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***6TH WORKSHOP
ON
TRANSPORT PHENOMENA IN TWO-PHASE FLOW***

PROCEEDINGS

EDITORS

CHRISTO BOYADJIEV

Institute of Chemical Engineering
Bulgarian Academy Of Sciences

JORDAN HRISTOV

Department of Chemical Engineering
University of Chemical Technology and Metallurgy, Sofia

***2001, September 11-16
BOURGAS
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MAILING ADDRESS

To: Prof. Chr. Boyadjiev
Systems Engineering laboratory
Institute of Chemical Engineering
Bulgarian Academy of Sciences
Acad. G. Bontchev Str. Bl. 103
1113 Sofia, Bulgaria

Phone: (+359-2) 979 32 75;
(+359-2) 979 704154
Fax: (+359-2) 979 523;
(+359-2) 979 734936
E-mail: chboyadj@bas.bg

PREFACE

The event held in Bourgas, Bulgaria, September 11-16, 2001 is a meeting of scientists from different areas of transport phenomena in two-phase flows. The discussion and the familiar atmosphere help the further collaboration between the people involved in that interesting area for better development of the changing world.

The book collects several jubilee lists of outstanding scientists contributed over the past 6 years to the development of the Workshop on "Transport Phenomena in Two-phase Flow".

We express our acknowledgements to all the institutions supporting the Workshop as well as all to our friends and colleagues contributing to the event.

The Editors

Bourgas
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BURNING OF A SLICK OF FUEL ON WATER

Qualitative analysis of the heat transfer model and the pre-boilover time on the basis of data available

J. HRISTOV

*Department of Chemical Engineering, University of Chemical Technology and Metallurgy 1756
Sofia, 8 Kl. Ochridsky str., Bulgaria, E-mail: jyh@adm1.uctm.edu*

Key words: fire, boilover, pool burning, flame height, pulsations

ABSTRACT The communication concerns the burning of a slick of fuel on water sublayer. The main efforts are stressed on the qualitative assessments of the heat transfer mechanisms and the prediction of the boilover onset. The analysis employed various data obtained by different research groups. The evaluation of the suitable functional relationships predicting the pre-boilover time was done on the basis of dimensionless forms of two types of models: Surface absorption models and In-depth absorption models

INTRODUCTION

Boilover is generally considered as one of the most dangerous fire phenomena in large-scale oil-tank fires. Fires in storage plants can still do happen and cause severe damage and high losses. The most dangerous phenomena occur when the burning fuel is expelled from the tanks due to the vaporization of the underlying liquid sublayer. Usually, this sublayer consists of water collected in the lower parts of the tanks due to condensation effects.

Fuel ejection phenomena during tank fires

When the fuel is burning the heat release from the flame heats the unburned fuel and the heat is transferred by conduction mainly toward the underlying waterbed. The burning fuel surface is heated to temperature significantly exceeding the fuel boiling point. The fuel bed forms a so-called "hot zone" with a homogeneous temperature profile in its depth over a certain distance from the burning surface. When the hot zone reaches the waterbed it starts to vaporize. The intensive vaporizing is followed by intensive elutriation of water droplets into the burning zone of the fire that makes the flame more violent. The violence of the fire flame increases due to the increased mass transfer surface the disrupted smooth fuel surface (pre-boilover period) by the water vapour bubbles erupting through it.

The most dangerous effect of the waterbed vaporization is the ejection of the fuel from the tank. The fuel ejection from the tanks could be separated in three categories [1]:

- **Slop over** occurs as a discontinuous frothing release of fuel from the tank on one side of its wall. The slop over is usually a result of firefighter attempts and may occur after a long period of firefighting.
- **Froth over** is a continuous low intensity fuel release (frothing) from the tank over its wall. The froth over is similar to the "rolling effect" occurring during the tank filling [1].

- **Boilover** is a violent ejection of the fuel that results in an enormous fire enlargement and formation of fireballs. The ejection concerns a frothing over the entire tank content. The spillage of the burning fuel causes an enormous danger for surroundings - equipment and humans.

Boilover - a special concern

The boilover phenomenon is attractive from a fundamental point of view that address to better understanding of its mechanism and theoretical prediction of the critical condition of its onset.

Blinov and Khudyakov [2] have reported a hot zone formation in the fuel layer during the burning process. The formation mechanism of such hot zone in an oil layer considers a distillation process of the oil components and heat conduction to the water sublayer and tank walls. The boilover phenomenon is quite complicated and at present is under intensive research [3-7].

The major efforts of the investigators have been stressed on the parameters of the fire subsystem: fuel layer/water sublayer [5-7] as condition predefining the boiler appearance and its intensity. The major factor of the process concerned are:

- Burning rate
- Time to start the boilover
- Boiler intensity
- Liquid temperature history
- Effect of the fuel boiling point
- Developing of the "hot zone" in the fuel layer and its time evolution.

The present communication focuses the efforts on the estimation of a map of the fuel/sublayer pre-history and overall data correlations addressed to the experimentally observed times of Pre-boilover burning as well as other parameters of the pool fires.

PROBLEM FORMULATION

The burning of fuel spilled on water may constitute a hazard, i.e. an important concern is the boilover. The term is usually applied to burnt of fuel in tanks as commented above. The term has been applied also to the burning of thin slicks of oils in order to limit the spill spread after an accidental release [8]. The scenario is commonly referred as thin-layer boilover.

Despite the fact the both cases are somewhat different in nature the common element is the water boiling at the fuel/water interface. This sets up general questions about the time for ignition and the onset of boilover, i.e. the time needed for the thermal wave to reach the fuel/water interface [9]. The problem linked to the thin layer boilover scenario is the uncontrolled nature of the combustion process [6]. The total fraction of fuel burnt before the boilover onset increase with the fuel layer thickness if the layer is thinner than 10 mm and remain constant for thicker layers [10]. The thick layer lead to a "hot zone" formation that results in low fuel consumption and explosive boilover in contrast to the thin-layer cases exhibiting smooth boilover onsets and high fuel consumption.

