EFFECT OF LIP HEIGHT ON PROPERTIES OF SMALL SCALE POOL FIRES

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ABSTRACT

An experimental technique is described for accurately measuring the steady-state fuel consumption rates in small scale pool fires, less than 7 cm in diameter. The technique is applied to studying ethanol fires burning in vessels of various geometries and constructed from various materials. The results indicate that the distance between the top of a vessel (lip height or freeboard) and the fuel surface influences profoundly the properties of liquid pool fires, including their structure and their burning rates.

For combustion in glass cylinders, the burning rates decrease exponentially with increasing freeboard until a critical height is attained. At this height, the fuel begins to burn on the inside of the vessel, and the burning rate tends to grow slightly. With a further increase of the lip height, flame instabilities develop leading ultimately to flame self-extinction. The exponential decline in fuel consumption with the lip height depends strongly on the vessel's material of construction. For fires in copper and mild steel cylinders, the ethanol starts to boil beyond a certain critical freeboard. The appearance of this phenomenon redefines the fuel consumption curve. Finally, free convection leads to non-negligible heat losses, especially from more conductive (copper and steel) vessels, with the burning rates becoming dependent on the outside surface area of the cylinders.

KEY WORDS: burning of liquids, pool fires, flammable liquid fires, lip height, ethanol fires

NOMENCLATURE

Roman symbols:	
c	specific heat (J/kg K)
d	diameter (m)
h	height of the fuel inlet nipple at the base of a fire vessel (m; Fig. 1)
Gr	Grashof number (unitless)
l	distance from the top of the crucible, downwards (m)
n	fuel consumption flux (kg/m^2 s)
Nu	Nusselt number (unitless)
Pr	Prandtl number (unitless)
q	heat transfer rate (W)
Q	heat release rate (W)
T	temperature (°C)
t	lip height or freeboard (m)
z	persistent flame height (m)
Greek symbols:	
α	constant defining exponential decrease in fuel consumption (unitless)

β	constant in the expression for the temperature profile (unitless)
λ	heat of vaporisation (J/kg)
Superscripts:	
*	denotes nondimensional quantities
Subscripts:	
conv	relates to free convection losses of heat
corr	denotes a variable corrected for the free convection losses
i, o	refers to inside and outside dimensions, *e. g.*, d_i - outside diameter
f	signifies burning at zero freeboard (fuel flashed with the rim)
fuel	relates to liquid fuel
ls	refers to liquid surface, *e. g.* - T_{ls} liquid surface temperature
t	relates to the lip height, *e. g.* - l_t distance from the fuel surface downward

INTRODUCTION

A large number of publications relating to burning of flammable liquids signifies the importance of the phenomenon in the fields of combustion and fire science. Since the early experimental studies conducted by Rasbash *et al.* [1], Blinov & Khudyakov [2] and Fons [3], and the semi-quantitative interpretation of the Blinov & Khudyakov results by Hottel [4], almost every aspect of pool fires has been explored. For example, Spalding [5] and Agoston [6] independently suggested an alternative (to Hottel) explanation, derived from the theory of the natural convection burning of fuels, for observed trends in the fuel combustion rates in pan fires. Since Spalding's approach did not incorporate the radiative and conductive heat transfer to the fuel, it was instantaneously refuted by Burgess & Grumer [7]. Gollahalli & Sullivan [8], and Drysdale [9] provided in-depth reviews of the pre-1985 literature related to pool fires.

Although there is a trend in more recent studies to concentrate on the important subject of flame radiation (*e g.* [10-12]), there is still a need to explain the effect of vessel geometry on characteristics of pool fires. The first step in this direction has been taken by Nakakuki [13] who conducted a numerical study to quantify the influence of wall thickness on the liquid burning rates. From this perspective, the present paper is a continuation of Nakakuki's work, examining the significance of lip height on properties of small scale pool fires.

There is no agreement in the experimental literature about the correlations between the lip height and the attributes of flammable liquid fires, and the theories developed by Hottel, Spalding and Agoston include no reference to the freeboard. For example, full scale experiments, using barrels up to 1.605 m in diameter, indicate that the burning rate decreases with the lip height [14]. Other data on small scale pan fires, controlled by heat conduction, also show that the burning rate slows down with the increasing freeboard [15]. But in an apparent contradiction to these results, the following statement was made at the 22nd Symposium on Combustion: *"It is well known that pool fires are very sensitive to the height of the container rim above the fuel. For example, the burning rate increases as the bounding rim increases above the fuel level"* [16].

