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Plume rise of smoke coming from free burning fires

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Abstract

In this paper, attention is focussed on the plume rise of smoke arising from free burning fires. Free burning fires have both geometric and emission characteristics quite different from common industrial emission sources. Experimental runs have been carried out in a wind tunnel in order to derive a simple expression to assess the plume rise of smoke arising from free burning fires. Moreover, the experimental expression has been compared with two models available from the literature. The presented experimental expression shows good agreement with these models, in particular for moderate wind speeds, showing a maximum difference of about 10%.

1. Introduction

Previous papers have presented various expressions to assess the plume rise of industrial emissions, most of which are semiempirical being derived from experiments carried out either at a large scale in the field or in wind tunnels. Only a few expressions have been derived from theoretical models.

However, none of these previously derived expressions can be applied generally, because the equations would lead to unrealistic estimates of plume rise if applied either to sources with characteristics different from those tested experimentally or systems that fall outside the assumptions used in deriving theoretical models.

The larger the difference between the situation modelled and the phenomenon responsible for the generation of the smoke, the more unrealistic will be the estimate of plume rise. This is indeed the case for a smoke plume that arises from free burning fires, the characteristics of which are very different from those of a common industrial source plume.

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In fact, in the case of free burning fires, the heat produced by the flames partly is radiated [1–3], instead of being released completely into the plume as for plumes generated by flare stacks [4, 5].

2. Approach to the problem

The assessment of rise of smoke plumes resulting from free burning fires must be done by implementing *ad hoc* models as those suggested by Mills [6] and Carter [7].

In particular, Mills suggests altering the Briggs formula [8] as follows:

$$\Delta h = \left[(\Delta h_B)^3 + \left[\frac{L}{2\gamma} \right]^3 \right]^{1/3} - \frac{L}{2\gamma} \tag{1}$$

This expression, which takes into account the diameter L of the fire, may be altered bearing in mind that:

$$\Delta h_B = 1.6\, F^{1/3} X^{2/3} u^{-1} \tag{2}$$

where:

$$F = 0.037\, Q_H \tag{3}$$

and assuming an ambient temperature $T_a = 293$ K.

Moreover, Mills assumes that the 30% of the heat released in the combustion is dispersed as thermal radiation in the surrounding area, also Mills assumes that the 70% of heat combustion is devoted to the plume rise.

As result of these assumptions the Briggs formula becomes:

$$\Delta h_B = 0.47\, Q_H^{1/3} X^{2/3} u^{-1} \tag{4}$$

Mills, therefore, modifies the Briggs formula in two ways:

(i) reducing the heat produced in combustion by about 30%, because this portion is dispersed in the environment as thermal radiation, and does not support the plume rise, (i.e. buoyancy of plume);

(ii) inserting in Briggs formula the term $L/2\gamma$ (where $\gamma = 0.6$, entrainment coefficient for buoyant plume rise) in order to take into account the initial diameter of the plume which is considered equal to the extent of the fire.

On the other hand, Carter suggests using Moore's formula [9], modified to exclude momentum.

Therefore Moore's modified formula becomes:

$$\Delta h = 0.512 \frac{f}{u} \Delta T^{0.125} \left[\frac{gQ}{C_p T_a} X^{*2} (X^* + 27L) \right]^{0.25} \tag{5}$$

where:

$$X^* = XX_t(X^2 + X_t^2)^{-0.5}$$

$$X_t = X_s X_n (X_s^2 + X_n^2)^{-0.5}$$

$$X_s = 120\, u\varepsilon^{-0.5}$$

$$X_n = 1920 + 19.2\, Z \qquad \text{or} \qquad 4224 \quad \text{if } Z > 120 \text{ m}$$

$$f = 0.16 + 0.007\, Z \quad \text{if } Z < 120 \text{ m}$$

$$f = 1 \quad \text{if } Z > 120 \text{ m} \qquad \text{or} \qquad u^{-2}\varepsilon > 2.5 \times 10^{-3}$$

Carter suggested the use of Moore formula on the basis of general considerations without bearing in mind the peculiar characteristics of free burning fires. Equation (5), therefore, is valid for the plume rise assessment for very hot smoke arising from any kind of sources (point or large types). To compensate for area source, Carter estimates the virtual location of an equivalent point source, below the level of the area source.

