

III. RELEVANT HYDRODYNAMIC PROBLEMS GAS-SOLID MFA BEDS WITH THE BASIC MAGNETIZATION MODES – BATCH SOLIDS MODE

III.1 Fluidization of pure magnetic particles or magnetizable composite particles

III.1.1. Experimental conditions - two main problems

Solids used. The investigations of MFAF have been developed mainly on the basis of pure magnetic particles. The use of admixtures of magnetic and non-magnetic particles is a rather new idea (Rosensweig, 1980a), 1980b) and will be reviewed further. The fundamentals of the MFAF hydrodynamics and the basic terms and definitions have been established with gas-fluidized beds consisting totally of magnetizable particles (iron, magnetite, nickel, or magnetic composites). Therefore, the review on the relevant hydrodynamic problems starts with such beds.

Table 2 contains the main data concerning the conditions of the principal investigations performed during the last 40 years (1960-2000). Almost all the materials employed in these fundamental studies belong to Geldart's group B (Geldart, 1973); thus they are "normally" fluidizable with a bubbling onset just beyond the minimum fluidization point (Yates, 1983; Kunii and Levenspiel, 1991). The investigations on the fluidization of cohesive (in the absence of a field) magnetic particle have been developed recently and will be discussed in a separate section of the paper.

Magnetic fields applied. An important problem not-discussed in all the reviews published since Bologna and Syutkin (19976) is the effect of the magnetic field topology on the results. The problem is discussed here from a position considering the effects of the magnetic system design on the experimental results obtained by various authors. The magnetic systems employed by various groups of researchers will be reviewed shortly in order to define their basic properties and further effects on the fluidization phenomena.

Ten years ago Penchev and Hristov (1990a, 1990b) have published comprehensive data about the magnetic systems and the experimental situations applied during a period of 30 years (1960-1990) Figures 15 and 16 reproduce that information. According to the analysis done by Penchev and Hristov (1990a) the magnetic systems can be divided into three major groups:

- *Magnetic system generating homogenous axial fields*
- *Magnetic systems generating non-homogenous axial fields.*
- *Magnetic systems for transverse fields*

Table 2
Pure magnetic particles and magnetizable composite employed in studies of
MFAF – major details

Reference	Material	Fraction, μm	Geldart's Group	Dc, mm	h_{mf} , mm	Ms, kA/m	
						Value	Source *
Filippov (1961a) (1961b) (1961c)	Magnetite	9-12	C	31 84		477.46	Penchev and Hristov (1990a)
		230-300	B				
Nekrassov and Chekin (1961) (1962)	Magnetite	53- 1680	A-B	100		No data	
Doichev et al (1965)	Magnetite sand	400-500	B	40		477.46	Penchev and Hristov (1990a)
Ivanov and Grozev (1970a) (1970b)	Ni-Cr Catalyst	400-500 600-750	B	30		No data	
		750-1000 1000-2000	B-D D				
Sonolikar (1972) (1974)	Iron Powder	24.4-60.3	Cover A and C groups			1687	Penchev and Hristov (1990a)
Bologa and Syutkin (1977)	Iron shots	0-40; 40-60; 60-90	A	78		No data	
		90-160; 160-200; 200-250 250-500	B				
Ivanov and Shoumkov (1976)	Fe-Cr Catalyst And Ammonia catalyst SA-1 (Russia)	13-250 250-750	B	30 140		No data	
		800-1000	D				
Shoumkov (1975) Shoumkov and Ivanov (1974)	Ammonia catalyst SA-1 (Russia)	130-250 250-500 630-750	B	80; 150; 300 500		No data	
Ivanov and Zrunchev (1969)	Ammonia catalyst					No data	
Zrunchev (1975a) (1975b)	Ammonia catalyst SA-1 (Russia)					No data	
Lucchesi et al. (1979)	Steel spheres	177 -180	B	?		No data	
	Composite beads	300 480	B B				
Rosensweig (1979) (1980a) (1980b) Rosensweig et al. (1981a)	Steel spheres	177 -180	B	76			
	Monel	177-250 159-177 250-297	B				
Sieggell (1982)	Magnetite	100-125 180-250	B	76.2			
	Steel spheres	850-1000	B-D				
Geuzens (1985)	Magnetite	120-210 210-420 420-670	B	152.4	150; 200	477.46	Penchev and Hristov (1990a)

