is general and suggests a complete magnetic field control over the entire particle bed. However, in the case of MDP it is valid to the zone in the vicinity of the grid rather than to the area of active bubble-particle interaction above the plate. To this end, new magnetic systems have to be designed and the design should be a result of a preliminary analysis referring to *what is needed to perform the process* but not to the style: *let's take that and see what would happen*.

5.3 Rationale of Magnetically Assisted Bubble Columns - operation and design

This text tries to draw some basic rules pertinent to correct design and performance of magnetically assisted bubble columns. The review performed in the previous pages shows how different research groups developed the issues as well as the type of problems they have met. Classical bubble columns (Fan, 1989) are beyond the topic of the present discussion but they will be used as a background in the case of additional magnetic field assistance referring to control of magnetic solid phase.

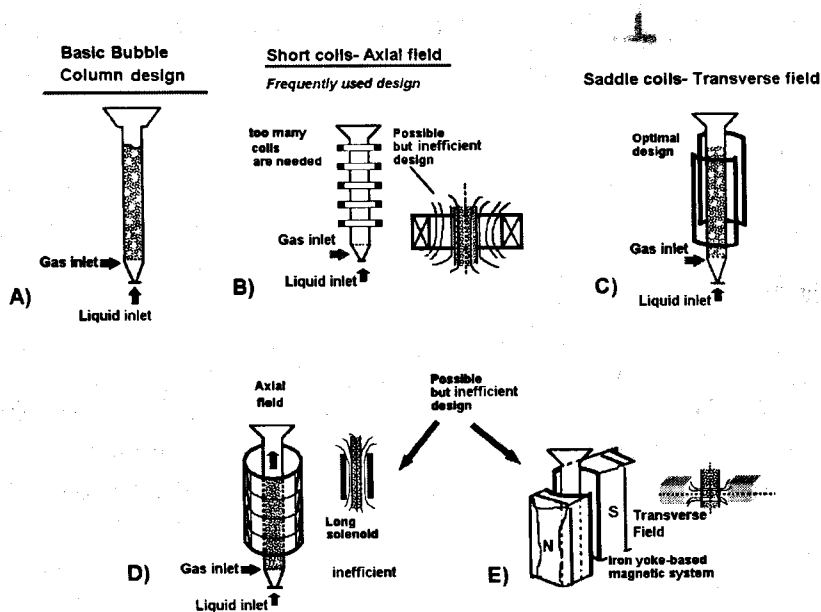


Fig. 47: Sketches of magnetically assisted bubble column pertinent to comments on the rationale of their design.

First of all, we have to bear in mind that magnetic fields act in short distances, so arranging a magnetic field surrounding a bubble column we might expect a device of narrow diameter comparing to the huge industrial counterparts. Hence, the magnetic assistance is invoked when:

- losses of precious magnetic catalysts are undesirable,
- the bubbling does not allow quite efficient suspension of fine solids,
- the liquid-solid slip velocity has to be increased but an upper limit imposed by low particle terminal velocity is imposed

- the process temperature is below the solid phase Curie's point, of course.
- The benefits of production of certain goods with magnetically assisted BC is so high, so the use of additional magnetic field, specific magnetic solids and sophisticated operating rules is a cost effective solution.

In the context of adequate design of devices some remarks will be drawn, among them (see Fig. 47 for relevant illustrations)

- The bubble columns are tall devices and the gas-liquid mass transfer depends on the pressure. The magnetic assistance has to be performed along the entire column length so an adequate preliminary analysis of magnetic system design has to be performed. In this context all axial field designed magnetic systems limit the column diameter within a 30% zone of coil (solenoid) radius close to the symmetry axis. The rest of the space inside the coil is unused and leads to energy waste. To this end the magnetic control of the entire column requires many short coils since the distance between two neighboring coils should be equal to the coil radius (the basic requirement to create a Helmholtz pair).
 - In this context we have two undesired limits with respects to column diameter inherently accompanied by an ineffective use of the magnetic field generated and the easily access to the device for process monitoring. These limits are inherent of axial magnetic systems. Certainly, we comment only systems based on short coils since they enable to enlarge the device by simple addition of new coils as the column height rises due to process requirements. Any single solenoids have no chance since they inherently limit the column diameter like the short coils but more undesirable issue is the totally missing access to the column wall. The waste of energy is also important since the field homogenous zone is limited not only along the radius but along the solenoid length as well. Iron yoke based magnetic systems like that used by Al-Qodah are quite inappropriate since they *do not meet* the requirements of adequate process design and performance outlined above.
- To this end the saddle coils used in some experiments reviewed here avoid almost all of the aforementioned problems since (see Fig. 47 too):
- 1) Efficient use of the space where the field is generated, i.e. the outside column diameter and the inner coil size are almost equal;
 - 2) Only two coils are needed instead numerous short counterparts;
 - 3) Large coil's "windows" allow easy access to column and process control.

- The basic knowledge about magnetic field generating devices (coils and solenoids) exists in the textbooks of physics, so correctly performed preliminarily analysis might avoid creation of inadequate experimental systems and industrial devices as well. Some of these comments are developed in the case of magnetically assisted airlifts (see 6.2.) too, so we refer to this text as an additional source of notes.
- Second and quite important problem in magnetically assisted column design is the organization of the fluid flows. To this end, the design is completely defined of the magnetization mode employed. With magnetization LAST mode, where all the solids are free suspended by the fluid flow and the field controls their mobility and aggregation only, all known designs from non-magnetic bubble columns are applicable. Obviously, the gas sparger design should enable production of small bubbles almost homogeneously distributed over the column cross-section.
- With Magnetization FIRST mode and required operations within MSB regimes, than is in fact a co-current G-L up-flow trough a packed bed, the gas and liquid flows should be premixed before entering the bed. This requires special design of the calming section if a supporting grid is used or use of supporting particle bed (Hristov and Hadzisavvas, 1997).
- The column should be non-magnetic, so potential problems concerning undesirable reactions of materials with process fluids have to be taken into consideration.

6. MAGNETICALLY ASSISTED AIRLIFTS

6.1 Foreword

Magnetically controlled airlifts form a relatively new branch in MFAF. The magnetic phase behaviour managed by the external field allows to control of several principle features pertinent to mass transfer operations performed by airlifts, among them: 1) Solids phase movements and consequently the liquid-solid slip velocity; 2) Gas holdup in the riser via liquid circulation velocity control and bubble break-up by the particle aggregates; 3) Remote liquid circulation control via the external field intensity affecting the particle bed hydraulic resistances.

Ten years ago Raja Rao et al. (1997) published a mass transfer oriented study with an internal-loop airlift controlled by an axial magnetic field (see

Fig. 48a). A year later Hristov (1998a) published his work on the magnetic field control of the liquid circulation in an external-loop airlift with a transverse field (Fig. 48b). These works were followed by a series of articles of Al-Qodah (Al-Qodah, 2000a, b; Al-Qodah and Al-Hassan, 2000) considering hydrodynamic regimes, bed expansion, gas-liquid mass transfer and antibiotic production (Al-Qodah and Lafi, 2001). Al-Qodah uses a system based on iron-yoke electromagnet with a limited height (see Fig. 48c) and to a great extent these works copy the style of Hristov (1998a) and Penchev and Hristov (1990a, b, c). Recently, studies on liquid circulation control, minimum stabilization, minimum fluidization conditions as well as flow transition were reported by Hristov (2005a, b).

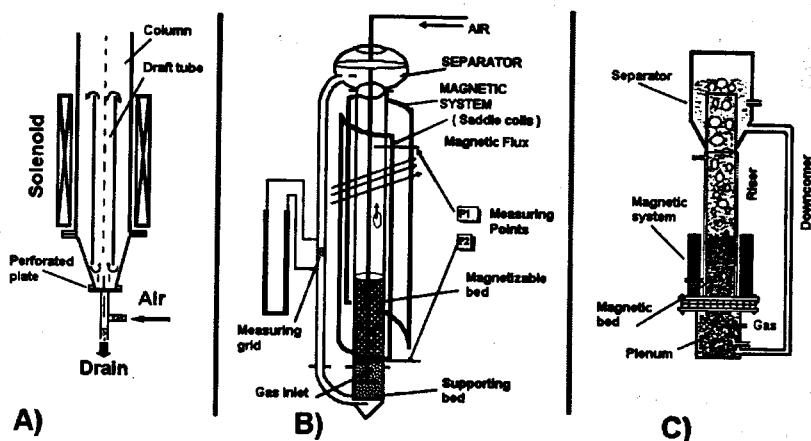


Fig. 48: Experimental set-ups of magnetically controlled airlifts

- Raja Rao et al. (1997)
- Hristov (1998-AL, 2005a,b)
- Al Qodah (2000a,b) ; Al Qodah and Al Hassan (2000)

All these works were developed independently (see Table 10) and to a greater extent they used the background of the gas-solids and liquid solids beds studied intensively during the past 45 years (Part 1, Part 5) taking into consideration the specific features of the airlifts, mainly: tall devices and inter-relation between the gas-flow rate and the liquid circulation velocity. The rationale of magnetically controlled airlifts is discussed next.

Table 10
Studies of magnetically assisted airlifts – experimental conditions

Work	Main problem	Field	Airlift	Liquid	Gas	Solids
Raja Rao et al. (1997)	Mass transfer	Axial Solenoid: 105 mm ID No information about the height but I might suggest it is less than the draft tube length	Internal-loop design Column: 91 mm ID and 700 mm in height Draft tube: 44 mm ID and 400 mm in height	Water based simulated Urea-Glucose wastewater with Phenol Water	Air	Microorganisms degrading phenol No magnetic solids as biosupports Bed support: Perforated plate
Al Qodah and Al Hassan (2000)	Hydrodynamics Phase holdup Mass transfer	Transverse Iron-yoke based electromagnet Pole height: 200 mm $B_{max} = 80 \text{ mT}$	External-loop design • Riser: 54 mm ID; 0.75 m in height • Downcomer: 0.18 mm ID; 0.75 m in height	Simulated water-based substrate for antibiotics production <i>P. Chrysogenum</i> Immobilized on magnetic beads	Air Introduced through a sintered gas distributor located below the supporting plate	Magnetic composites with Fe_3O_4 Cores covered by activated carbon (AC 1 and AC2) and zeolite (Z1): • AC1: $\rho_s = 3020 \text{ kg/m}^3$ $d_p = 0.9 \text{ mm}$ $B_s = 590 \text{ mT}$ • AC2: $\rho_s = 3230 \text{ kg/m}^3$ $d_p = 1.0 \text{ mm}$ $B_s = 590 \text{ mT}$ • Z1: $\rho_s = 3500 \text{ kg/m}^3$ $d_p = 1.1 \text{ mm}$ $B_s = 590 \text{ mT}$ Bed support: Perforated plate
Al Qodah (2000b)	Hydrodynamics Antibiotics production					
Al Qodah and Lafi (2000)	Modelling Experiments					
Hristov (1998a)	Liquid Circulation Friction factor	Transverse Saddle coils: 205 mm ID 1500 mm in height $H_{max} = 50 \text{ kA/m}$	External-loop design • Riser: 140 mm ID; 2.0 m in height • Downcomer: 50 mm ID; 2 m in height Without supporting plate; supporting granular bed is used	Water	Air Introduced through a draft tube into the bulk of the supporting granular bed	Fluidization: Metallurgical dross $\rho_s = 2100 \text{ kg/m}^3$ $d_p = 0.8 - 1.0 \text{ mm}$ $M_s = 0.050 \text{ kA/m}$ Supporting bed: Ammonia catalyst H Topsoe KM-1 $\rho_s = 5100 \text{ kg/m}^3$ $d_p = 1.8 - 2.0 \text{ mm}$ $M_s = 236.4 \text{ kA/m}$
Hristov (2005a)	Hydrodynamics Magn. FIRST mode Liquid Circulation Modelling Regime transition					
Hristov (2005b)	Minimum stabilization Minimum fluidization					

6.2. Rationale of magnetically controlled airlifts and design outcomes thereof

Airlifts are encountered in two principal designs (Chisti, 1989): external-loop airlifts (ELA) and internal-loop airlifts (ILA) schematically showed in Fig. 49a, b. The main process of solids fluidization takes place in the riser that primarily determines how the external magnetic field sources have to be implemented to a given airlift design. With two principle magnetic systems in hand that is an axial field generated by coils (or solenoids) and saddle coils for transverse fields, we can see how they can be applied to the existing airlift designs. The basic principle is that the field has to act efficiently upon the magnetic solids. The magnetic system has to create a homogenous field with minimum loss of energy and to affect as much as possible the mobility of the solids. Further, airlifts are tall devices and the magnetic system has to be built up in a way that will be able to control the entire reactor volume without inefficient consumption of energy and materials. The next comments will elucidate these thoughts helped by the illustration in Fig. 49.

Hence, with the axial fields for example, taking into consideration their principle feature to create homogeneous fields near the axial symmetry line, the most suitable airlift design is that with internal loop (ILA), i.e. the case in Fig. 49d similar to that developed by Raja Rao et al. (1997). Increase in the size of the vessel affects mainly its diameter, but the zone between the draft tube and the vessel walls is with completely inhomogeneous magnetic field. Hence, any particles that might escape from the draft tube and circulate in the external volume will be attracted towards the coil and immobilized at the vessel wall. Besides, the energy needed by the coil in its greater part is consumed to create a field in a zone (outside the draft tube) without magnetic particles that is a quite inefficient solution. Similarly, transverse field applications (see the example of saddle coils in Fig. 49f) meet problems with the inefficient use of volumes over which the magnetic fields are generated that are also useless designs. In general, the ILA design is inapplicable to magnetically controlled airlifts due the large volumes of the downcomers wasting magnetic field (axial or transverse) energy.

External-loop airlift design allows the solids to be concentrated in the riser only that is almost the same as in bubble columns and gas or liquid magnetically controlled beds (Part 1, Part 5). The conditions requiring minimized energy losses with maximum homogeneous zones may be

satisfied by the saddle coils only due to two principle features of their design: 1) Saddle coils (Fig. 49e) allow to extend the field zone over the entire reactor volume (the riser); 2) The field is homogenous up to 99 % of the inner coil radius that minimizes the volume of the inefficient zone and allows a homogenous particle distribution across the riser cross-section.

