ANALYSIS OF PLUME RISE TIME IN THE NEAR AND FAR FIELD

(A note in response to the work by T. Tanaka, T. Fujita and J. Yamaguchi, "Investigation into rise time of buoyant fire plume fronts", International Journal on Engineering Performance-Based Fire Codes, Vol. 2, No. 1, pp. 14-25, 2000)

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ABSTRACT

The rise times of fire-induced buoyant plumes in a free space and vertical shafts were investigated by Tanaka et al. using experiments involving the burning of methanol with heat release rates ranging from 2.6 kW to 2500 kW. It was found that the travel time of a fire plume front is proportional to the 4/3 power of the height from the source in a free space. However, some poor agreement can be recognized in some of the large scale data in the region near the fire source, especially for heat release rates of 400 kW to 2500 kW. This article analyses Tanaka's plume rise data in a free space and attempts to explain the behavior of the plume front near the fire source and in the plume region using theory. A theoretical fit to Tanaka's data can be obtained by changing the near-field coefficient, and the analysis also shows a trend in the variation of the near-field coefficient with the dimensionless source strength.

1. INTRODUCTION

Small-scale and large-scale experiments were conducted by Tanaka et al. [1] to investigate the rise time of transient fire plumes above finite fire sources in a free space, an open shaft and a closed shaft. In the small scale free space experiments, methanol pools in trays of diameters ranging from 0.12 m to 0.30 m were used. Square trays of methanol were used in the large-scale experiments to produce fire sources of 1.0 m x 1.0 m and 2.5 m x 2.5 m. Thermocouples located at fixed heights above the fire source were used to measure the plume rise time indicated by a sudden rise in temperature of the thermocouples due to the contact of the rising plume front with the thermocouples. The results of the experiments showed that the non-dimensional travel time of the plume front is proportional to the 4/3 power of the non-dimensional height above the fire source for small fires with heat release rates of 16.3 kW and below. However, the data from the fires in the large-scale experiments with heat release rates of 400 kW and 2500 kW do not appear to follow the 4/3 power relationship. This was attributed partly to the lag time required for the large fires to reach their steady-state heat release rates and partly to the data acquisition intervals which were not short enough to measure the travel times accurately.

The plume rise time is very much dependent on the velocity of the plume, and research into the near-field and far-field regions of the fire plume indicates that temperature and velocity variations in the region near the fire source is different from that far away from the source. In this analysis, a theoretical correlation for the plume rise time is derived using plume velocity correlations with the flame height taken as the demarcating point between the near-field and far-field regions of the fire plume. The theoretical time for plume rise is then compared with Tanaka's data and an attempt is made to obtain a close fit with the experimental data.

2. THEORETICAL ANALYSIS OF PLUME RISE TIME

The plume velocities in the flame (near-field) and plume (far-field) regions, from Quintiere and Grove [2], are respectively,

$$\frac{dz}{dt} = w_m = C_{v,f}(gz)^{1/2}, \quad z \le z_f \tag{1}$$

$$\frac{dz}{dt} = w_m = C_v (gD^*)^{1/2}\left(\frac{D^*}{z}\right)^{1/3}, \quad z \ge z_f \tag{2}$$

where z is the height above the fire source, w_m is the plume velocity, $C_{v,f}$ and C_v are the coefficients based on velocity in the flame and plume regions respectively and g is the gravitational acceleration. The value of C_v is assumed to be 0.35(3.87) = 1.35 where 3.87 is the steady value from Quintiere and Grove and 0.35 is deduced from Tanaka's far-field plume rise result. Assuming the same effective decrease in the flame in the near-field, the value of $C_{v,f}$ is assumed to be 0.35(2.3) = 0.81 where 2.3 is the steady value from Quintiere and Grove.

The velocities correlations are integrated using Heskestad's correlation for flame height,

$$\frac{z_f}{D^*} = 3.97 - 1.02\frac{D}{D^*} \tag{3}$$

The results obtained for the plume rise time in the near and far field are respectively,

$$t\left(\frac{g}{D^*}\right)^{1/2} = \left(\frac{2}{C_{v,f}}\right)\left(\frac{z}{D^*}\right)^{1/2}, \quad z \le z_f \tag{4}$$

$$t\left(\frac{g}{D^*}\right)^{1/2} = \left(\frac{2}{C_{v,f}}\right)\left(\frac{z}{D^*}\right)^{1/2} + \left(\frac{3}{4C_v}\right)\left[\left(\frac{z}{D^*}\right)^{4/3} - \left(\frac{z_f}{D^*}\right)^{4/3}\right], z \ge z_f \tag{5}$$

The theoretical plume rise equations are plotted for different values of D/D* as shown in Fig. 1. In the near-field flame region and the far-field plume region, the non-dimensional plume rise time is proportional to the 1/2 power and 4/3 power of the non-dimensional height above the source respectively. In the enlarged region shown in Fig. 2, it is observed that the non-dimensional plume rise time increases with larger fire sources.

