Air Entrainment Flow Field Induced by a Pool Fire

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A laser Doppler velocimeter (LDV) was used in conjunction with a quiescently seeded ambient enclosure to study the mean and transient flow field induced by a 7.1-cm toluene pool fire. Radial and axial mean velocity data are presented in the form of a vector plot to elucidate the flow patterns. A component of the vorticity deduced from the velocity field shows a rapid increase near the maximum location of the visible flame interface. The results show that the mass of air set in motion by the fire is much larger than the mass that is entrained into the visible flame and the vorticity interfaces. The results highlight the need for use of a specific unambiguous definition of entrainment when comparing experimental data and correlations. The probability density functions (pdfs) of radial and axial velocities reveal both outward and inward instantaneous motion of air as well as recirculation. The outward motion is caused by expansion and the inward motion is caused by the vorticity generated by the density gradient. A net inward motion is caused leading to entrainment. The transient measurements are of value to the development of improved understanding and analyses of fire induced flows.

INTRODUCTION

Entrainment rate of air into a pool fire determines flame size and shape, degree of partial premixing, and consequently smoke production, radiant emission and fuel depletion. These parameters are important in models of hazard, egress time and suppression techniques for a variety of fires. Motivated by these applications, measurements of entrainment rates into pool fires have been made in the past by many investigators [1–8].

The entrainment rate is defined as the increase in the axial mass-flow rate of the gases with distance from the pool surface

$$m'_{\text{ent}} = 2\pi \frac{d}{dz} \int_0^R r \rho v \, dr, \qquad (1)$$

where z is the distance from the pool surface, v is the velocity in the axial direction, ρ is the density, r is the radial distance from the axis, and R is infinity [9, 10]. If a radial location at which the axial velocity is zero can be found at each z, then the integral in Eq. 1 can be evaluated by equating R to the radius of this location.

Early measurements relied on the use of Eq. 1 to obtain entrainment rate based on an estimate of the integral using mean temperature and mean velocity data in conjunction with the ideal gas law [1]. It was recognized by the same researchers [2] that the cross-correlations between density and velocity in the fire introduced a large error in the data. A second difficulty is associated with the small value of the axial velocity at large radii. Finally, numerical integration and differentiation are needed for obtaining the entrainment rate using Eq. 1. Approximate Gaussian radial profiles for axial velocity and temperature-rise were assumed in order to complete the integration of Eq. 1.

Zukoski and coworkers [3, 4] used a technique based on measurement of species concentrations in a hood designed to form a steady (in the mean) interface of combustion products above a gaseous fire. Based on the concentration measurements, the amount of air entrained into the fire per unit mass of injected fuel can be found. The total air entrainment rate is then deduced using the input fuel-flow rate. These experiments provide a mean entrainment rate. The influences of the size and presence of the species collection hood and the

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upper layer on the flow field are discussed in the references above. Two different sized hoods were used for near-fire and far-field measurements. It was assumed that the data resulting from the hood experiments approximate the mass entering the visible fire plume based on the observation that the stable interface does not allow air to enter the hood at other locations [3–4, 11]. Allowing the combustion products to escape from the top of the hood rather than spill over from the sides led to substantially lower entrainment rates, emphasizing the influence of the hood design on the resulting data [8]. A related technique based on providing just enough air to cause zero pressure drop across an exit orifice plate was used in Ref. 5. An unknown choice of R is indirectly made and the velocity field may be significantly affected by the equipment used in these techniques.

Recently, a laser Doppler velocimeter (LDV) has been used to study the flowfield in a pool fire [6]. Entrainment rates were obtained using simultaneous measurements of temperature using a thermocouple and velocity using the LDV. Although the technique for measurement of velocity is vastly improved, the difficulties of deciding the appropriate R, the low values of the velocity at large R, and the need for numerical integration and differentiation persist. A value of R slightly larger than the pool radius was used in this work [6].