Table 2

Pure magnetic particles and magnetizable composite employed in studies of
MFAF – major details (continued)

Reference	Material	Fraction, μm	Geldart's Group	Dc, mm	h_{bed} , mm	Ms, kA/m	
						Value	Source
Casal (1982)	Nickel	120-177 177-250 297-400 400-500	B	51		485.42	Penchev and Hristov (1990a)
Arnaldos (1986), Arnaldos et al (1996, 1987)	Iron	250-420 420-500	B				
Penchev and Hristov (1990a) (1990b)	Ammonia catalyst	Narrow fractions $d_{\text{pmin}} = 100\mu\text{m}$ $d_{\text{pmax}} = 800\mu\text{m}$	B	65	65 100 130	236.34	Penchev and Hristov (1990a)
Hristov (1996)	Magnetite	Narrow fractions $d_{\text{pmin}} = 100\mu\text{m}$ $d_{\text{pmax}} = 500\mu\text{m}$	B			477.46	
Hristov (1998)	Iron	100-200	B			1687.04	
	Invar	200-315	B			381.97	
	Metal. dross	Narrow fractions $d_{\text{pmin}} = 100\mu\text{m}$ $d_{\text{pmax}} = 800\mu\text{m}$	B			56.50	
	Girdler catalyst G3L	Narrow fractions $d_{\text{pmin}} = 100\mu\text{m}$ $d_{\text{pmax}} = 400\mu\text{m}$	B			50.133	
Saxena and Shrivastava (1990)	Steel spheres	125-355 $d_{\text{pav}} = 262\mu\text{m}$		101.6		1687.04	Penchev and Hristov (1990a)
Saxena and Shrivastava (1991)	Iron shots	262; 624;	D D				
Saxena et al.(1994)		624; 733;1511;	B B-D	101.6			
Saxena and Wu (1999)		1416	D	101.6			
Zimmels et al (1991)	Fe/polyester Composite (2700 kg/m ³)	231	B	89	?	?	
Contal (1994) Contal et al (1992)(1998)	Iron	700 -1000	D	90	88	1687.04	Penchev and Hristov (1990a)
Sajic et al (1992)	Composite (4050 kg/m ³)	320		110		?	
Lin and Leu (1994) (1996)	Iron	210-250 $d_{\text{pav}} = 230\mu\text{m}$		50	90	1687.04	Penchev and Hristov (1990a)
Jovanovic et al. (1987) (1989) (1996)	Ferrite (4560 kg/m ³) Composite (1710 kg/m ³)	240 (320) 630	B B	110	160 (100) 280	?	

III.1.2. Homogeneous magnetic fields employed (1960-1989)**III.1.2.1. Axial fields**

The magnetic systems (Fig. 15) used for more than three decades have been built up on the basis of solenoids (long or short) generating axial magnetic fields (i.e. parallel to the fluid flow). The basic constructions were commented on earlier (II.2). As noted by Penchev and Hristov (1990a) the