3. COMPARISON WITH TANAKA'S DATA

An initial attempt is made to fit the theoretical plume rise equations to Tanaka's data shown in Fig. 3. The plume rise equations with $C_{v,f}$ assumed to be 0.35(2.3) = 0.81 and C_v assumed to be 0.35(3.87) = 1.35 are plotted alongside with Tanaka's data in Fig. 4. From the plot, the theoretical curves lie between the data for the smaller fires (D/D* ≤ 1.62) and the larger fires (D/D* ≥ 1.69). It is clear that this curve fit is not ideal and a refinement is necessary. It is found that by adjusting only the near-field coefficient based on velocity, improved curve fit results can be obtained as shown in Fig. 5. For data from D/D* = 1.35 (2.6 kW) to D/D* = 1.62 (16.3 kW), a theoretical fit can be obtained by letting $C_{v,f}$ = 1.8. For D/D* = 1.69 and D/D* = 2.03, a curve fit is obtained by letting $C_{v,f}$ = 0.7 and 0.5 respectively. Such a theoretical fit to the experiment data suggests that the flame region has a significant effect on the plume rise time in the near-field, especially for large fires. As the near-field coefficient is dependent on the radiation fraction, using the steady value of 2.3 from Quintiere and Grove, the radiation fraction in the flame region is obtained to be 0.78, 0.30 and 0.22 for D/D* = 1.35 to 1.62, D/D* = 1.69 and D/D* = 2.03 respectively.

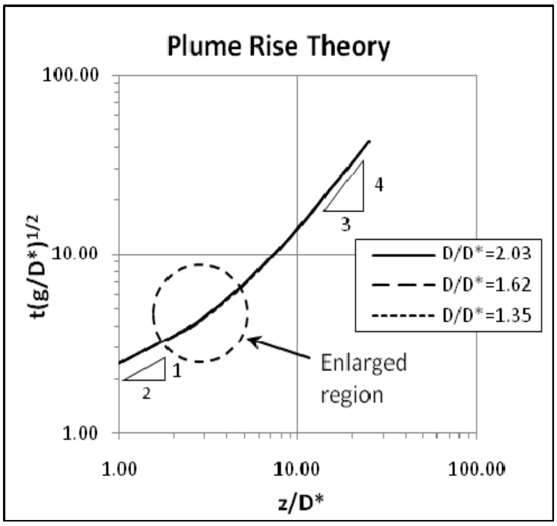

Fig. 1: Plume rise theory

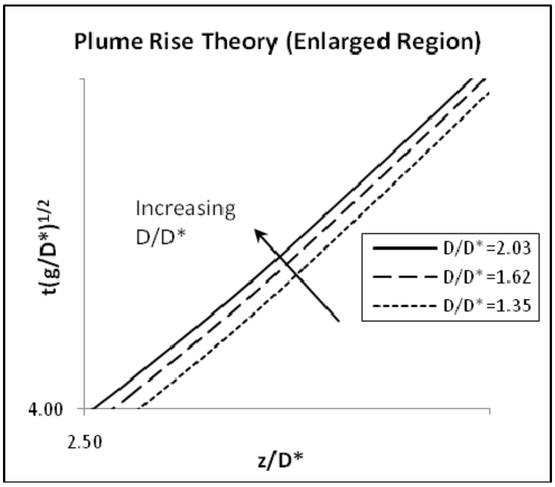

Fig. 2: Enlarged region

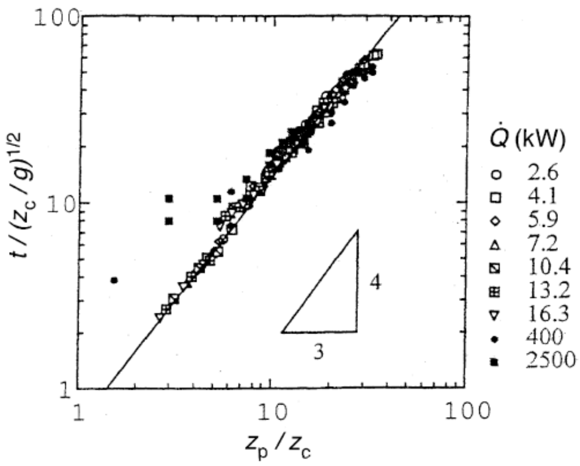

Fig. 3: Experimental data from Tanaka et al.

4. A FURTHER LOOK AT THE NEAR-FIELD COEFFICIENT

The above analysis of the near-field coefficient is extended by plotting the variation of the near-field coefficient with the non-dimensional source strength. From Fig. 6, it is observed that $C_{v,f}$ appears to be a function of Q_D^* before reaching a steady value of 1.8 at $Q_D^* \approx 0.3$. However, due to the inadequate number of data points for $Q_D^* < 0.3$, a firm conclusion cannot be reached.