If a radial distance R (which is in general a function of z), at which the axial velocity v is zero is found and if the density at this location is equal to the ambient density ρ_∞ then mass continuity requires that there be a radial inflow with velocity u, with rate equal to the entrainment rate defined above

$$m'_{\mathrm{ent}} = 2\pi\rho_\infty uR. \qquad (2)$$

Thomas et al. [7] used seeded ambient and strobe lights to attempt a measurement of the radial velocity in order to use Eq. 2 for finding the entrainment rate directly. The quality of the early light sources and photographic film prevented accurate quantitative measurements. These authors discussed the fact that different choices of the surface across which the entrainment flow occurs lead to vastly different values. If two-dimensional velocity data are available, then mass flow rates across any surface in the flowfield can be calculated from the magnitude of the normal velocity component if the local density is known simultaneously [7].

Correlations of entrainment rates [11] have been based on selected data from hood-based experiments involving particular pool size range. Furthermore, a single data set covering a range of axial locations and test conditions using the same measuring instrument and surrounding conditions is not available for the calibration and evaluation of the correlations and analytical and numerical fire models. Basic understanding of the fire-induced flow can also be enhanced significantly by considering transient measurements and statistics of entrainment rates. The need for such data concerning fire-induced flows has been identified by Baum and McCaffrey [12].

Motivated by this, a study of the flow field in the vicinity of a toluene pool fire was completed. Measurements of two-dimensional mean velocity vectors in the vicinity of the fire are presented followed by estimates of the entrainment flow rate for various selections of the radial position R. An estimate of mass flow rate entering a surface representing the farthest visible flame boundary is obtained using the two-dimensional velocity data. Comparison with an existing correlation and existing experimental data is given. Finally, the probability density functions (pdfs) of radial and axial velocities are presented, showing the phenomenon of "instantaneous extrainment" and the transition of the flowfield from an axisymmetric radial flow to an axisymmetric vertical flow. The results of the study are useful in evaluating phenomenological and numerical models of fire-induced flows and an improved understanding of the mechanisms underlying diffusion flames.

EXPERIMENTAL METHODS

The experimental apparatus is shown schematically in Fig. 1. The fire burning toluene in a seeded flow of room air was stabilized on a 7.1-cm water-cooled burner fed at the bottom.

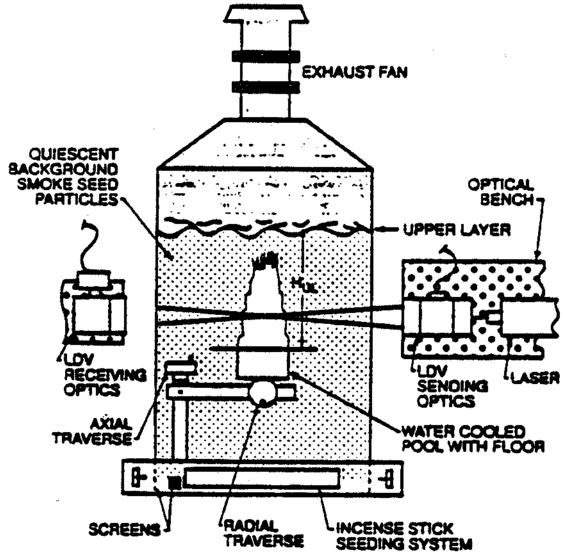

Fig. 1. A sketch of the experimental apparatus for measuring fire induced-flow-field velocities using a laser Doppler velocimeter (LDV).

The fuel consumption rate was 83 mg/s with a lip height of 0.2 cm. A sheet-metal floor of diameter of 51 cm was attached to the pool rim. The fire was enclosed in a 100 × 100 cm cross section Plexiglas enclosure with a 300 cm height and a controlled exhaust flow. Based on flow visualization and velocity data, the flows along the enclosure walls did not affect those near the fire. The controlled exhaust allowed a stably stratified layer of combustion products with a height of 64 cm above the pool surface for all measurement locations.

Room air flowed into the enclosure at the bottom over a batch of four lighted incense sticks on each side through fine wire screens. Measurements of oxygen concentrations (using sampling and gas chromatography) in the enclosure away from the fire showed that the incense sticks caused negligible vitiation. Burning rate with and without incense sticks were also identical within the present measurement accuracy of 0.5 mg/s.