Since pool fires are widely used for testing, understanding of their behaviour is necessary for the successful interpretation and modelling of test results. With this purpose in mind, the present paper considers a simple system of ethanol burning in glass, copper and mild steel cylinders, and studies the characteristics of the resulting flames.

EXPERIMENTAL SET-UP

A need to maintain a constant level of fuel inside the vessel during combustion led the development of the experimental apparatus, which is illustrated in Fig. 1. The apparatus consists of an interchangeable cylindrical vessel mounted on an adjustable stand, a constant head device positioned on a load cell, and a recirculating peristaltic pump. Vessel geometries and their materials of construction are listed in Table 1. To help identify the attainment of the steady-state burning rate, the support of the vessel incorporated a housing for a thermocouple which could be moved vertically during the runs. A PC-based data acquisition system recorded the thermocouple's signal once every 2 s.

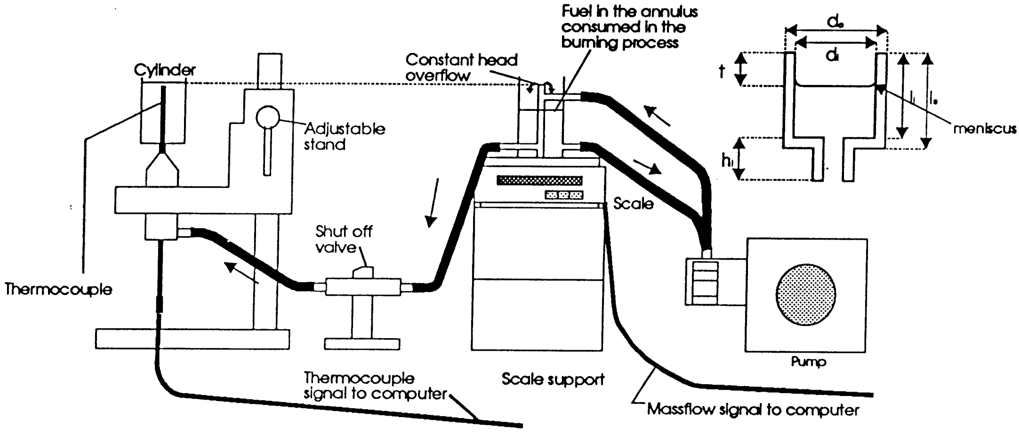

Figure 1. Schematic diagram for measuring burning rates of small fires.

Table 1. Geometry and material of construction of vessels used in the current investigation. For all cylinders, the fuel inlet nipples were 23.5 mm in length (h_i in Fig. 1) and 6.4 mm in outside diameter.

no.	material	d_i (mm)	d_o (mm)	l_i/d_i	l_o-l_i (mm)
1	glass	45.2	50.0	0.22	2.4
2	"	"	"	0.45	"
3	"	"	"	0.98	"
4	"	"	"	2.04	"
5	copper	47.3	51.1	0.25	1.8
6	"	"	"	1.08	"
7	"	"	"	2.01	"
8	mild steel	67.1	69.7	0.93	1.0

The constant head device supplies fuel to the fire vessel at a pre-set liquid head. The device operates on the principle that fuel for burning is withdrawn from a cylinder whose liquid level is maintained constant. Referring to Fig. 1, the fuel in the inner tube is continuously replenished by recirculating the liquid between the annulus and inner tube. A small throughput peristaltic pump equipped with Viton tubing (50 cm^3/min) accomplishes this task. The excess of fuel delivered by the pump, but unused in the burning process, flows down along the outside wall of the inner tube to mix with the fuel in the annulus. The decline of the liquid level in the annulus indicates the amount of liquid actually burnt in the fire vessel. This mass is recorded every 2 s by a balance interfaced with a data logger. The balance rests on concrete support to attenuate vibrations caused by the normal operation of the laboratory. The constant head device stores 50 g of fuel available for burning and is uses 3.2 mm in diameter PVC tubing for the fuel transfer to and from the pump.

It should be appreciated that in the course of experimentations, the lip height decreases from its pre-selected value. This is because, the ethanol in the fire vessel heats up and thermally expands reducing its density. The change in the freeboard is in the order of 1 mm for glass cylinders, which induce steep temperature gradients within the fuel, and around 5 mm for longer copper cylinders, when entire fluid contained in the cylinder approaches its boiling point. For this reason, the lip height data were recorded immediately following an experiment.

For clarity, error bars were not incorporated in illustrations included in this paper. However, the freeboard measurements could be reproduced to within 0.5 mm and the steady-state fuel consumption rates to within 0.04 g/min. We also calculated the instantaneous consumption rates of fuel by fitting a straight line to 10 consecutive data points, and then computing the noise (or r.m.s. deviation) from the linear mass consumption rates. For all experiments, the maximum r.m.s. deviation remained below 0.06 g/min. Figure 2 illustrates a sample outcome of this procedure.