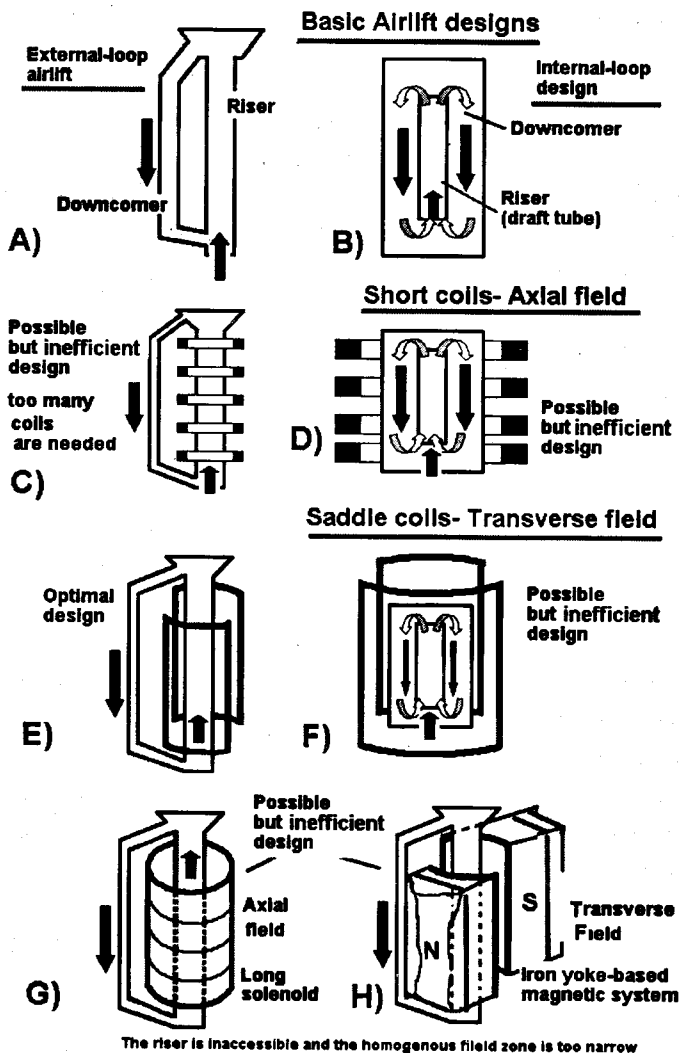


Fig. 49. Rationale of magnetically controlled airlift designs. *Present work: author's standpoint and development of the idea.*

The axial magnetic systems cannot compete in case of airlifts due to two principle deficiencies : 1) Narrow homogeneous zone (that requires narrow risers) and large inhomogeneous zone that consumes a lot of energy; 2) There is a need of a large number of short coils to cover the entire riser with a magnetic field (see Fig. 49c). Similarly, the employment of solenoids (Fig. 49g) makes the system useless since the riser is inaccessible for any auxiliary equipment and the process control is hard to be handled.

Any other magnetic systems based on iron yokes (like those of Al-Qodah) are quite inadequate since they can create fields only over a short range of the riser and have a narrow homogenous zone around. These magnetic systems were commented in details in Part 1. The only possible application is to small scale laboratory airlifts with shallow magnetic beds. Increase in both the column diameter and the bed depth yields enormous increase in the amount of iron required to build the magnetic systems. Further, these magnetic systems have narrow homogenous zones (about 30 % close to the symmetry axis) that limit in size the risers. The remaining gaps (between the riser and the poles) are empty and form the principle magnetic resistance (i.e. energy consumption) of the system. The above thoughts illustrated by Fig. 49 are additionally supported by Table 11.

6.3. Magnetically controlled airlifts – an analysis

According to the classification scheme the magnetic airlifts can operate with Magnetization FIRST mode with controlled gas-flow that resembles the *Gas-Scan* mode of the bubble column dynamics. On the other hand, Magnetization LAST mode is also applicable referring to solids motion and aggregations affecting the bubble break up with consequent effects on the liquid circulation and the gas-hold-up as well. The analysis performed next tries to follow the main idea of the present reviews and to allow a parallelism between bubble columns and airlifts. It addresses several principle problems, among them:

- **Magnetization FIRST/LAST mode**
- **Bed expansion/Collapse**
- **Minimum stabilization and fluidization conditions**
- **Liquid Circulation control, loop friction coefficient control and regime transition**
- **Bed porosity profiles.**

Table 11
Magnetic field systems and airlift designs – applicability to build magnetically controlled airlifts

MAGNETIC SYSTEM 	AXIAL	AXIAL	TRANSVERSE	TRANSVERSE
AIRLIFT DESIGN 	Short coils	Solenoids	Saddle coils	Iron-yoke based electromagnets
External-loop	- Advantages: 1) Easy to build the magnetic system - Disadvantages: 1) To many coils are needed 2) Difficult to arrange the experimental set-up because the magnetic 3) Strong axial fluid mixing imposed by the field lines	Inapplicable	Quite applicable - Advantages: 1) Easy to build the magnetic system 2) The magnetic field covers the entire riser 3) Low consumption of wire and energy 4) Homogenous field over the magnetic bed 5) Easy access to the working volume through the windows of the saddle coils.	Inapplicable Huge amount of copper and iron are needed. Small homogenous zone
Internal-loop	- Advantages: 1) Easy to build the magnetic system 2) Easy to arrange the set-up - Disadvantages: 1) Not too much coils are needed but their diameter should be too large. 2) Easy arrangement of the experimental set-up because the magnetic 3) Waste of energy in the zone occupied by the downcomer Applicable to small laboratory units	Inapplicable	Inapplicable due to waste of energy imposed by the large volume of the downcomer	Inapplicable Huge amount of copper and iron are needed. Small homogenous zone

6.3.1. Magnetization FIRST mode – bed behaviour

- **Observations (Hristov, 2005a,b)**

In an airlift, the liquid velocity depends on the gas flow rate in the riser. Despite the fact that the liquid is the fluidizing medium (the gas introduces the energy) due to the greater density and viscosity, the only independent variable is the gas velocity U_G . The state diagram $U_G = f(H)$ in Fig. 50 shows the principle regimes of the bed as the gas flow rate is increased. These regimes are shown schematically in Fig. 51. The initial bed plays a role of a fine gas distributor for the gas-liquid bubbling bed above it (Fig. 50) and it is stable up to the velocity U_{Ge} . At the point of U_{Ge} the bed begins to expand slowly, but without unrestricted mixing motions of particles. Thus, it demonstrates the well-known behaviour of a magnetically stabilized bed (MSB) in accordance with the Magnetization FIRST mode (Part 1). The upper limit of the stabilized bed is its breakdown at the fluidization onset, i.e. the velocity U_{Gmf} .

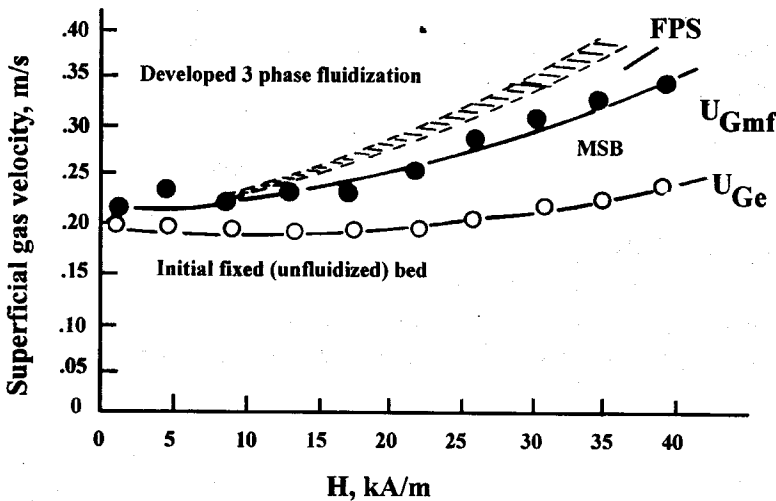


Fig. 50: State diagram of gas-liquid fluidized magnetizable solids in a transverse magnetic field. Metallurgical dross Initial bed height, $h_{bo} = 100$ mm. I- initial fixed (unfluidized) bed; II - MSB; III - developed three-phase fluidized bed; IV - three-phase fluidization of particle strings (chains of particles). After Hristov (2005a).):

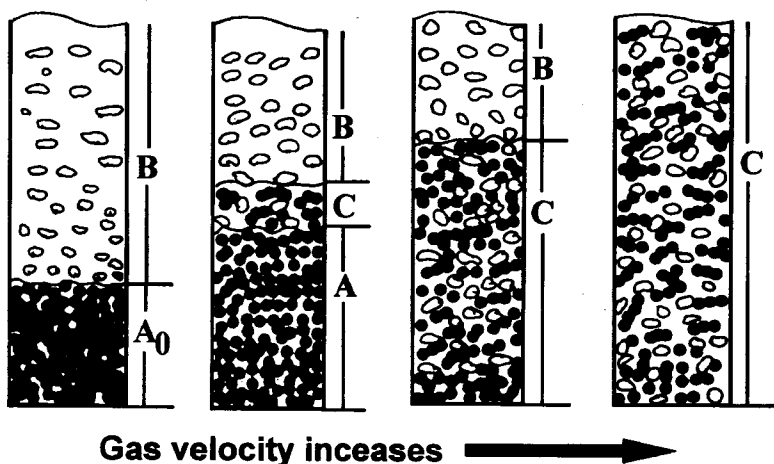


Fig. 51: Bed behaviour -schematically (Hristov, 2005a):

A_0 - Initial static bed; A - stabilized bed; B- two-phase (gas-liquid) section; C- three-phase (gas-liquid-solid) fluidized section

The bed expansion curves are shown in Fig. 52. After the fluidization onset (velocity U_{Gmf}) the bed height increases with the increase of the gas velocity. In the regime of developed fluidization the bed height reaches 3 to 8 times the initial fixed bed height. This is similar to that one obtained with a transverse magnetic field where fluidization is carried out by gas (Part 1) or liquid (Part 5). At higher gas velocities, *no bed contraction was observed* as it is seen in non-magnetic fluidization (Fan, 1989). This can be attributed to the field homogeneity in the axial direction (due to the coils extension along the entire riser length) and to the field orientation transverse to the fluid flow.

The weak decrease in the bed height with increasing in the gas velocity at $U_G < U_{Ge}$ is due to the detachment of the top layer of particles by gas bubbles bursting at the A/B interface (see Fig. 51a). This forms a thin zone C (Fig. 51b) with weakly fluidized particles, without a fluidization of the entire particle bed. This phenomenon cannot be suppressed by the increased field intensity, but it does not affect significantly the fluidization behaviour. It will not be discussed further here.

In an airlift the liquid circulation depends on the gas velocity (Fan, 1989) and the gas hold-up in the riser. One could suppose that the hydraulic resistance of the initial static bed (or the stabilized bed) is greater than that of the two-phase bubbling section. Thus, the bed resistance determines the

liquid circulation velocity: experimental data at various field intensities are presented in Fig. 53a. From the data plotted it follows that at low and medium field intensities the increase of liquid velocity is parallel to increase of the gas flow. These results (see Fig. 54) are similar to the results obtained in airlift reactors without magnetic fields (Chisti, 1989) and resemble slightly the results of Al-Qodah (2000a, b)-see Fig. 53b. However, some opposite effects occur at higher field intensities, which can be explained by the bed structure and the liquid hold-up data.

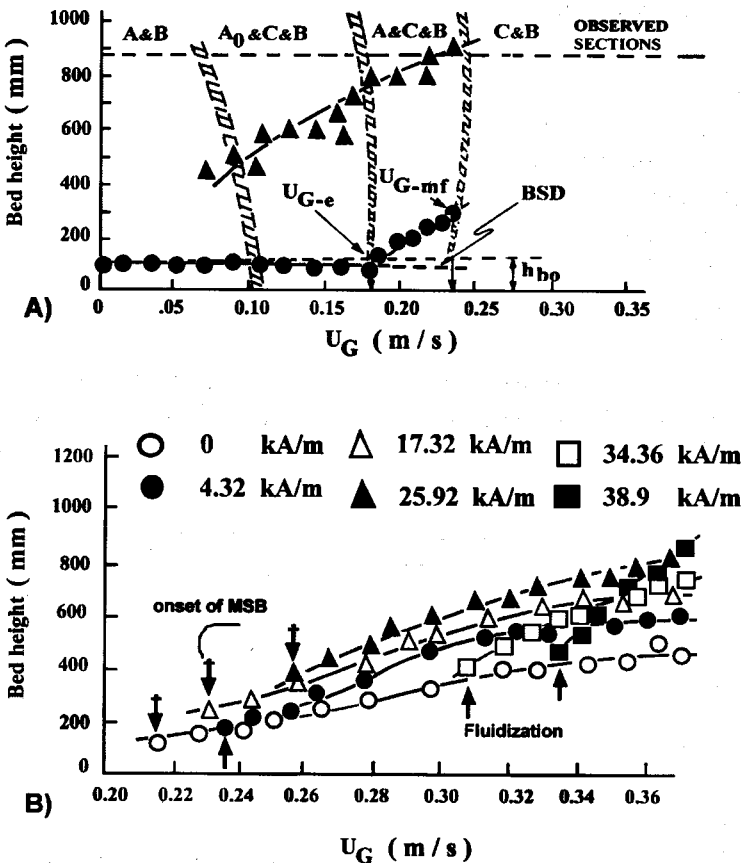


Fig. 52: Bed expansion: a) Stabilized bed expansion characteristics (Hristov, 2005a): Circles- the evolution of the A₀/B interface; Triangles- the evolution of C/B interfaces. Metallurgical dross, Initial bed height, h_{b0} = 100 mm.

In the external-loop airlift discussed here (i.e. the device investigated by Hristov, 2005a, b) there is a particle bed with controllable packing situated near the joint between the downcomer and the riser. It is clear that the hydraulic resistance of that bed will influence the liquid circulation rate along the reactor loop, or in other words the particle bed contributes to the total friction factor of the airlift (Chisti, 1989). The bed expansion and the relevant hydraulic resistance of the magnetized bed depend on both the liquid and the gas velocities that are interrelated. The gas velocity will be used as a unique independent parameter to further explain the complex phenomena affecting the liquid circulation velocity.

Generally, at low field intensities, increasing in gas flow rate decreases the apparent density of the gas-liquid mixture in the riser due to the increased gas hold-up, so the liquid circulation rate increases. Moreover, the increasing gas velocity leads to an expansion of the packed bed, as well as to consequent bed stabilization and decreasing hydraulic resistances or friction factors respectively. This is valid for all the regimes observed for the solid phase (static bed, stabilized bed and fluidization).

