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PREDICTION OF THE PRE-BOILOVER TIME OF TANK FIRES (scaling of 1-D heat transfer models)

Paper 05-86

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ABSTRACT

The communication concerns a major problem of accident prevention due to fires. The efforts are stressed on the scaling of the heat transfer models developed by different research groups. The prediction of the boilover onset through suitable functional relationships predicting the pre-boilover time was done in a dimensionless form. The efforts have been stressed the fuel layer/waterbed parameters predefining the "boilover" appearance

INTRODUCTION

Storage plant fires can still do happen and cause severe damage and high losses. The "boilover" occurs when the burning fuel is expelled violently from the tanks due to the vaporization of the underlying water, usually collected due to condensation effects [1, 2]. The efforts have been stressed the fuel layer/waterbed parameters [3-8] predefining the "boilover" appearance and its intensity. The general question in all these investigations is about prediction of the time *for the boilover onset* [9], and the boilover intensity. The present analysis considers the prediction of the boilover time onset through a scale analysis of 1-D heat transfer models. The models under consideration are well-know and published in the literature and all of them consider the heat transfer through the fuel layer. The approach accounts the fact that in practice the *fuel layer thickness* is the *only known quantity* before the fire accidents or the laboratory experiments. The models considered were arranged in two groups[10]: 1) Surface Absorption Models (SAM) with a energy balance incorporating a volumetric source term [2, 5, 6, 9] and 2) In-Depth Absorption Models (DAM) with a volumetric heat source depending on the vertical co-ordinate [1, 6, 7, 12]. All these models accept a *Dirichlet boundary condition* at the burning fuel surface (see details in Ref. 14). The analysis hereafter is addressed to a DAM model under *new boundary condition*.

PROBLEM FORMULATION

The recent analysis [10, 13,14] indicated that the correct approach is to employ 1-D In-Depth Absorption Model (1a) with a *Stefan boundary condition* (1d) instead the Dirichlet boundary condition (1c) used by the models published. The model equation and boundary conditions are:

$$\frac{\partial T}{\partial t} = a_F \frac{\partial^2 T}{\partial y^2} - \mu q_s'' \exp(-\mu y) \tag{1a}$$

IC: $t = 0 \quad T = T_\infty$ (1b)

BC: $y = y_s(t)\ T = T_s \qquad q_s'' = H_v \rho_F r(t) + - \lambda_F \left.\frac{\partial T}{\partial y}\right|_{y=y_s(t)}$ (1c)

where $$r(t) = \frac{\partial y_s(t)}{\partial t} = \frac{\dot{m}}{\rho_F S} \tag{2}$$

is the *surface regression rate* (a function of the fuel properties and the vessel size [16,17]). The net heat flux to the fuel surface is scalable through the equation [17]

$$\dot{q}_s'' = \left(\chi/\pi\right) \rho_\infty C_p \left[T_\infty^f g\left(T_f - T_\infty^f\right)\right]^{1/2} \sqrt{D} \tag{3}$$

The fraction of the total heat released χ is independent of the pool diameter [16,17]. The contact line between the fuel and the water sublayer assumes

$$\dot{q}_c'' = - \lambda \left(\partial T/\partial y\right)_{fuel} = - \lambda \left(\partial T/\partial y\right)_{water} \tag{4}$$

but all the models discussed here consider only *the top layer condition*. Generally, the solutions look for the time, t, corresponding to the case $T_{y=0}$ = *boiling temperature of the water* as a boilover onset criterion (*y=0 corresponds to the fuel-water interface*)

SCALE ANALYSIS

Characteristic Scales

The characteristic scale employed here are well-known from the analysis of the transient heat transfer problems in slabs [18]. The following scales and dimensionless variables were selected: Length: The initial fuel layer depth y_0, so $y^* = y/y_0$; Temperature: The ratio $\Theta = (T - T_s)/(T_s - T_s)$ or $\Theta = (T - T_b)/(T_S - T_\infty)$; Time: a specific time $t_0 = \frac{y_0^2}{a_F}$,

Dimensionless Groups Evaluation

The dimensionless form of the heat conduction equation is

$$\frac{\partial \Theta}{\partial t^*} = Fo \frac{\partial^2 \Theta}{\partial y^{*2}} + \quad N_{VA} \exp\left[-(\mu y_0) y^*\right] \tag{5}$$

where

$$Fo = \left(a_F t_0 / y_0^2\right) \text{ and } N_{VA} = \left[t_0 \left(\mu\ \dot{q}_{s0}\right) / \rho_F C_p \left(T_s - T_\infty\right)\right] \tag{6}$$

and the *Buger number* (μy_0) *defined through the initial fuel layer thickness*. The scaling equation (3) transforms N_{Fd} in a form specific for the pool fires:

$$N_{Fd} = t_0 \left[(4/\pi) \mu \chi / (T_s - T_\infty) \right] \sqrt{D} \left[g T_\infty (T_f - T_\infty) \right]^{1/2} \tag{7}$$

