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QUALITATIVE ANALYSIS OF A BURNING SLICK OF FUEL ON A WATERBED

Similarity analysis of the relevant models published and the pre-boilover time data

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ABSTRACT

The communication concerns a major problem of accident prevention due to fires. The efforts are stressed on the qualitative assessments and the similarity analysis of 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.

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 [3-7] predefining the "boilover" appearance and its intensity. The term, commonly referred as "thin-layer boilover", has been applied also to the burning of thin slicks of oil spills spread after accidental releases [7,8].

Present Target

This general question is about the *time for the of boilover onset* [9], so two targets could be formulated i) Models developed analysis and *dimensionless groups evaluation;* ii) Experimental data treatment in a dimensionless functional relationships.

The analysis considers *single layer models only* for clarity of the explanation. The models considered are arranged in two groups [10] (Table1): 1) **Surface Absorption Models (SEM)**. The energy balance does not incorporate a volumetric source term [2,5, 6,9] and 2) **In-Depth Absorption Models (DEM)**. The energy balance concerns a volumetric heat source depending on the vertical co-ordinate [1,6, 7,12,].

In fact, it seems *strange, there are no solutions* (or analysis) of the models [10] *performed in non-dimensionless forms*. Thus, efforts below are stressed on *the dimensionless groups, scaling* and *arrangement of functional relationships.*

Physical Conditions of the Burning Layer

The heat release rate from pool fire can be expressed as [13-15]:

$$Q = \rho_\infty C_p \left[T_\infty^f g\left(T_f - T_\infty^f\right)\right]^{\frac{1}{2}} D^{\frac{5}{2}} \qquad (1)$$

The net heat feedback per unit area reaching the surface of the burning liquid is a fraction χ of the total heat released (χ is independent of the pool diameter) [16,17]:

$$q_r'' = \left({}^{4\chi}\!/_{\pi}\right)\rho_\infty C_p \left[T_\infty^f g\left(T_f - T_\infty^f\right)\right]^{1/2} \sqrt{D} \qquad (2)$$

The basic assumption of the models is *no connective motion* and that *the radiation is fully absorbed at the surface* $y = y_s(t)$, where the energy balance is:

$$q_s'' = H_V \rho_F r(t) + q_c'' \qquad (3)$$

while the boundary condition at the burning surface

$$q_c'' = -\lambda\left(\partial T/\partial y\right)_{y=y_s(t)} \qquad (4)$$

where $$r(t) = \frac{\partial y_s(t)}{\partial t} = \frac{\dot{m}}{\rho_F S} \qquad (5)$$

is the surface regression rate (a function of the fuel properties and the vessel geometry [16,17]).

The contact line between the fuel and the water sublayer assumes

$$q_c'' = -\lambda\left(\partial T/\partial y\right)_{fuel} = -\lambda\left(\partial T/\partial y\right)_{water} \qquad (6)$$

but all the models discussed here consider only the top layer condition. Generally, the solutions look for the time, t, corresponding to the case $T_{y=0} = \textit{boiling temperature of the water}$ as a boilover onset criterion ($y = y_0$ at the fuel/water interface).

ANALYSIS

Moving Boundary or Fixed boundary problem?

The surface regression rate, $r(t)$, is a complex function of the fuel properties and the vessel geometry [5-7,17]. Generally, the models created are *moving-boundary problems*. The further analysis considers them as fixed boundaries problems in *order to evaluate the main dimensionless groups controlling the process*. This approximation tend to establish *gradually*: i) the complex nature of the heat conduction due to burning surface of the fuels and ii) to separate the dimensionless group predicted by the scaling of the terms of the equations and boundary conditions

Dimensionless variables
The following scales and dimensionless variables were selected:

Length: The initial fuel layer depth y_0, so $y^* = y/y_0$

Temperature: The ratio $\Theta = (T - T_\infty)/(T_s - T_\infty)$ or $\Theta = (T - T_b)/(T_S - T_\infty)$;

Time: a specific time t_0, $t^* = t/t_0$ (see further)

Dimensionless groups

- Surface absorption models
  The dimensionless form of (**M1**) is

$$\partial\Theta/\partial t^* = \left(a_F t_0/y_0^2\right)\left(\partial^2\Theta/\partial y^{*2}\right) \tag{7}$$

The only possible dimensionless group is the Fourier number $Fo = \left(a_F t_0/y_0^2\right)$. The condition $T = Ts$ (at the moving surface) does not form a specific dimensionless group.