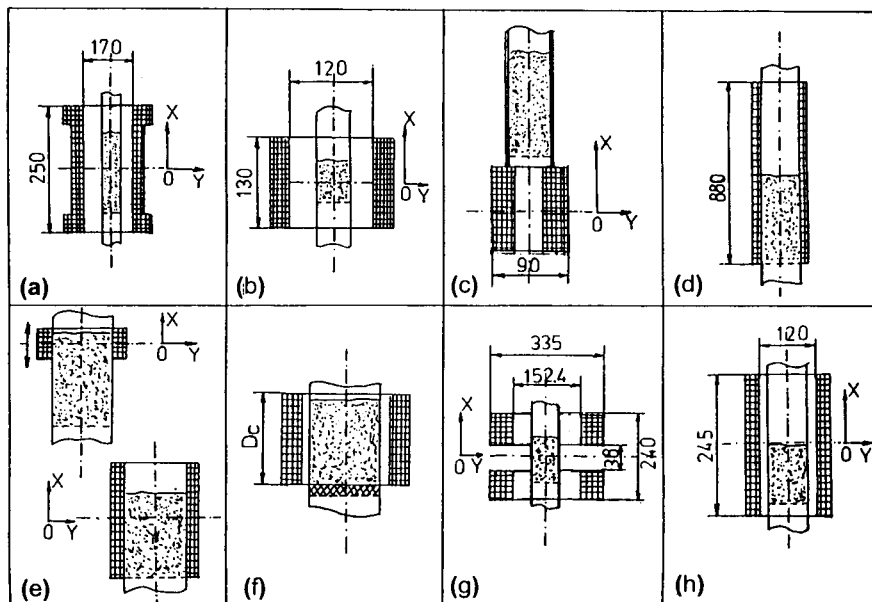


Fig. 15: Experimental situations in studies performed till 1989. From Penchev and Hristov (1990a) - Adapted and developed

- a) Kirko and Filippov (1960), Filippov (1961a, 1961b, 1961c) - a solenoid with a compensation;
- b) Ivanov and Grozev (1970b)- a short solenoid;
- c) Doichev *et al.* 1965)- a short solenoid;
- d) Sonolika *et al.* (1972) - long solenoid;
- e) Ivanov and Shumkov (1976)- short solenoids;
- f) Shumkov (1975) - short solenoids;
- g) Rosensweig (1979, 1980a,), Rosensweig *et al.* (1981a)- Helmholtz coils
- h) Casal J (1982) and Arnaldos (1986), Arnaldos *et al.*, 1986, 1987) -a moderate length solenoid.

magnetic system creating homogeneous field has been employed by Filippov (1961a, 1961b, 1961c) and Kirko and Filippov (1960), Sonolika *et al.* (1972), Rosensweig (1979, 1980a) and Casal (1982), Arnaldos (1986) and Arnaldos *et al.* (1986, 1987), Geuzens (1985), Geuzens and Thoenes (1988).

III.1.2.2. Transverse fields

In contrast to the applications of axial fields, the use of transverse fields (Fig.16) has not been so popular among the investigators. Probably one of the reasons is the use of magnetic systems based on electromagnets that contain iron details (Nekrassov and Chekin 1961,1962; Katz and Sear, 1969; Zrunchev, 1970). Rosensweig made an attempt to use a magnetic system based on permanent magnets. All of these magnetic systems have significant disadvantages discussed earlier (see the basic designs in II.2.1.2). This limits the use of such electromagnets for laboratory use only. Moreover, the required amounts of iron and the weights of such electromagnets are terrible. The second and more important disadvantage is the strong non-uniformity