In any case, however, the plume rise of free burning fires is brought about mainly by the buoyancy force and the height of the plume rise is equal to the real height of the emission because the geometric height of the source (fire) is negligible.

Furthermore, the passage from the flame to the smoke happens continuously, therefore in the assessment of the plume rise it is possible to consider the plume as single element composed by flame and smoke jointly.

Bearing this in mind, in this paper the plume rise assessment has been developed by considering that the heat of combustion is scattered partly in the environment as thermal radiation and the remaining heat of combustion is released to the smoke. The present plume rise assessment uses an expression similar to that of CONCAWE [10] adopted for flare stacks [4], and to Briggs expression as follows:

$$\Delta h = K \frac{Q_h^a X^b}{u^c} \tag{6}$$

The constant K and the exponents a, b, c have been evaluated by experimental measurements in a wind tunnel.

The term Q_h represents the convective heat flow released to the smoke and is evaluated as follows:

$$Q_h = (1 - E)\, Q_H$$

where Q_H represents the total heat flow while E represents the fraction of heat flux released in the environment as thermal radiation. Therefore E depends on the kind of fuel burning in the fire.

3. Experimental runs

Laboratory-scale tests of free burning pools of liquid were performed in a wind tunnel using diesel fuel and a mixture of lubricant oil with exhausted diesel [11, 12].

The wind tunnel utilized is characterized by a rectangular section, of dimensions 1 m × 1.2 m and an overall length of 6 m. Wind simulation has been performed by conveying air into the working chamber through a helical suction fan, which assured an air speed ranging from 0.1 to 1 m/s. Using the lower value of air speed we can expect the concept of *Re* independence to be valid during the tests [13].

A neutrally stable atmospheric boundary layer was simulated using a 38 mm high fence similar to the one proposed by Castro [14].

Flame buoyancy was varied by using bowls with different diameters and different quantities of fuel inside the containers. Bowls were lain low in a pit, while their upper edges were flush with the bottom of the wind tunnel.

Fuel vapor was lit after preheating the liquid with a bunsen burner, positioned just outside the wind tunnel under the bowl (see Fig. 1).

After reaching the fire point, the warming of the fuel was stopped by shutting off the bunsen burner, the pools were allowed to burn freely afterwards.

The smoke plume centreline was observed and its average height recorded by photography (exposure time 30 s) through the transparent wall of the wind tunnel at different downwind distances.

In order to easily record the plume rise (Δh) a transparent square grid, with sides of 2.5 cm, was fixed onto the transparent wall of the wind tunnel (see Fig. 1).

The main experimental parameters are shown in Table 1 while the results are reported in non dimensionalised variables in Fig. 2.

In particular the experimental results show that the maximum plume rise (Δh_{max}) was observed at a distance from the burning pool 45 times the diameter of the burning pool.

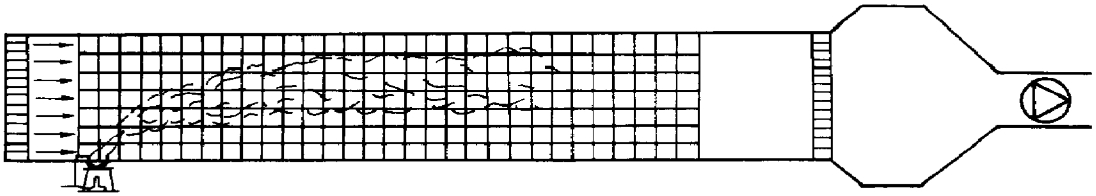

Fig. 1. General view of wind tunnel including the square grid for recording the plume heights.

TABLE 1

Range of the main geometric and operational parameters used for wind tunnel experiments and burning fuel characteristics

Wind tunnel characteristics	
Height	1.00 m
Width	1.20 m
Length	6.00 m
Thermal conditions in wind tunnel:	Neutral to isothermal
Operational parameters	
Wind speed	0.5–0.9 m/s
Diameter of pools	5.4–11.1 cm
Dimensionless number at source	
Froude	0.23–1.53
Reynolds	1807–6673
Burning fuel[a] *characteristics*	
Mass burning rate	0.015 kg/m^2 s
Low heat value	10800 kcal/kg

[a] Mixture of diesel fuel and lubricant oil.