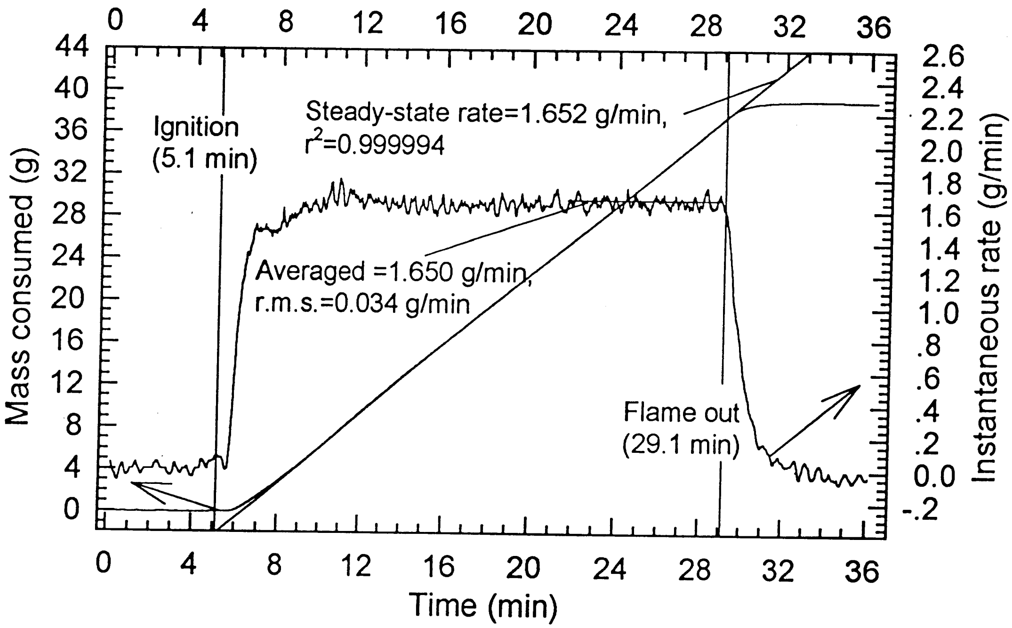

Figure 2. Instantaneous and steady-state ethanol consumption rates in copper cylinders; d_i=47.3, d_o=51.1 and t=2.9 mm.

EXPERIMENTAL OBSERVATIONS AND DISCUSSION

Fires in Glass Vessels

The relationship between the fuel consumption flux (defined as the rate of fuel consumption per cross-sectional area of the vessel) and the lip height initially follows an exponential decline, as illustrated in Fig. 3 for fires in glass cylinders. In this region, the experimental points obtained from tests with vessels of different lengths are satisfactorily correlated by the empirical expression,

$$n = n_f \exp(-\alpha t^*), \tag{1}$$

where n denotes the fuel consumption flux, t* is the lip height nondimensionalised with the vessel's inside diameter, α is a fitted parameter, and n_f can be interpreted as the consumption flux for liquid flashed with the burner's rim. Here, n_f corresponds to 0.0204 kg/m^2 s and α to 3.62. A small effect of the vessel size on the burning rates is observed only for the shortest cylinder (l_i=0.22 d_i), with the least square procedure yielding α=3.02.