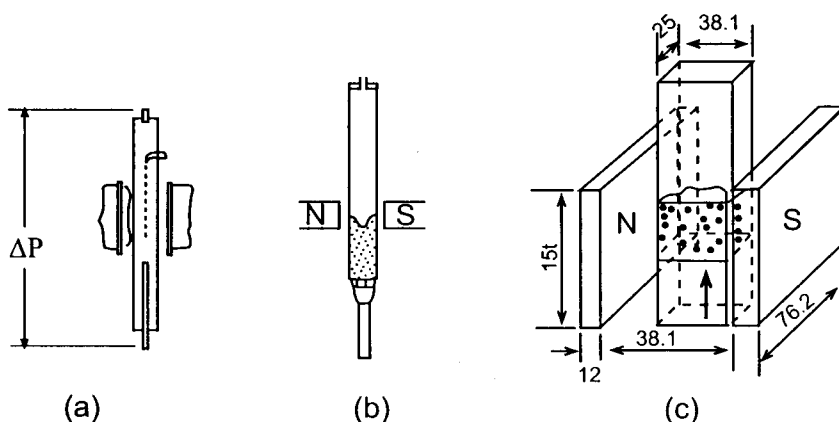


Fig. 16: Experimental situations concerning the applications of transverse fields till 1989. Adapted and developed from Penchev and Hristov (1990b)

- a) Nekrassov and Chekin (1961,1962)- electromagnet (see also Fig. 1d)
- b) Zrunchev (1970); Ivanov and Zrunchev (1970)- (electromagnets with flat poles) (see also Fig. 6a)
- c) Rosensweig (1980a) - permanent magnets

along the lateral symmetry axis, i.e. from the centre of the gap toward the pole as commented earlier. Both disadvantages, the first one caused by the uneconomical use of materials and the small working volume, and the second one due to principal problems of the lateral magnetic gradients, hindered the applications of transverse field for many years.

III.1.3. Magnetic systems employed since 1990

III.1.3.1. Axial fields

The axial homogeneous fields employed since 1990 (Table 3) have been generated by:

- Helmholtz coils (Penchev and Hristov, 1990a; Hristov, 1996; Hristov, 1998; Lin and Leu, 1994, 1996; Saxena *et al.* 1994; Saxena and Wu, 1999)
- Solenoids (Ushiki *et al.* 1991; Sajc *et al.*, 1992, 1996; Jovanovic *et al.*, 1996)

Figure 17 presents the systems employed by Saxena's group (Saxena and Shrivastava, 1991; Wu *et al.*, 1997a, 1997b).

- Barcker type magnetic systems (see Fig. 5c) employed by Zhu and Li (1994, 1996a, 1996b) are shown in Fig. 18. A similar magnetic system has been used by Zimmels *et al.* (1991) and Lin and Leu (1996).

It is important to note the more professional use of magnetic systems generating homogeneous field in the recent investigations, or in other words the "era of solenoids" disappears. The Helmholtz coils and Barcker systems create axial fields in larger volumes than the solenoids and assure easy control of the working volume due the significant gaps between the coils.

III.1.3.2. Transverse fields

A) "Saddle" - shaped coils

Ten years ago (1990) an attempt to overcome the problems of the transverse field magnetic systems commented above has been done by Penchev and Hristov (1990b). The application of saddle shaped coils (See also Fig. 6c) has offered a new trend toward the build-up of large-scale devices due to three principal advantages:

- The zone with a homogeneous field may reach about 98% of the volume inside the windings and
- The reduced amounts of a copper wire with respect the requirements of the axial magnetic systems).
- The field orientation does not allow a channelling in the bed.

The saddle coils have been employed successfully for studies on

preliminarily gas-fluidized beds (Hristov, 1998)

B) Permanent magnets

- Permanent magnets have been employed in the further studies of Contal *et al* (1994, 1996, 1998). Figure 19 illustrates the experimental conditions created by such magnetic system (Contal, 1994).

Table 3
Magnetic system employed and principal experiments performed – major details