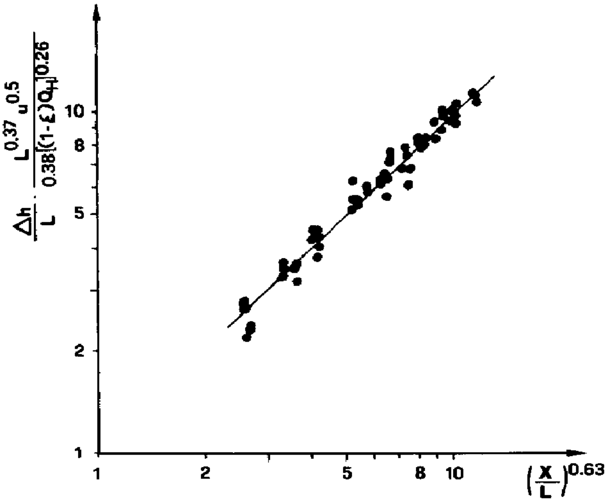

Fig. 2. Experimental results for wind tunnel tests.

By elaborating with the least square method the experimental data the values of the constant K and the exponents a, b and c of eq. (6) can be assessed:

$$\Delta h = 0.38 \frac{[(1-E)Q_H]^{0.26} X^{0.63}}{u^{0.5}} \tag{7}$$

which is valid for $X/L < 45$.

The maximum difference between experimental data and eq. (7) is about 35%.

For $X/L=45$ expression (7) becomes:

$$\Delta h_{\max}=4.2\,\frac{[(1-E)Q_{\mathrm{H}}]^{0.26}L^{0.63}}{u^{0.5}} \tag{8}$$

For distances farther than 45 times the diameter of the burning pool the plume heights were steady.

4. Validation of the model

As stated in Section 2, the models to assess the plume rise of a free burning pool must be developed *ad hoc* because the geometric and emission characteristics of the sources (free burning fires) are very different from the common industrial sources (stacks).

Among the expressions presented in the literature only the Mills formula may be applied specifically to the problem examined in this paper, while the Carter formula may also be applied to other emissions.

The Carter formula is, therefore, characterized by a higher degree of uncertainty because of general usefulness, being less specific than the Mills formula.

In this paper, however, both models examined (Mills's and Carter's) will be compared with the experimental data by means of experimental runs carried out in a wind tunnel.

Furthermore, for both the models of Mills and Carter it was assumed that the maximum plume rise ($\Delta h_{\max}$) is obtained at a downwind distance from the burning pool of $X=45\ L$, where the smoke plume was fully aligned to the wind direction.

In fact, in the aforesaid models there does not seem to appear a limitation on the plume rise Δh, but it is quite clear that the plume cannot increase indefinitely.

4.1 Mills's model

The Mills model may be rewritten explicitly as follows:

$$\Delta h=\left[(0.47\,Q_{\mathrm{H}}^{1/3}X^{2/3}u^{-1})^{3}+\left[\frac{L}{2\gamma}\right]^{3}\right]^{1/3}-\frac{L}{2\gamma} \tag{9}$$

where [15]: $Q_{\mathrm{H}}=(\pi L^{2}/4)mh_{\mathrm{c}}$; $m=h_{\mathrm{c}}\,1000\,(h_{\mathrm{v}}+C_{\mathrm{p}}\Delta T_{0})^{-1}$ for liquid with boiling temperature higher than ambient temperature; and $m=h_{\mathrm{c}}\,(1000\,h_{\mathrm{v}})^{-1}$ for liquid with boiling temperature lower than ambient temperature.

A comparison between the above mentioned Mills formula and the experimental relation presented in Section 3 may be made if one only considers the term

$$\Delta h_{\mathrm{B}}=0.47\,Q_{\mathrm{H}}^{1/3}X^{2/3}u^{-1}$$

and comparing with the experimental equation (7), thus examining the following ratio:

$$R=\frac{\Delta h_B}{\Delta h}=1.34\ Q_H^{0.073}X^{0.037}u^{-0.5}$$

obtained by considering $E=0.3$ congruently with Δh_B.