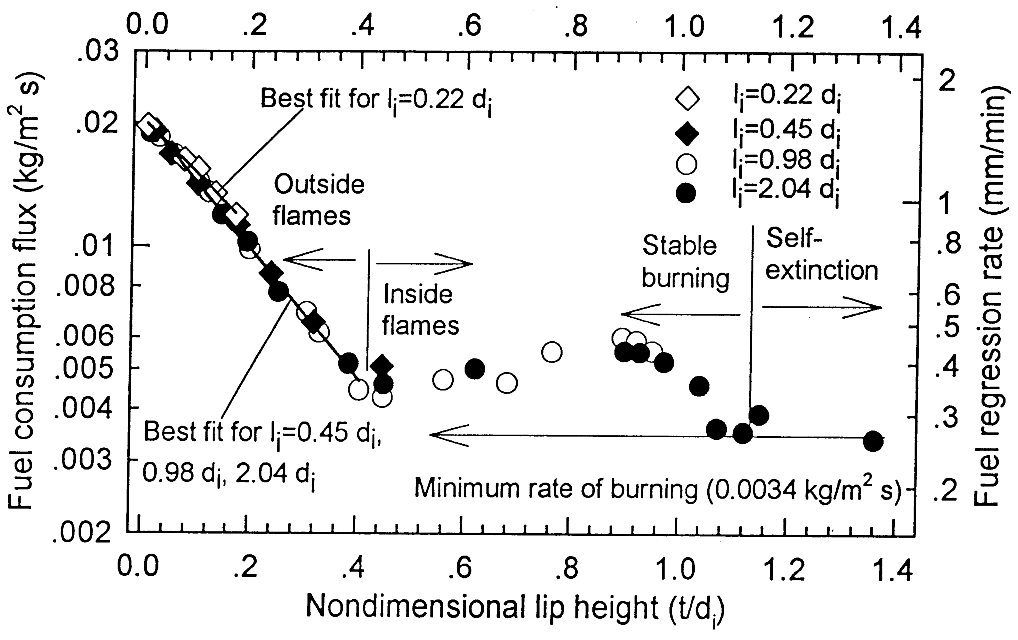

Figure 3. Variation of burning rate of ethanol with the lip height in glass cylinders. All cylinders have the same inside and outside diameters (d_i=45.2, d_o=50.0 mm, respectively), but differ in length.

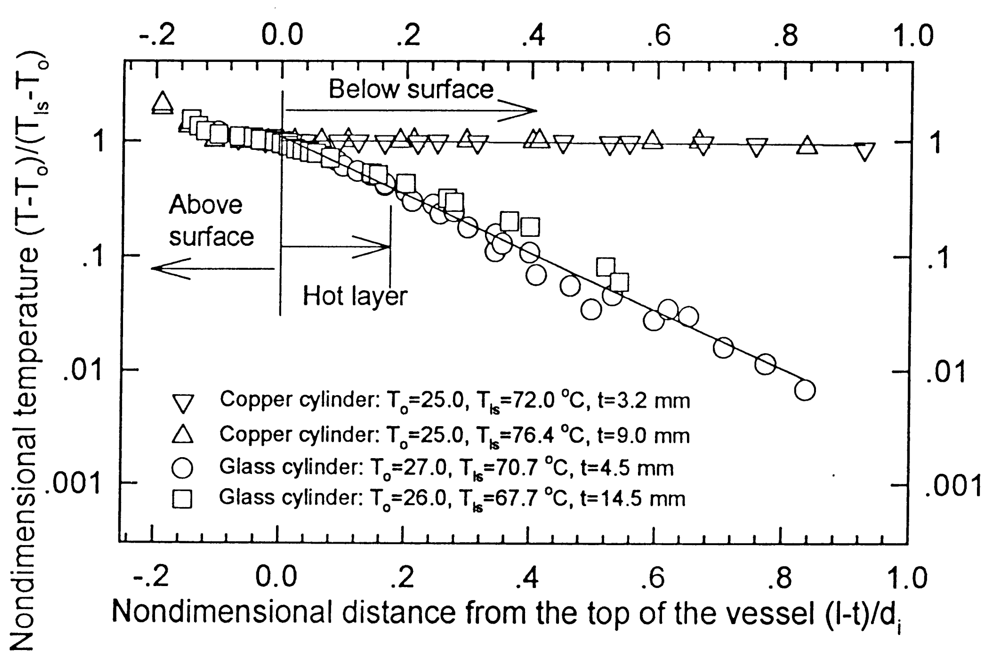

Figure 4. Temperature profiles along the centre axes of glass and copper cylinders during burning of ethanol fuel. Glass cylinder geometry: d_i=45.2, d_o=50.0 mm, l_i=0.45d_i; copper cylinder geometry: d_i=47.3, d_o=51.1 mm, l_i=1.08d_i.

Physical phenomena taking place in the liquid account for the observed difference in the value of the exponential parameter. A shallow layer of hot liquid forms immediately below the liquid surface (Fig. 4). If this layer comes in contact with the bottom of the fire vessel, an increased mixing leads to more efficient heat transfer from the wall to the liquid, and hence to the higher combustion rates.

The exponential presentation of the temperature results in Fig. 4 was initially suggested by Khudyakov (as reported in [7]), who defined the exponential parameter as the ratio of the regression rate of the liquid to its thermal diffusivity. This implies that the temperature profile should depend strongly on the lip height, especially for glass cylinders where n declines from around 0.02 to 0.004 kg/m^2 s. As shown in Fig. 4, our results do not support such a conclusion, with the temperature profile displaying little dependence on the fuel consumption rate, for a given vessel material. However, the Khudyakov expression - $T^*=\exp(-\beta l_t^*)$, where l_t^* is a nondimensional distance below the burning liquid - provides a convenient tool for correlating the temperature profiles with the freeboard. For the present ethanol data, the value of β becomes 5.8 and 0.09 for glass and copper vessels, respectively.