Reference	Magnetic system	Solenoid dimensions, mm	Field, kA/m	Dc, mm	D/Dc	Major experiments performed (mode)
Filippov (1961a) (1961b) (1961c)	Short solenoid with a compensation	L= 250 D= 170	Axial homogeneous 9.6 - 12	84	2.02	• Bed expansion • Pressure drop (FIRST)
Nekrassov and Chekin (1961) (1962)	Stator	Poles height- 300 mm D - no data	Transverse rotating homogenous	100	No data	• Pressure drop (FIRST) • Bed effective Viscosity (FIRST)
Doichev et al (1965)	Short solenoid	L - undefined D= 90 mm	Axial symmetry non-homogeneous	40	No data	• Bed expansion (LAST) • Pressure drop (LAST)
Ivanov and Grozev (1970a) (1970b)	Short solenoid	D = 120 mm L = 130 mm	Axial symmetry non-homogeneous	30	4	• Minimum fluidization velocity (FIRST) • Bed expansion (FIRST)
Sonolikar (1972) (1974)	Long solenoid	D ≈ Dc			≈ 1	• Minimum fluidization velocity (FIRST)
Ivanov and Shoumkov (1976) Shoumkov (1975) Shoumkov and Ivanov (1974)	Short solenoids	L= Dc		30 140 80; 150; 300 500	≈ 1.1	• Minimum fluidization velocity (FIRST) • Bubble frequency • Bubble size • Bed parameters effect on Umf • Porosity distributions
Lucchesi et al. (1979)	Helmholtz coils	No data	Axial Homogeneous 0 - 6 kA/m	No data	No data	• Transition velocity (onset of fluidization) • Pressure drop (FIRST)
Rosensweig (1979) (1980a) (1980b) Rosensweig et al. (1981a)	Helmholtz coils	See Fig. 15g	Axial Homogeneous	76	2.0	• Transition velocity (onset of fluidization) • Pressure drop • Solids discharge (FIRST)
Rosensweig (1980a)	Permanent magnets	See Fig. 16c	Transverse 45 kA/m	Fig. 16c	-	• Transition velocity (onset of fluidization)
Siegell (1982)	Helmholtz coils	See Fig. 15g	Axial Homogeneous	76.2		• Velocity profiles • Axial gas distribution (FIRST & LAST)
Casal (1982) Arnaldos (1986), Arnaldos et al (1996, 1987)	Solenoid	L= 245 D= 120	Axial Homogeneous	51	2.35	• Transition velocity (onset of fluidization) • Pressure drop • Bed porosity • Bed hysteresis behaviour (FIRST)

Table 3
Magnetic system employed and principal experiments performed –
major details (continued)

Reference	Magnetic system	Solenoid dimensions, mm	Field, kA/m	Dc, mm	D/Dc	Major experiments performed (mode)
Geuzens (1985)	Solenoid	L= 800 D= 450	Axial Homogeneous	152	2.96	- Transition velocity (onset of fluidization) - Pressure drop - Axial and radial gas distribution
Penchev and Hristov (1990a)(1998)	Helmholtz coils	ID = 200	Axial	65	3.07	- Stabilization onset - Bed expansion - Fluidization onset - Particle materials (magnetic) properties effects
(1990b) (1998)	Saddle coils	ID = 200 L = 400	Transverse		3.07	
Hristov (1996)	Square Helmholtz coils	500x500 mm	Various orientations From axial to transverse	50	10	- Field orientation effects on the bed stabilization and bed expansion - Pressure drop
Saxena and Shrivastava (1990) (1991) Saxena et al.(1994) Saxena and Wu (1999)	Helmholtz coils	See Fig. 17	Axial	101.6	3.52	- Pressure drop - Porosity variations - Field effect on minimum fluidization velocity
Zimmels et al (1991)	Barcker system 6 coils	ID= 180 mm	Axial 0- 72 kA/m	89	2.022	- Pressure drop hysteresis phenomena - Bed hysteresis behaviour in accordance with the magnetization mode
Contal (1994) Contal et al (1992) (1998)	Permanent magnets	See Fig. 19	Transverse 0 - 50 kA/m	90	-	- Pressure drop - Bed expansion - Minimum fluidization velocity
Saije et al (1992) Jovanovic et al. (1987) (1989) (1996)	Solenoid)	L= 330 mm D = 1.1 Dc	Axial 0- 10 kA/m	110	1.1 Dc h _w /L= 2.06 and 1.17	- Pressure drop - Bed expansion - Minimum fluidization velocity - Bubble frequency - Bubble size
Lin and Leu (1996)	Barcker system 5 coils	ID= 226 mm	Axial 0- 3 kA/m	50	3.22	- Pressure drop - Bed expansion - Minimum fluidization velocity - Voidage distribution