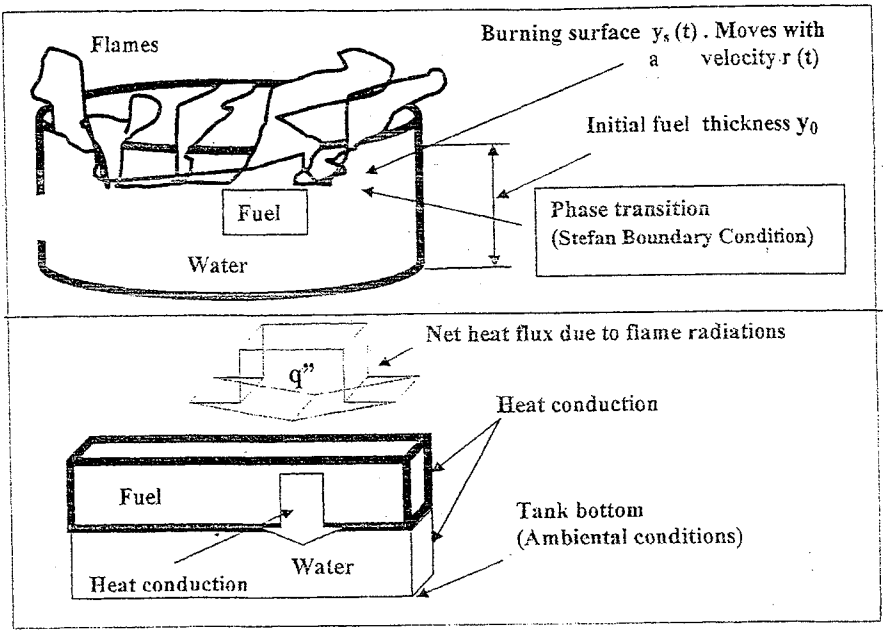

Fig. 1 Schematic presentations of the situation studied

On the other hand the *Stefan boundary condition* takes the following dimensionless form:

$$\frac{q_s'' y_0}{\lambda (T_s - T_\infty)} = \frac{H_V \rho_F y_0}{\lambda (T_s - T_\infty)} r(t) - \frac{\partial \Theta}{\partial t^*} \tag{8a}$$

$$B_{SA} = \frac{N_{DHS}}{Ste} = \frac{\partial \Theta}{\partial y^*} \tag{8b}$$

The left-hand side defines the group B_{SA} analogous to the ***Biot number***

$$B_{Si} = \frac{q'' y_0}{\lambda_F (T_s - T_\infty)} \tag{9}$$

The phase transition results in the **Stefan number** [13]: $Ste = \frac{C_P (T_S - T_\infty)}{H_V}$. The "moving heat source" represented by the *burning fuel surface* gives

$$N_{DHS} = \frac{y_0 r(t)}{a_F} \tag{10}$$

a dimensionless group analogous to the *Peclet number*, $Pe = (ul/a)$, in the case of a convection and a moving heat source [18]

Dimensionless group minimization

Concerning the Stefan boundary condition (8b) a new group could be developed

$$Hp = \frac{B_{SA}\, Ste}{N_{DHS}} = \frac{q_s''}{\rho_F r(t) H_V} = \frac{\dot{q}_s''}{\dot{m}'' H_V} \tag{11}$$

The Hp number is a constant upon a particular situation- ***pool diameter, fuel and fuel thickness***, i.e. macroscopic data that *are known before the experiments* or accidents. However, $Hp << 1$ due to the higher values of $H_V \sim O(10^6)\, J/kg$ typical for the hydrocarbons.

Scaling Estimations of the Fuel Initial Temperature Effect [10]

Recently, the data of Arai et al.[19] (a unique report published on the initial fuel temperature effect on the pre-boilover time) have been treated by Hristov [10]. It was found that

$$Fo^e = \frac{t_{B0}(\text{exp eriment})}{t_0} \sim (\Delta\Theta_0)^{*2} \tag{12}$$

where $\Delta\Theta_0 = (T_{0f} - T_i)/(T_{bf} - T_{bw})$ correspond to the *water boiling point* usually assumed at about 80 °C. This assumption [1-9, 11, 12, 14], *incorporated in all the physical model of the boilover onset prediction*, is a matter of argument. It will be commented further, during the scaling procedures. Therefore, at $T = T_{Wb}$ the time t_{B0} can be predicted through correlation of the Hp number.

