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PROCEDURE FOR CALCULATING THE AIR ENTRAINMENT INTO TURBULENT POOL AND JET FIRES

by

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SUMMARY

In the recent edition of the *SFPE Handbook of Fire Protection Engineering*[1], correlations for calculating air entrainment into pool and jet fires below the flame height have been developed. An example for using these correlations is presented in this work, together with expressions for air entrainment above the flame tip which allow the determination of a virtual source origin for a pool fire.

I INTRODUCTION

The air entrainment into a fire is a necessary ingredient in room fire models for calculating, for example, the growth of the ceiling smoke layer and vent sizes.

Correlations for air entrainment into (unrestricted) turbulent pool fires of varying source diameter have been presented in the *SFPE Handbook*[1], as shown in Figure 1. These correlations[1] were developed based on (a) numerous experimental data (Beyler[2], Cetegen *et al*[3], Becker[4], Toner[5], Delichatsios and Orloff[6]), and (b) similarity arguments. An important experimental input for the similarity analysis was the fact that the air entrainment below the vertical flame extent is independent of the heat release rate $\dot{Q}$, (References 2, 3, 4, 5, 6, see also Figure 2) and depends only on the pool diameter, D, and the distance from the pool surface, Z. These entrainment results and correlations are reproduced in Figure 1, which is applicable for $Z < Z_f$ = flame height.

Far above the vertical flame extent ($Z >> Z_f$) the air entrainment into the buoyant plume is given by the following relation[3,4,5]:

$$\dot{m} = C \frac{\dot{Q}_{conv}^{1/3}}{(\rho_\infty C_p T_\infty g)^{2/3}} Z^{5/3} \text{ for } Z >> Z_f \qquad (1)$$

wherein $\dot{Q}_{conv}$ is the convective heat release from the fire, and the denominator contains ambient air properties and the gravitational acceleration.

Experimental results[3,4,5,7] show that the dimensionless coefficient C in Equation 1 is independent of density even for strong density variations, an observation which is also consistent with air entrainment measurements in momentum jets having strong density variations (Ricou-Spalding[7]):

$$C = .21 \qquad (2)$$

The experimental results of Cetegen *et al*[3] which provide Equation 1, are shown in Figure 3.

We present in this work an example to illustrate how to use the correlations in Figure 1 to predict air entrainment into pool fires below the vertical flame extent. In addition, we also demonstrate how to use the results in Figure 1 in conjunction with the air entrainment Equation 1 in the buoyant plume above the flames in order to determine a virtual fire origin so that one can also use Equation 1 for intermediate heights $Z \gtrsim Z_f$.

II COMMENTS ON CORRELATIONS AND LIMITATIONS

The examples we present here are applicable only for turbulent buoyant jet flames and pool fires which do not represent a mass fire situation[1]. More precisely the present work is limited to pool fires wherein the visible flame height extends beyond the neck-in area of the flame (see Figure 4) in contrast to a large area pool fire which may produce relatively short flames (see Figure 5).

For the present case of Figure 4, one can assume that there are two regimes: (l) below the vertical extent of the flame for which the entrainment relationships of Figure 1 are applicable, and (2) above and far above the flame extent wherein entrainment relationships are applicable for turbulent point source buoyant releases, such as Equation 1. Finally, we propose that these entrainment relationships have an overlap at $Z \doteq Z_f$.

Next, we illustrate an algorithm based on the results of Reference 1 (see also Figure l) for calculating entrainment rates in pool fires represented by Figure 4.

II.I An Algorithm for Calculating Entrainment Rates into Pool Fires

II.1.a Computation Steps

Define the characteristics of a pool fire.