Geometrical characteristics of both the pool and the fuel layer have a great impact on the burning rate and the pre-boilover time [9,11]. The burning rate does not depend on the fuel layer thickness if the initial layer is thicker than 10 mm and decrease with thinner layers.

Table1. Boilover - a collection of literature data concerning some major experiments

REFERENCE	FUEL	Pan diameter, m	Fuel layer thickness, m	Water layer thickness, m	F/D , FW and W/D ratios
Broekmann and Schecker, (1995) [1]	- Solvent A ♣ - Solvent B ♣ - Gasoil ♣ - Arabian light crude oil - Forties crude oil - Solvent B + light gasoline - Solvent B + petrolether - Gasoil - Gasoline	0.19	0.16		F/D =0.842
		0.5	0.5		F/D =1
		1	0.3 and 0.5		F/D =0.3 and 0.5
		1.91	1		F/D =0.523
Garo & Vantelon (1999) [5]	- Toluene - n-octane - hexadecane as component of the fuel tested - Crude oil - Heating oil	0.06 m deep pans :	Range of 2 - 20 mm	From 57 to 39 mm ! F+W = 59 mm	<u>15 cm pan:</u> F/D = 0.013-0.1 F/W = 0.035 - 0.0357 W/D = 0.28 - 0.38 <u>23 cm pan:</u> F/D = 0.00869 -0.065 F/W = 0.035 - 0.0357 W/D = 0.182 - 0.247 <u>30 cm pan:</u> F/D = 0.0066-0.005 F/W = 0.035 - 0.0357 W/D = 0.14 - 0.19 <u>50 cm pan:</u> F/D = 0.004 -0.03 F/W = 0.035 - 0.0357 W/D = 0.114 - 0.084
		0.15 0.23 0.3 0.5			
Koseki et al (1991) [30]	- Arabian light crude oil - Kerosene	0.3	0.035		F/D = 0.116
		0.6	0.020		F/D = .033
			0.069		F/D = 0.115
		1.0	0.020		F/D = 0.02
			0.04		F/D = 0.04
			0.06		F/D = 0.06
			0.1		F/D = 0.1
		2.0	0.020		F/D = 0.01
Arai et al. (1990) [21]	16 fuels (not listed here)	0.048	0.003;		<u>4.8 cm pan:</u> F/D = 0.208 (F=2 mm) and 0.062 - 0.208 <u>9.8 cm pan:</u> F/D = 0.0306-0.102 <u>20.3 cm pan:</u> F/D = 0.014-0.049
		0.098	0.010		
		0.203			
Imamura et al. (1992) [27]	Toluene n-decane Albera Sweet crude oil	0.074 and 0.1 depth	0.002-0.015		<u>12 cm pan:</u> F/D = 0.016-0.125
		0.12 and 0.02 depth 0.048			

NOTES: 1) ♣ -Not-hot-zone-forming fuels; 2) F-fuel layer; W-water layer; D-pan diameter

The further analysis is based on two major results available in the literature published:

- Models developed
- Experimental data concerning the pre-boilover time

Models developed

Twardus and Brzustowski [12] did the first attempt by a development of simple one-dimensional model with heat losses towards the water sublayer. Latter the model was developed to incorporate the radiative absorption in the fuel [13]. More realistic model incorporating the radiative feedback of the flame and the turbulent buoyant motion has been developed by Alramadhan et al. [10]. Garo at al. [6] reported recently one-dimensional both single and double layer models.

General consideration of the models

The heat release rate from pool fire can be expressed as (Drysdale, 1985 [14]; Cox, 1995 [15]; Wu et al, 1997 [16]) :

$$\dot{Q} = \rho_{\infty} C_p [T_{\infty} g(T_f - T_{\infty})]^{\frac{l}{2}} D^{\frac{5}{2}} \quad (A1)$$

The net heat feedback per unit area of the burning liquid is a small fraction of the total heat released and can be represented by the fraction χ that is independent of the pool diameter [17,18]. Thus the heat flux per unit area reaching the surface is

$$\dot{q}_s'' = \chi \frac{4\rho_{\infty} C_p [T_{\infty} g(T_f - T_{\infty})]^{\frac{l}{2}} D^{\frac{5}{2}}}{\pi} \quad (A2)$$

A schematic of the problem is shown on Fig. 1. Assuming no convective motion and that the radiation is fully absorbed at the surface $y = y_s(t)$ the energy balance is:

$$\dot{q}_s'' = H_v \rho_F r(t) + \dot{q}_c'' \quad (A3)$$

where

$$\dot{q}_c'' = -\lambda \left. \frac{\partial T}{\partial y} \right|_{y=y_s(t)} \quad (A4)$$

the surface regression rate

$$r(t) = \frac{\partial y_s(t)}{\partial t} = \frac{\dot{m}}{\rho_F S} \quad (A5)$$

Under this assumption the vaporization rate can be expressed as

$$r(t) = \frac{\dot{q}_s'' - \dot{q}_c''}{H_v \rho_F} \quad (A6)$$

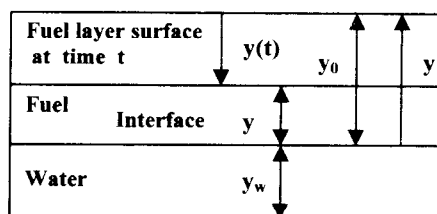
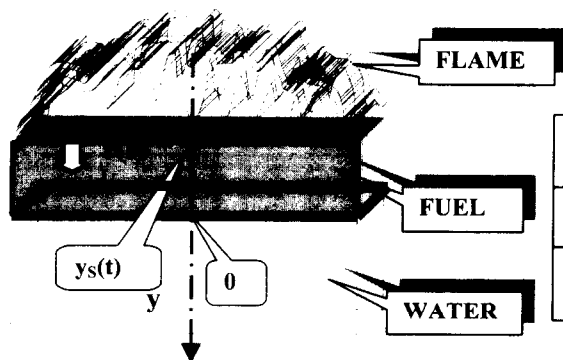


Fig.1. Schematic presentation of the problem

Fig.2 Schematic of the mathematical models

Table 2. Surface Absorption Models (SAM)