Where are we going with the Developed Dimensionless Groups?

The scaling and the dimensionless group developed *significantly minimize the number of the process variables*. The dimensionless time of the transient heat conduction problem assumed as a model determines the development of the dimensionless temperature Θ. In the conventional heat transfer analysis we are looking for the temperature profile developed as a function of time and under the control of the boundary condition (by the *Biot number* upon convection heat exchange at the phase boundary). In the present case *the boundary condition is controlled by the Hp number* since the *radiation heat transfer* from the lame to the fuel surface *is assumed only*. The prediction of the pre-boilover time considers *the opposite problem*: if the temperature upon the boilover onset conditions *is known* (Θ_{B0}), what is the time for that if the process is controlled by the boundary (through *the Hp number*) and the source term N_{VA}. Taking into account the interrelation between the B_{SA} and N_{VA}, we can decide that the source term is represented by the *Buger number* $Bu = \mu y_0$, since

$$N_{VA} = Bu.B_{SA} = Bu.\left(\frac{N_{DHS}}{Ste}\right)Hp \sim const.Bu.Hp \tag{13}$$

Following the rule of the dimensionless analysis if we have three terms of the governing equation, the resulting dimensionless groups are two (**Bu** *and* ***Fo***). The dimensionless temperature can be expressed as function of

$$\Theta = f(Fo, N_{VA}, Hp) = f(Fo, Bu, Hp) \tag{14}$$

At $t = t_{B0} \rightarrow \Theta = \Theta_{B0} = const.$, so we can re-write (14) as

$$Fo = \Phi^{-1}\left[(\Theta_{B0})^p (Bu)^n (Hp)^m\right] \tag{15}$$

Functional Relationship

The form of the function (15) can be defined through data fitting and a regression analysis of experimental data. However, some preliminary considerations could help the data arrangement:

1) The pre-boilover experimental time[1-9, 11, 12, 14, 15] is proportional to the initial fuel thickness y_0, so

$$t_{B0} \sim y_0 \Rightarrow \underbrace{\left(\frac{t_{B0}}{t_0}\right)}_{Fo} \sim \left(\frac{y_0}{t_0}\right) \Rightarrow Fo \sim \frac{y_0}{\left(\frac{y_0^2}{a_F}\right)} \Rightarrow Fo \sim \frac{1}{y_0} \Rightarrow Fo \equiv \frac{1}{Bu} \tag{16}$$

This semi empirical scaling permits to develop a dimensionless relationship in the form

$$Fo \equiv \left(\frac{\Theta^2_{B0}}{Bu}\right)Hp \tag{17}$$

Physically, the factor $\left(\frac{\Theta^2_{B0}}{Bu}\right)$ depends only on the initial fuel thickness and the Buger coefficient μ, while the *main factors controlling the process* depend on the phenomena *at the flaming surface* represented by the Hp number.

DATA FITTING AND CORRELATIONS

The data fittings demonstrated below elucidate the physics of the problem, so some particular scaling relationships will be commented.

Scaling to the Generation Number N_{VA} and More Dimensionless Groups

The number N_{VA} expressed through the scaling equation (3) can be presented as

$$N_{VA} = (\mu y_0) N_u \tag{18a}$$

where

$$N_0 = q_{s0}\, y_0/\lambda(T_s - T_\infty) = \left(\Gamma/\sqrt{y_0/D}\right) y_0^{1.5} \qquad (18b)$$

and

$$\Gamma = (4\chi/\pi)(\mu y_0)\left[\rho_\infty C_p \left[T_\infty g(T_f - T_\infty)\right]^{\frac{1}{2}}/\lambda(T_s - T_\infty)\right] \qquad (18c)$$

The term Γ can be assumed as a constant depending only on the fuel characteristics and the initial fuel thickness. The attenuation term $(\mu y_0)exp\left[-(\mu y_0)y^*\right]$ was evaluated[10] that : The Buger number (μy_0) varied from 0.5 to 5 (data of Refs 6,7,17,20-22 treated) approximately and the exponent $exp\left[-(\mu y_0)y^*\right]$ reached its maximum of 1 at the fuel surface. Thus, we have

$$Fo = \Phi\left[(\mu y_0)^n (Ste)^m (N_0)^p\right] \approx \Phi\left(\Delta\Theta|^{water}_{boiling\ point}\right)\left(\Gamma/\sqrt{y_0/D}\right) Bu^n \qquad (19)$$