Diameter : D (m)

Fuel Type

ΔH_c Heat of combustion per unit fuel mass (kJ/kg)

S Stoichiometric ratio air to fuel

χ_A Efficiency of combustion

T_∞ Ambient temperature in K (e.g. 300K)

χ_R Radiant fraction (based on the theoretical heat release rate)

C_p Specific heat at ambient conditions (1 kJ/kg)

p_∞ Ambient density (1.2 kg/m^3)

$\dot{Q}_{th}$ Theoretical heat release rate

$$\dot{Q}_{th} = \dot{m}_f \, \Delta H_c,$$

Chemical heat release rate

$$\dot{Q}_{chem} = \chi_A \, \dot{Q}_{th},$$

Convective heat release rate,

$$\dot{Q}_{conv} = \dot{Q}_{th} \left(\chi_A - \chi_R\right)$$

Mass fuel flow rate (kg/s)

1. Calculate the fire Froude number

$$Fr = Q_D^* \frac{1}{\left[\dfrac{\Delta H_c \, \chi_A}{(S\chi_A + 1)\, C_p \, T_\infty}\right]^{3/2} \sqrt{(1 - \chi_R/\chi_A)}}$$

where:

$$Q_D^* = \frac{\dot{Q}_{th} \, \chi_A}{\rho_\infty \, C_p \, T_\infty D^2 \sqrt{gD}}$$

2. Find the flame height based on the following equations.

$$\frac{Z_f}{D} = 1.35 \text{ x } 10^4 \, Fr^2 \quad \text{for } Fr \le 8.6 \text{ x } 10^{-3}$$

$$\frac{Z_f}{D} = 22.54 \, Fr^{2/3} \qquad 8.6 \text{ x } 10^{-3} \le Fr \le 10 \text{ x } 10^{-2}$$

$$\frac{Z_f}{D} = 12.52 \, Fr^{2/5} \qquad \text{for } Fr > 10 \text{ x } 10^{-2}$$

3. Find entrainment rate from the top of the pool fire to a height Z if $Z \le Z_f$.

a) $$\frac{\dot{m}_{ent} \, Fr}{(\chi_A \, S + 1)\, \dot{m}_f} = .086 \, (Z/D)^{1/2} \qquad Z/D < 1.0$$

b) $$\frac{\dot{m}_{ent} \, Fr}{(\chi_A \, S + 1)\, \dot{m}_f} = .093 \, (Z/D)^{3/2} \qquad 1.0 < Z/D < 5.0$$

c) $$\frac{\dot{m}_{ent} \, Fr}{(\chi_A \, S + 1)\, \dot{m}_f} = .018 \, (Z/D)^{5/2} \qquad Z/D > 5.0$$

4. Find the entrainment rate for $Z \ge Z_f$.

$$\frac{\dot{m}_{ent} \, Fr}{(\chi_A \, S + 1)\, \dot{m}_f} = .21 \left((Z + Z_v)/D\right)^{5/3}$$

where the virtual source is defined by:

$$\frac{Z_v}{D} = -\frac{Z_f}{D} + 10.21 \, Fr^{2/5}$$

and the flame height has been determined earlier in Part II.1.a.2.

II.1.b A Note on the Derivation of Part 4 in Section II.1.a

The derivation of the entrainment relationship

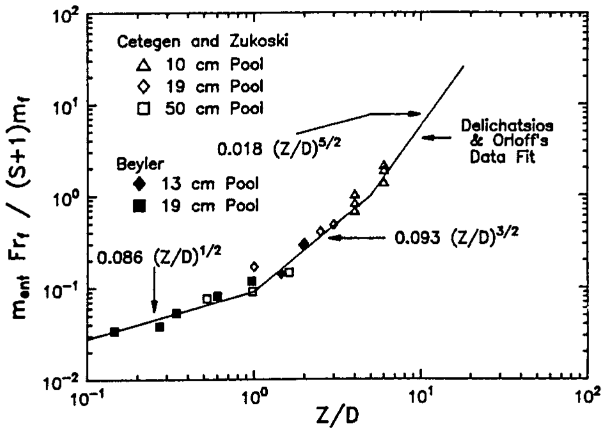

Figure 1: Air entrainment rates into turbulent jets and pool fires below the flame tip.

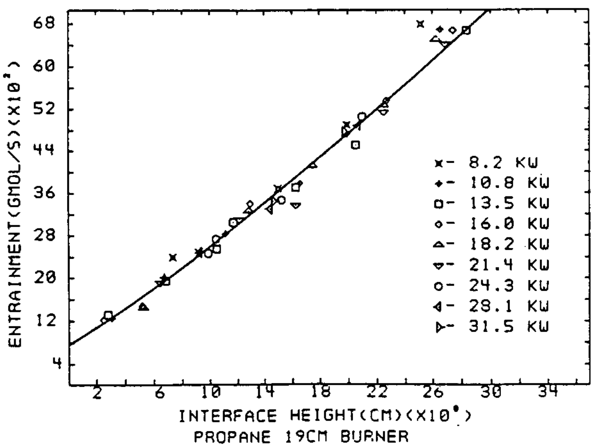

Figure 2: Air entrainment into a 19 cm propane burner pool fire below the flame tip. These results illustrate that air entrainment is independent of heat release rate, Q (taken from Reference 2).