However, at high fields the bed remains packed in two regimes: static bed and MSB. In the former bed the increasing gas flow required for the onset of MSB (due to the increased magnetic interparticle forces) diminishes the liquid hold-up in it. Beyond a certain value the volume fraction of gas in interstices of MSB is so high that the bed is practically "dry" and little liquid flows from the downcomer via the bed toward the riser. In other words, the gas pressure inside the particle bed is greater than the hydrostatic pressure produced by the liquid in the downcomer, so the liquid flow practically stops. Under such conditions, the airlift is close to a bubble column. Al-Qodah (2000b) has commented this phenomenon because of the interpretations of Livingston and Zang (1993). The situation is known as the regime of "stalled" bed of the solid phase (Douek et al., 1995; Livingston and Zang, 1993). According to Al-Qodah (2000b) the pressure drop between the riser and the downcomer is not sufficient to create a liquid circulation. However, this explanation is incomplete. Upon the regime of a "stalled" bed, the gas hold-up in the riser is higher than that under the conditions of a normally circulating airlift. Thus, the driving pressure drop would be greater in the case of a "stalled" bed. However, the inlet gas pressure is so high that it practically stops the liquid inflow from the downcomer. Macroscopically,

these results confirm those obtained with airlifts using mechanical valves in downcomers (Verlaan, 1987; Bendjaballah et al., 1999).

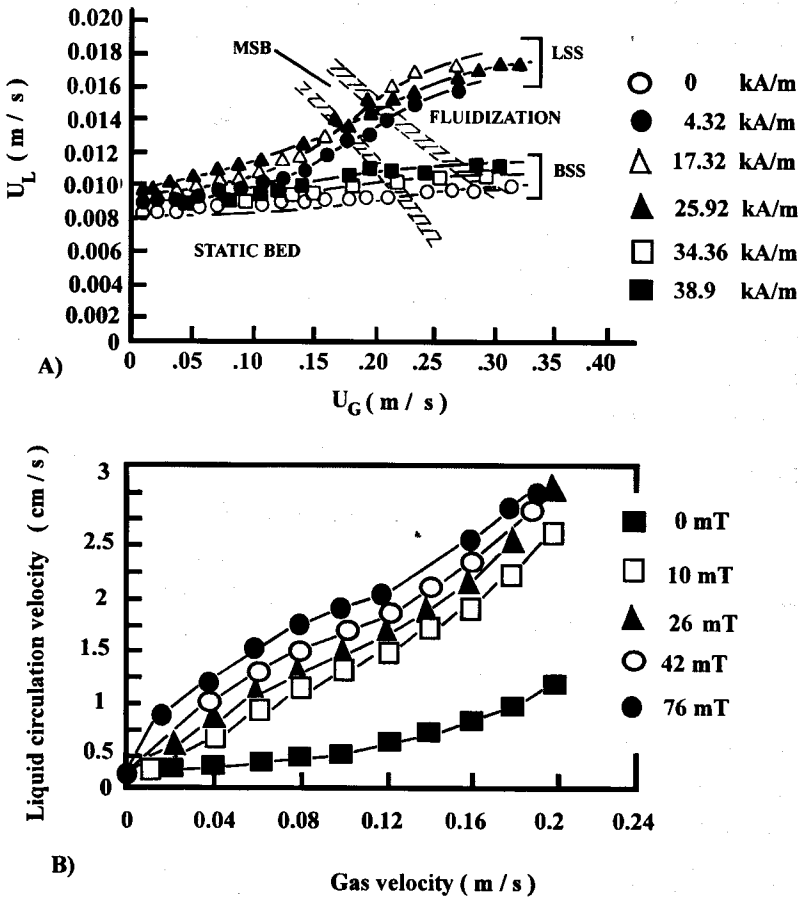


Fig. 53: Liquid circulation velocity as a function of the gas superficial velocity in the riser. a) (Hristov, 2005a): Metallurgical dross, Initial bed height, $h_{bo} = 200$ mm. b) Al Qodah (2000a,b). Note: The figure was redrawn electronically by the present author due to the low quality of the published original.

The above briefs explain the complex phenomena controlled by two independent physical actions on the particle bed: the gas flow and the magnetic field. In order to present the explanation in a more acceptable form an equivalent electric scheme of the airlift is shown in Fig. 55.

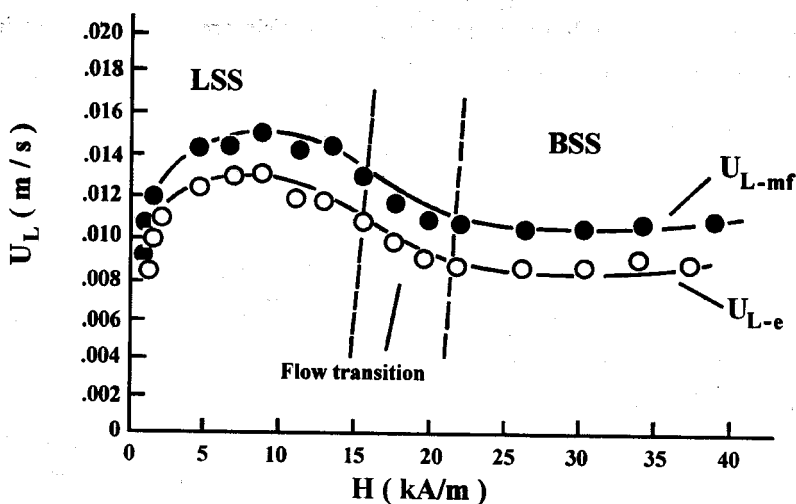


Fig. 54: Liquid velocity as a function of the magnetic field intensity (Hristov, 2005a). For the corresponding gas velocity and other details refer to the state diagram in Fig. 53a. The flow regimes were determined visually and classified in accordance with the taxonomy of Epstein (1981).

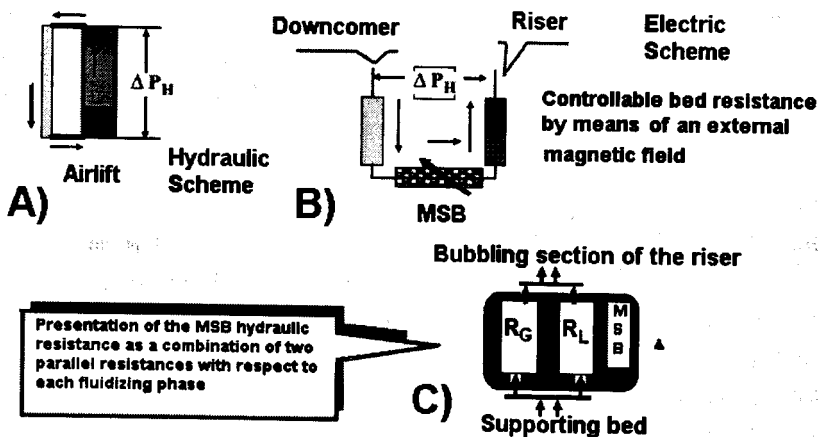


Fig. 55. Schematic presentation of the hydraulic resistance of the airlift loop (Hristov, 2005a):

- a) Hydraulic scheme; b) Electric scheme; c) MSB resistance presented as two single-phase resistances.

6.3.2. Minimum fluidization points with Magnetization FIRST mode: visual detection and simple correlations

The minimum fluidization point was determined when the increasing gas-liquid upflow starts to destroy the expanded stabilized bed, as shown in Figs. 56a,b,c. The minimum fluidization velocity of the gas phase, U_{G-mf} , increases monotonically with field intensity, as shown in Fig. 56a, while the corresponding liquid velocity exhibits strongly non-linear behaviour, as shown in Fig. 56b, possibly due to the changing regimes of the airlift device (see comments below and in 3.5.2, too). The correlation between the critical gas and liquid velocities is illustrated by Fig. 56c, which confirms the classical method of Fan (1989). Three regions of the curve are worth commenting: i) the initial increase of the minimum liquid fluidization velocity within the range of relatively low field intensities ($H \leq 9 \text{ kA/m}$) can be attributed to the increased stability of the interparticle contacts; ii) as gas velocity increases (within the range of moderate field intensities) the descending curve confirms the classical results of non-magnetic three-phase fluidized beds (Fan, 1989); iii) beyond a certain field intensity ($H > 25 \text{ kA/m}$) the minimum liquid fluidization velocity increases again, possibly because of stronger interparticle contacts or due to increased gas hold-up of the expanded stabilized bed (Hristov, 2005). The latter implies that at such high gas velocities the expanded bed is relatively "dry", and the gas pressure hinders the liquid inflow from the downcomer into the magnetic bed. Therefore, at both low and high field intensities liquid circulation velocity is so low that the device operates most likely as a bubble column (Hristov, 2005a).

The processing of the descending part of the curve (airlift regime) of Fig. 56c yields the following empirical correlation for minimum fluidization (Hristov, 2005b):

$$U_{L-mf} = 0.009 (U_{G-mf})^{-1.875} \quad (41)$$

in the field intensity range of $4000 \leq H \leq 2600 \text{ A/m}$

A similar data processing of the corresponding velocities U_{L-e} and U_{G-e} in the descending part of the liquid velocity curve (see Fig. 56d) yields the following correlation for the onset of MSB, (Hristov, 2005b):

$$U_{L-e} = 0.0073 (U_{G-e})^{-0.333} \quad (42)$$

in the range $9000 \leq H \leq 2600 \text{ A/m}$

These are simple data correlations apart from the examination of particle material properties and field intensity effects. More detailed correlations are performed in 6.3.3

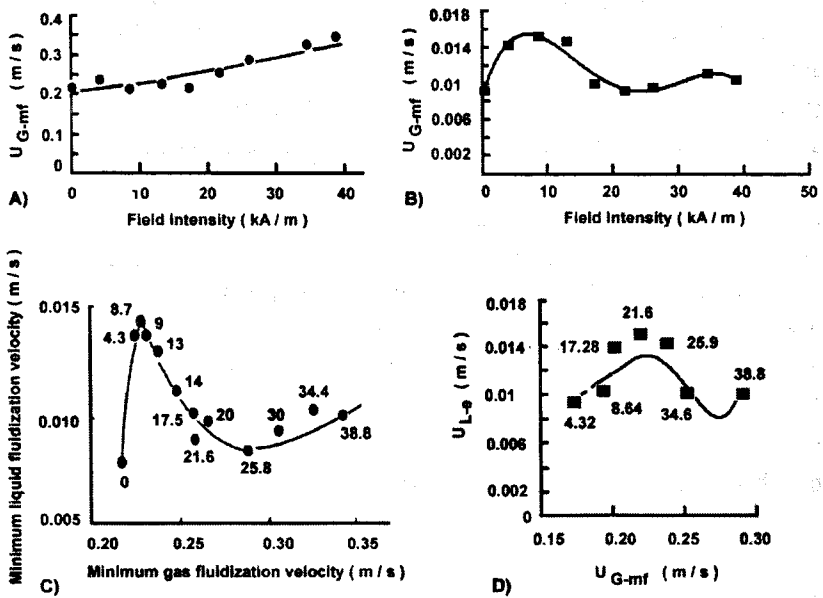


Fig. 56: Minimum fluidization velocities by visual detection (Hristov, 2005b)

- Minimum gas fluidization velocity as function of field intensity.
- Minimum liquid fluidization velocity as function of field intensity.
- Minimum liquid fluidization velocity (U_{L-mf}) as a function of minimum gas fluidization velocity (U_{G-mf}).
- Minimum fluid velocities at the onset of stabilized MSB:

$$U_{L-e} = f(U_{G-e})$$

Notes: i) Metallurgical dross: Initial bed height, $h_{bo} = 170 \text{ mm}$; ii) Solid lines in sub-figures a, b, c and d are only aids, generated by high-order polynomials, for better understanding of trends; iii) Number near labels in sub-figures c and d indicate applied field intensity.

6.3.3. Transition points - graphical data processing (Hristov, 2005b)

In the absence of a magnetic field, the onset of three-phase fluidization corresponds to the point at which the bed begins to expand (Fan, 1989). However, this approach is not applicable here since when the MSB expands, it remains structured and fixed, and not fluidized. This approach is however suitable for determining the onset of MSB (velocity U_{G-e}) only. Obviously, as it was proven (Hristov, 2005a) that at its transition points, the magnetizable bed changes its internal structure, i.e., its hydraulic resistance, thus affecting the liquid circulation velocity-see Fig. 57a. These facts motivated Pozarac and Petrovic (1988) to develop a simple graphical method for non-magnetic three-phase airlifts by noting that at the onset of fluidization the slope of the U_L-U_G curve changes as shown in Fig. 57b). Physically, this means that beyond minimum fluidization the bed expansion results in decreasing liquid velocities due to increasing hydraulic resistance. Thus, at this transition point the derivative $\partial U_L/\partial U_G$ changes. This simple fact is the basis of the graphical data processing utilizing two straight-line approximations of the sections of the experimental U_L-U_G curve: the section of the packed bed and the section of the fluidized bed. The intersection of these line segments defines the minimum fluidization point. This method is termed the "*two-line method*" (Hristov, 2005b).

Both physics and observation reveal two critical points of transition with changing bed structures for the *onset of MSB* and at *minimum fluidization*. The experimental points of the *S-shaped* curve of Fig. 57a (Hristov, 2005b) can be approximated by three straight-line sections corresponding to *initial fixed bed*, *MSB* and *fluidized regime* as it is illustrated by Fig. 57b. The intersections of two of these three sections define the two transition points: MSB (velocities, U_{L-e} and U_{G-e}) and minimum fluidization. Hence, following Posarac and Petrovic (1988), this technique is termed a *three-line method* (Hristov, 2005b).

6.3.4. Transition points - results provided by the three-line method

Values of U_{G-e} (U_{L-e}) and U_{G-mf} (U_{L-mf}) determined visually and by the three-line method are presented in Table 12 and Fig. 58. The three-line method somewhat overestimates (see Fig. 58) the visually determined values of the critical velocities and there is a systematic error depending on field intensity. Precisely, this implies that the graphical method accumulates errors with decreasing slopes of the experimental curves as the field intensity is

Table 12
Critical velocities in the airlift riser. Initial bed height = 150 mm. After Hristov (2005b)

H kA/m	$U_{G-\bullet}$ m/s		$U_{L-\bullet}$ m/s		U_{G-mf} m/s		U_{L-mf} m/s	
	graphical	visual	graphical	visual	graphical	visual	graphical	visual
0	0.198	0.190	0.008	0.12	0.217	0.200	0.008	0.011
4.32	0.217	0.200	0.014	0.016	0.235	0.230	0.014	0.018
8.64	0.198	0.170	0.014	0.016	0.225	0.240	0.015	0.022
12.96	0.235	0.170	0.014	0.017	0.235	0.230	0.014	0.020
17.28	0.217	0.200	0.100	0.013	0.217	0.225	0.10	0.015
21.60	0.180	0.198	0.0087	0.12	0.253	0.230	0.093	0.010
25.92	0.217	0.220	0.093	0.013	0.289	0.250	0.096	0.11
34.36	0.253	0.220	0.0101	0.012	0.325	0.300	0.0109	0.012
38.88	0.289	0.250	0.0104	0.0125	0.343	0.320	0.0104	0.015

increased (see Fig. 53a and Fig57a) albeit the acceptable error under 8% in U_{G-mf} determination.