MODEL	SOLUTION	Reference
One-dimensional single layer conduction model M1 $\frac{\partial T}{\partial t} = a_f \frac{\partial^2 T}{\partial y^2}$ IC: $t = 0 \quad T = T_\infty$ BC: $y = y_s(t) \quad T = T_s$ $y \rightarrow \infty \quad T = T_\infty$	Temperature distribution $\frac{T - T_\infty}{T_s - T_\infty} = \exp \left[-\frac{r}{a_f} (y - y_s(t)) \right]$ Assumptions: $a_f \approx \text{const.}$ $r(t) = r = \text{const.}$ $a_f \approx a_w$	Blinov and Khudyakov (1961) [2] Wu et al. (1997) [16] (Garo et al, 1999) [5]
One-dimensional single layer conduction model M1 $\frac{\partial T}{\partial t} = a_f \frac{\partial^2 T}{\partial y^2}$ IC: $t = 0 \quad T = T_\infty$ BC: $y = y_s(t) \quad T = T_s$ $y \rightarrow \infty \quad T = T_\infty$	Temperature distribution $\frac{T - T_i}{T_{bf} - T_i} = \Theta = \exp \left(-\frac{y_0^2}{a_f t_{b0}} \frac{y}{y_0} \right)$ at $t_{b0} \ll t_b$ $\Theta_{bw} = (T_{bw} - T_i) / (T_{bf} - T_i)$ at small $(y_0^2 / a_f t_b) \propto O(1)$ $\Theta_{bw} = 1 - \exp(\tau_{bw}^2) \text{erfc}(\tau_{bw})$ $\tau_{bw} = \left[(\lambda_f \lambda_w) (a_f t_{b0})^2 \right] / [y_0 (1 - t_{b0} / t_b)]$	Blinov and Khudyakov (1961) [2] Arai et al. (1990) [21]
One-dimensional two layer conduction model M2 $\frac{\partial T}{\partial t} = a_f \frac{\partial^2 T}{\partial y^2} ; \quad \frac{\partial T}{\partial t} = a_w \frac{\partial^2 T}{\partial y^2}$ IC: $t = 0 \quad T = T_\infty$ BC: $y = y_s(t) \quad T = T_s$ $y = 0, \quad -\lambda_f \frac{\partial T}{\partial y} \Big _{y=0} = -\lambda_w \frac{\partial T}{\partial y} \Big _{y=0+}$ $y \rightarrow \infty \quad T = T_\infty$	Average regression rate (Garo et al, 1994; 1999a) $r = \frac{l}{H_f \rho_f} \left[\chi \cdot \dot{q}'' - \frac{a_f \lambda_f (T_s - T_\infty)}{y_0 (\sqrt{a_f} + \sqrt{a_w})^2} \right]$ Assumptions: $a_f \approx \text{const.}$ $r(t) = r = \text{const.}$ $a_f \approx a_w$ and $a_{EQ} = \frac{\gamma y_0}{a_f} (\sqrt{a_w} + \sqrt{a_f})^2$	Wu et al. (1997) [16] (Garo et al, 1994; 1999a) [6,9] Garo and Vantelon, (1999) [5]

Table 3. In-Depth Absorption Model (DAM)

MODEL	SOLUTION	Reference
One-dimensional two layer conduction model M4 $\frac{\partial T}{\partial t} = a_F \frac{\partial^2 T}{\partial y^2} + \frac{\partial \dot{q}_r''}{\partial y}$ $\dot{q}_r'' = \dot{q}_s'' r \cdot \exp[-\mu_F(y_0 - y(t))]$ IC: $T(y, t) = T_\infty, \quad -y_w \leq y \leq y_0$ BC: BC 1: $y = y_0 - (\dot{m}''/\rho_F)t \quad \dot{q}_{rs}'' = \dot{m}'' L_v + \lambda_F \left. \frac{\partial T}{\partial y} \right _{y(t)}$ $T_s < T_b$ BC2: $t > 0 \quad y = 0 \quad -\lambda_F \left. \frac{\partial T}{\partial y} \right _{y=0^+} = -\lambda_w \left. \frac{\partial T}{\partial y} \right _{y=0^-}$ BC3: $T_{y=0^+} = T_{y=0^-} \quad y = -y_w \quad -\lambda_w \left. \frac{\partial T}{\partial y} \right _{y=-y_w} = 0$	Numerical solution <i>Assumptions:</i> No hot zone formation	Garo et al. (1999b) [7]
$\rho_F C_p \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial y^2} + \dot{q}_r \mu \exp(-\mu y)$ BC: $y = y_s(t) \quad T = T_s$	Numerical solution <i>Assumptions:</i> - The thermal properties of the liquid are constant and equal to those at 298K - Heat is diffused faster than the regression rate	Inamura et al. (1992) [27]
$\frac{\partial T}{\partial t} = a_F \frac{\partial^2 T}{\partial y^2} + \frac{\partial \dot{q}_r''}{\partial y} \quad \dot{q}_r'' = \dot{q}_s'' \exp(-\mu y)$	Numerical solution <i>Assumptions:</i> No hot zone formation	Garo et al. (1998) [6]
$\frac{\partial T}{\partial t} = \frac{\partial}{\partial y} \left(a_F \frac{\partial T}{\partial z} \right) + r_a \frac{\partial T}{\partial z} + \frac{\mu}{\rho_F C_p} \dot{q}_r'' \exp(-\mu y)$	Numerical solution <i>Assumptions:</i> Hot zone formation	Broekmann and Schecker (1995) [1]

Structures of the models

The models developed are summarized in Tables 2 and 3. All of them are one-dimensional models from a principle point of view concerning the energy balance approach for the burning fuel layer. They can be separated into two major groups (the separation done here):

- Surface Absorption Models (SEM).** The energy balance does not incorporate a volumetric source term. The radiation reflux to the fuel surface is taken into account through the boundary condition at the top of the fuel layer.
- In-Depth Absorption Models (DEM).** The energy balance concerns a volumetric heat source depending on the vertical co-ordinate.

Generally there were no solutions of the all the summarized models that were performed in dimensionless forms. It seems strange, since such approach does not allow evaluation of the major effects controlling the fuel burning and the probabon of the thermal wave towards the fuel/water interface.