A single-channel, dual-beam, forward-scattered LDV with a frequency shifter and a counter processor was used to measure velocities in the radial and axial directions. Velocity vector measurements were obtained at a grid spacing of 1 × 1 cm between 3.5 and 5.5 cm radial distance and 1–10 cm height above the pool and at a grid spacing of 2 × 1 cm between 6.5 and 12.5 cm radial distance and 1–10 cm height above the pool. In addition radial velocities were measured at 4.5, 6.5, and 11.5 cm radii up to a height of 35 cm to the extent permitted by the burnout of the seed particles in the flame. The uncertainty in the velocity data was estimated to be ±10% using the method of Adrian [14] and the measurements were repeatable within these limits. The two-dimensional velocity data were used to check conservation of mass over individual measurement cells using constant ambient density at radial locations above 4.5 cm. The results showed maximum errors of ±30%. These are much less than those reported in past studies [6], and are satisfactory based on the coarseness of the grid and the uncertainty in the velocity data.

A cylindrical hood made out of stainless steel sheet with 60 cm diameter and 60 cm depth was used to collect the exhaust products leaving the flame at a height of 36 cm. The collection hood allowed a stable layer to be formed inside it. Major gaseous species were collected and analyzed with a gas chromatograph to obtain an independent measurement of entrained mass flow using the method of Zukoski and coworkers [3, 4]. These measurements also allowed an estimate of the combustion efficiency needed for interpretation of the entrainment data in terms of the correlation of Delichatsios [11].

A video record obtained with 1/500 s shutter speed was used to construct average and maximum flame shapes using 10 frames. The mass flow into the visible interface was estimated using the two-dimensional velocity data and the flame images for comparison with the total air flow set in motion.

RESULTS AND DISCUSSION

Figure 2 shows a two-dimensional vector plot of the measurements of mean velocities around the fire. Although data on only one side of the fire were collected, these have been plotted on both sides to emphasize the mean axisymmetry of the fire. The mean visible flame interface is plotted as the solid line and the farthest position of the visible flame interface is plotted as

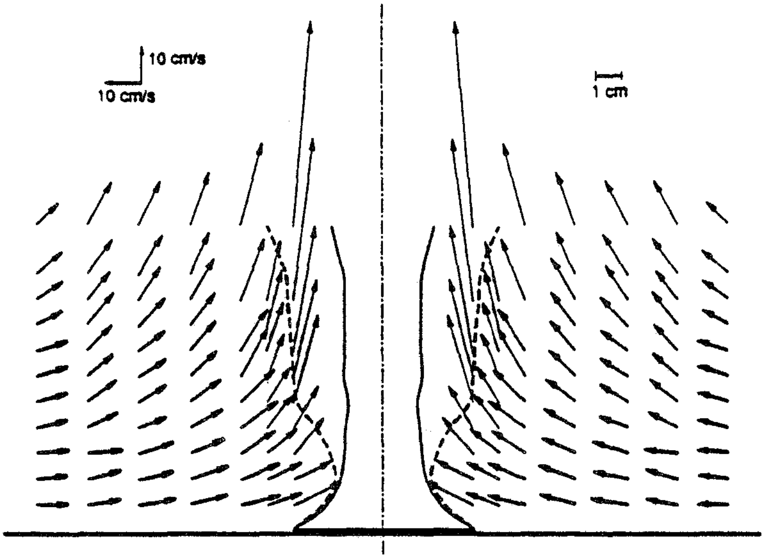

Fig. 2. Velocity vectors around a 7.1-cm toluene fire obtained using the facility shown in Fig. 1.

the dashed line. Near the liquid surface, these are close to each other but vary by up to 0.25 pool diameters near a height of 1 diameter. The measurements show that a radial inflow is established even at a distance of 11.5 cm (greater than 1.5 diameters) from the fire. Part of the inflow at large radii turns and flows in the vertical direction while the remaining flow leads to an increase in radial inflow velocity to compensate for the reduction in area. As the visible flame interface is approached the flow accelerates and turns upward to become predominantly vertical due to the combined action of the density gradient and the expansion generated by the heat release. The experimentally observed flow field is qualitatively similar to that discussed in detail in the analysis of Baum and McCaffrey [12].

A consequence of the velocity field shown in Fig. 2 is that the choice of R in Eq. 2 for estimating the mass of air set in motion by the fire has to be relatively large. A second observation from Fig. 2 is that out of the air mass set in motion only a small part crosses the visible flame interface. The definition of entrainment based on mass flow entering the visible flame interface implied in the combustion literature is therefore not identical to the fluid mechanical definition given by Eq. 1. The measurements shown in Fig. 2 are useful in revealing these facts.