- In-depth absorption models
  The dimensionless form of (**M2**) is

$$\partial\Theta/\partial t^* = \left(a_F t_0/y_0^2\right)\left(\partial^2\Theta/\partial y^{*2}\right) + \\ + \quad \left[\left(\mu\, q_{s0}\, t_0\right)/\rho_F C_p (T_s - T_\infty)\right]\exp\left[-(\mu y_0) y^*\right] \tag{8}$$

and contains two dimensionless groups only:

$$Fo = \left(a_F t_0/y_0^2\right) \text{ and } N_{VA} = \left[t_0\left(\mu\, q_{s0}\right)/\rho_F C_p (T_s - T_\infty)\right] \tag{9}$$

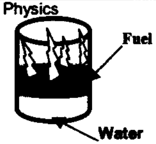
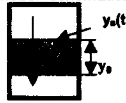
and the *absorption attenuation group* (μy_0). In a more general form **N_{VA}** is as a *generation number* (Q_g) [18].The equation (2) transforms **N_{VA}** as :

$$N_{VA} = t_0\left[(4/\pi)\mu\chi/(T_s - T_\infty)\right]\sqrt{D}\left[g T_\infty^f \left(T_f - T_\infty^f\right)\right]^{1/2} \tag{10}$$

SAM – Analysis of Model Yields
The asymptotic analysis oriented towards the boilover onset prediction *should use* the time scale t_{B0}. Some results [6, 9] expressed as $Fo^e = a_F t_{B0}/y_0^2$ [10] are summarized in Table 3. $Fo^e = a_F t_{B0}/y_0^2$ is always lower than unity. Thus, assuming that the fuel layer controls of the thermal resistance [18] the solution is S2 (Arai et al. [19]-See Table 2), i.e the *lumped capacitance solution* [20]).

The temperature of the burning fuel surface $T_{bF} = T(y_s(t))$ is the boundary condition of the moving surface that requires a *knowledge of r(t) in order to calculate* $y_s(t)$ explicitly. Garo et al. [6, 9] showed that the approach works well with an average value

Table 1. 1-D Single-layer models developed

MODEL	**SCHEMATIZATION**
SAM **M1**] $\frac{\partial T}{\partial t} = a_F \frac{\partial^2 T}{\partial y^2}$ **IC:** $t = 0 \quad T = T_\infty$ **BC:** $y = y_s(t) \quad T = T_s$ $y \to \infty \quad T = T_\infty$	Physics 
DAM **M2** $\frac{\partial T}{\partial t} = a_F \frac{\partial^2 T}{\partial y^2} + \frac{\partial q_r^*}{\partial y}$ $q_r^* = q_s^* \exp(-\mu y)$ **IC:** $t = 0 \quad T = T_\infty$ **BC:** $y = y_s(t)\; T = T_s$	Model -schematically 

$R_{AV} = < r(t) >$ (See Table 3) calculated through the initial parameters of the process (*that practically simplifies the moving boundary problem*). At $T = T_{Wb}$ the value of t_{B0} can be predicted through *Fo*.