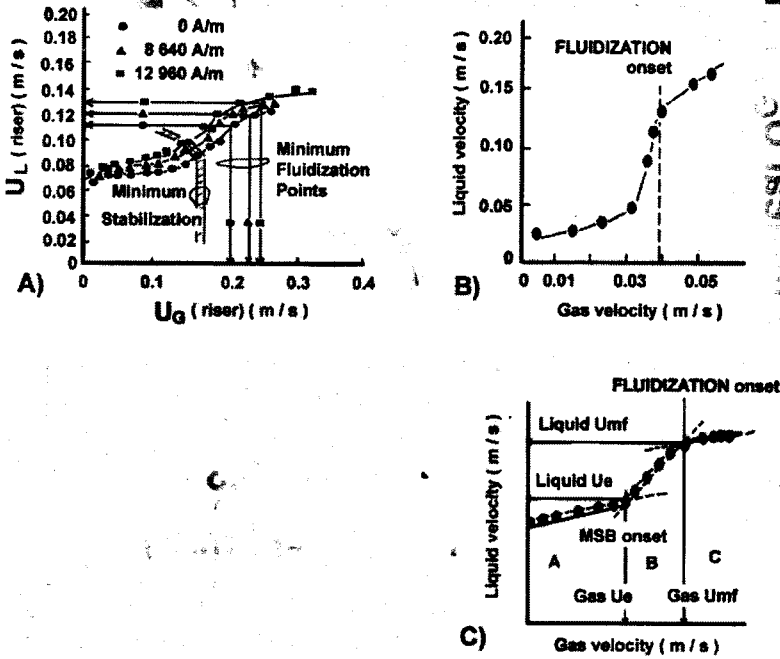


Fig. 57: Determination of critical velocities –experimental data and basic idea of the graphical method. After Hristov (2005b).

- Liquid circulation velocity as a function of superficial gas velocity in the riser. After Hristov (2005b).. Metallurgical dross; Initial bed height, $h_{bo} = 200$ mm.
- Graphical method of Pozarac and Petrovic (1988) adapted from original work
- Graphical method developed in Hristov (2005b). Dotted lines approximate sections corresponding to *initial static bed*, *stabilized MSB* and *fluidized bed*

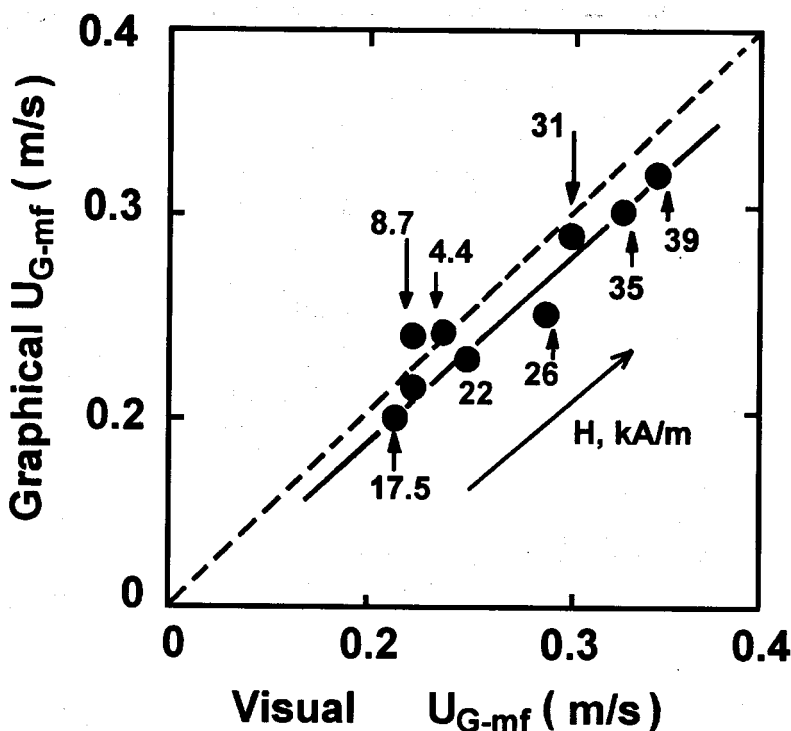


Fig. 58: Parity plot of visual observations and results obtained by graphical three-line method. After Hristov (2005b). Metallurgical dross: Initial bed height, $h_{b0} = 120 \text{ mm}$. Arrows indicate magnetic field intensities.

6.4. Critical velocities - dimensionless relationships

6.4.1. Minimum fluidization point

The simple pressure-balance model of Onken and Trager (1990), provides that

$$U_L = \Omega U_G^{ng} \quad (43)$$

where Ω is a dimensionless friction coefficient (Hristov, 2005a). This classical relationship is usually expressed as (Bello, 1981 and Bello et al., 1984)

$$U_L = \omega (A_d / A_r)^m U_{Gr}^{0.44} \quad (44)$$

where the dimensionless term $\omega (A_d / A_r)^m$ represents the friction factor of the airlift loop.

The analysis of Hristov (2005b) proposes the following relationship between the critical velocities at the two transition points, so it will be convenient to express the velocity correlations as:

$$\frac{U_L}{U_L|_{H=0}} = \Omega_M \left(\frac{U_G}{U_G|_{H=0}} \right)^{n_g} \quad (45)$$

where Ω_M represents the cumulative effect of the magnetic field on the loop hydraulic resistance (Hristov, 2005a,b). Taking into consideration the non-linear relationship noted earlier the ascending and descending sections of the curve in Fig. 56c were processed separately to result in the following relationships for the ascending section of the curve, i.e. $dU_{L-mf} / dU_{G-mf} > 0$:

$$\frac{U_{L-mf}}{U_{mfo}} = 1.0817 \left(\frac{U_{G-mf}}{U_{G-mfo}} \right)^{5.44} \quad (46)$$

and for the descending section of the curve, i.e. $dU_{L-mf} / dU_{G-mf} < 0$:

$$\frac{U_{L-mf}}{U_{mfo}} = 1.587 \left(\frac{U_{G-mf}}{U_{G-mfo}} \right)^{-0.804} \quad (47)$$

6.4.2. Minimum stabilization point

It is well documented that the fluid velocity required to transform a fixed bed into MSB increases with the increasing field intensity (Part 1). The non-linearity of the relationship $U_{L-e} = f(U_{G-e})$ resembles that one already demonstrated by liquid circulation velocity as shown in Fig. 54 and Fig. 56c due to the changes in the fluidization regimes. That is, for weak magnetic fields the hydraulic resistance is relatively low and the liquid is the main fluidizing agent (Liquid Supported Solids, LSS), while for strong fields the

gas is the main fluidizing agent solids (Bubble Supported Solids, BSS). These definitions are based on Epstein's (1981) taxonomy (see Hristov (2005a) for details).

Thus, the ascending section of this curve ($dU_{L-e}/dU_{G-e} > 0$) for $0 \leq H \leq 9000$ A/m is approximated by (Hristov, 2005b)

$$\frac{U_{L-e}}{U_{L-mfo}} = 1.027 \left(\frac{U_{G-e}}{U_{L-mfo}} \right)^{2.1} \quad (48)$$

while for the descending section the corresponding equation is

$$\frac{U_{L-e}}{U_{L-mfo}} = 1.587 \left(\frac{U_{G-e}}{U_{L-mfo}} \right)^{-0.8} \quad (49)$$

6.4.3. Incorporation of the field effect in the airlift friction factor Ω_M (Hristov, 2005b)

The correlations (41) and (42) provide numerical values for the pre-factor Ω_M that depends on both the properties of the particles and the field intensity, as well as the air-lift loop design. Actually the dimensionless correlations (46) to (49) have pre-factors nearly equal to 1, suggesting the exclusion of magnetic field effect. However, for completeness we shall incorporate field intensity in the friction factor Ω_M (Hristov, 2005a), that is,

$$\Omega_M = \omega_0 \left[1 + \left(\frac{h_{b0}}{d_r} \right) \left(\frac{H}{Ms} \right)^K \right] \quad (50)$$

where H/Ms is dimensionless field intensity (Hristov, 1996, 2002). Values of Ms for various materials are available elsewhere (Penchev & Hristov, 1990a,b; Part 1).

In Eq. (50) ω_0 is the bed friction coefficient in the absence of the particle bed. With $\omega_0 \approx 1$ (Hristov, 2005a) (see comments next) and at zero field intensity, equations (47), (44) and (45) become similar to Eq. 43 for non-magnetic airlifts. The task needs some preliminary assumptions concerning mainly the scaling expressed by Eq. 45 (Hristov (2005a) assumed the exponent n_g to be 0.4 similarly to non-magnetic airlifts (Onken and Trager,

1990), thus permitting the concentration of all effects of field intensity and particle properties in the friction factor Ω_M . Therefore the scaling equation becomes

$$\frac{U_L}{U_L|_{H=0}} = \omega_0 \left[1 + \left(\frac{h_{b0}}{d_r} \right) \left(\frac{H}{Ms} \right)^K \right] \left(\frac{U_G}{U_G|_{H=0}} \right)^{0.4} \quad (51)$$

Taking into account the results developed by Hristov (2005a), we have

$$\frac{U_{L-mf}}{U_{L-mf0}} = 1.058 \left[1 + 21.40 \left(\frac{H}{Ms} \right)^{-0.315} \right] \left(\frac{A_d}{A_r} \right)^{0.74} \left(\frac{U_{G-mf}}{U_{G-mf0}} \right)^{0.4} \quad (52a)$$

At zero field intensity Equation (52a) reduces to

$$\left(\frac{U_{L-mf}}{U_{L-mf0}} \right)_{H=0} = 1.058 \left(\frac{A_d}{A_r} \right)^{0.74} \left(\frac{U_{G-mf}}{U_{G-mf0}} \right)_{H=0}^{0.4} \quad (52b)$$

where, for the present airlift design (Hristov, 2005a,b), we have $A_d/A_r = 0.1736$. The equation (52b) is in agreement with the correlations for the non-magnetic airlift mentioned above (see also Table 13).

The same approach applied to minimum stabilization provides

$$\frac{U_{L-e}}{U_{L-mf0}} = 1.255 \left[1 + 2.634 \left(\frac{H}{Ms} \right)^{-\frac{1}{4}} \right] \left(\frac{A_d}{A_r} \right)^{0.74} \left(\frac{U_{G-e}}{U_{G-mf0}} \right)^{0.4} \quad (53)$$

Again, as $H \rightarrow 0$, we have $\frac{U_{L-e}}{U_{L-mf0}} = 1.255 \left(\frac{A_d}{A_r} \right)^{0.74} \left(\frac{U_{G-e}}{U_{G-mf0}} \right)^{0.4}$, that is a relatively good approximation since at low field intensities the stabilization point is difficult to detect (Hristov, 1996).

Table 13

External-loop magnetic air-lifts. Comparative information concerning the device geometry and the friction factors. Adapted from Hristov (2005a)

Reference	D_r m	D_d m	A_d/A_r -	h_r or h_d m	Data correlations
Magnetically controlled airlifts					
Al-Qodah and Al Hassan (2000)	0.0054	-	0.16	$h_r = 0.75$ m	$\varepsilon_r = 0.452 U_G^{0.4727} \exp(0.0077 B)$ $0 < U_g < 0.20$ m/s; $5 < B < 76$ mT
Al-Qodah (2000a)	0.045	0.018		$h_r = 0.7$ m $h_d = 0.72$ m	
Al-Qodah (2000b)	0.045	0.018		$h_r = 0.75$ m $h_d = 0.78$ m	
Hristov (1998a)	0.140	0.05	0.127	$h_r = 2.0$ m $h_d = 1.8$ m	$U_L = \Omega_M \left(\frac{A_d}{A_r} \right)^{0.74} U_G^{0.4}$ $\Omega_M = \omega_o \left(\frac{H}{Ms} \right)^K$ $0 < H < 42$ kA/m
Hristov (2005a,b)	0.140	0.05	0.127	$h_r = 2.0$ m $h_d = 1.8$ m	$U_L r = \omega \left[\frac{A_d}{A_r} \right]^n U_G r^{0.44}$ $0 < H < 42$ kA/m
Non-magnetic airlifts					
Bello et al. (1984, 1985a,b)	0.152	0.051 0.076 0.102	0.11±0.44	$h_d = 1.8$ m $h_r = 1.8$ m	$U_L r = \omega \left[\frac{A_d}{A_r} \right]^n U_G r^{0.44}$ $n = 0.74 \pm 0.04$ $\omega = 1.55$
Bello (1981)	0.152				$n = 0.78 \pm 0.08$ $\omega = 0.66$
Verlaan (1987)	0.2	0.1	0.25	$h_r = 3.23$ m	$U_L = a U_{Gr}^b$ $b = 0.44 (\pm 0.01)$
Verlaan et al. (1989)	0.225 0.20	0.150 0.140	0.445 0.500	$h_r = 10.5$ m $h_r = 3.2$ m	$U_L = a U_{Gr}^b$ $b = 0.44 (\pm 0.01)$
Onken and Trager (1990)	0.10	0.05	0.25	$h_r \approx 8.5$ m	$U_L = U_{Gr}^n$ $n = 0.4$
Merchuk & Stein (1981)	0.14		1	$h_r = 4.5$ m	$\frac{U_{Gr}}{\varepsilon_r} = 1.03 (U_L + U_{Gr}) = 0.33$

6.5. Liquid Circulation – A further analysis referring to data treatment and correlations

The results of Hristov (1998a, 2005a,b) and those of Al-Qodah (2000a) commented so far reveal a remote control of the liquid circulation velocity by the intensity of the external field affecting the hydraulic resistance of the particle bed at the bottom of the riser. The approach requires a controllable particle arrangement and mobility. The solution reported by Hristov (2005a) addresses a particle bed with a controllable pressure drop that replaces the mechanical butterfly valve employed by Verlaan (1987) to control the hydraulic resistance of the downcomer. The basic idea is explained schematically in Fig. 59.

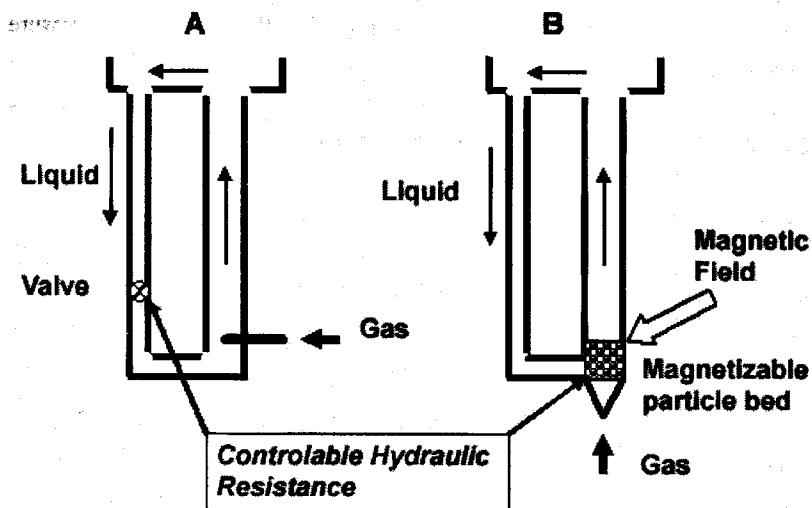


Fig. 59: Airlifts with an external loop – the basic idea of the controlled liquid circulation. After Hristov (2005b). **Left** - liquid circulation control by means of a mechanical valve -adapted from (Verlaan, 1987). **Right** - replacement of the mechanical valve by a magnetizable particle bed.