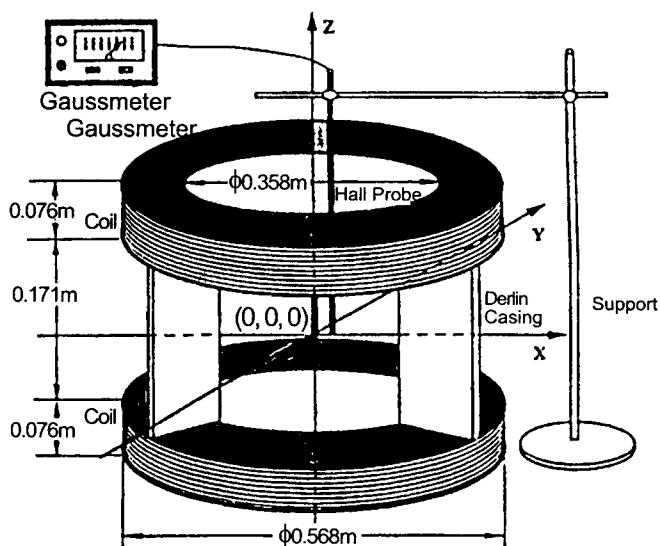


Fig. 17: Helmholtz coils employed by Saxena's group. Basic design (Wu *et al.*, 1997b)

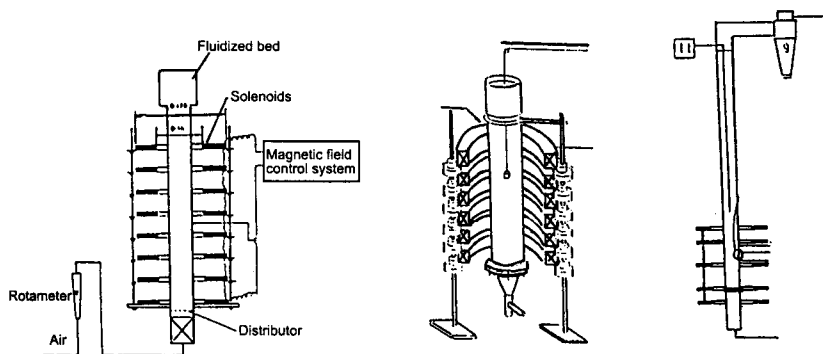


Fig. 18: Backer type magnetic system for axial fields

a) Magnetic systems employed by Zhu and Li (1994,1996).

Adapted from (Zhu and Li, 1994).

b) Magnetic system of Zimmels *et al.* (1991)

c) Magnetic system of Lin and Leu (1994, 1996)