Note that in early experiments on burning of liquid fuels in cylinders, the location of the fuel interface was not maintained stationary (*e. g.* Blinov & Khudyakov [2]). Rather the fuel surface was allowed to regress as the fuel in a cylinder was being exhausted. Consequently, the results were reported as a fuel regression rate, in units of length per time; traditionally in mm/min. In more recent investigations, the fuel level was adjusted with a manually controlled levelled reservoir [16,17]. The collected data were converted to the fuel regression rate. Because of this tradition, a second ordinate axis was added on the right hand side of Fig. 3, by dividing the fuel consumption flux by the density of ethanol (780 kg/m^3, [18]).

It is also interesting to compare our results with the published data. According to Blinov and Khudyakov [2], the fuel consumption velocity is at its maximum for cylinders less than 1 cm in diameter, then the velocity goes through a minimum for pool fires in vessels 5 and 30 cm in diameter, to increase and level off for large fires in pans more than 100 cm in diameter. This observation is valid for a wide range of fuels, although for alcohol fires the minimum in the burning velocity is not well defined [19]. Actually, for cylinders more than 2.5 cm in diameter, the burning rate of methanol fires remains constant at around 1.4 mm/min [20], increasing to approximately 1.7 mm/min for pans larger than 1.5 m in diameter [21]. These results for methanol fires correspond very well to the ethanol data plotted in Fig. 3 which tend to 1.6 mm/min, in the limit of small freeboards.

Structure and Size of Flames

There exists a critical lip height at which the combustion at the top of the glass vessel can no longer be sustained. At the lip height of around 0.4 d_i, we observe rapid fluctuations between two flame structures, which are illustrated in Fig. 5. With respect to Fig. 5, the outside flame possesses a typical laminar structure with an oscillating tip. The inside flame, on the other hand, is characterised by twin-peak flames moving around the circumference of the glass vessel. A cavity created by the hydrodynamic effect of the drawn-in air forms at the base of the peaks.

The twin-peak structure predominates above a $t/d_i=0.5$ and remains stable up to $t/d_i=0.9$, leading to the increase in the fuel consumption rates (Fig. 3). Beyond the latter limit, the flame becomes chaotic in appearance, as the heat transfer to the fuel surface is not sufficient for maintaining the combustion. A rapid succession of barely visible and very long flames is observed. We surmise that the accumulation of fuel vapours inside the vessel, in the course of the low rate combustion, followed by a sudden flaring may account for this observation. Above $t/d_i=1.13$, evaporation of fresh fuel is not sustainable and the fires burn only until the accumulated vaporised fuel in the vessel is exhausted. It is interesting to note that in this study, no combustion has been observed for burning rates below 0.0034 kg/m^2 s, as shown in Fig. 3.

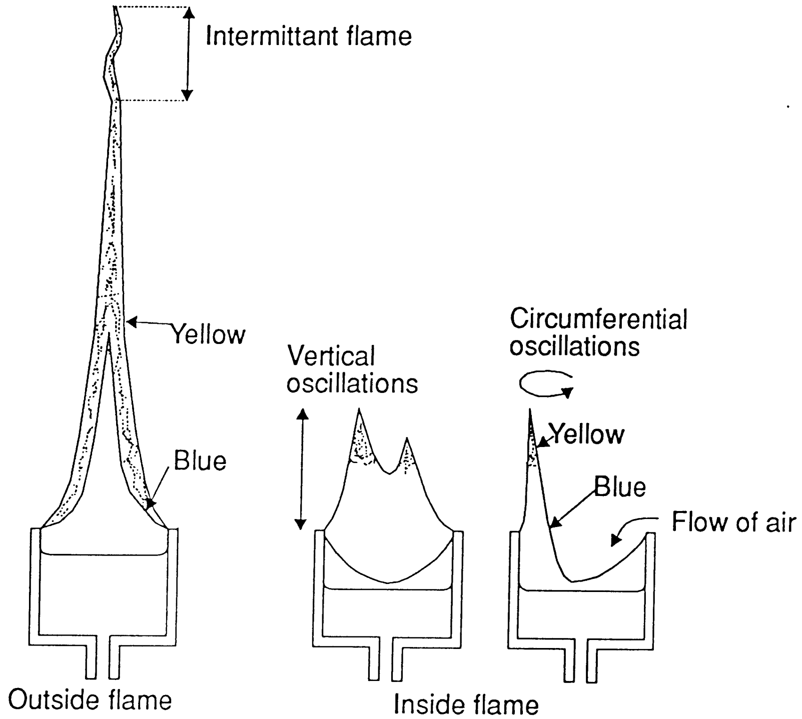

Figure 5. Flame structure during burning of ethanol in glass vessels.