6.5.1. Airlift geometry and a background from the literature pertinent to non-magnetic devices

The attempt to correlate the data needs clarification of the position of the magnetically controlled airlifts among those ones reported in the literature.

The data summarized in Table 13 show almost complete information available on magnetically controlled external-loop airlifts and some important studies of non-magnetic devices. More detailed and comprehensive information is available elsewhere (Chisti, 1989; Onken and Trager, 1990). The next target of the comparison is to apply directly the empirical correlations available to the new situation with a special emphasis on the magnetic field control. The information in Table 10 and Table 13 indicates that the Al-Qodah's airlifts are very small in size, while those investigated by Hristov (1998a, 2005a, b) are close to the non-magnetic device of Bello (1981; Bello et al., 1984, 1985a, b).

6.5.2. Liquid Circulation - regression correlations (Hristov, 2005a)

- *Background of the correlations used*

In accordance with Onken and Trager (1990) the hydrostatic pressure between the downcomer and the riser, ΔP_H , as the driving force, is equal to the sum of the dynamic pressure drops in the loop (assuming a complete degasing and zero gas hold-up in the downcomer)

$$\Delta P_H = \sum \Delta P_i = \Delta P_T + \Delta P_{B+F} \quad (54a)$$

where ΔP_T is the pressure drop in the tubes (riser and downcomer) and ΔP_{B+F} is due to the particle bed and the fittings (joints). Expressing the pressure drops through the friction factors f_i , i.e.

$$\Delta P_i = \frac{f_i}{2} \rho_L U_L^2, \quad (54b)$$

the liquid circulation velocity U_L can be expressed according to Onken and Trager (1990) as

$$U_L = \sqrt{\frac{2 \cdot \varepsilon_{Gr} \cdot g (h_0 - h_r)}{\sum f_i}} \quad (54c)$$

The gas velocity and the gas holdup can be related by the following expressions of Shipley (1984).

$$\varepsilon_{Gr} = C U_G^{a_g} \quad (55)$$

Chisty (1989) proposes $C \approx 1.2 \text{ s/m}$ and $a_g \approx 0.9$

This permits liquid circulation velocity U_L to be expressed as (see Eq. 43, too)

$$U_L = U_G^{a/2} \frac{\sqrt{2C g (h_0 - h_r)}}{\sqrt{\sum f_i}} = \Omega \cdot U_G^{n_g} \quad (56a)$$

where

$$\Omega = \frac{\sqrt{2C g (h_0 - h_r)}}{\sqrt{\sum f_i}} \quad (56b)$$

The shorter form of Eq. 56a was used by Onken and Trager with $n_g = 0.4$ and Kawagoe and Robinson (1980) with $n_g = 0.48$ for external loop airlifts. Both values are close to $a/2 \approx 0.45$ likewise to Eq. (55) and Eq. (56a). In both cases: $\Omega = 1$. On the other hand, for airlifts with $h_r/D_r > 1$ the ratio A_d/A_r is an important hydraulic factor. Using this ratio Bello et al. (1984, 1985a, b) proposed the relationship (see Table 13, too)

$$U_{Lr} = 1.55 \left(\frac{A_d}{A_r} \right)^{0.74} U_{Gr}^{1/3} \quad (57)$$

The equations (55) and (56) are valid for $A_d/A_r = 0.10 - 0.44$ (Bello, 1981, Bello et al., 1984, 1985a, b).

6.5.3. Magnetic field effect incorporated – the airlift regime

The subtitle strongly appeals that all the data and further processing of them concern only the *airlift regime* and the transition effects towards a bubble column regime are excluded. In terms of the present study abbreviation, this implies the zones labelled by LSS in Fig. 53a and Fig. 54.

The simplest way to incorporate the magnetic field effect is to express its effect on the airlift friction coefficient ω . We assume that the Bello's

equation with $n_g = 0.74 \pm 0.04$ can be used due to the similar geometries of the airlifts (see Table 13) and the further data treatments pay attention to the friction factor Ω . The data correlations performed by (Hristov, 1998a) provide

$$U_L = \Omega_M \left(\frac{Ad}{Ar} \right)^{0.74} U_G^{0.4} \quad (58)$$

where Ω_M represents the hydraulic effect of the magnetizable bed. The power-law form was chosen (Hristov, 1998a) to express Ω_M , namely

$$\Omega_M = \Omega_{M0} \left(\frac{H}{Ms} \right)^{K\Omega} \quad (59)$$

where H/Ms is the dimensionless field intensity (Hristov, 1996; Part 1)

The results shown in Fig. 53 are redrawn in Fig. 60 in accordance with Eq. (58). The non-linear regression analysis (Hristov, 2005a) provides $K_\Omega = 1.59$ and Ω_{M0} within the interval from 0.935 to 0.95. From a practical point of view it was accepted $\Omega_{M0} = 1$ (Hristov, 2005a) that is consistent with the equations of Onken and Tager (1990) and Kawagoe and Robinson (1980) - see the comments about Eq. (56b).

Equation (59) demonstrates the main effect of the magnetic field on the total friction factor. However, it has a deficiency, since $\Omega_M = 0$ at $H = 0$ is incorrect from a physical point of view. A more refined relationship concerning Ω_M is proposed to include the ratio $\frac{h_{b0}}{d_r}$ (Hristov, 2005a)

$$\Omega_M = \omega_0 \left[1 + \left(\frac{h_{b0}}{d_r} \right) \left(\frac{H}{Ms} \right)^K \right] \quad (60)$$

where ω_0 is the friction coefficient in the absence of a particle bed.

Thus, the equation (58) becomes (Hristov, 2005a)

$$U_{Lr} = \omega_0 \left[1 + \left(\frac{h_{b0}}{d_r} \right) \left(\frac{H}{Ms} \right)^K \right] \left(\frac{Ad}{Ar} \right)^{0.74} (U_{Gr})^{n_g} \quad (61a)$$

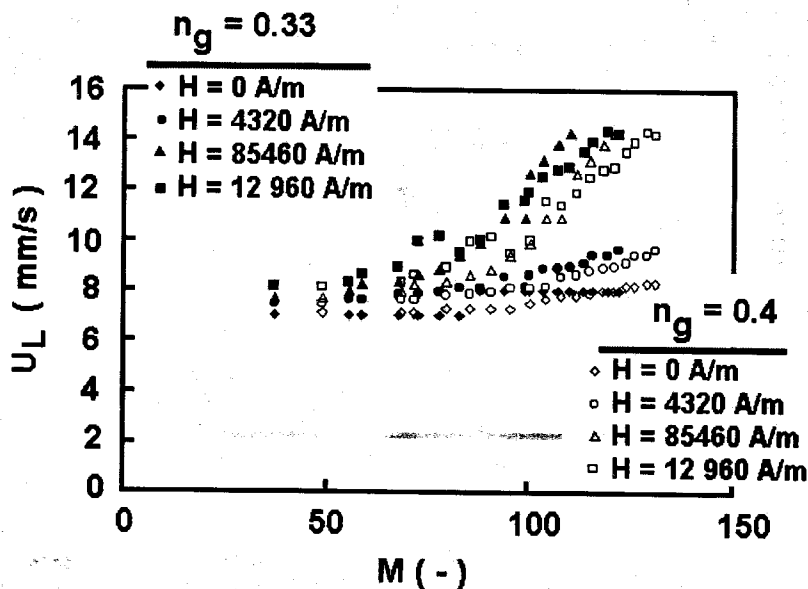


Fig. 60: Variations of U_L with the gas velocity -according to Eq. (58).

Effect of the field intensity. $M = \left(\frac{A_d}{A_r} \right)^{0.74} U_{Gr}^{n_g}$. After Hristov (2005a).

Taking into account the data and conditions in (Hristov, 1998a, 2000a, b), the rising sections of the curves $U_L = f(H)$ and $U_L = f(U_G)$ (see the zones labelled LSS in Fig. 53a and Fig. 54 were approximated as

$$U_{Lr} = \left[1 + 0.75 \left(\frac{H}{Ms} \right)^{\frac{3}{2}} \right] \left(\frac{A_d}{A_r} \right)^{0.74} (U_{Gr})^{0.4} \quad (61b)$$

under the assumption $\Omega_{M0} = \omega_0 = 1$ (see the comments pertinent to Eq. (59)).

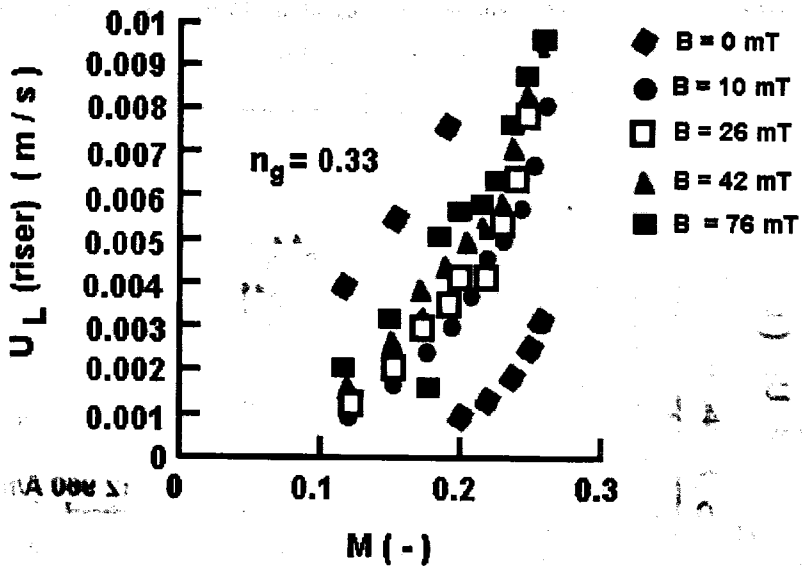


Fig. 61: Data of Al-Qodah (2000a, b) treated in accordance with Eq. (58)

where $M = \left(\frac{A_d}{A_r} \right)^{0.74} U_{Gr}^{n_g}$. After Hristov (2005a).

This expression is relatively simple and fits well the only parts of the curves where the liquid circulation velocity increases with the increase in the gas velocity. In other words, we have a situation similar to the non-magnetic beds, but with a remote control of the bottom friction of the airlift. Moreover, these results are consistent with the data of Al-Qodah (2000a, b) (see Fig. 53b) showing only the positive effects on the liquid circulation velocities. The entire data in Hristov (2005a) were treated with $n_g = 0.4$ in order to focus the attention on the magnetic field effects on the airlift friction factor. Similarly, the data of Al-Qodah (2000a, b) were treated in Hristov (2005a) (see Fig. 61) in accordance with Eq. (58). The data processing yielded an average exponent $n_g = 0.33$ (close to 0.4 employed in the above data processing).

6.6. Transition to a Bubble Column Regime (Hristov, 2005a)

6.6.1. Data analysis

Nevertheless, there are results provoking questions about the transition

between the airlift and the bubble column regime. This transition is detectable from the slopes of the liquid velocity curves corresponding to the zones labeled **BSS** (bubble-supported solids) in Fig. 53a and Fig. 54. The attempt to incorporate the field intensity effects in the friction factor only (as it was demonstrated above) yielded the plot in Fig. 62a,b) as a function of $\Omega_M = f\left(\frac{H}{Ms}\right)$ for two values of the exponent n_g .

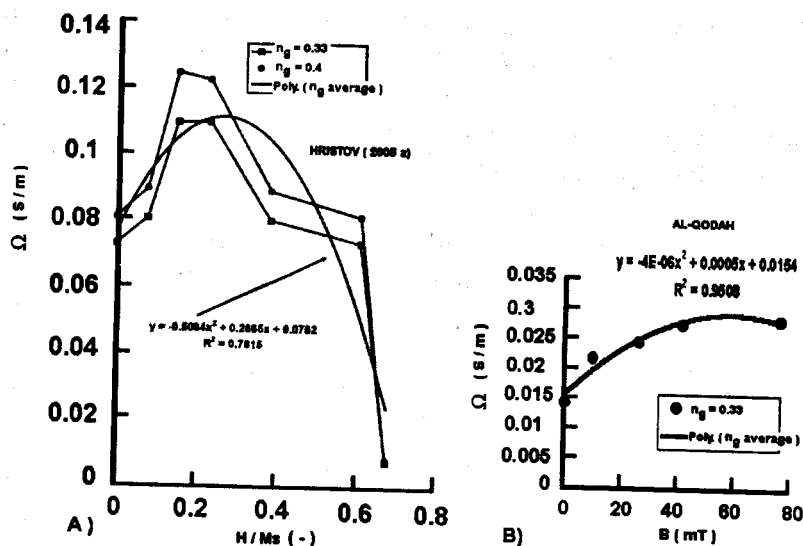


Fig.62: Variations of Ω_M with the magnetic field – data summarized from two independent studies, but treated in a common manner. After Hristov (2005a).

a) Present work: Ω_M v/s $\left(\frac{H}{Ms}\right)$ at two values of n : $n = 0.44$ and $n=1/3$. Data extracted from Fig. 60.

a) Data of A-Qodah (2000a,b) extracted from the results presented in Fig.61.

The plot in Fig. 62a clearly indicates a zone of maxima in the friction factors separating the airlift regime and the onset of the transition towards a bubble column regime. According to the terms of Eqs.56a, b this indicates an increased effect of the field on the structure of the particle bed and

consequently to its permeability with respect to the liquid. The value of Ω_M at small H/Ms indicates an increase in bed porosity due to the magnetic field stabilization effect allowing stable but loose particle beds. The opposite tendency in the behaviour of Ω_M at high H/Ms could be attributed to the compressing effect of the higher magnetic field intensities (high H/Ms ratios hinder the bed expansion) that results in lower permeabilities with respect to the liquid.

The processing of the data of Al-Qodah (2000a, b) performed by Hristov (2005a) yielded a plot (see Fig. 62b) corresponding to the region with small H/Ms . In fact, Al-Qodah (2000a, b) has reported only one curve detected (the present author's assumption) as corresponding to **BSS** and a negligible slope of the $U_L = f(U_G)$ curves. The airlift-bubble column (**AL/BC**) transition commented upon by Al-Qodah cannot be detected from his results.