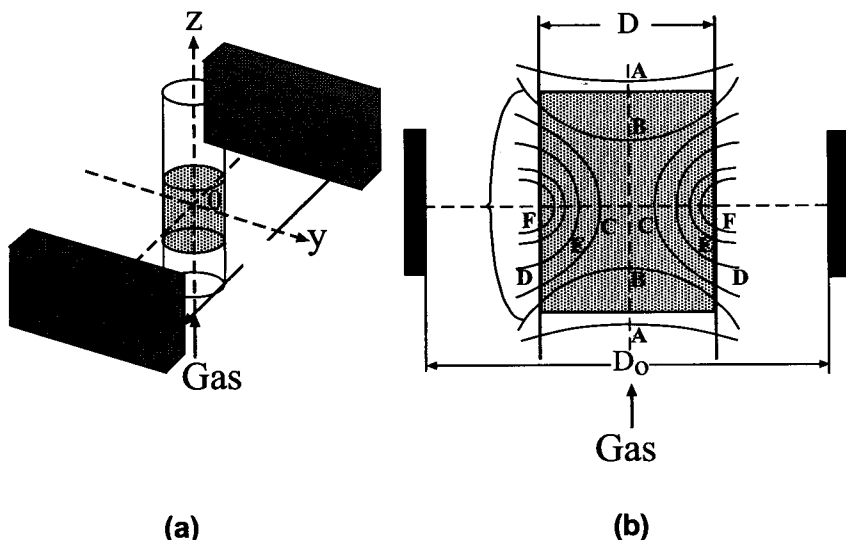


Fig. 19: Magnetic system generating a transverse magnetic field by permanent magnets. Adapted from Contal (1994).

- a) Space location of the magnets and the column
- b) Field topology. A determination of the homogeneous field zone.

III.1.3.3. Magnetic systems for transverse rotating magnetic fields

The magnetic systems (both for axial and transverse fields) commented above (III.2.1-2.4) generate field that do not change its orientation in the space. Nekrassov and Chekin (1961, 1962) (see Fig.1d) have employed a rotating transverse field generated by three-pole stator of an electric motor (50Hz AC current supply). The system has not been employed more than 40 years. Recently Lu and Li (2000) applied similar inductors for fluidization of cohesive admixtures of magnetic and non-magnetic particles (see the special section further).

III.1.3.4. Magnetic systems generating homogenous fields with neither axial nor transverse orientations

A system of square Helmholtz coils (Fig.20) supported by a non-magnetic frame (allowing a rotation around its lateral axis) has been conceived by Hristov (1996). The system permits easy change of the field orientation to a desired angle with respect to the column axis (fluid flow direction). Moreover, the swing allows the inclination of the column axis too.

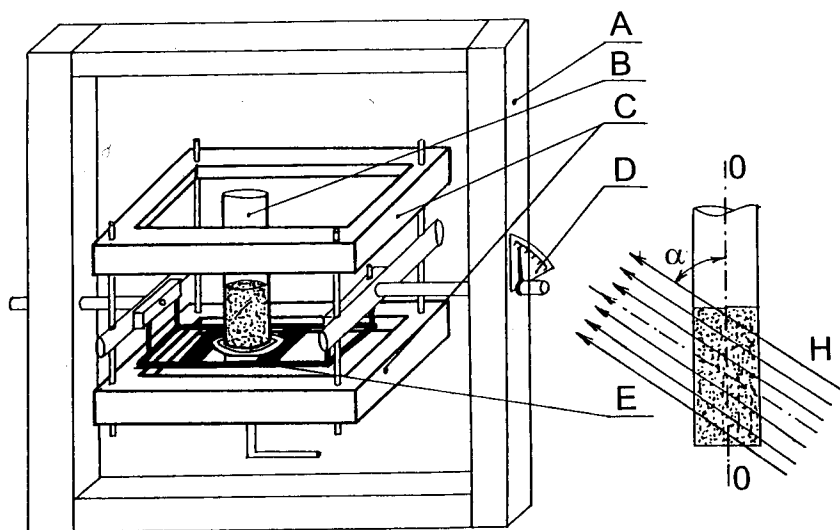
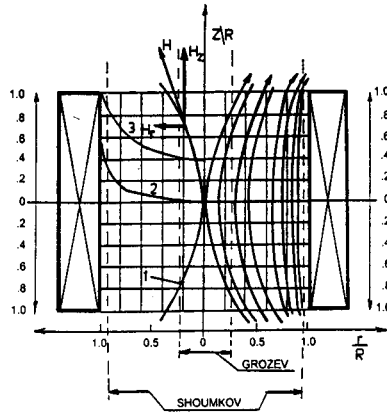


Fig 20: Square Helmholtz coils (Hristov, 1996) generating homogeneous fields with various directions: A- support; B- column; C- magnetic system; D-measuring scale; E-a swing for the column support; Inset- the definition of the angle α between the column axis (fluid flow) and the field lines)