The terms $Q_H^{0.073}$ and $X^{0.037}$ play a negligible role in the plume rise assessment.

In fact by putting $A=Q_H^{0.073}X^{0.037}$ one may consider that the value of the term A is between 2 and 3. Such a range corresponds to a variation of Q_H between 5000 and 20000 kcal/s and to a downwind distance X less than 2000 m.

The trend of the function R is shown in Fig. 3 and a good agreement may be observed between the Briggs equation and the experimental one (eq. 7), above all for wind speeds moderately high ($u>8$ m/s) the function R is approximately equal to unity ($R\approx 1$).

The difference between the Briggs formula and the eq. (7) is quite high for low wind speeds, less than $2\div 3$ m/s, which are not significant considering the very high plume rise reached by the smoke.

Furthermore the correction made by Mills in the Briggs expression shifts the curves shown in Fig. 3 downward, in particular those curves which refer to higher values of the term A, i.e., higher Q_H and X values.

This fact makes the R ratio approximatively equal to unity for those wind speeds generally applied in the assessment of atmospheric dispersion of smoke arising from free burning pools.

A more detailed comparison between the Mills model and the experimental model worked out in wind tunnel runs is shown in Fig. 4. For moderate wind speed (5 m/s) the experimental expression is lower than the Mills model

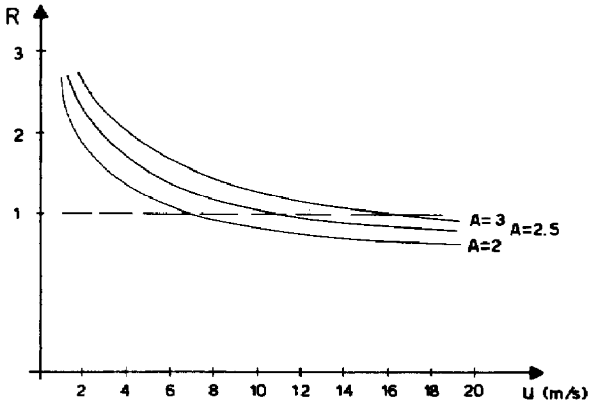

Fig. 3. Trend of the ratio $R=\Delta h_B/\Delta h$ vs. wind speed.

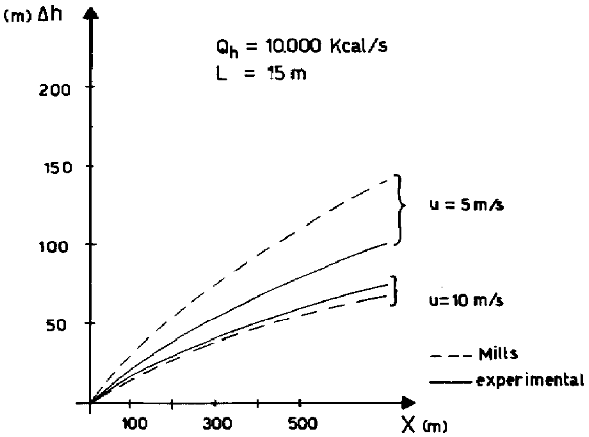

Fig. 4. Comparison between the Mills model and the experimental model.

prediction by about 40%, for higher wind speed (10 m/s) the gap, in excess, is only about 9%.

Obviously the aforesaid considerations are valid bearing in mind a medium value of $E=0.30$. In fact for different emission factor values the Mills equation does not consider different E values.

4.2 Carter's model

A detailed comparison between Carter's formula and the experimental expression (7) derived from wind tunnel runs, is more complicated because the two models are structured in different ways.

Nevertheless, a comparison can be made between the three models, Carter's, Mills's model and the experimental equation (7), on the basis of an example, a fire of carbon disulphide, developed by Carter. The comparison has been done for a wind speed of 10 m/s and for burning pools of different diameters (2, 5, 10, and 20 m). The results of the comparison are shown in Fig. 5.

Despite the general validity of Carter's formula, i.e. not specifically for free burning fires, it shows in the example chosen good accordance with our experimental equation, with maximum difference of about 10%.