It is noted that only a part of the oxygen that flows into the visible flame interface with the air is involved in the actual chemical reactions. Therefore, even a smaller fraction of the oxygen set in motion by the fire is consumed by it. The remaining oxygen together with the nitrogen set in motion mixes with the combustion products and reduces their relative concentrations and temperature in the upper layer and the exhaust flow.

A single component of the mean vorticity is computed from the velocity data. Radial profiles of vorticity at three locations above the pool surface are shown in Fig. 3. At all three heights, vorticity is negligible in the quiescent far-field and increases near the maximum visible flame interface shown for reference in Fig. 3. Thus the radius of maximum visible flame interface and the radial extent of fluid containing vorticity are comparable. Entrainment into this interface is calculated using the normal component of velocity and ambient density. Due to the proximity of this location to the flame, the choice of ambient density provides an upper bound on the mass flux of material entering the visible flame.

Figure 4 shows a relationship between the entrained mass and height above the pool surface expressed in coordinates suitable for comparison with the correlation of Delichatsios [11]. The Froude number for the flame, Fr_f,

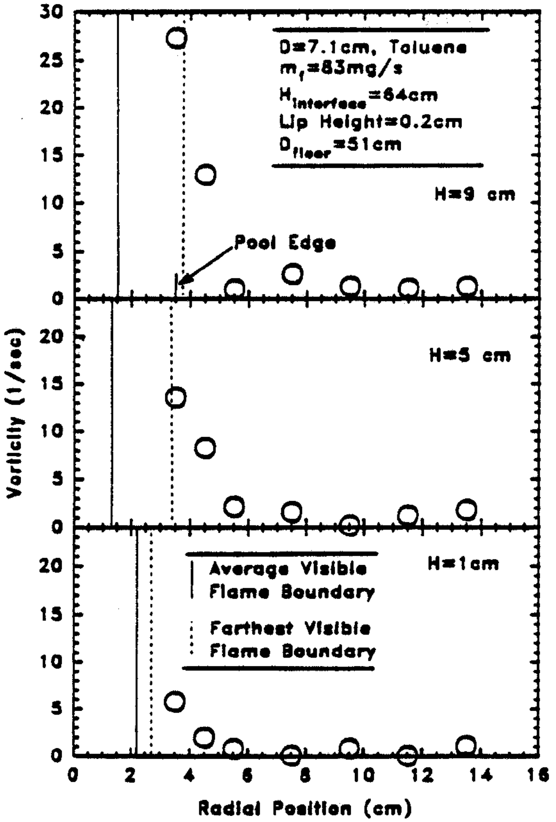

Fig. 3. Radial distribution of a vorticity component at three different heights.

involves specification of the radiation heat loss fraction X_R which was taken as 32% for the present flame following past work in this laboratory [13]. The present measurements of exhaust species including soot particles yielded a combustion efficiency X_C of 95%. The stoichiometric air to fuel ratio S was calculated using complete combustion to CO_2 and H_2O.

Present entrainment measurements based on data obtained at three different radial positions (R = 4.5, 6.5, and 11.5 cm) as well as estimates of entrainment into visible flame boundary are shown. The data based on the 11.5 cm position show that the mass-flow rate of air set in motion by the fire is a factor of up to 6 higher than the estimates based on the correlation of Delichatsios [11]. The estimates of mass flow rates based on the two smaller radial positions are lower and the data based on R = 4.5 cm are close to the entrainment into the visible flame boundary shown by dark circles. Several measurements from past work have also been shown in Fig. 4. The correlation of Delichatsios [11] was developed using the data of Zukoski and coworkers [3, 4] and shows satisfactory agreement with these. The data of Weckman [6] are based on measurements of axial velocities in the fire and appear to be in reasonable agreement with the estimates of flow into the visible fire. The data of Thomas