6.6.2. Simple Model (Hristov, 2000a)

The transition regime was investigated by Verlaan (1987-Chapter 5) based on a simple power law relationship (See Table 13) $U_{Gr} = aU_{Lr}^b$. This analysis is based on previous studies of Joshi and Sharma (1979) predicting the liquid circulation in a bubble column. The expression of Joshi and Sharma (1979) is

$$U_{CL} = 1.18 \left[g D_c \alpha (U_{GS} - U_{b,\infty}) \right]^{0.33} \quad (62)$$

where $U_{b,\infty}$ is the bubble rise velocity in an infinite liquid flow field and U_{GS} is the slip velocity between the gas and the liquid phases in accordance with the two-phase flow drift flux model (see below).

The most common model describing the liquid circulation in an airlift is the momentum model (Chisti, 1989; Bello et al., 1985a, b; Onken and Trager, 1990). The simple pressure balance (Chisti, 1989; Verlaan, 1987; Onken and Trager, 1990) yields:

$$\int_0^{h_r} g \cdot \varepsilon_{Gr}(z) dz - \int_0^{h_d} g \cdot \varepsilon_{Gd}(z) dz = K_f \cdot U_L^2 \quad (63)$$

where $K_f = \sum \frac{f_i}{2}$ is the total friction factor with respect to the liquid phase.

Assuming a zero gas hold-up in the downcomer, the equation (63) gives a

relationship equivalent to Eq. 56a

$$U_L \equiv \frac{U_{Lo}}{K_f} \sqrt{\varepsilon_{Gr}} \quad (64a)$$

$$\text{with } U_{Lo} = \sqrt{g \cdot h_r} \quad (64b)$$

with the assumption $h_o = 0$ i.e. the gas inlet is at the riser bottom. With the gas-liquid slip velocity U_{GS} we have

$$\varepsilon_{Gr} \approx \frac{U_{Lo}}{U_{GS} + U_{Lo} \sqrt{\varepsilon_{Gr}}} \quad (65)$$

The velocity U_{Lo} is a *characteristic velocity scale for buoyancy driven flows*- the two phase flow in the airlift riser is an example of such a type of flow. According to Chisti (1989) U_{Lo} is defined by the Froude number $Fr = \frac{U_{Lr}^2}{g \cdot h_r}$ (Bello et al., 1985a), if the riser height h_r is used as a *length scale*.

Obviously, the **AL/BC** transition regime depends on the existence of strong liquid circulation cells in the riser typical of the bubble column regime. In the analysis of Joshi and Sharma (1979) this heterogeneous circulation flow pattern exists when the slip velocity U_{GS} is greater than the bubble rise velocity in an infinite liquid $U_{b,\infty}$. When the slip velocity 0 is calculated, the circulation velocity can be obtained from Eq. (63). Verlaan (1981, 1989) suggested a simple criterion of discrimination between the two types of flow as equality between the liquid superficial velocity U_{Lr} and the circulation velocity U_{CL} , i.e.

$$U_{Lr} \approx U_{CL} \quad (66a)$$

Thus, according to (64a,b) we have

$$\frac{U_{Lo}}{K_f} \sqrt{\varepsilon_{Gr}} = 1.18 \left[g D_c \varepsilon_{Gr} (U_{GS} - U_{b,\infty}) \right]^{0.33} \quad (66b)$$

The slip velocity is a dependent parameter since according to the simplest relationship of Wallis (1969) we have

$$U_{GS} = U_r \varepsilon_G (1 - \varepsilon_G) = U_{Gr} (1 - \varepsilon_G) - U_{Lr} \varepsilon_G \quad (67)$$

Equation. (67) does not take into account the bubble dynamics usually represented by the bubble rise velocity $U_{b,\infty}$. On the other hand, the well known correlation of Zuber and Findlay (1965) $U_{GS} = U_{b,\infty} \varepsilon_G (1 - \varepsilon_G)^m$ cannot be employed either since in a bubble column the induced circulation cells cannot be represented by a single distribution parameter. An alternative to employ the correlation of Hills (1976) (see also Chisti, 1989) was established by Hristov (2005a), namely

$$\varepsilon_G = \frac{U_{Gr}}{0.24 + 1.35(U_{Gr} + U_{Lr})^{0.93}} \quad (68)$$

where the term 0.24 is an average value of $U_{b,\infty}$ in most of the studies of Newtonian liquids used (Chisti, 1989). Therefore, we can obtain a set of equations (65), (66b) and (68) that could be expressed in dimensionless forms (Hristov, 2005a), namely

$$\frac{U_{CL}}{U_{Lo}} = 1.18 \left[g D_{bc} \varepsilon_{Gr} \left(\frac{U_{GS}}{U_{Lo}} - \frac{U_{b,\infty}}{U_{Lo}} \right) \right]^{0.33} = \frac{1}{K_f} \sqrt{\varepsilon_{Gr}} \quad (69a)$$

$$\varepsilon_{Gr} = \frac{1}{\frac{U_{GS}}{U_{Lo}} + \sqrt{\varepsilon_{Gr}}} \quad (69b)$$

$$\varepsilon_{Gr} = \frac{j_g}{B_0 + 1.35(j_g + j_l)^{0.93}} \quad (69c)$$

$$\text{where, } B_0 = \frac{U_{b,\infty}}{U_{Lo}}, \quad j_l = \frac{U_{Lr}}{U_{Lo}} \quad \text{and} \quad j_g = \frac{U_{Gr}}{U_{Lo}} \quad (69d)$$

are dimensionless velocities (Hristov, 1999; 2005a).

Expressing U_{GS}/U_{Lo} from (58b) and substituting in (58a) we read

$$1.18 \left[g D_c \varepsilon_{Gr} \left(\frac{1}{\varepsilon_{Gr}} - \sqrt{\varepsilon_{Gr}} - B_0 \right) \right]^{0.33} = \frac{1}{K_f} \sqrt{\varepsilon_{Gr}} \quad (70a)$$

$$\varepsilon_{Gr} = \frac{j_G}{B_0 + 1.35(j_G + j_L)^{0.93}} \quad (70b)$$

For the airlift studied by Hristov (2005a, b) $U_{Lo} = 4.429 \text{ m/s}$, so $B_0 = 0.054$ and the ranges of variations of j_g and j_L are: For j_G from 0 to 0.022 and for j_L from 0 to 0.00256.

6.6.3. Transition criterion and airlift friction factors

The critical range of transition detected in Fig. 54 corresponds to field intensities of 15-20 kA/m in the experiments performed by Hristov (2005a) (see the dashed lines in Fig. 54 and the zone of separation of the curves in Fig. 53a) and higher. This intensity estimation allows to detect, from both Fig. 53a and Fig. 54 that the gas velocity in the riser is about 0.1 m/s and the corresponding liquid velocities range from 0.008 to 0.011 m/s. The use of these values in Eq. (70b) yields $\varepsilon_{Gr} \approx 0.228$ a value similar to those obtained by Verlaan (1987, 1989) and the total friction factor derived from (70a) is $K_f \approx 0.397$. Notice, this is the lowest value of K_f since it was detected (Hristov, 2005a) from the zone corresponding to the onset where liquid circulation rate starts to decrease.

The question about the range of variation of the total friction factor K_f at the transition points as well as the corresponding gas holdups in the riser was discussed by Hristov (2005a). A graphical solution is provided by the plot in Fig. 63a, where the right-hand side of Eq. (7a) is plotted for various values of K_f as a function of the gas holdup ε_{Gr} . The intersections with the line corresponding to the left-hand side of the same equation (the thicker dashed line) give solutions of Eq. (70a) (in fact this a solution giving points of $U_{GS} \approx U_{CL}$) with respect to ε_{Gr} , at different values of K_f . The intersections indicate realistic values of ε_{Gr} within the range 0.1 – 0.5 (more precisely 0.1-0.3) corresponding to values of K_f from 0.3 to 0.6. This graphical solution of Eq. (70a) confirms the estimations done above that the transition zone corresponds to $\varepsilon_{Gr} \approx 0.228$ and $K_f \approx 0.4$.

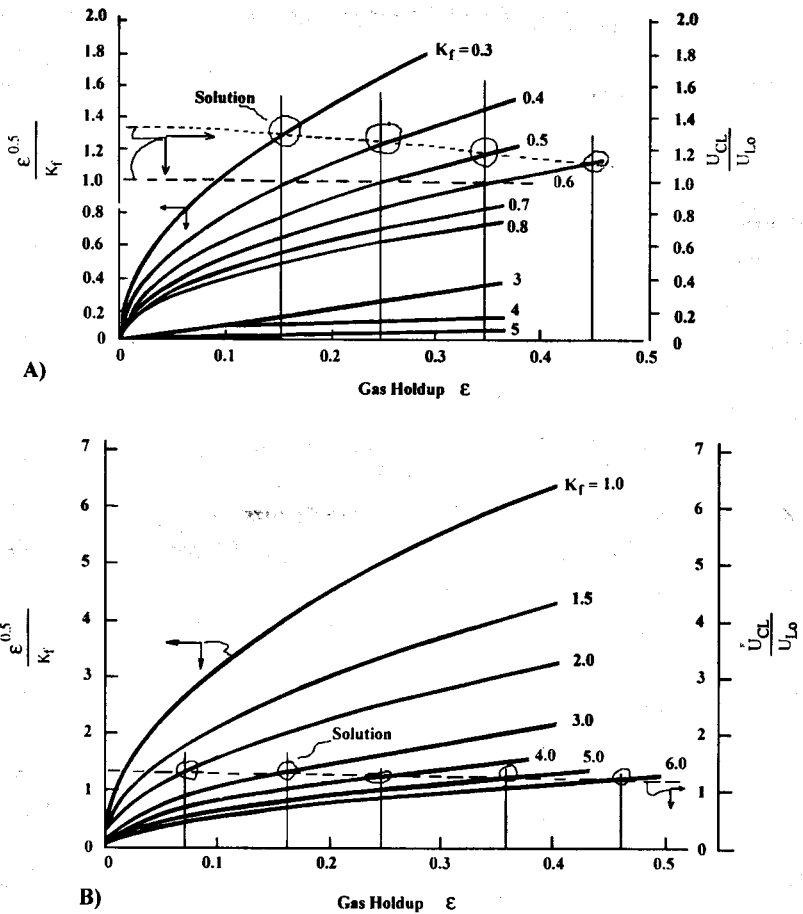


Fig. 63: Graphical presentation of the solutions of Eq. (70a). After Hristov (2005a).

- a) Case of application of the criterion (66a)
- b) Case of application of the criterion (71) with $\alpha = 10$.

This value of K_f is relatively low with respect to those reported for non-magnetic external loop airlifts. For instance, $K_f = 2.77-7.38$ for internal loop-reactors (Bello et al., 1985a -Table 5.6) for $h_r = 1.22-5.07$ m that gives U_{Lo} in the range of 2.07 to 2.59 m/s. Chisti (1989) collected data for K_f for external-loop reactors in the range of 5.3 to 7.08 (Bello, 1981) and 1.83 (Verlaan, 1987) and 5.53 (Merchuk and Stein, 1981) for

$A_d/A_r = 0.2-1.8$ and $h_r = 1.5-8.5$ m. The corresponding range of U_{Lo} is from 1.3 to 4.08 m/s at an average value of $K_f = 5.0$ (Chisti, 1989-p.211).

The question about the reasons for low values of K_f came up in Hristov (2005a). The analysis performed in this study provided that despite the type of the "valve", magnetic or mechanical, the values of the total friction factor should be similar. A simple test was performed by Hristov (2005a) with Eqs. (70a,b)(see Fig. 63b), but in this case the criterion (66a) was modified to

$$U_{Lr} \approx \alpha U_{CL} \quad (71)$$

For simplicity of explanation the plots in Fig. 63b were performed with an arbitrary value of $\alpha = 10$, but the values of K_f and ε_{Gr} used corresponded to those of airlifts employing mechanical valves (Verlaan, 1987; Bendjabalah et al. 1999). This *ad-hoc* performed numerical test provided reliable results in contrast to the results obtained with the criterion (66a). A straightforward explanation (Hristov, 2005a) is attributed to the fact that Eq. (56a) gives

$$\Omega = \sqrt{C} \frac{U_{Lo}}{\sqrt{K_f}} \quad (72)$$

Assuming $C \approx 1.2$, as mentioned earlier, the values of Ω plotted in Fig. 62a correspond to the total friction factors of $K_f \approx 1000$ and higher. These results coincide with the data of Verlaan ($K_f > 400$ - Table 1-Chapter 5) and of Bello (1981) for the AL/BC transition. The same treatment of the data of Al-Qodah with $U_{Lo} \approx 2.712$ m/s yields a similar curve- see Fig. 62b. Therefore, the suggested criterion (66a) is not exact as it was established by Hristov (2005a). This is in agreement with the conclusion of Verlaan et al. (1989) that it is impossible to determine a separate transition gas velocity, but only a range of gas velocities can be denoted where the circulation velocity equals the superficial liquid velocity. Moreover Verlaan et al. (1989) stated that if the superficial liquid velocity obviously exceeds the liquid circulation velocity, then the airlift is operated as a bubble column. The two later statements confirm the application of the modified criterion (71) providing adequate results, but the value of the pre-factor α needs justification.

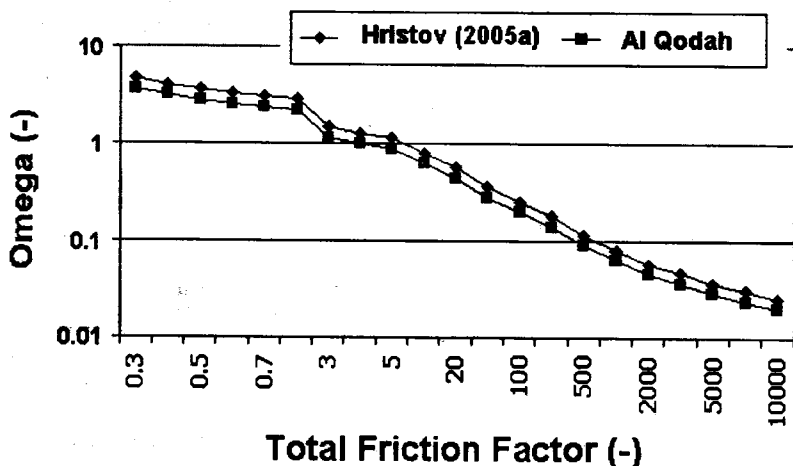


Fig. 64: Variations of Ω with the total friction factor K_f for magnetically controlled beds. The plots span a range of K_f larger than those of (Hristov, 2005a) and the works of Al Qodah (2000a,b). After Hristov (2005a).