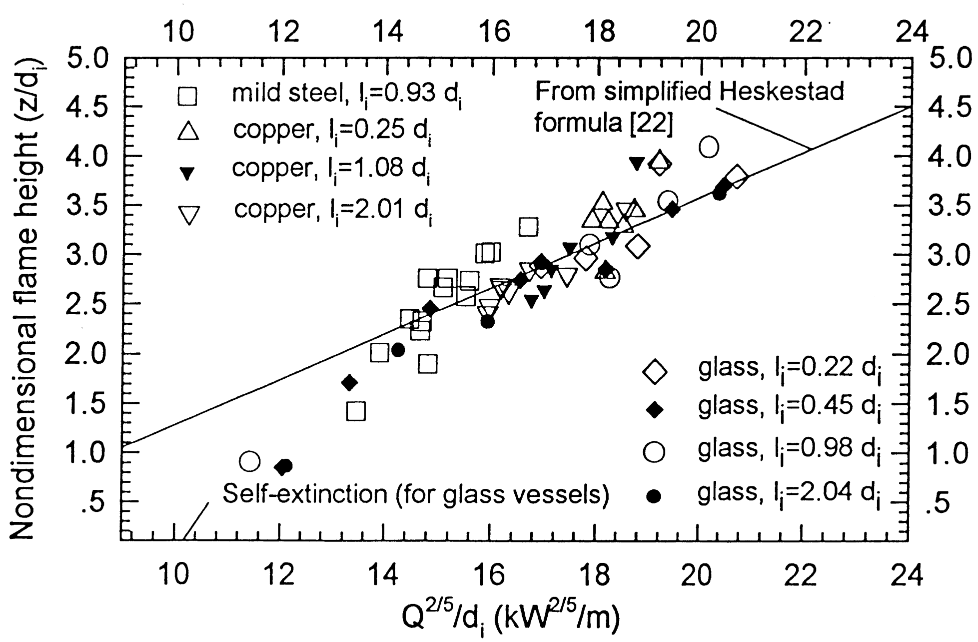

Figure 6. Correlation between the persistent flame height and the heat release rate. Note that the data are plotted using linear rather than logarithmic axes.

A series of experiments determined the extend of the persistent and fluctuating flame regions. We collected the results for the outside burning regime, where the flame anchored itself near the rim of the vessel, with fires burning progressively over a thicker layer of evaporated fuel, as the freeboard was increased. The outside burning was observed for all fires in copper and mild steel vessels, and for $t/d_i<0.4$ in the case of glass cylinders.

As reviewed by Drysdale [9], for a wide spectrum of fires, the nondimensional analysis allows to correlate the flame height results with the rate of heat release using the Froude and Grashof numbers, leading to a simplified expression developed by Heskestad [22],

$$\frac{z}{d_i} = 0.23\frac{Q^{\frac{2}{5}}}{d_i} - 1.02, \qquad 7 < \frac{Q^{\frac{2}{5}}}{d_i} < 700 \quad kW^{\frac{2}{5}}/m, \tag{2}$$

where Q denotes the rate of heat release calculated from the fuel consumption data assuming the complete combustion. The Heskestad expression accounts well for all data points, except for results near the minimum burning rate (see Fig. 3, just below $t/d_i=0.4$), where the flame height decreases towards zero, as the $Q^{2/5}/d_i$ tends to 10.3 $kW^{2/5}/m$ (Fig. 6). This is expected since below this limit no sustained burning occurred.

Fires in Copper and Steel Vessels

Being a good thermal conductor, copper efficiently transfers the heat away from the flame attachment zone. This results not only in better heat transfer into the fuel, but also in larger heat losses due to the natural convection. These losses are manifested by the overall decrease in the fuel consumption flux, as the length of the copper cylinders is varied from 0.25 to 2.01 d_i; see Fig. 7. Note that the vessel surface temperature is rather uniform, around 61 °C, with the axial temperature profile similar in appearance to the temperature distribution within the liquid (see Fig. 3, for the copper results). This behaviour is quite different than observed previously for fires in glass containers. Furthermore, as the lip height increases, at a critical freeboard the liquid starts to boil affecting the slope of the exponential line correlating the fuel consumption flux with the lip height. The onset of the boiling transition itself is a function of the length of the fire vessel. We surmise that more heat per unit mass of liquid is transferred from the walls of the vessels, for longer freeboards. However, larger heat losses occurring for longer cylinder defer the boiling transition.