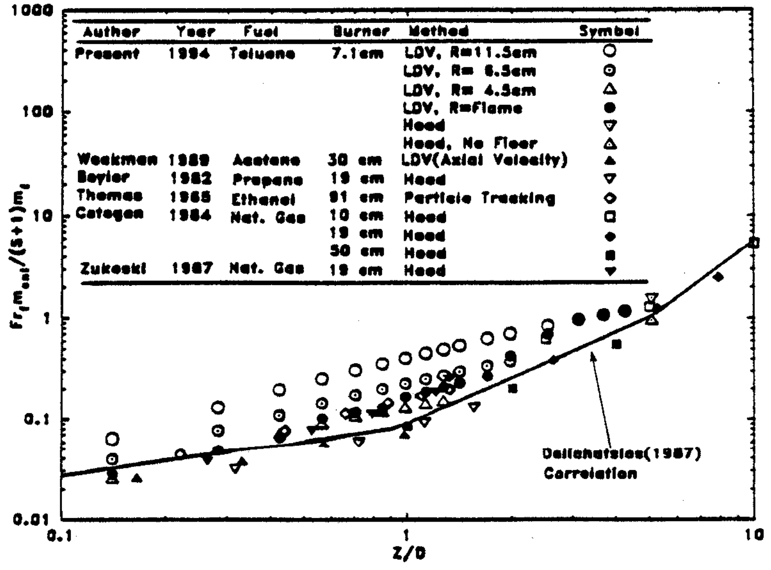

Fig. 4. Comparison of present experimental data concerning entrainment mass-flow rates with past measurements and a correlation from the literature.

et al. [7] are obtained from velocity measurements very near the edge of the pool and therefore are similar to the present $R = 4.5$ cm measurements and the correlation.

It is noted that the correlation shows slope changes near $z/D = 1$ and $z/D = 6$. A single set of experimental data from the literature are not available to confirm these slope changes. The experimental data from the literature in different z/D regimes are obtained either from different pool fires or from different measurement techniques such as smaller sampling hood diameter in case of Toner et al. [4]. The present experimental data for entrainment into the visible flame show the slope changes. Zukoski and coworkers used two different hood sizes [3, 4] to obtain an approximately correct transition between the two height regimes.

A single measurement with and without a floor at a height of 5 diameters was obtained using the technique of Zukoski and coworkers [3, 4]. A metal hood scaled with the pool diameter and with unity aspect ratio (depth equal to diameter) to obtain similarity with the hood size reported in Ref. 3 was used. In the first attempt the hood increased the burning rate by approximately 30% revealing the intrusive nature of this techniques for liquid-fueled pool fires. The mass-flow rate of cooling water was increased to compensate for the effects of hood in order to obtain data with identical burning rate. The resulting entrainment data are in reasonably good agreement. The measurement without the floor shows that the entrainment rate increases as a result of the presence of the floor.

Baum and McCaffrey [12] discussed that the fire-induced flow field is inherently transient but transient measurements were not available for inclusion in their analysis. The data resulting from the present LDV measurements are transient and reveal some interesting features of the flow field. The findings and the data can also be of substantial use in the evaluation of current and future field models of fires. The pdfs of radial velocity, u, and axial velocity v at three different locations in the fire-induced flow field are shown in Figs. 5 and 6. The pdfs are plotted as a function of the velocity values for heights above the pool surface ($z = H$) of 1, 5, and 9 cm at a radial location of 4.5 cm. The mean (with an overbar) and RMS (with an apostrophe and an overbar) radial and axial velocities are noted in Figs. 5 and 6.