Further, the range of the friction factors for the magnetic airlift does not differ significantly from that established for non-magnetic devices. The analysis of the data obtained in (Hristov, 2005a) and those reported by Al-Qodah (2000a,b) confirms the existence of maxima in the curves $\Omega = f(H/Ms)$ and coinciding with the minimal friction factors of the magnetic bed- see Fig. 64 .

6.7. Bed Expansion and Phase Holdups

Very often bed expansion and phase holdups are commented parallel to the observations of bed behaviour. Airlifts have a special feature such the inherent dependence of the liquid velocity on the gas flow rate that with further effects of the magnetic field controlled solid phase make the problem complex. This implies that the effects of all macroscopic process variables of bed expansions, the fluidization regimes and the liquid circulation dependence on both the gas flow and the field intensity need preliminarily to be defined. From this standpoint, with knowledge of the available regimes, liquid circulation and airlift friction factor control we may address the bed expansion and the phase holdups.

6.7.1 Bed expansion-porosity evolution

Bed porosity defined as a fraction of the bed volume occupied by both the liquid and gas indirectly represents the bed height. According to Al Qodah and Al Hassan (2000b) the overall bed porosities may attain 70 % - see Fig. 65a. In relation to Fig. 65a, increase in field intensity allows high gas velocities to be employed to expand the bed with Magnetization FIRST mode. Further, with Magnetization LAST mode the overall bed porosity attains the same levels - see Fig. 65b. Al Qodah has derived empirical relations valid for both magnetization modes

Al-Qodah (2000b)

$$\varepsilon = 0.611U_G^{0.1853}B^{0.1588} \quad (73a)$$

Al-Qodah (2000a)

$$\varepsilon = 0.4527U_G^{0.423} \exp(0.0077B) \quad (73b)$$

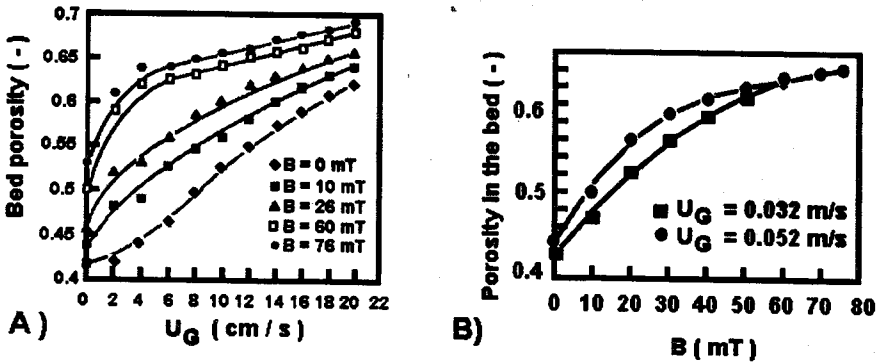


Fig. 65: Bed porosity evolution with variations of the gas flow rate in small scale external-loop airlift. Data of Al Qodah and Al Hassan (2000). Details about experimental conditions are available in Table 10

a) Magnetization FIRST mode.

b) Magnetization LAST mode.

without a discrimination in bed regimes and their effects on ε .

Each of the expressions (73a,b) has two terms in its right-hand side. The first term is classical to the airlifts and resembles the equation of Shipley (1984) used in this work earlier. The second term seems logical in the case of

Magnetization FIRST mode, but with Magnetization LAST it looks strange since increase in magnetic field intensity (Magn. LAST) collapses the bed and the its porosity has to decrease at fixed gas velocity due to two principle reasons: 1) increase in the size of particle aggregates and augmentation of the string-string forces of attraction, and 2) decrease in liquid circulation velocity due to increase of bed hydraulic resistance. It might be more logical if bed porosity decreases with augmentation in field intensity but no physical explanation of results reported by Al-Qodah exists in the published articles. Besides, in the Al-Qodah reports (Al-Qodah, 2000a, b; Al-Qodah and Al-Hassan, 2000) there is no enough information how bed height (porosity) varies within the regimes attained as the macroscopic variables (gas flow and field intensity) controlling the bed change. Most probably Eqs. (73a, b) were used to fit data with both modes (see Fig. 67a, b commented below) without bearing in mind that with both magnetization modes the field intensity plays opposites roles to the bed overall porosity. It might be suggested that Eq. (73a, b) just fits the experimental points without any deep look at the process physics. In this context, the approximation (73b) is physically correct (at $B = 0$) while (73a) is certainly not since at $B = 0$ it becomes $\varepsilon = 0$. In this perspective, further systematic experiments and analyses concerning bed regimes, effects on the porosity profile evolution are needed.

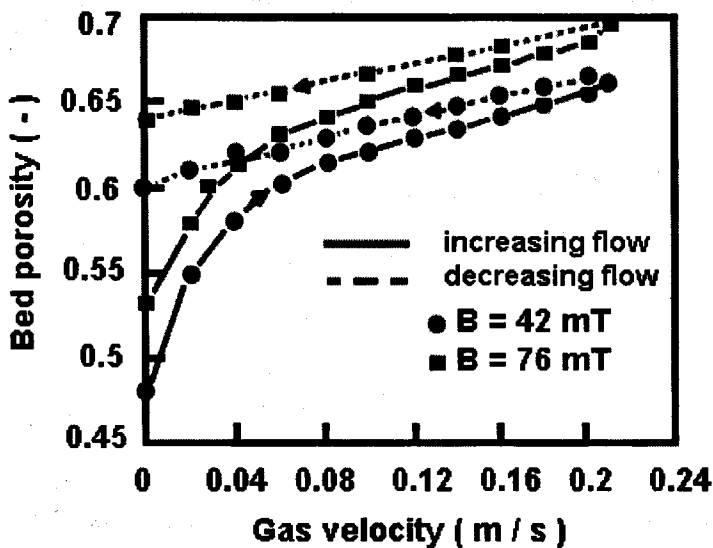


Fig. 66: Bed expansion hysteresis with magnetization FIRST mode. After Al Qodah (2000a).

As it might be expected variations in the gas flow rate with the magnetization FIRST mode leads to hysteresis in the bed height (porosity) (see Fig. 66) that confirms the results with gas-solids (Part 1, Part 2) and liquid-solids (Part 5) beds.

7.7.2. Phase holdups

➤ Riser gas holdup

Riser gas holdup is the most important issue in airlift hydrodynamics since it directly determines the mixing of phases, gas-liquid and liquid-solids contact areas and the overall mass transfer rate. In magnetically assisted airlifts the riser gas holdup strongly depends on the magnetization mode chosen, namely:

- With Magnetization FIRST mode, the stabilized bed at the bottom plays a role of a gas distributor, so above the bed top surface we have a two-phase section as in non-magnetic gas-liquid airlifts. Obviously the effective work of the magnetic bed as a gas sparger depends on the stability of the interparticle forces and the porous structure created in the upper part of the stabilized bed. These are comments laying on engineering intuition but no results have appeared so far in the literature. Beyond the minimum fluidization point, the increase in gas velocity augments the riser gas holdup and the magnetic particles and aggregates in motion play as bubble breakers thus increasing the gas-fluid contact area.
- Magnetization LAST mode is practically what in fact we do with Magnetization FIRST beyond the minimum fluidization point but in opposite order. That is, increase in field intensity, at fixed gas flow rate, may increase the aggregate size resulting in the bed collapse and the increase friction factor of the loop. With increase in field intensity the bed is approaching the **frozen regime** (analog of the Stabilized bed with Magnetization FIRST) since all the particles rest at the bottom and we get a two-phase (G-L) riser.

The results of Al-Qodah (200b) obtained with both magnetization modes are shown in Figs.(67a, b).

One important point we have to consider is that the liquid circulation velocity plays a substantial role in the riser gas holdup formation. From the results concerning the liquid circulation velocity it becomes clear that the bed porosity as well as the riser holdup may be controlled by the field intensity

solely at a fixed gas flow rate either with Magnetization FIRST or LAST mode. This is an explicit macroscopic result but the intimate mechanisms considering the liquid-gas slip velocity affecting the gas bubble break-up and the coalescence pertinent to liquid velocity in the riser controlled by the friction factor of the loop are not evaluated.

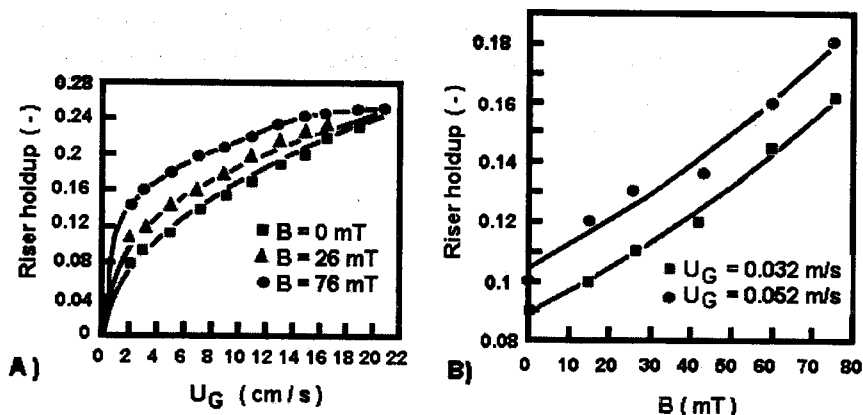


Fig. 67. Riser gas hold-up evolution with variations of the gas flow rate. Effect of field intensity with both magnetization modes. After Al Qodah and Al Hassan (2000).

- Magnetization FIRST mode.
- Magnetization LAST mode.

➤ Bed holdups

Bed holdup as a term considers participation of all the phases and discrimination of the contribution of each of them to the evolution of the overall bed expansion. Expressing the initial solids content in the bed as $\varepsilon_{S0} = (G/\rho_s)/Ah_{b0}$, the solids holdup can be expressed to the relative bed as (Al-Qodah, 2000a)

$$\varepsilon_{Sb} = 1 - \varepsilon_{S0} \left(\frac{h_{b0}}{h_b} \right) \quad (74)$$

Further, the average gas holdup in the three-phase bed is

$$\varepsilon_{Gb} = \varepsilon_{Gr} - \varepsilon_{Ga} \quad (75a)$$

$$\varepsilon_{Ga} = (h_r - h_w)/h_r \quad (75b)$$

where h_r is the riser height, h_w is the water height in the manometer corresponding to the static pressure on the bed surface. That is ε_{Ga} is the gas holdup in the two-phase section of the riser above the bed. Consequently the

liquid holdup in the bed is $\varepsilon_{Lb} = 1 - \varepsilon_{Gb} - \varepsilon_{Sb}$.

The experimental results of Al Qodah (2000b) concerning phase holdup evolution with gas flow rate and field intensity variations are shown in Figs.68a-f.

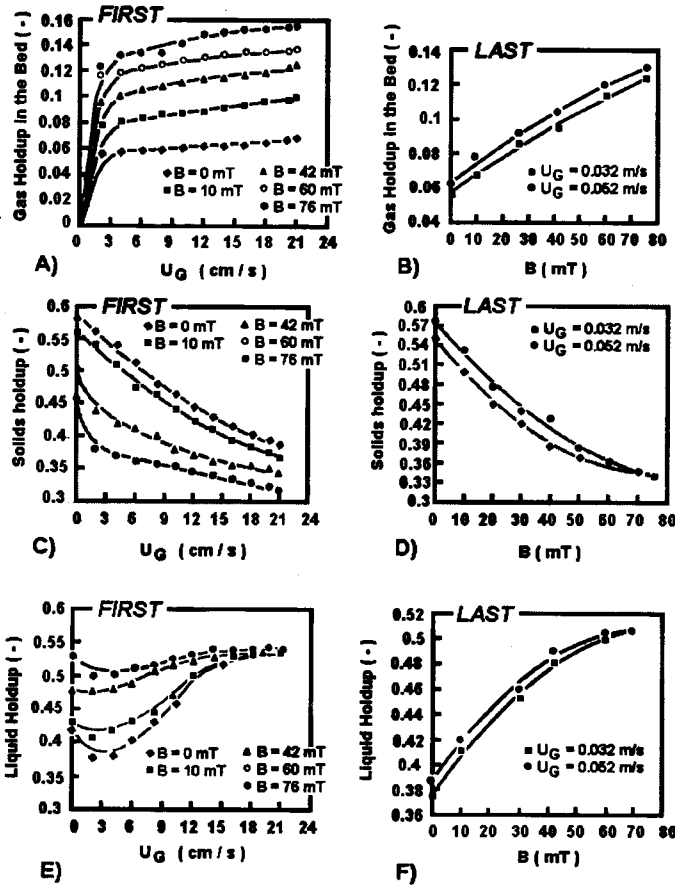


Fig. 68: Bed holdups in an external-loop airlifts as a function of gas velocity. Data of Al Qodah and Al Hassan (2000).

- a) Gas hold-up in the bed. Magnetization FIRST mode.
- b) Gas hold-up in the bed. Magnetization LAST mode.
- c) Solids holdup in the bed. Magnetization FIRST.
- d) Solids holdup in the bed. Magnetization LAST.
- e) Liquid holdup in the bed. Magnetization First.
- f) Liquid holdup in the bed. Magnetization LAST.

The bed gas-holdup data were correlated with

$$\varepsilon_{Gb} = (0.0404 + 0.033U_G) B^{0.229} \quad (76)$$

that obviously fits well the experimental data but without physical sense since in the absence of field ($B = 0$) it becomes that $\varepsilon_{Gb} = 0$ that is by far incorrect; the definitions of the holdups above are equally valid for magnetic and non-magnetic beds. Besides, if the term in (76) pertinent to the field intensity contribution is missing, the remaining term (in brackets) has no physical sense teaching that at $U_G = 0$ (that is $U_L = 0$) the bed holdup is 4%.

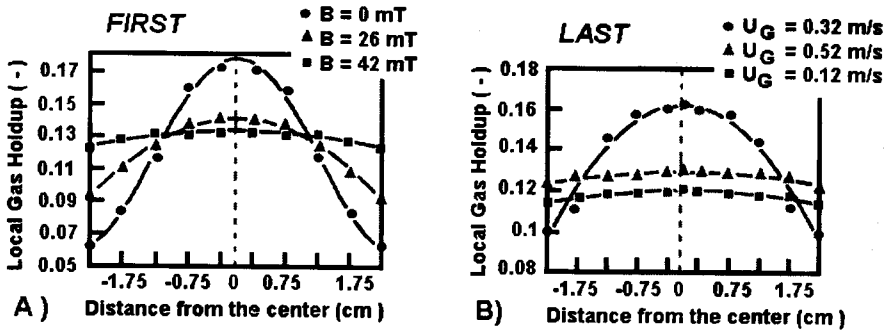


Fig.69: Radial gas hold-up distribution in the riser. After Al Qodah and Al Hassan (2000).