The further analysis focuses on the scaling and dimensionless group as well as on experimental data arrangement according to them

ANALYSIS

Dimensionless variables

The limited number of specific scales leads to some problems in the choice of the transformation of the equations into dimensionless ones. The following dimensionless variables were selected for the present analysis:

Length: The initial fuel layer depth y_0 , so $y^* = \frac{y}{y_0}$

Temperature: The ratio $\Theta = \frac{T - T_s}{T_s - T_\infty}$ or $\Theta = \frac{T - T_b}{T_s - T_\infty}$

Radiation heat reflux: $(\dot{q}'')^* = \frac{\dot{q}_r''}{\dot{q}_{s0}''}$ where $\dot{q}_{s0}''$ is given by equation (A2)

Time: a specific time t_0 , $t^* = \frac{t}{t_0}$. The real values of t_0 will be specified further as a result of the

analysis of the real phenomena. There is an opportunity to employ the ratio: $t_0 = \frac{a_F}{y_0}$ [19].

However, for the pre-boilover time is needed to find a more realistic value that is available from the experiments.

Dimensionless groups

- Surface absorption models

The dimensionless form of the equation of the fuel layer is

$$\frac{\partial \Theta}{\partial t^*} = \left(\frac{a_F t_0}{y_0^2} \right) \frac{\partial^2 \Theta}{\partial y^{*2}} \quad (1)$$

The only possible dimensionless group is the Fourier number $Fo = \frac{a_F t_0}{y_0^2}$. This form of Fo includes a specific time scale t_0 that must be defined from the specificity of the burning process, but not on the thermal conductivity problem [19].

- In-depth absorption models

The dimensionless form of the equation of the fuel layer is

$$\frac{\partial \Theta}{\partial t^*} = \left(\frac{a_F t_0}{y_0^2} \right) \frac{\partial^2 \Theta}{\partial y^{*2}} + \left[\frac{\mu \dot{q}_{s0} t_0}{\rho_l C_p (T_s - T_\infty)} \right] \exp[-(\mu v_0) y^*] \quad (2a)$$

There are two dimensionless groups:

The **Fourier number** $FO = \frac{\alpha_F t_0}{y_0^2}$ (2b)

and N_{VA} number

$$N_{VA} = \left[\frac{\mu \dot{q}_{s0}}{\rho_F C_p (T_s - T_\infty)} t_0 \right] \quad (2c)$$

representing the accumulation of the thermal energy in the fuel layer, and

the absorption attenuation group μy_0 .

Taking into account the scaling equation (A2) for $\dot{q}_{s0}$ the group N_{VA} can be expressed as

$$N_{VA} = \left[\frac{\mu \dot{q}_{s0} t_0}{\rho_F C_p (T_s - T_\infty)} \right] = \frac{4}{\pi} \mu \chi D^{\frac{1}{2}} \frac{[g T_\infty (T_f - T_\infty)]^{\frac{1}{2}}}{(T_s - T_\infty)} t_0 \quad (3)$$

Assessments of the order of magnitude of the dimensionless groups

Taking into account that the entire analysis is oriented towards the prediction of the boilover onset the time scale must be defined by the pre-boilover time t_{BO} . Summaries of the experiments on the pre-boilover time are available in Table 3 in a wide range of pan diameters and fuel layer thicknesses.

The values of t_{BO} obtained experimentally are summarized in Table 4. The data of burning fuels corresponds to initially equal fuel properties imposed by the ambient conditions close to those of the water sublayer.

Fourier number

The Fourier number $FO = \frac{\alpha_F t_0}{y_0^2}$ can be expressed as $FO^e = \frac{\alpha_F t_{BO}}{y_0^2}$ (based on experimental data) in order to evaluate the order of magnitude of that group at the boilover onset. The data are summarized in Table 4. They indicate several major facts:

- The Fourier number calculated with $t = t_{BO}$ is always lower than unity. Thus, the fuel layer can be assumed as a thermally thick (Kreith, 1973). Therefore, the temperature distribution in depth the burning fuel can be expressed by [20]

$$\frac{T(y, t) - T(y_s(t))}{T_i - T(y_s(t))} = \operatorname{erfc}\left(\frac{y}{2\sqrt{at}}\right) = \operatorname{erfc}\left(\frac{l}{\sqrt{FO}}\right) = \left(\frac{l}{\sqrt{FO}} \frac{y}{y_0}\right) \quad (4)$$

Here the reference temperature $T(y_s(t))$ corresponds to an isothermal boundary condition at the burning liquid surface. The result is very close to that predicted by the one-dimensional model conceived by Arai et al. [21] (see Table 2). In this situation knowledge of the surface regression rate $r(t)$ is needed to calculate the values of $y_s(t)$. As reported by Garo et al. [6.9] this approach works well with the introduction of an average regression rate calculated on the basis of the initial

Table 4. Pre-boilover time of fuel burning upon different initial conditions and evaluation of the model parameters. Data summarized from the experiments of Garo et al. [6,9]. Heating oil as a fuel.

Present author calculations.

D m	y_0 mm	t_{B0} sec	U_1 mm/s $\times 10^3$	Fo^c $\frac{at_{B0}}{y_0^2}$
0.15	19	945	20.1	0.223
	17	830	20.48	0.245
	15	750	20.0	0.284
	13	625	20.8	0.316
	11	550	20.0	0.388
	9	450	20.0	0.474
	7	340	20.58	0.593
	5	220	22.72	0.755
	4	165	24.42	0.889
	3	150	20.0	1.422
	2	90	22.22	1.940
0.23	17	710	23.94	0.209
	15	620	24.193	0.235
	13	530	24.528	0.268
	11	450	24.44	0.318
	9	340	26.470	0.358
	7	265	26.41	0.464
	5	215	23.25	0.736
	4	125	32.0	0.667
	3	75	40	0.711
	2	30	66.66	0.642
0.3	17	530	32.075	0.156
	15	475	31.578	0.180
	13	440	29.54	0.268
	11	300	36.66	0.318
	9	275	32.75	0.0358
	7	190	36.84	0.464
	5	110	45.44	0.736
	4	70	57.142	0.667
	3	50	60.0	0.711
	2	30	66.66	0.642
0.5	15	345	43.478	0.130
	13	265	49.056	0.134
	11	190	57.89	0.135
	9	200	75.0	0.210
	7	90	77.77	0.156
	5	70	71.42	0.239
	4	45	88.88	0.240
	3	15	200	0.142
	2	30	66.66	0.642

Table 5. Pre-boilover time of fuel burning upon different initial conditions and evaluation of the model parameters. Data summarized from the experiments of Garo et al. [6,9]

Effect of the fuel type. Present author calculations.