Let us incorporate the natural convection losses into the fuel burning rate. Neglecting the heat re-radiated from the liquid surface and the heat liberated due to the condensation of water on the fuel surface, the heat transferred from the flame to the fuel is separated into the heat used to evaporate the liquid (q_{fuel}) and the heat removed by the ambient air (q_{conv}),

$$q = q_{fuel} + q_{conv} \tag{3}$$

The term q_{conv} can be estimated from the expressions for the Nusselt number found in [23],

$$\begin{aligned}
&\textit{vertical wall:} & Nu_{vw}^{\frac{1}{2}} &= 0.825 + \frac{0.387\,(Gr\,\mathrm{Pr})^{\frac{1}{6}}}{[1+(\frac{0.492}{\mathrm{Pr}})^{\frac{9}{16}}]^{\frac{8}{27}}} \\
&\textit{cylindrical surface:} & Nu_{cs} &= Nu_{vw}(1+1.43[(\frac{l_o}{d_o})Gr^{-\frac{1}{4}}]^{0.9}), \\
&\textit{horizontal plate:} & Nu_{hp} &= 0.54\,(Gr\,\mathrm{Pr})^{\frac{1}{4}}
\end{aligned} \tag{4}$$

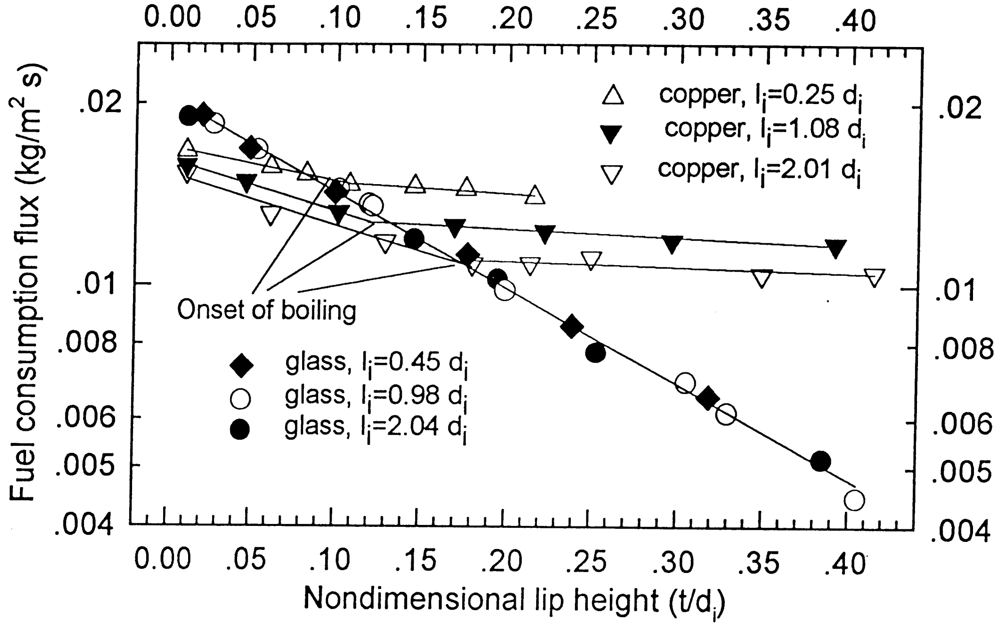

Figure 7. Effect of cylinder length on the burning rates of ethanol fires; diameters of glass cylinders are d_i=45.2, d_o=50.0 mm, and copper cylinders are d_i=47.3, d_o=51.1 mm, respectively.