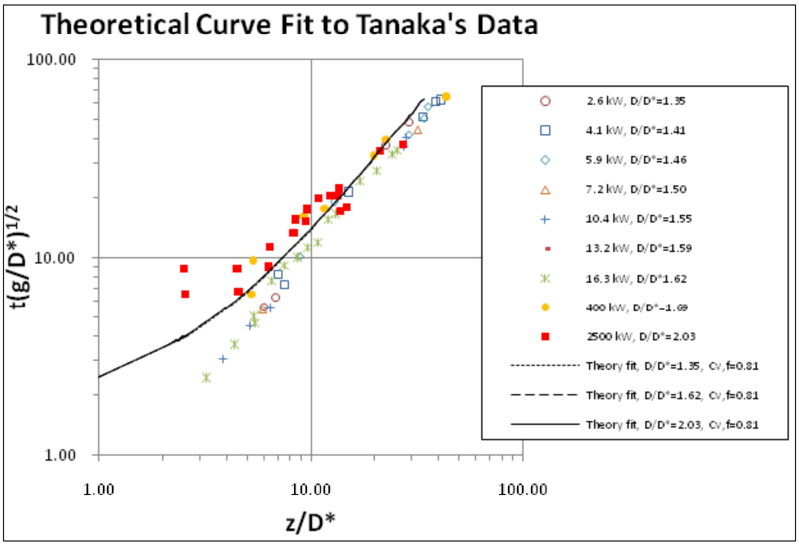

Fig. 4: Initial attempt on theoretical curve fit to Tanaka's data

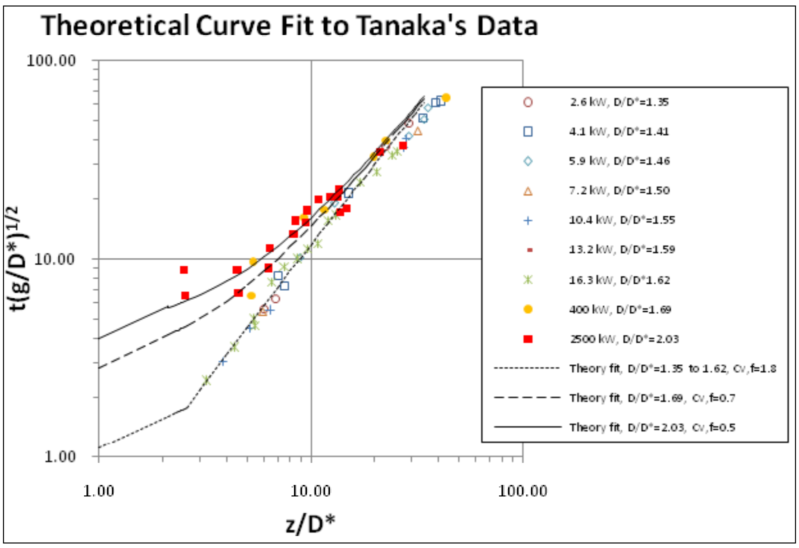

Fig. 5: Improved theoretical curve fit to Tanaka's data

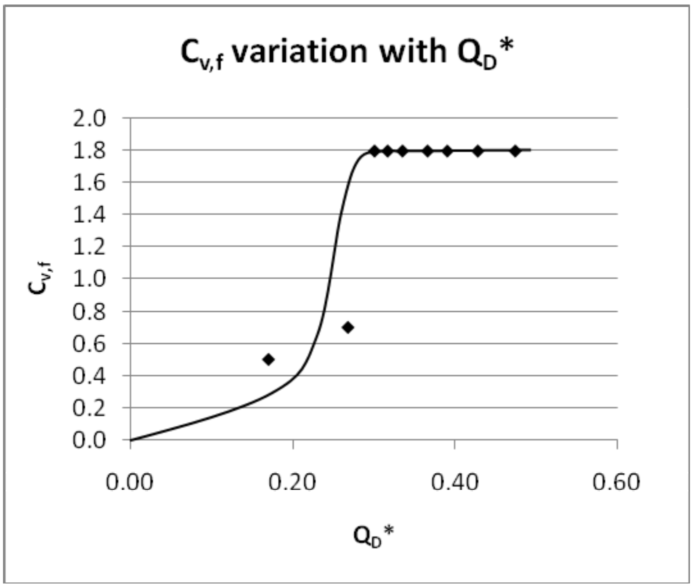

Fig. 6: Variation of the near-field coefficient with dimensionless source strength

5. CONCLUSION

An analysis of the experimental data from Tanaka et al. on the rise times of buoyant fire plume fronts has been made by comparing the data with theoretical plume rise equations derived from velocity correlations in the near and far field. The results show that a theoretical curve fit to the experimental data is possible for both small and large fire sources if $C_{v,f}$ is a function of Q. However, due to the inadequate number of data points, the relationship between $C_{v,f}$ and Q_D^* is inconclusive. It seems that more work is needed in the flame region especially for $Q_D^* < 0.3$.

NONMENCLATURE

C_v coefficient based on velocity in the far field
$C_{v,f}$ coefficient based on velocity in the near field
D diameter of pool, m
$D*$ characteristic length, m
g gravitational acceleration, ms^{-2}
Q_D^* non-dimensional source strength based on diameter
t time, s
w_m centerline velocity of plume, ms^{-1}
z height above source, m
z_f flame height, m

REFERENCES

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