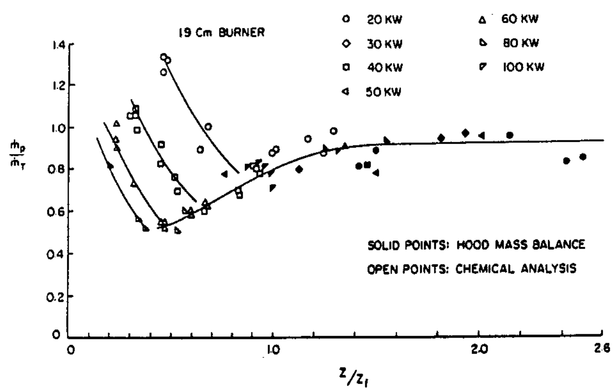

Figure 3: Air entrainment into the buoyant plume above the flame tip (taken from Reference 3). The reference value, $\dot{m}_T$, in the ordinate is given by Equation 1 in the text.

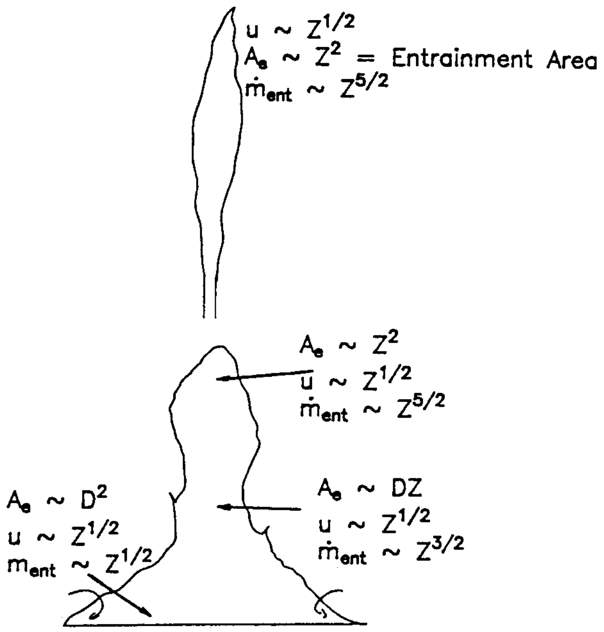

Figure 4: A turbulent jet flame and a pool fire configuration for which the present results for the buoyant plume above the flame tip are applicable ($Z_f \gtrsim D/2$).

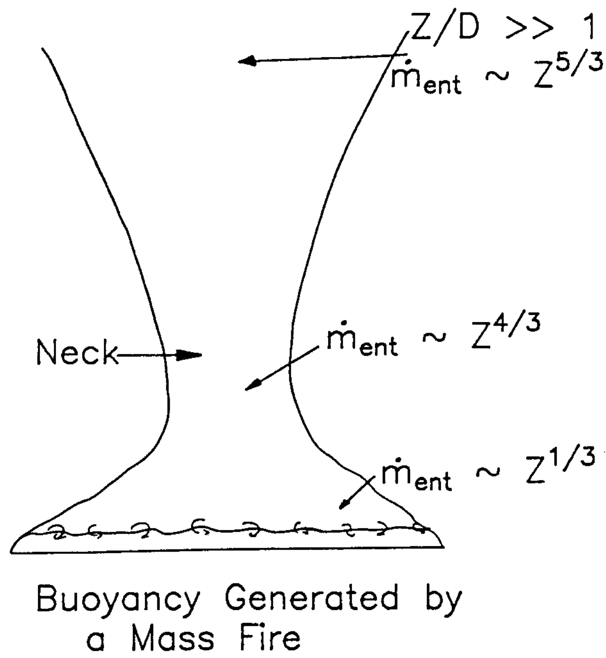

Figure 5: A very large pool fire ("mass" fire) situation for which the present results for the buoyant plume above the flame tip are not applicable ($Z_f < D/2$). In a "mass" fire situation the flame height is independent of the pool diameter and depends only on the heat release rate per unit area (this situation is included in the first flame height equation of Section II.1.a.2).