Scaling $Fo \sim (\text{initial fuel layer conditions})$ **[10]**
Some semi-empirical scaling relationships could compensate the deficiency of **SAM**: i) The values of Fo^e increase as y_0 decreases (Table 2) and depend on the ratio y_0/D [10]. Thus, $Fo^e = f(y_0/D)$ follows the experimental data [4-9] and the fact the small fire burning rate (e.g. *r(t)*) depends on the pool diameters [6, 9, 17]. The recent attempts [10] yielded in (data from Table 3):

$$Fo^e = f(y_0/D) Fo^e \sim (y_0/D)^{-0.5} \tag{11}$$

Arai et al.[19] reported that the pre-boilover time depends on the initial fuel temperature. The scaling [10] in terms of Fo^e and the reduced temperature $\Delta\Theta_b = (T_{bf} - T_i)/(T_{bf} - T_{bw})$ gave $Fo^e \sim (\Delta\Theta_b)^{-2}$. Both terms, $(y_0/D)^{-0.5}$ and $\Delta\Theta_b$, compensate the deficiency of SAM with respect to *dimensionless terms contributing* the burning rate dependence on the initial fuel bed conditions. The fit [10] of data in Table 3 indicates $Fo^e/\Delta\Theta_b^2 \sim (y_0/D)^{-0.5} D^{-1.5}$

$$\text{or} \quad t_{B0} \sim \left(\Delta\Theta_b^2/a_F\right)\sqrt{y_0}\,(y_0/D) \tag{12}$$

---

[1] The DEM model of Broeckmann and Schlecker [1] is not commented due to the complexity of the evaluation of the hot zone motion through the fuel layer.

Table 2. Solutions

SOLUTION
Analytical : [2,5,6,9,16] **S1** $\frac{T - T_\infty}{T_s - T_\infty} = \exp\left[-\frac{r}{a_F}\left(y - y_s(t)\right)\right]$ Assumptions a_F = const. $r(t)$ const, $a_F \approx a_w$
Analytical : [2, 19] **S2** $\left[(T - T_i)/(T_{bF} - T_i)\right] = \exp-\left[\left(y_0^2/a_F t_{b0}\right)(y/y_0)\right]$ at $t_{B0} << t_b \quad \Theta_{bw} = (T_{bw} - T_i)/(T_{bF} - T_i)$ at small $\left(y_0^2/a_F t_b\right) \propto O(1)$ $\Theta_{bw} = 1 - \exp\left(\tau_{B0}^2\right)\mathrm{erfc}(\tau_{B0})$ $\tau_{B0} = \left[(\lambda_F/\lambda_w)(a t_{B0})^{\frac{1}{2}}\right] \Big/ \left[y_0\left(1 - t_{B0}/t_b\right)\right]$
DEM. No analytical solutions are available. **Numerical solution [6]** ***Assumptions:*** **No hot zone formation**
Numerical solution [19] ***Assumptions: 1)*** **The thermal properties of the liquid are constant and equal to those at 298K .2) Heat diffuses faster than the regression rate**

Table 3. Data summarized from the experiments of Garo et al. [6,9]. Heating oil as a fuel.

D, (m)	y_0, (mm)	t_{B0} ♣ (sec)	U_T ♣ (mm/s) x10³	Fo^e ♣	R_{AV}H (mm/s) x 10²	Δ/y_0 (-)
0.15	19	945	20.1	0.22	0.01	0.46
	17	830	20.48	0.24		0.45
	13	625	20.8	0.31		0.43
	9	450	20.0	0.47		0.43
	7	340	20.58	0.59		0.41
	4	165	24.42	0.88		0.39
	2	90	22.22	1.94		0.18
0.23	17	710	23.94	0.21	0.011	0.45
	15	620	24.19	0.23		0.44
	13	530	24.52	0.27		0.43
	9	340	26.47	0.36		0.38
	4	125	32.0	0.66		0.28
	3	75	40	0.71		0.205
	2	30	66.66	0.64		0.093
0.5	15	345	43.47	0.13	0.017	0.37
	13	265	49.05	0.13		0.32
	11	190	57.89	0.13		0.27
	7	90	77.77	0.15		0.18
	5	70	71.42	0.24		0.2
	3	15	200	0.24		0.05
♣- calculated in [9] ; σ-present work;H- from [6]						