- Field effect on radial gas-holdup distributions. Magnetization FIRST mode.
- Field effect on radial gas-holdup distributions. Magnetization LAST mode.

Important facts relevant to phase holdup evolutions with variation in both the gas flow and field intensity are their radial distributions (See Fig. 69a, b). With both magnetization modes the increase in fluid turbulence makes the radial gas holdup profile flat. The last implies that either increase in gas velocity with Magnetization FIRST or increase in field intensity (Magnetization LAST) increase the local fluid velocity streamlining the particles that yields intensive gas bubble break-up and reduction in the liquid-gas slip velocity (due to increase in the loop friction factor). These effects

finally equalize the phase distribution across the riser cross-section and eliminate preferential flow paths along the column axis in the case of non-magnetized beds. These comments, in fact, match the observations with magnetically assisted bubble columns studied separately from the magnetic airlifts,

7.8. Final Comments and Main Results Outline Pertinent to Magnetic Airlifts

1) It demonstrates the applicability of a magnetically stabilized bed for a remote control of liquid circulation velocity in an external loop airlift. The controlled interparticle structure of MSB allows to rule its permeability with respect to the gas-liquid flow passing through it. Moreover, the bed plays a role of a gas distributor for the two-phase (gas-liquid) section of the riser above. The variation of the magnetic field intensity gives possibilities to vary the liquid circulation velocity and the gas-holdup in the riser in an easy way without mechanical devices, nor the need of variation in gas velocity.

2) Data correlations in forms similar to those employed for non-magnetic airlifts have been developed for better understanding of the mechanism of the magnetic field control of the airlift friction factor.

3) An analysis of the transition from airlift to a bubble column regime (Hristov, 2005a) is performed in a manner similar to that applied to non-magnetic airlifts. The range of the friction factors for the magnetic airlift does not differ significantly from that established for non-magnetic devices. The analysis of the data obtained by Hristov (2005a, b) and those reported by Al-Qodah confirms the existence of maxima in the curves $\Omega = f(H / Ms)$.

4) The simple model of the AL/BC transition (Hristov, 2005a) indicates that the criteria for that transition (Eq. 66a) should be justified, but in general both of them (Eq. 66a and Eq. 71) provide reliable results.

7. CLOSING COMMENTS

The present reviews went through numerous topics of the hydrodynamics of magnetically assisted gas-liquid-solid fluidized beds with a unified approach enabling to bring together many non-systematized results and data. The systemization was performed at two hierarchically organized levels. The

first level is the creation of a classification based on the non-magnetic Fan's systematization, but pertinent to the specific features of the magnetic field assisted fluidization. Nowadays, this classification scheme is unique and allows to analyze the up-to-date status of magnetically assisted three-phase fluidized bed and to figure potential research branches both in deep process studies and development of new devices.

The second level is pertinent to detailed analysis of processes and devices in accordance with the classification drawn and discussion basic hydrodynamic parameters such as gas holdup, minimum fluidization velocity, etc. The major part of the review is devoted to bubble column performance under various circumstances imposed by the flow and magnetization modes. They were systematically reviewed so far in reference to a scheme already established in the previous parts of the review series. This approach allows easily comparison of the bed behaviours and a collection of data enabling further analysis. Comments doing relationships to the non-magnetic bubble column hydrodynamics persist in the text but they only explain what could be the probable reason of a certain physical effect rather than to translate facts to the language of the classical non-magnetic G-L-S fluidized bed hydrodynamics. Besides, the discussion here tries to arrange the data on magnetically assisted bubble columns in a manner that is common for non-magnetic three-phase fluidization reactors and to make it friendlier to people working on three-phase fluidization but not experience with magnetic fields. In this context, some problems occurring during the review will be briefly outlined next, among them:

- The technique of gas liquid-solid MFAF is approximately 20 years old (1987-2007). However, in contrast with the gas-fluidized counterparts (and to some extent with L-S beds- see Part 5) the G-L-S branch is practically undeveloped. Serious steps toward detailed analysis of bed hydrodynamics and enlargement of the devices should be done. As usual, the key problem is the choice of a suitable magnetic system. The dominating axial magnetic systems are well known among the scientist working on MFAF, but the small zones with homogeneous field distributions are still obstacles to their implementation in large-scale devices. To this end two special sections devoted to rationales of magnetically assisted bubble columns and airlifts were developed in the present review.
- Unfortunately the results published so far do not allow development of a

systematic meta-analysis of data as it was done in Part 5 with L-S beds. Two principal reasons for that exist : 1) Insufficient amount of data published in literature ; 2) The data published in various articles are presented in a manner by far different from that established in non-magnetic three-phase fluidization (Fan, 1989). To this end, it is hard to apply the two basic approaches in G-L-S fluidization hydrodynamics, i.e. the Drift-Flux method and the Bubble-wake model. It is a pity but the results published and collected in this review do not allow fitting these models and getting new results. It might suggest these comments as well as the analyses in the subsections of the review will appeal more systematic studies and successful implementation of the knowledge of non-magnetic G-L-S beds to the magnetically assisted counterparts.

- Magnetically assisted airlifts form the second principal branch of the review. These are promising results but further studies on gas holdup, liquid circulation, field flow profiles, etc, are required.
- In contrast to the previous parts of the review, no scaling and dimensional analyses were performed here. The thorough examination of the existing information in both magnetic and non-magnetic G-L-S fluidization reveal that scaling through non-dimensional numbers is not well developed; as it is demonstrated by the collection of information in the book of Fan (Fan, 1989). In some studies correlation in dimensionless forms really exist but they are by far from generalization allowing application to magnetically assisted beds. Dimensional analyses and scaling applications are hindered by incomplete information about the G-L-S hydrodynamics and the field effects on it. In this context, a potential development of either the Drift-flux model or the Bubble-wake-model would provide information how the field affects their basic parameters and give a ground to develop scaling and dimensional analysis.
- In contrast to the other magnetically assisted fluidization techniques the slurry bubble columns with axial fields reached first an industrial level of application in China by application of the SRNA catalyst to hydrogenation of olefins (Zong, 2007). This serious breakthrough of the youngest branch of MFAF shows that even with undeveloped theory some applications are possible by trial-error approaches but systematic studies are of a paramount importance for the further development of MFAF.
- Finally, we hope that this review will provide comprehensive information

to the readers, draw new ideas and help the people interested in this fluidization branch in their studies.

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LIST OF SYMBOLS

A_c - bed cross-sectional area, (m^2)

A_d - downcomer cross-sectional area, (m^2)

A_r - riser cross-sectional area, (m^2)

a - interfacial area, Eq. (18) (m^2/m^3)

a_g - dimensionless exponent defined by Eq. (55), (-)

a_L - dimensionless coefficient in Eq. (5)

a_H - coefficient in Eq. (10b), (m/A)

B - magnetic field induction, (T) (sometimes the induction is expressed in Gauss, i.e. $1Gs = 1.10^{-4} T$)

B_0 - dimensionless bubble rise velocity, Eq. (69d)

b_H - coefficient in Eq. (5), (m/kA)

D_c - column diameter, (m)

d_p - particle diameter, (m)

d_r - riser diameter, (m)

d_b - bubble diameter, (m)

$d_{b(max)}$ - maximum bubble size, (m)

d_{b-avs} - average bubble diameter in a slurry, (m)

F_H - magnetic force, (N)

- F_d -drag force, (N)
- F_g -gravity force, (N)
- F_p - pressure induced forces, (N)
- F_σ - surface tension force, (N)
- f_l - local friction factor, Eq. (54b), (-)
- G_b - bed weight, (kg)
- g -normal gravity acceleration, $g = 9.81 \text{ m}^2/\text{s}$
- j_G - dimensionless gas velocity ,Eq. (69d)
- j_L - dimensionless liquid velocity ,Eq. (69d)
- H - magnetic Field intensity, A/m (in some cases the field intensity is expressed in *Oe* (Oersteds))
- H_c - critical field intensity defined by Eq. (9), (A/m)
- H_d - a parameter defined by Eq. (31b), (A/m)
- H_0 -characteristic field intensity (Magn. LAST) corresponding to $\varepsilon \rightarrow 1$, (A/m)
- h_b -bed height, (m)
- h_{b0} -initial bed height, (m)
- h_{dis} - distributor (condensed bed) height, (m)- the case of BC with MDP
- h_r - riser height, (m)
- h_d - downcomer height, (m)
- h_0 - height of gas inlet above the riser bottom, (m)
- K - dimensionless exponent in Eq. (50), (-)
- K_Ω - dimensionless exponent in Eq. (59), (-)
- K_s - liquid-solid mass transfer coefficient , (m/s)
- K_{m2} - empirical constant in Eq.(8) and Eq. (33), ($\text{Pa}/\text{m}^2 \text{ A}^2$)
- k_G and k_S -dimensionless coefficients definid by Eq. (16a,b,c)
- Ms -- magnetization at saturation, (A/m)
- m -dimensionless exponent defined by Eq. (44), (-)
- m_p - magnetic particles mass, (kg)
- n_g -exponent in Eq. (43) and Ew. (56a), (-)

- P - pressure, (Pa)
 ΔP - pressure drop, Pa
 $\frac{dP}{dz}$ - axial column pressure gradient, (N/m³)
 r - radius or radial distance-see the context, (m)
 R - column radius, (m)
 s - exponent in Eq. (10a), (dimensionless)
 t_{s-ret} - average solids retention time, (s)
 U - superficial velocity, (m/s)
 U_b - bubble rise velocity, (m/s)
 $U_{b,\infty}$ - bubble rise velocity is an infinite liquid, (m/s)
 U_L or U_{Lr} - superficial liquid velocity in the airlift riser, (m/s)
 U_L - superficial liquid velocity, (m/s)
 U_{L-e} - superficial liquid velocity at the onset of MSB, (m/s)
 U_{L-mf} - minimum liquid fluidization velocity, (m/s)
 U_{L-mf0} - minimum liquid fluidization velocity in absence of a field ($H=0$), (m/s)
 U_{CL} - liquid circulation velocity in a cell (bubble columns)-see Eq. (62), (m/s)
 U_G - superficial gas velocity, (m/s)
 U_G or U_{Gr} - superficial gas velocity in the riser, (m/s)
 U_{G-e} - superficial gas velocity at the onset of MSB, (m/s)
 U_{G-mf} - minimum gas fluidization velocity, (m/s)
 U_{G-mf0} - minimum gas fluidization velocity in absence of a field ($H=0$), (m/s)
 U_{GS} - gas-liquid slip velocity, (m/s)
 U_e - minimum fluid stabilizing velocity (at the onset of MSB), (m/s)
 U_{mf} - minimum fluidization velocity, (m/s) U_{mf0} - minimum fluidization velocity in absence of a magnetic field, (m/s)
 U_{mf-M} - minimum fluidization velocity of magnetic particles, (m/s)
 U_{mf-N} - minimum fluidization velocity of non-magnetic particles, (m/s)

U_0 - operating liquid superficial velocity of multistage BC with MDP. (m/s)

U_t -particle terminal velocity, (m/s)

U_{t-M} - magnetic particle terminal velocity, (m/s)

U_{t-N} - non-magnetic particle terminal velocity, (m/s)

W_s - total mass pf solids , (kg)

z axial coordinate or distance –see the context, (m)

Greek Letters

α - a proportionality factor , Eq. (71), (-)

Γ_{size} - probability to form a bubble of a given diameter, Eq. (21a), (-)

$\Gamma_{low\ velocity}$ - probability to get low bubble rise velocity , Eq. (21b), (-)

ϵ - bed porosity (phase holdup) , (-)

$\bar{\epsilon}$ - overall bed porosity, (-)

ϵ_0 - porosity of the initial unfluidized bed (Magnetization FIRST mode)

ϵ_G - gas holdup, (-)

ϵ_{G0} - centre-liner local gas holdup, Eq. (16a), (-)

$\bar{\epsilon}_G$ - overall gas holdup, (-)

ϵ_{Gr} - mean gas holdup in the riser, (-)

ϵ_{Gd} - mean gas holdup in the downcomer , (-)

ϵ_L -liquid holdup, (-)

$\bar{\epsilon}_L$ -overall liquid holdup, (-)

ϵ_S - local solids phase holdup, (-)

$\bar{\epsilon}_S$ - centre-line local solids phase holdup, Eq. (16b), (-)

ϵ^0 - bed voidage (porosity) of non-magnetized three-phase bed (Magn. LAST), (-)

ϵ^H - actual bed voidage (porosity) of magnetized three-phase bed (Magn. LAST), (-)

ϵ_{mf}^H - bed voidage at minimum fluidization conditions and $H \neq 0$ (Magn. LAST), (-)

ϵ_{fL} - liquid-solid holdup in the L-S zone (BC with MDP), (-)

ϵ_{fS} - solids holdup in the in the L-S zone (BC with MDP), (-)

ϵ_{mf} - bed porosity at the onset of MSB

η_L -fluid dynamic viscosity, (Pa.s)

μ - magnetic permeability, (WbA/.m) or (H/m)

μ_0 - magnetic permeability of free space, Wb/A.m

ρ_G - gas density, (kg/m³)

ρ_S - particle density, (kg/m³)

ρ_L -liquid density, (kg/m³)

σ -liquid surface tension, (N/m)

ν - fluid kinematic viscosity, m²/s

$\Phi = r/R$ - dimensionless radial co-ordinate, (-)

Ω -dimensionless friction factor, Eq. (43), (-)

Ω_M - dimensionless pre-factor for magnetically controlled airlifts, defined by Eq. (45)

Ω_{M0} - zero-field dimensionless pre-factor for magnetically controlled airlifts, defined by Eq. (59)

ω -specific friction factor defined by Eq. (50) and Eq. (51), (-)

ω_0 - dimensionless pre-factor (friction coefficient at zero field) for magnetically controlled airlifts, defined by Eq. (50)

Dimensionless Groups

$Fr = \frac{U_{Lr}^2}{g.h_r}$ - Froude number defined by the specific velocity U_{L0} Eq. (64b),
(-)

Subscripts

f -fluid

G- gas

g -gas

L -liquid

S -solid

Abbreviations

BC – Bubble Column

BSC – Bubble Slurry Column

BSD- Bed Surface Decrease (due to bursting gas bubbles and particle suspension)

BSS- Bubble Supported Solids

DVL - dimensionless voidage number

FB- fluidized bed

G-S - Gas-Solid

CB – condensed (frozen) bed (Magnetization LAST)

L-S - Liquid-Solid

LSS – Liquid Supported Solids

MFAF - Magnetic Field Assisted Fluidization

MDD – magnetic distributor downcomer (see Part 4)

MDP - magnetic distributor plate

MSB – Magnetically Stabilized Bed

PS MSFB- magnetically partially stabilized fluidized bed

MSFB- magnetically stabilized fluidized bed

SB – settled (de-fluidized) bed (Magnetization FIRST)

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