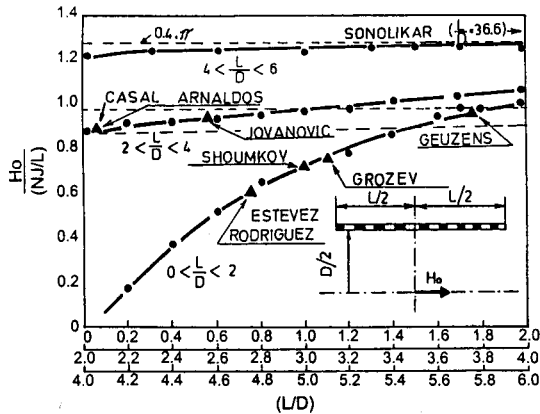
III.1.4. Non-homogeneous magnetic fields with axial symmetries

III.1.4.1. Short solenoids (1960- 1980)

The non-homogeneous fields generated mainly by short solenoids need special attention. In all the previous reviews the results obtained with these devices have been discussed together with those from homogeneous magnetic fields. The group of Ivanov, in contrast to the other investigators (from Western Europe and America), has employed non-homogeneous fields with axial symmetries (Fig.15, b, e, f.). Hristov (1994) has calculated the field distributions in the solenoids employed by Grozev and Shumkov (Fig. 21a) by a computer code created on the basis of the methodology described by Montgomery (1969). Figure 21a clearly indicates the non-homogeneous field distributions of both the axial (H_z) and radial (H_r) field vector components.



(a)



(b)

Fig.21: Field distributions in short solenoids employed till 1980. Adapted from Hristov (1994).

- a) Field distribution in the solenoids employed by Grozev and Shumkov. The vertical dashed lines define the working zones employed by these authors. It is clear that there is an increased field line concentration near the windings.
- b) Normalized field intensity at the solenoid center as function of the solenoid ratio L/D . A comparative study of all the solenoids employed by different research groups. The years in the brackets are not added because one author (or a group) employs a certain solenoid without changes in all the experiments.

III.1.42. Short solenoids employed since 1980

Estevez *et al.* (1991), Rodriguez (1995), Rodriguez *et al.* (1995) have employed short solenoids with very low ratio $L/D = 0.75$. The group of the late Prof. Jaraiz has employed this design for many years in the University of Salamanca, Spain.

III. 1.4.2. A comparison between the solenoids employed

In order to elucidate the position of the short solenoids among the other ones and to avoid further conflicts on the problem (see further discussion) two comparative plots are shown in Figs, 21b. They employ normalized field intensity calculated as

$$\frac{H}{0.4\pi \frac{NI}{L}} = \frac{B}{\sqrt{1+B^2}} \quad (13)$$

Figures Fig. 25b,c indicate that field homogeneity of 75 % in the axial direction has been created in the solenoids of Casal (1982), Arnaldos (1986) and Arnaldos *et al.* (1986, 1987) as well as in the experimental set-ups of Jovanovic and Geuzens. Sonolika (1972) has created the best field homogeneity.

The plots indicate that the dominating solenoid design has L/D ratio in the range $1.7 < L/D < 2.75$ (see also Table 3). The increase of the L/D ratio leads to better fields, but hinders the visual observations of the bed behaviour. The later is the main reason for the use of solenoids with designs assuring almost homogeneous fields (Casal, Arnaldos, Jovanovic and Geuzens).

The results obtained in non-homogeneous field created by short solenoid will be discussed in a separate section.

III.2. Magnetization FIRST (Solids Batch) (Pure Magnetic Particles) – Results

III. 2.1. Experimental findings

III. 2.1.1. Regimes and phenomena description by phase diagrams

- **Filippov's postulations and axioms**

The simultaneous action of the fluid flow and magnetic field has been presented by Filippov (1961a) with a phase diagram (Fig.22.) The