In-DEPTH ABSORPTION MODELS
The number **N_{VA}** expressed in the form (10) can be presented as

$$N_{VA} = \left[(\mu/y_0)(a t_o)\right]\left[\left(\dot q_{s0}\, y_0\right)/\lambda\left(T_s - T_\infty\right)\right] \tag{13}$$

or with $t_0 = y_0^2/a \quad \Rightarrow \quad N_{VA} = (\mu y_0) Ki_q$ where $Ki_q = \dot q_{s0}\, y_0/\lambda(T_s - T_\infty)$ is the *Kirpichev heat transfer number* [21,22] (employed in the Russian literature). *In the Western works there is not specific name of that group (see Thomas [23])* .Taking into account the scaling equation (2) the specific form of the *Kirpichev number* is [10]:

$$Ki_q = \left(4\chi/\pi\right)(\mu y_0) x \\ x\left[\rho_\infty C_p\left[T_\infty^f g\left(T_f - T_\infty^f\right)\right]^{\frac{1}{2}} D^{\frac{1}{2}} y_0 \Big/ \lambda(T_s - T_\infty)\right] \tag{16a}$$

$$\text{or} \quad Ki_q = \left(\Psi_0/\sqrt{y_0/D}\right) y_0^{1.5} \tag{16b}$$

where

$$\Psi_0 = (4\chi/\pi)(\mu y_0)\left[\rho_\infty C_p\left[T_\infty g\left(T_f - T_\infty\right)\right]^{\frac{1}{2}} \Big/ \lambda(T_s - T_\infty)\right] \tag{16c}$$

Ψ_0 can be assumed as a constant depending only on the fuel characteristics and the initial fuel thickness.

Both values of $\mu\left(m^{-1}\right)$ and χ are specific characteristics of the fuel [17], *so the DAM equation can be expressed as*

$$\partial\Theta/\partial t^* = \partial^2\Theta/\partial y^{*2} + Ki_q \exp\left[-(\mu y_0) y^*\right] \tag{17}$$

The attenuation term $(\mu y_0)\exp\left[-(\mu y_0) y^*\right]$ may be evaluates as follows [10]: i) The product (μy_0) varies from 0.5 to 5 (data of [6,7,17,24-26] treated) approximately, ii)The exponent $\exp\left[-(\mu y_0) y^*\right]$ reaches its maximum of 1 at the fuel surface. Following the form of (16), the Fourier number can be expressed in a suitable functional form:

$$Fo = \Phi\left[(\mu y_0)(Ki_q)\right] \approx \Phi\left(\Delta\Theta\Big|_{\substack{\text{water}\\ \text{boiling}\\ \text{point}}}\right)\left(\Psi_0\Big/\sqrt{y_0/D}\right)(\mu y_0) \tag{18}$$

CRITICAL COMMENTS
Fixed or moving boundary problem
The use of y_0 in Fo^e should overestimate t_{B0}, since the layer diminishes continuously. The fact that *Fo< 1* at $t = t_{B0}$ may be interpreted as [10]:

$$Fo^e = a_F\Big/\left(y_0^2/t_{B0}\right) = a_F \big/ (\textit{diffusivity of the hot wave}) \tag{19}$$

The term "*diffusivity of the hot wave*" conceived in [10] tries to clarify the heat transfer mechanisms of the burning layer instead the term "*velocity of the thermal wave*" $U_T = y_0/t_{B0}$ [6,9] (see Table 3). The use of the mean values of the regression rate R_{AV} allows calculating the fuel layer unburned at $t = t_{B0}$

expressed as (Δ/y_0), where $\Delta = R_{AV}t_{B0}$. The last right column of Table 3 clearly indicates that at $t = t_{B0}$ almost 50-60 % of the initial fuel layer is burnt, so $U_T = y_0/t_{B0}$ and the *hot wave diffusivity* are idealizations using macroscopic data defined easy by experiments. The thin fuel layers ($<3+5\,cm$) [6, 9] are more relevant to the fixed boundary approach (the SAM equations) and due to a small fraction of the liquid burnt before the boiler onset.