For all the experiments

D= 0.15 m; y_0 = 13 mm

Burning data Fuel	a m ² /s	t_{B0} sec	Fo^c $\frac{at_{B0}}{y_0^2}$
Crude oil	0.679	669	0.269
Heating oil	0.877	670	0.348
Hexadecane	0.724	924	0.397
n-Decane	0.768	1095	0.498
Xylene	1.096	730	0.474
n-Octane	0.841	912	0.454
Toluene	0.951	582	0.327

Table 6 Pre-boilover time of fuel burning upon different initial conditions and evaluation of the model parameters. Data summarized from the experiments of Koseki et al. (1991) [30]

Arabian light crude oil as fuel.

Present author calculations.

D m	y_0 mm	t_{B0} sec	U_1 mm/s $\times 10^3$	Fo^c $\frac{at_{B0}}{y_0^2}$
0.3	35	612	57.189	
0.6	20	492	40.65	0.0835
	69	942	73.248	0.0134
1	20	681	42.735	0.0795
	40	978	40.899	0.041
	60	1310.4	45.875	0.0246
	100	1926	51.921	0.0130
2	20	411	48.66	0.0697
2.7 sq. (3.05)	27	402	67.164	0.0374

parameters of the process (Table 2 -second row/second column). Giving $T|_{fuel/water} = T_{wb}$ the pre-boilover time can be predicted calculating the value of Fo .

Similar approach has been employed by Wu et al. [16] where the characteristic time $t_c = t_{B0}$ for the thermal front to reach the fuel/water interface can be derived by the scaling equation (A2) as:

$$t_c \approx \frac{y_0^2}{a_F + y_0 r} \quad (5)$$

It is close to the time scale of the pure heat transfer process, but incorporates the effect of the surface regression rate.

Generally the problem discussed is a moving-boundary problem due to the continuously decreasing fuel layer depth. This point of view will not be developed here.

➤ The fact that the $Fo < 1$ at the boilover onset may be interpreted as follows. The Fourier number can be expressed as

$$Fo^e = \frac{a_F t_{B0}}{y_0^2} = \frac{a_F}{y_0^2 t_{B0}} = \frac{\text{thermal diffusivity of the fuel layer}}{\text{diffusivity of the hot zone}} \quad (5)$$

Thus, the experiments indicate that $a_F \leq \frac{y_0^2}{t_{B0}}$. The term "diffusivity of the hot zone" is a term not employed earlier. Its introduction can help the better understanding of the heat transfer mechanisms in the burning layer like the term "velocity of the thermal wave" $U_T = \frac{y_0}{t_{B0}}$ (see Table 4 and Table 6) employed in the other studies of Garo et al. [6,9].

➤ The values of Fo^e increase as the fuel thickness decreases. Furthermore, it is strongly affected by the pan diameter and the ratio $\frac{y_0}{D}$. Figure 3 shows the variations of the Fourier number

Fo^e with the ratio $\frac{y_0}{D}$. The best data fitting by exponents $Fo^e \sim \exp\left(k \frac{y_0}{D}\right)$ indicates that an average value of $k = -25.125$. It is clear that this relationship is not useful for engineering calculations. The next attempt to fit the data in a power law form yields $Fo^e \sim \left(\frac{y_0}{D}\right)^{-0.704}$ that is more useful for practical calculations.

The above comments about the relationship $Fo^e = f\left(\frac{y_0}{D}\right)$ follow not only from the experimental data discussed here, but from the fact that the case of liquid burning in small fires the burning rates (the regression rate respectively) depend on the pool diameters.

As commented by Hamins et al. [18] the ratio of the heat of vaporization (gasification) H_v of the fuel and its ideal heat of combustion H_c is

$$\chi = \frac{H_v}{H_c} = \frac{\dot{Q}_s}{\dot{Q}} = \frac{1}{B} \quad (6)$$

i.e., to the fraction of the heat reflux to the fuel surface. The number B is known as "the diffusive transfer number" (Spalding, 1955 [22]). The value of χ is independent of the mass vaporization rate (i.e. the surface regression rate) and depends mainly on the intrinsic properties of the fuels [18]. Burgess and Hertzberg [23] showed that plots of $\dot{m}''$ for hydrocarbons for large pool diameters were well correlated by the B number (χ^{-1}).

Hamins et al. [18] commented the B number correlation for intermediate sized pool fires. The data commented here are from the intermediate sized pool experiments (see Table 1 and Table 2). Hamins et al. [18] correlated the ratio $(\dot{m}''/B)$ as a function of the pool diameter (Fig. 12 of [18]) for burning hydrocarbons. The correlations indicates that ratio $(\dot{m}''/B)$ reaches an asymptotic value at $D > 2.5$ m, while for $D < 1$ m the slope of the line is very sharp.

Therefore the correlation $Fo^e = f\left(\frac{y_0}{D}\right)$ looks for the adequate contribution of the fact that burning increases with the pan diameter for intermediate sized pool fires. The plots on Fig. 3 show that the line corresponding to $D=0.5$ m is practically horizontal and does not exhibit a strong dependence on $\frac{y_0}{D}$.