The preliminary scaling of yielded $Fo \sim (N_{DHS})^{-1}$ and $Fo \sim Ste^2$. Thus, the regression of the data of Garo et al.[6,9] (see details in Ref.14) in the form $Fo = A + B.N_0^m Ste^n N_{DHS}^p$ gives a linear fit (Fig.1) at 0.95 confidential interval

$$\left(Fo\, N_{DHS}/Ste^2\right) = 0.88 - 0.016 N_0 \qquad (20)$$

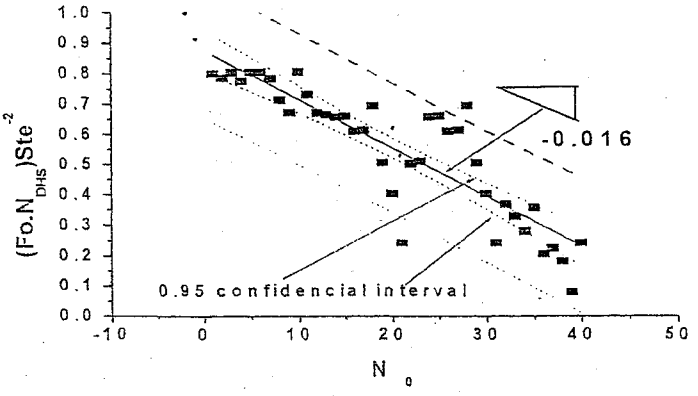

Fig. 1. Data fitting of the results of Garo et al. [6,9]

at $Ste = 0.728$ and $0.2 < N_{DHS} < 1.9$, for variations of N_0 within the $0.05 < N_0 < 90$.
The last data fitting considers mainly the effect of the various dimensionless groups developed in order to evaluate the contribution of the particular physical effects.

Scaling to Hp number (minimized amount of dimensionless groups) [13, 14]

The same data (of Garo et al. [6,9] scaled to the Hp number are shown on Fig. 2.

where $$M_1 = \frac{Fo}{(\Theta_{B0})^2} = f(Hp)^m \qquad (21)$$

Therefore, the potential functional relationship could be expected in the form $Fo \sim \frac{1}{Hp^m}$

This scaling is confirmed by the data of Koseki et al.[8] (see Fig. 2b)

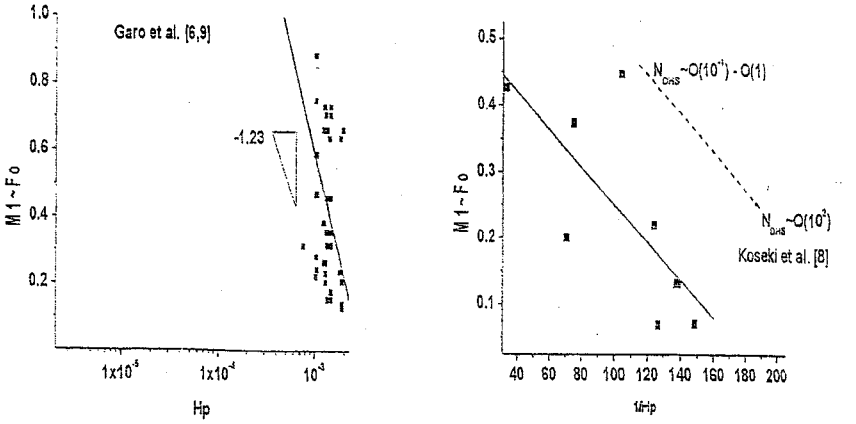

Fig. Scaling $Fo \sim f(Hp)$

a) Data of Garo et al. [6,9] ;b) Data of Koseki et al. [8] arranged as two groups demonstrating the effect of the *pseudo* Peclet number N_{DHS}

SHORT ANALYSIS

Analysis of the Generation Number Effects

From fundamental point view and as well as for the safety engineering purposes *two limiting situations* are interested:

1) $Fo \to \infty$, i.e. *no boilover occur practically.*

2) $Fo \to 0$, that means an *immediate boilover.*

The case $Fo \to \infty$ means that $N_{DHS} \to 0$ (see 21) that could occur if: $r(l) \to 0$ (difficult to burn fuel) or $y_0 \to 0$ (extremely thin fuel layer), or $a_F \to \infty$ (that is impossible, since a_F is a transport property of the medium).

2) The case, $Fo \to 0$, means $y_0 \approx 0$ (no fuel layer exist , that is non-sense) or $a_F \to \infty$ which I unrealistic as commented above.