Scaling relationships –physical facts accounts
The analysis of SAM leads to dimensionless scaling groups incorporating several physical facts: i) The increase y_0 increases $t = t_{B0}$; ii) The increase of $\Delta\Theta_b$ leads to lower a_F and longer t_{B0} . iii) Higher D, higher burning rate, higher heat reflux to the surface [6, 9], faster boilover onset.

Dimensionless groups – are they sufficient?
All the facts mentioned above are incorporated in the form of (12) and (16) due to the use of adequate governing equations. Thus, DAM's do not require additional scaling procedures. Therefore, the SAM formulation has a deficiency. Moreover, does the boundary condition at the fuels surface is correct? If the $T = T_s$ at $y = y(t)$ is replaced by the constant flux boundary conditions expressed by Eq. (4) the ***Nva group and its consequent forms occur directly from the dimensionalization procedure.*** However, both models have a common deficiency concerning the *phase transition* at the burning surface and the *regression rate.*

More adequate condition at the burning surface
Starting intuitively, because of the knowledge of physical phenomena controlling the process, the more adequate boundary condition conceived here is the energy balance (3). Concerning (4) and the dimensionless variables the new form of (3) is

$$q_s'' y_0/\lambda(T_s - T_\infty) = [H_V \rho_F y_0/\lambda(T_s - T_\infty)]r(t) - \partial\Theta/\partial t^* \quad (20)$$

The left side of (20) is Ki_q in its basic form. A simple manipulation of the first term of the right-hand side of (20) (incorporating the thermal diffusivity) yields in:

$$[(H_V \rho_F y_0)/\lambda(T_s - T_\infty)]r(t) =$$
$$= \underbrace{[(H_V \rho_F)/\rho_F C_P(T_S - T_\infty)]}_{Bu} \times \underbrace{[y_0 r(t)/a_F]}_{N_{DHS}} = Bu\, N_{DHS} \quad (21)$$

The dimensionless numbers formed are:

$$Bu = \left(Heat\ for\ vaporization \middle/ \begin{matrix} Heat\ to\ bring\ liquid \\ to\ boiling\ point \end{matrix} \right)$$

known as Bullygin number [27]. The group N_{DHS} has no specific name and can be defined as the ratio

$$N_{DHS} = \left(\begin{matrix} Diffusifity\ of \\ Moving\ Heat\ Source \end{matrix} \middle/ Thermal\ Diffusivity \right)$$

where *Moving Heat Source* in the specific situation here is the *burning fuel surface*. In the present 1-D problem formulation, the burning surface is a *Line Heat Source* [28]. N_{DHS} resembles the *Peclet number*, $Pe = (ul/a)$, in the case of a convection and a moving heat source [28] (p. 387). Thus, the more adequate formulation of (18) is:

$$Fo = \Phi[(\mu y_0)\ (Ki_q)(Bu)\ (N_{DHS})] \quad (22)$$

Dimensionless groups-some comments and data
The variations of Fo^* and both Bu and N_{DHS} just defined are summarized in Table 4. For example the product $(Ki_q\ Bu) = q_s''\ y_0 H_V/\lambda(T_b - T_i)^2$, (where $T_b = T_s$ and $T_\infty = T_i$) gives a new dimensionless group. The denominator of it confirms the empirically conceived ratio $\Delta\Theta_b = (T_{bf} - T_i)/(T_{bf} - T_{bw})$ and the regression fit $Fo^* \sim (\Delta\Theta_b)^{-2}$.

Table 4. Treatment of the data of Arai et al. (1990). onset. D=0.048 m; y$_0$=10 mm.