➤ The data obtained by Arai et al (1990) indicate that the pre-boilover time depends on the initial fuel temperature. These data were treated here in terms of Fourier number at $t = t_{BO}$ and the dimensionless ratio $\Delta\Theta_b = \frac{T_{bf} - T_i}{T_{bf} - T_{bw}}$ introduced here. The dimensionless ratio $\Delta\Theta_b$ is introduced *ad hoc* in the present paper in a form similar to the right hand side of Eq. (6). It concerns the boiling points of the liquid involved in the heat transfer process. The main reasons for that are:

- The temperature at the burning surface is practically equals the temperature of fuel saturation, i.e. the fuel boiling temperature.
- The water sublayer explodes when it reaches its boiling point.
- Thus, higher initial temperature of the fuel, shorter pre-boilover period. On the other hand smaller difference between the boiling points of the liquid and the fuel, shorter pre-boilover period.

The data treated in that manner are summarized in Table 7 and shown on Fig. 4. The data fitting indicate that it can accept that $Fo^e \sim (\Delta\Theta_b)^{2.2}$, so the further data treatment will be carried out with $\Delta\Theta_b^2$. The variations of the ratio $Fo^e/\Delta\Theta_b^2$ with the dimensionless fuel layer thickness $(y_0/D)^{-0.5}$ are illustrated on Figs. 5a,b. The introduction of the group $(y_0/D)^{-0.5}$ instead $(y_0/D)^{-0.701}$ established earlier is more intuitively taking into account the physics of the process rather than the frame imposed by the model. The power of 0.5 is more convenient from an engineering point view rather than the power 0.7. The group $(y_0/D)^{-0.5}$ tries to compensate the deficiency of the Surface Absorption Models with respect to a relationship between the mass burning rate (the surface regression rate respectively) and the geometry of the source of energy transferred to the surface of the fuel. The dimensionless forms of SAM's (see Table 2) do not give

◆ D=0.15m ■ D=0.23m ▲ D=0.3m ● D=0.5m

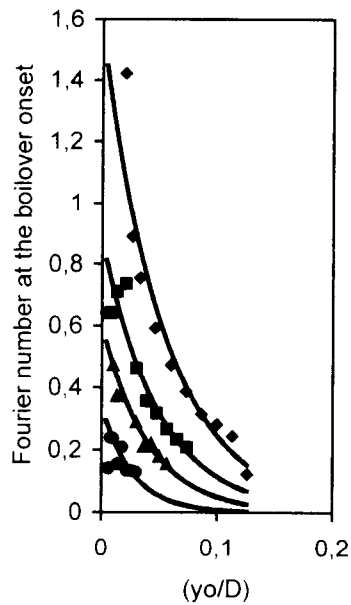


Fig.3 Variations of the Fourier number at $t = t_{B0}$ with the ratio (y_0/D)

● Toluene ■ Ethyl Benzene
▲ n-Decane

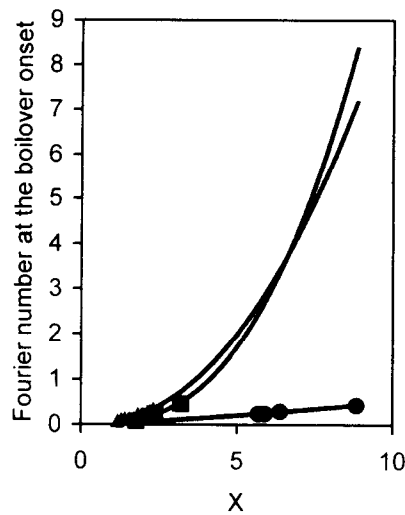


Fig. 4. Variations of the Fourier number at $t = t_{B0}$ with the ratio

$$X = \Delta\theta_c = \frac{T_{sc} - T}{T_{sc} - T_{sc}}$$

.Data of Arai et al.(1990)

Table 7. Data of Arai et al. (1990) concerning the effect of the initial fuel temperature on the boilover onset. Data treatment (present author) in terms of Fourier number.
Pan diameter, $D=0.048$ m; Fuel layer thickness, $y_0=10$ mm.

Fuel	T_i , K	t_{B0} , sec	U_{T_s} , mm/s x 10^3	$Fo^c = \frac{at_{B0}}{y_0^2}$	Boiling point, K
Toluene $a_f = 1.03 \cdot 10^{-7}$ m^2/s	293	420	23.809	0.432	383.2 *
	318	284	35.211	0.292	
	323	237	42.194	0.421	
	325	218	45.87	0.458	
	341	134	74.62	0.746	
Ethyl Benzene $a_f = 0.888 \cdot 10^{-7}$ m^2/s	355	99	101.01	1.01	409.2*
	293	512	19.531	0.455	
	323	275	36.36	0.244	
	330	206	48.543	0.183	
n-Decane $a_f = 0.753 \cdot 10^{-7}$ m^2/s	345	96	104.166	0.0852	433.2*
	293	451	22.172	0.340	
	323	292	34.246	0.220	
	348	158	63.291	0.119	
	355	141	70.291	0.106	
	362	93	107.526	0.07	

* Data from Garo et al. (1999a) [6]; ♣ - present author calculations;

dimensionless terms contributing in that direction. Similar motivation was used to introduce the dimensionless boiling ratio $\Delta\Theta_b$ into the data correlations.

The plot on Fig. 5a indicate the relationship $\frac{Fo^e}{\Delta\Theta_b^2} = f\left(l/\sqrt{y_0/D}\right)$ is almost linear in the form

$$\frac{Fo^e}{\Delta\Theta_b^2} = A + C\left(l/\sqrt{\frac{y_0}{D}}\right) \quad (7)$$

The slopes of the plots (the values of C respectively) Fig. 5a decrease as the pan diameter is increased.

The regression fits for data of Garo et al. [6,9] shown on Fig. 5a, indicate that $C \sim D^{-1.7}$ while $A \sim D^{-1.5}$. It is possible to assume that for further data treatments the form of (7) can be expressed as

$$\frac{Fo^e}{\Delta\Theta_b^2} \sim \left(\frac{y_0}{D}\right)^{-0.5} D^{-1.5+1.7} \quad (8)$$

□ Final remarks on the Surface Absorption Models

The data treatment from various experiments and sources give a tentative information how to arrange an engineering oriented relationship to predict the pre-boilover time. Some of the analyses performed above employ strictly the available dimensionless groups, that in the case of a simple model M1 is only the Fourier number Fo .

The further analysis is purely qualitative and intuitive based on the behaviour of the real burning system and the data available and the physics of the process, rather than on the strictly rules of the dimensional analysis.