in part four (4) (Section II.1.a) has been obtained in the following way. First notice that for large distances from the source, the entrainment for the buoyant plume becomes:[3]

$$(Z >> D)$$

$$\frac{\dot{m}_{ent}\,Fr}{(\chi_A\, S + 1)\,\dot{m}_f} = .21\, Fr^{1/3}\,(Z/D)^{5/3} \qquad (3)$$

One can show that Equation 3 is exactly the same as Equation 1 by noticing that

$$\dot{Q}_{conv} = \dot{Q}_{th}\,(\chi_A - \chi_R).$$

We assume that this equation can be extended down to the flame tip by using a virtual origin correction, Z_v, for the distance Z from the source:

$$\frac{\dot{m}_{ent}\,Fr}{(\chi_A\, S + 1)\,\dot{m}_f} = .21\, Fr^{1/3}\left(\frac{Z + Z_v}{D}\right)^{5/3} \qquad (4)$$

By requiring that at the flame tip the entrainment rates are the same as calculated in Part 3, Section II.1.a, ($Z \le Z_{fl}$) and by using Equation 3 ($Z \ge Z_{fl}$), one can obtain an equation for the location of the virtual origin. Furthermore, one would note[1] that at the flame tip

$$\frac{\dot{m}_{ent}}{\dot{m}_f(\chi_A\, S + 1)} = 10$$

so that Equation 4 gives when applied at $Z = Z_{fl}$

$$\frac{Z_v}{D} = -\frac{Z_f}{D} + 10.2\, Fr^{2/5} \qquad (5)$$

II.1.c A Note on the Calculation of Fire Froude Number (Part 1, Section II.1.a)

In case the properties of the fuel (i.e. ΔH_c, S, χ_R, χ_A) are not known one has to use default values, as for example, assuming that the fuel is propane.

III Sample Calculations for Pool Fires

We follow the procedure outlined in Section II.

<u>First Case</u>

Kerosene pool fire

D = 1.33 m
$\dot{Q}_{th}$ = 4 MW
S = 15
ΔH_c = 44 kJ/g (see, e.g., *SFPE Handbook*)
χ_R = . 4 (assumed)
χ_A = 1 (assumed)
$\dot{m}_f$ = $\dot{Q}_{th}/\Delta H_c$ = 100 g/s

1. Calculate Fire Froude Number.

$$FR = Q_D^* \frac{1}{\left(\frac{\Delta H_c}{(S + 1)\, C_p\, T_\infty}\right)^{3/2}(1 - \chi_R)^{1/2}}$$

$$Q_D^* = \frac{4000}{1.2 \times 1 \times 300\,(1.33)^2\sqrt{9.8 \times 1.33}} = 1.74$$

$$\left(\frac{\Delta H_c}{(S + 1)\, C_p\, T_\infty}\right)^{3/2}(1 - \chi_R)^{1/2} = 20.11$$

$$Fr = \frac{Q_D^*}{20.11} = .0864$$

2. Find Flame Height.

Then $$\frac{Z_f}{D} = (22.54)\,[.0864]^{2/3} = 4.4$$

3. The required location for entrainment is at Z = 15 m > Z_{fl} = 5 . 8 m. One must go to Step 4.

4. First find virtual origin.

$$\frac{Z_v}{D} = -\frac{Z_f}{D} + 10.21\,(.0864)^{2/5}$$

$$= -4.4 + 3.83 = -.57$$

Hence:

$$\frac{\dot{m}_{ent}}{(S + 1)\,\dot{m}_f}\,Fr = .21\, Fr^{1/3}\left(\frac{15}{1.33} - .570\right)^{5/3}$$

$$\frac{\dot{m}_{ent}}{(S + 1)\,\dot{m}_f} = \frac{10.82}{Fr^{2/3}} = \frac{10.82}{(.0864)^{2/3}} = 55.27$$