On the other hand, Mill's model also shows agreement with the experimental data.

5. Conclusions

The rise of smoke plumes arising from free burning pools should not be assessed by means of analytical expressions reported in the literature for common industrial emissions such as stacks, because of substantial differences between the two types of emissions.

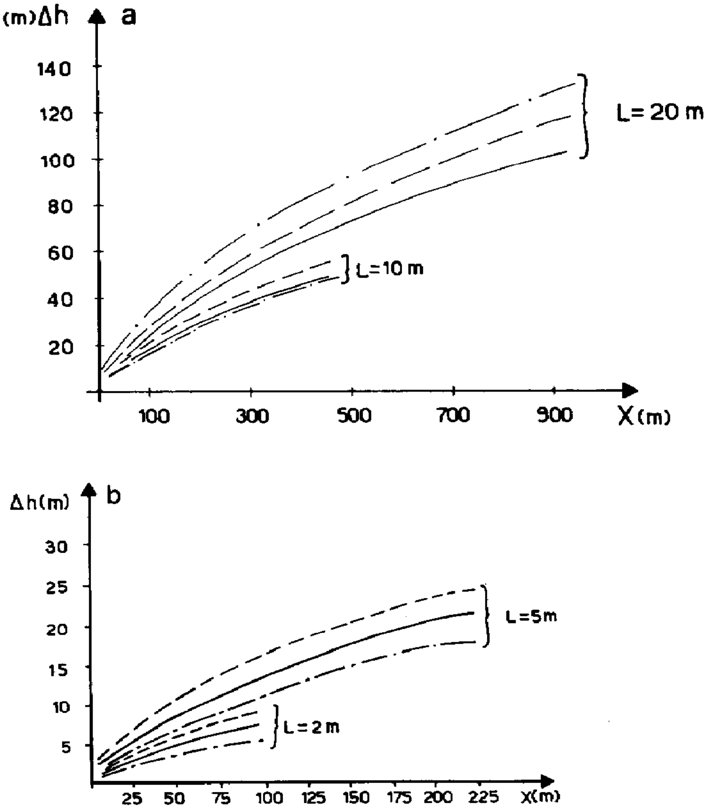

Fig. 5. Comparison among the models of Mills (– – –), Carter (– · –) and that derived from experiments (—). (a) $L=20$ m and $L=10$ m; (b) $L=5$ m and $L=2$m.

The present paper describes experimental runs carried out in a wind tunnel, which enables the derivation of a simple expression to assess the plume rise from free burning fires.

The experimental model takes into account that, in the presence of flames, the combustion heat is partly dispersed in the environment as thermal radiation and partly transferred to the smoke.

The experimental expression has been compared with two existing models from the literature; that of Mills, specific for the case considered, and that of Carter which is of general validity, not particular to fires, but applicable to very hot smoke.

Good agreement has been noted, with differences of about 9%, between the experimentally derived relation and the Mills model for moderately high wind speed, that is, in the range of wind speeds most significant for reducing the very high plume rise otherwise reached by smokes.

Also the Carter equation, despite its general validity, has shown good agreement with our experimental equation, with maximum differences of about 10%.

Notation

C_p	specific heat of liquid fuel (kcal/kg K)
E	fraction of radiant emission
f	plume rise factor
F	buoyancy flux (m^4/s^3)
g	acceleration due to gravity (m/s^2)
h_c	heat of combustion (kcal/kg)
h_v	heat of vapourisation (kcal/kg)
Δh	plume rise (m)
Δh_B	plume rise calculated by using the Briggs equation (m)
L	diameter (m)
m	mass burning rate ($kg/m^2 s$)
Q	convective heat output ($kcal/m^2 s$)
Q_h	heat rate released to the smoke (kcal/s)
Q_H	total heat rate (kcal/s)
T_a	ambient temperature (K)
T_b	boiling temperature of liquid fuel (K)
T_s	smoke temperature (K)
ΔT	$T_s - T_a$
ΔT_0	$T_b - T_a$
u	wind speed (m/s)
Z	height (m)
X	downwind distance (m)
γ	entrainment coefficient for buoyant plume rise
$\in$	environmental temperature gradient ($K/m \cdot 10^2$)

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