Assuming an average value of -1.5 for the power of the pan diameter in (8) the Fourier number at the boilover onset can be expressed as

$$Fo^e \sim B_o \Delta\Theta_b^2 \left(\frac{y_0}{D}\right)^{-\frac{1}{2}} D^{-\frac{3}{2}} \quad (9a)$$

where the dimension of B_o is [m]

or in two direct forms

$$t_{Bo} \sim \frac{\Delta\Theta_b^2}{a_F} y_0^{\frac{1}{2}} \frac{l}{D} \quad (9b)$$

$$t_{Bo} \sim \frac{\Delta\Theta_b^2}{a_F} y_0^{\frac{1}{2}} \left(\frac{y_0}{D}\right) \quad (9c)$$

Despite the semi-empirical approach in deriving the form of (9a) and (9b) the needed relationship for t_{Bo} incorporates several physical facts:

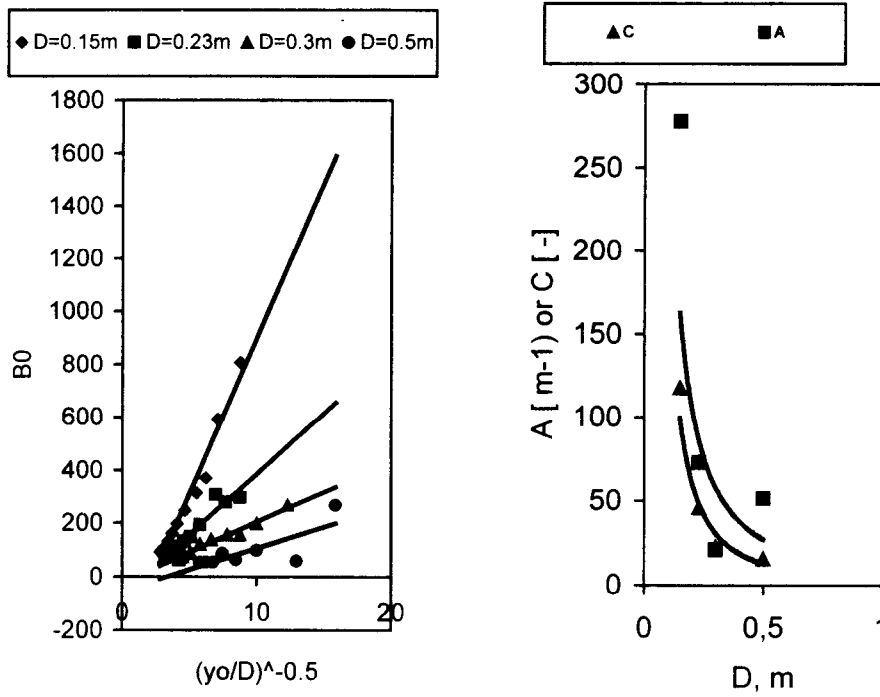


Fig. 5 Variations of $B0$ with dimensionless fuel layer thickness
a) Effect of the pan diameter
b) Variations of the coefficients of regression equation with D

- The increase of the fuel layer thickness y_0 increases the pre-boilover time.
- The increase of $\Delta\Theta_b$ leads to increase of t_{B0} , i.e. higher fuel boiling point and lower fuel initial temperature delay the boilover onset. The lower thermal diffusivity a_F , the longer pre-boilover period.
- The increase of the pan diameter (see 9b) reduces the pre-boilover time t_{B0} , since higher pan size, the higher thermal penetration rate which is consistent with the increased burning rate and increased heat reflux to the fuel surface (the comments of Hamins et al. [18] and the experiments of Garo et al. [6,9]). As an additional comment it can note that Arai et al. [21] give that the ratio $\dot{q}_r''/\dot{q}_s''$ varies with the pan diameter ($\dot{q}_r''/\dot{q}_s'' = 0.5 \div 1.0$ for pan diameters within the range from 0.05 m to 50 m). Thus, higher pan diameter, the higher heat reflux ratio, the faster boilover onset.
- Furthermore, the form of (9c) indicate to two other physical facts that are not incorporated into the SAM models, but follow implicitly from the nature of the burning:
 - ❖ The calculations with the value of the initial fuel thickness y_0 should overestimate the pre-boilover time, since the fuel layer continuously

decreases due to the burnt fraction of it. So, temperature profile inside the fuel layer will depends on $\sim l/y(t)$ rather than y_0 .

- ❖ Smaller pan size, the higher heat losses through the walls. This is a well-known fact for the intermediate sized experiments usually carried out on the boilover. These, discussed here belong to that range of pan sizes.

The number N_{VA}

$$N_{VA} = \left[\frac{\mu \dot{q}_{s0} t_0}{\rho_f C_p (T_s - T_\infty)} \right] = \frac{4}{\pi} \mu \chi D^{\frac{1}{2}} \frac{[g T_\infty (T_f - T_\infty)]^{\frac{1}{2}}}{(T_s - T_\infty)} t_0 \quad (10a)$$

can be interpreted as

$$N_{VA} = \left(\frac{\mu}{y_0} a t_0 \right) \left[\frac{\dot{q}_{s0} y_0}{\lambda (T_s - T_\infty)} \right] = \frac{\text{heat flux through the fuel surface}}{\text{heat flux through the fuel layer}} \quad (10b)$$

Assuming that the time scale is $t_0 = \frac{y_0^2}{a}$ the yield is

$$N_{VA} = \left(\frac{\mu}{y_0} a t_0 \right) \left[\frac{\dot{q}_{s0} y_0}{\lambda (T_s - T_\infty)} \right] = (\mu y_0) Ki_q \quad (10c)$$

where $Ki_q = \left[\frac{\dot{q}_{s0} y_0}{\lambda (T_s - T_\infty)} \right]$ is the Kirpichev heat transfer number [23,26].