Hence:

$$\dot{m}_{ent} = 16 \cdot (100)\, 55.27 = 88.5 \text{ kg/s}$$

<u>Second Case</u>

Fuel and its properties as before

$D = 4$ m
$\dot{Q}_{th} = 36$ MW
$\dot{m}_f = \dot{Q}_{th}/\Delta H_c = 900$ g/S

1. Calculate Fire Froude Number.

$$Fr = Q_D^* \frac{1}{\left(\frac{\Delta H_c}{(S+1)\,C_p\,T_\infty}\right)^{3/2}(1-\chi_R)^{1/2}}$$

$$Fr = \frac{.99}{20.11} = .0496$$

2. Find Flame Height.

$$\frac{Z_f}{D} = (22.54)\,[.0496]^{.666} = 3.04$$

3. The required location for entrainment is at $Z = 15$ m $> Z_f = 12$ m. One must go to Step 4.

4. First find virtual origin:

$$\frac{Z_v}{D} = -\frac{Z_f}{D} + 10.21\,(.0496)^4 = .3056$$

Then

$$\frac{\dot{m}_{ent}}{(S+1)\,\dot{m}_f}\,Fr = .208\,Fr^{1/3}\left(\frac{15}{4} + .03\right)^{5/3}$$

$$\frac{\dot{m}_{ent}}{(S+1)\,\dot{m}_f} = \frac{1.872}{Fr^{2/3}} = 13.83$$

Hence

$$\dot{m}_{ent} = 199.1 \text{ kg/s}.$$

IV Conclusions

In this short paper, an algorithm and sample examples have been presented for calculating entrainment rates into (round) pool fires based on correlations which have recently appeared in the *SFPE Handbook*. Well established experimental evidence for supporting those correlations has been assembled here by using original sources. A virtual source origin for the plume above the flame tip has been determined by matching mass entrainment measurements below and above the flame tip (only for cases represented by Figure 4). No attempt was made here to compare this virtual source expression with other virtual source expressions in the literature (see, for example, Cox and Chitty[9] wherein various virtual source expressions are summarized). Finally, there is not enough quantitative evidence to establish how to extend the present correlations below the flame tip (see Figure 1) to non-circular fires (see Cox and Chitty[9] for some limited data).

Nomenclature

C	dimensionless constant for Equation 1, $C = .21$
C_p	specific heat of air
D	pool diameter
Fr	fire Froude number
g	gravitational acceleration
$\dot{m}_{ent}$, $\dot{m}_p$	entrainment rate up to a height Z
$\dot{m}_f$	mass flow rate
$\dot{Q}_{chem}$	chemical heat release rate $\equiv \chi_A\,\dot{Q}_{th}$
$\dot{Q}_{conv}$	convective heat release rate $\equiv (\chi_A - \chi_R)\,\dot{Q}_{th}$
$\dot{Q}_{th}$	theoretical heat release rate
S	stoichiometric oxidant to fuel mass ratio
T_∞	ambient air absolute temperature
Z	distance from pool surface
Z_f	"visual" flame height
Z_v	virtual source origin based on entrainment rates
ΔH_c	theoretical heat of combustion per unit fuel mass
ρ_∞	ambient air density
χ_A	efficiency of combustion
χ_R	radiant fraction

References

1. Delichatsios, M.A., *The SFPE Handbook of Fire Protection Engineering*, National Fire Protection Association, Quincy, MA, U.S.A., pp. 1-306.
2. Beyler, C.L., Ph.D. Thesis, Harvard University, 1983.

3. Cetegen, B.M., Zukoski, E.E., and Kubota, T., *Combustion Science and Technology*, **39**, 1984, p. 305.
4. Becker, H.A. and Yamazaki, S., *Combustion and Flame*, **33**, 1978, p. 123.
5. Toner, J.S., Ph.D. Thesis, California Institute of Technology, 1987.
6. Delichatsios, M.A. and Orloff, L., *Twentieth Symposium (International) on Combustion*, The Combustion Institute, 1984, p. 367.
7. Delichatsios, M.A., *Combustion Science and Technology*, **60**, 1988, p. 253.
8. Ricou, F.P. and Spalding, D.B., *J. Fluid Mechanics*, **11**, 1961, p. 21.
9. Cox, G. and Chitty, R., *Combustion and Flame*, **60**, 1985, p. 219.