Fuel	T$_i$, K	Fo^* ♣	T$_b$, K	$r(t)$ m/s x10^5	Bu	N_{DHS}
Toluene	293	0.43	383		2.16	1.35
	318	0.29			3.01	
a_Fx10^7.	323	0.42			3.27	
1.03	325	0.45	[6]	1.35	3.38	
m^2/s	341	0.74			4.66	
	355	1.01			6.97	
Ethyl	293	0.45	409		1.79	1.69
Benzene	323	0.24			2.31	
a_Fx10^7	330	0.18	[6]		2.51	
0.88 m^2/s	345	0.08		1.5	3.10	
n-	293	0.34	433		0.87	1.58
Decane	323	0.22			1.12	
a_Fx10^7	348	0.11			1.44	
0.753	355	0.10	[6]	1.19	1.57	
m^2/s	362	0.07			1.72	

Data fits
The preliminary scaling yields in $Fo \sim (N_{DHS})^{-1}$ and $Fo \sim Bu^2$. The regression of the data of Garo et al. [6] (Table 3) in the form $Fo = A + B.Ki_q{}^m Bu^n N_{DHS}{}^p$ gives a linear fit (Fig.1) at 0.95 confidential interval

$$(Fo\, N_{DHS}/Bu^2) = 0.88 - 0.016Ki_q \quad (23)$$

at $Bu = 0.728$ and $0.2 < N_{DHS} < 1.9$, for variations of Ki_q within the range $0.05 < Ki_q < 90$.

This first attempt, gives a satisfactory result. The further data treatment would confirm or enhance, or rejected, its form.

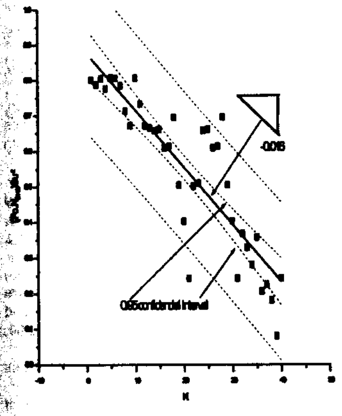


Fig. 1 . Data fit of the results of Garo et al. [6,9] in the form (22). Eq 23 gives the particular regression.

Brief Asymptotic Analysis
The physical data and the scaling allow derived allow a brief asymptotic analysis. 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: $r(t) \to 0$ (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). The second case, $Fo \to 0$, means $y_0 \approx 0$ (no fuel layer exists, that is non-sense) or $a_F \to \infty$ which I unrealistic as commented above.

The intermediate case could be analyzed through the plot on Fig.1. At $Ki_q \to 0$ (i.e. no burning fuel exists, $y_0 \approx 0$ or extremely narrow vessel ($D \approx 0$), the value of $Fo \to 1$ (really $A \approx 0.88$). This means that (following the general form (22)) the expression (19) (conceiving the idea of the diffusivity of the hot wave) $a_F \approx (y_o{}^2/t_{B0})$) could be utilized. Therefore, at $Fo \to 1$ the thermal time scale $t_0 = (y_0{}^2/a_F)$ defines the pre-boilover time. As $Fo << 1$, i.e. large Ki_q numbers that should be exhibited by large pool fires on waterbeds) the idea of (19) should fail since it means that hot zone propagates faster that the temperature field, that is unrealistic. Therefore, at large values of Ki_q no pure heat conductivity transfer should be considered in the fuel layer. It seems that the convections effects in both the fuel layer and the waterbed take important roles, which is not investigated yet.

BRIEF CONCLUSIONS

The analysis passed through many points of the simplified modeling a very violent and dangerous phenomenon occurring in open tank fires. The analysis reached two results: 1) To consolidate the data published in various sources, but without any *transport phenomena analysis performed till now.*

2) The formation of a power-law equation (defining the pre-boilover time) through an elucidation of the main dimensionless groups and their contributions.

The dimensionless equations are easily transformable as charts or simple formulae suitable for engineering uses. We suggest that present analysis would provoke more unified presentation and data treatment of the results from the boilover experiments

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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, m/s
t_b - Time for burning, time
t_{B0} - pre-boilover time, time
T_∞ - the ambient temperature, K
T_f - average flame temperature (typically $T_f \approx 1100K$, Cox (1995) [14], 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

$\Delta = R_{AV}\, t_{BO}$ -fuel layer thickness burnt at $t = t_{BO}$

Superscripts

f- flame

Subscripts

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

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