Taking into account the scaling equation (A2) in the case of a burning liquid and radiative nature of the heat feedback to the surface the specific form of the Kirpichev number is

$$Ki_q = \frac{4}{\pi} \chi \frac{\rho_\infty C_p [T_\infty g (T_f - T_\infty)]^{\frac{1}{2}} D^{\frac{1}{2}} y_0}{\lambda (T_s - T_\infty)} \left(\frac{\mu a t_0}{y_0} \right) \quad (A4)$$

Both the absorption coefficient $\mu(m^{-1})$ and the fraction of the heat reflux χ (the diffusive transfer number $B = l/\chi$) are specific characteristics of the fuel (see Table 8)

Thus with $t_0 = \frac{y_0^2}{a}$ the dimensionless form of the equation (2a) is

$$\frac{\partial \Theta}{\partial t^*} = \frac{\partial^2 \Theta}{\partial y^{*2}} + Ki_q (\mu y_0) \exp[-(\mu y_0) y^*] \quad (11)$$

The Kirpichev number depends on the simultaneously on the pool diameter and the fuel layer thickness. This on a general form the solution of (11) may be presented as

$$\frac{T(y, t) - T(y_s(t))}{T_i - T(y_s(t))} = \Phi[Fo, Ki_q, (\mu y_0)] \quad (12)$$

Table 8 Fractions of the heat reflux and the absorption coefficients of some fuels discussed here.

Fuel	Heat reflux data		Heat absorption data		μy_0	
	χ $\times 10^3$	Source	μ , m^{-1}	source	min	max
Heating oil	2.4	Garó et al. (1999a) [6]				
Heating oil			262	Garó et al. (1999b) [7]	0.524 $y_0 = 2 \text{ mm}$	4.978 $y_0 = 19 \text{ mm}$
Weathered oil (20% water)	1.8	Garó et al. (1999a) [6]				
Crude oil			369	Garó et al. (1999b) [7]		
Alberta sweet oil			445♣	Inamura et al. (1992) [27]	0.89 $y_0 = 2 \text{ mm}$	6.675 $y_0 \sim 15 \text{ mm}$
Toluene	13	Hamins et al.(1996) [18]	140	Garó et al. (1999b)	1.82♣ $y_0 = 13 \text{ mm}$	
Toluene			145♣	Inamura et al. (1992) [27]	0.29 $y_0 = 2 \text{ mm}$	2.175 $y_0 \sim 15 \text{ mm}$
n- Decane			160	Garó et al. (1999b) [7]	1.88 $y_0 = 13 \text{ mm}$	
Hexane			412	Burgess et al.(1961) [26]		

Notes: ♣ - at 298K; ♠ - calculated by the present author (see the data in Table 5)

The order of magnitude of the second right-hand term of (12)

The factor $(\mu y_0) \exp[-(\mu y_0)y^*]$ may be evaluates as follows:

- (μy_0) was calculated for some fuels (Table 8). It varies approximately from 0.5 to 5.
- The exponent $\exp[-(\mu y_0)y^*]$ reaches its maximum of unity (1) at the fuel surface.

The Kirpichev number.

The number can be expressed as:

$$Ki_q = \frac{4}{\pi} \chi \frac{\rho_s C_p [T_s g(T_s - T_\infty)]^l}{\lambda (T_s - T_\infty)} \left(\frac{\mu a t_0}{y_0} \right) D^{1/2} y_0 = \Psi_0 \frac{l}{\sqrt{y_0}} y_0^{1/3} \quad (13)$$

where $\Psi_0 = \frac{4}{\pi} \chi \frac{\rho_s C_p [T_s g(T_s - T_\infty)]^l}{\lambda (T_s - T_\infty)} \left(\frac{\mu a t_0}{y_0} \right)$ can be assumed as a constant that depends only on the fuel characteristics and the initial fuel thickness.

Following the result (12), if the temperature profile across the fuel is known the Fourier number can be expressed in a suitable functional form:

$$Fo = \Phi^{-1} \left[\frac{T(y,t) - T(y,(t))}{T_i - T(y,(t))} \right]^p (\mu, y_0)^n (Ki_q)^m \approx \Psi_0 \left(\Delta\Theta|_{\text{water boiling point}} \right)^p \left(\frac{y_0}{D} \right)^l (\mu, y_0)^n \quad (14)$$

where p , m and n are powers that should be determined by a data fitting procedure.

Assuming that $T(y,t)$ at the fuel/water interface at the water boiling point its is possible to define the value of the Fourier number and the pre-boilover time $t_{Bo} = Fo \frac{y_0^2}{\alpha}$.

□ Final remarks on the In-Depth Absorption Models (DAM)

The analysis done on the basis of the dimensionless group N_{VA} and the consequent expression of the Kirpichev number Ki_q in the form (A4) give a ground for regression derived relationships between the dimensionless groups for prediction of the Fourier number corresponding to the time of the boilover onset.

The relationship (14) was derived in a general form, but it shows that the DAM's are more adequate in heat transfer description. The expression of the Kirpichev number Ki_q in the form (13) shows that the correlations must includes terms concerning the effects of both the pan diameter and the fuel thickness-pool diameter ratio. This confirm the analysis done earlier of SAM on the base of experimental data and intuitive assessments of the physics of the phenomena.

Further work on the establishment of suitable engineering equations on the basis of the relationship (14) should be done.

CONCLUSIONS

The analysis done here employed various data obtained in different experimental situations. Starting from the physical models concerning the heat transfer across the burning fuel layer and the qualitative assessments of the contribution of the parameters of the process a common approach for prediction of the pre-boilover time was drawn.

The in-depth absorption models are more adequate from a physical point of view. They include the contribution of the pool diameter and the fuel layer thickness pool diameter ratio through the Kirpichev number expressed through the scaling equation (A2).

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SYMBOLS

C_p - specific heat at constant temperature and ambient temperature for air, J/kgK
 D - diameter of the pool, m
 H_v - the latent heat of vaporization, kJ/kg
 $\dot{m}''$ - mass burning rate per unit area of the pool, kg/m²s
 $\dot{Q}$ - 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 $T_f \approx 1000\text{ K}$, Cox (1995), 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_w - water layer depth, m
 $y_s(t)$ - the location of the fuel surface at a specific time, m

Greek letters

ρ - density, kg/m³
 λ - thermal conductivity, W/mK

Subscripts

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

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