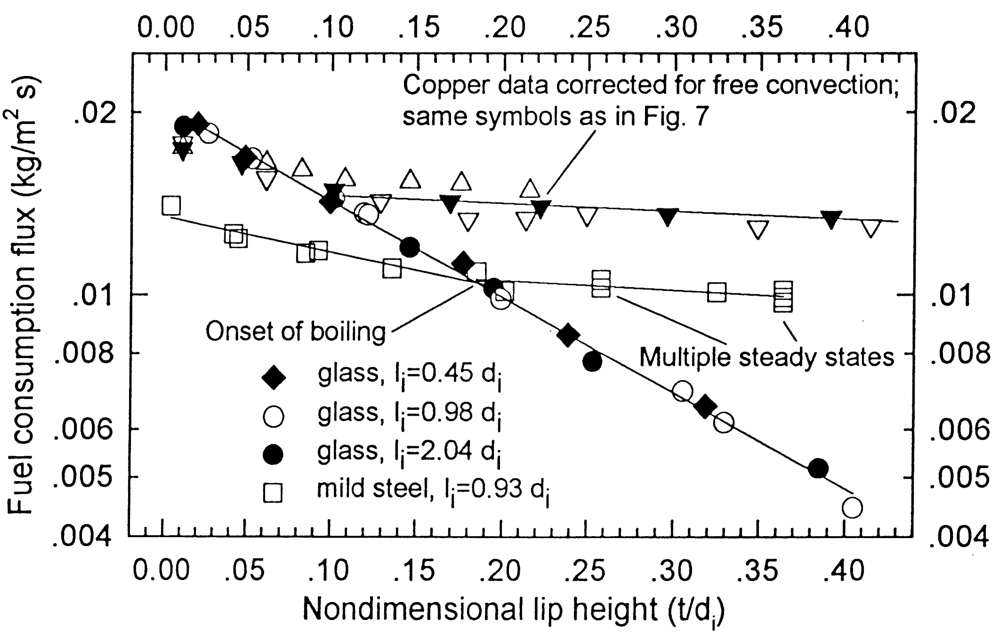

Figure 8. Comparison among burning rates of ethanol fires in glass, copper (corrected for natural convection) and mild steel vessels. Free convection losses for copper vessels are 1.34, 2.60 and 3.54 W, for l_i=0.25, 1.08 and 2.01 d_i cylinders.

where Gr, Nu and Pr have their traditional meaning of Grashof, Nusselt and Prandtl numbers, and the characteristic dimension for the horizontal circular plate (vessel bottom) is taken as $0.9d_o$. Consequently, the fuel consumption rate in copper cylinders is corrected according to the relation,

$$n_{corr} = n + \frac{q_{conv}}{c(T_{ls} - T_o) + \lambda}, \qquad (5)$$

where the denominator in the second term on the right hand side signifies the heat needed for fuel evaporation per unit mass.

As illustrated in Fig. 8, the copper results are significantly pulled together by applying the correction, and it is gratifying to observe that before the onset of boiling, the glass and copper results corrected for the natural convection coincide. We suggest that in this region the expression (1) is modified according to

$$n_{corr} = 0.0204 \exp(-3.62 t^*). \qquad (6)$$

For fires in copper vessels, after the boiling transition, the exponential decline is described well by a single relation,

$$n_{corr} = 0.015 \exp(-0.30 t^*). \qquad (7)$$

Since the location of the boiling transition, which depends on the vessel length, has not been incorporated in the correction, the copper data for $t/d_i > 0.1$ still display minor dependence on the cylinder size (Fig. 8).

Two distinct burning regimes also arise in the course of ethanol burning in mild steel vessels, as shown in Fig. 8. The flames in the mild steel vessel possessed more turbulent structure because of a larger vessel diameter. Hence, these results cannot be directly compared with the data for copper and glass vessels. It is interesting to note that above $t/d_i = 1.2$ for the steel cylinders, the burning rate of ethanol is not a unique function of the lip height, but tends to oscillate among several values. The origins of this phenomenon remain unclear at the present time.

CONCLUSIONS

In this investigation, we concentrated on elucidating the effect of lip height on the burning rates and on the flame size of small scale pool fires. Specifically, we measured burning rates of ethanol fires in copper, mild steel and glass vessels of various lengths. Otherwise, the geometry of the vessels was maintained constant, subject to the availability of tube sizes for vessel construction. The present work led to the following findings:

- There exists an exponential relationship between the steady-state burning rate and the freeboard. The relationship applies only to flames burning at the top of the vessel, with the fuel vapour diffusing upwards from the liquid surface. The appearance of inside burning increases the rate of combustion at longer lip heights, followed by another decline and self-extinction. We feel that the last effect is limited only to pool fires of small and intermediate diameters.

- The simplified Heskestad correlation estimates accurately flame heights for small freeboards. However, as the lip height increases the correlation becomes less exact. This is because the relationship between the flame height and the rate of heat release is modified by the appearance of the minimum rate of fuel consumption necessary for sustained combustion.

- Natural convection greatly influences the burning rates in vessels made from conductive materials. This effect manifests itself by a marked reduction in the rate of fuel consumption with increasing length of cylindrical vessels. On the other hand, the heat transfer from glass vessels to the ambient air is independent of cylinder length, since the heat losses are confined to a small area localised near the flame attachment zone.

- Finally, we observed the onset of fuel boiling in copper and steel cylinders. In longer cylinders, the boiling occurred at progressively increasing freeboards, dramatically altering the burning rates and making them weakly related to the lip height.

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