The intermediate cases could be analyzed through the plot on Fig.1. At $N_0 \to 0$ (i.e. no burning fuel exits, $y_0 \approx 0$ or extremely narrow vessels ($D \approx 0$), the value of $Fo \to 1$

(really) $A \approx 0.88$. Therefore, at $Fo \to 1$ the thermal time scale $t_0 = \left(y_0^2/a_F\right)$ defines the pre-boilover time. As $Fo << 1$, i.e. large N_0 numbers that should be exhibited by large pool fires on waterbeds) the idea of the hot zone [1,6,9] is non-sense since it means that the hot zone propagates faster that the temperature field, that is unrealistic. Therefore, at large values of N_0 no *pure heat conductivity transfer should be considered* in the fuel bed. It seems that the convection in both the fuel and the water take an important role, which is *not investigated yet.*

Analysis of the *Hp* Number Scaling

The analysis performed leads to

$$Fo^* = \frac{t_{B0}}{\left(\frac{y_0^2}{a_F}\right)} \equiv \frac{1}{Bu}\frac{1}{Hp} \equiv \frac{1}{y_0}\frac{1}{q''} \equiv \frac{1}{y_0\sqrt{D}} \tag{22a}$$

or in a dimensional form

$$t_{B0} \sim y_0 \frac{1}{\sqrt{D}} \sim \left(\frac{y_0}{D}\right)\sqrt{D} \tag{22b}$$

The recent attempts[10] through *direct empirical regression analysis* of the data of Garo et al [6,9] yielded

$$Fo^* = f(y_0/D) = Fo^* \sim \left(\frac{y_0}{D}\right)^{-\frac{1}{2}} \tag{23a}$$

and

$$\therefore \quad Fo^*/\Delta\Theta_b^2 \sim \left(\frac{y_0}{D}\right)^{-\frac{1}{2}} D^{-\frac{5}{2}} \tag{23b}$$

or in a dimensional form

$$t_{B0} \sim \left(\frac{\Delta\Theta_b^2}{a_F}\right)\sqrt{y_0}\left(\frac{y_0}{D}\right) \tag{23c}$$

Both dimensional scaling relationships are practically identical since the fuel layer thicknesses and the pan diameters in the experiment of Garo et al.[6,9] are of similar orders of magnitude $O\left(10^{-2} \quad m\right)$. Therefore, we could *scale rigorously* that upon these laboratory conditions $\sqrt{y_0} \approx \sqrt{D}$, that practically leads to similar results.

CONCLUSIONS

The scale analysis developed *basic dimensionless groups* controlling the process of the fuel layer burning. The simple scaling through the *Buger number Bu* and the developed *Hp number* allows generating *simple charts for particular fuels and tank dimensions.* Moreover, the scaling could be considered as instructive for further data treatments from experiments on boilover predictions. The unified data treatment through dimensionless groups should allow more comparable data to be reported. The unified approach could serve as a basis for computer model for emergency control predicting the potential pre-boilover explosion time after the fire onset.

The analysis allows evaluating some deficiency of the models analyzed: 1) One-dimensionality that must be compensated by the scaling equation (3); 2) The criterion for the boilover onset assumed at the water boiling point. If the water sub-layer is considered upon superheated condition (see comments on Ref. 14) the water temperature must be assumed as 270 ° C that generates a factor of about 10 in the scaling estimation (12) for example. All this problems needs more detailed analysis and more adequate models of the heat transfer under hydrocarbon fire on waterbeds.

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NOMENCLATURE

C_p - specific heat air (eq. 1), J/kgK
D - diameter of the pool, m
Hv- the latent heat of of vaporization , kJ/kg
$\dot{m}''$ - mass burning rate pool, kg/m^{2}s
$\dot{Q}$ -heat release rate from the burning liquid layer, W
r(t) - surface regression rate, mm/s
t_b - Time for burning, time
t_{BO} - pre-boilover time, time
T_∞ - the ambient temperature, K
T_f - average flame temperature (typically $T_f \approx 1000K$, K
T_i - initial fuel temperature, K
T_{bf} - boiling temperature of the fuel, K
T_{bw} - boiling point of the water, K
T_s -vaporization temperature of the fuel, K
y - vertical co-ordinate, m
y_0 - initial fuel layer thickness, m
$y_s(t)$ - the location of the of the fuel surface at a specific time, m

Greek letters
ρ -density, kg/m^3
λ - thermal conductivity, W/mK

Superscripts
f- flame

Subscripts
a - air
c - conductivity
EQ - equivalent
f - flame
F - fuel
s - surface
v- vapour
w - water
∞ - ambient conditions

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