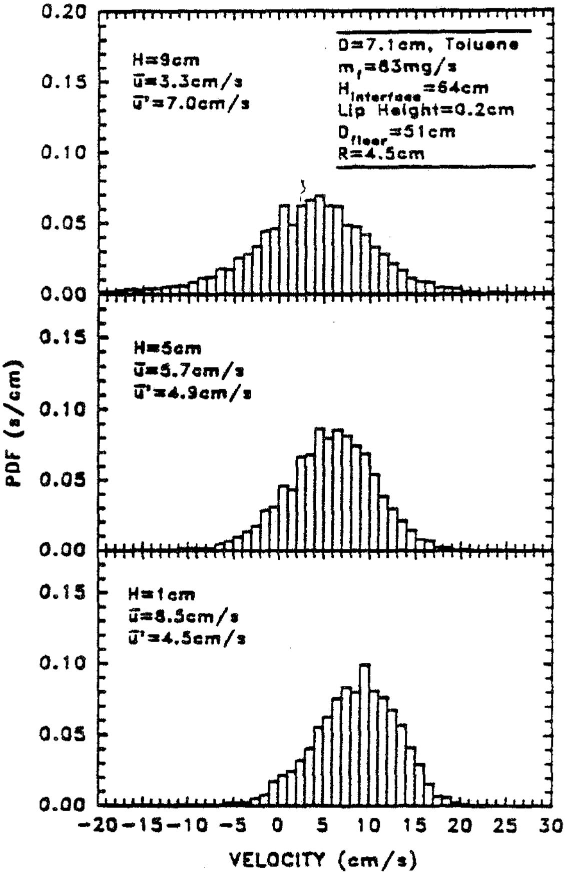

Fig. 5. Probability density functions (pdfs) of radial velocity at three different heights at a radial location close to the visible fire interface.

As expected, the entrainment flow near the floor is dominated by the radial velocity with an average u of 8.5 cm/s compared with the average velocity of 3.2 cm/s in the vertical direction. Velocities in both directions have a significant fluctuating component. At the two higher locations, the average vertical velocity is larger than the average radial velocity and large fluctuating intensities (between 50% and 100%) persist.

At all locations studied, the transient measurements show finite probability of significant negative radial and axial velocities. The negative radial velocity implies outward motion of the material from within the flame. This phe-

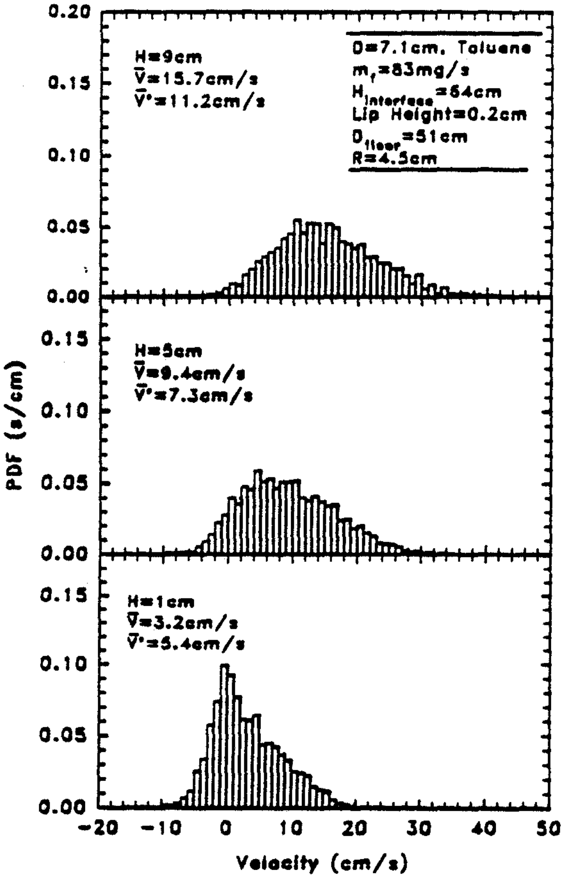

Fig. 6. Probability density functions (pdfs) of axial velocity at three different heights at a radial location close to the visible fire interface.

nomenon can be defined as "extrainment" and can have an impact on the processes of additional air preheat, partial premixing, and ambient vitiation, which can influence the turbulent diffusion flame structure. The downward motion shown by the negative axial velocities can also lead to similar phenomena. Furthermore, significant negative fluctuating axial velocities imply turbulent transport in that direction questioning the parabolic flow assumptions used in some numerical models.

As discussed in Ref. 12, the positive radial velocities (inward—note that the sign convention of Ref. 12 is reversed here) are created by the vorticity generated by the density gradients and the negative radial velocities (outward) are generated by the velocity potential caused by expansion due to heat release. On average, the radial velocity is inward in confirmation of the finding of Ref. 12 that the vorticity generation dominates the volumetric expansion. However, at an instant in time, the expansion can cause a large instantaneous outflow velocity. As pointed out in Ref. 12, analyses of transient fire-induced flows remain to be developed. It is believed that present and similar measurements will be of value in the development of such analyses.

CONCLUSIONS

The present work has led to the following conclusions:

1. Optical velocity measurement with a quiescently seeded ambient air can lead to useful mean and transient measurements of fire-induced flows. The present measurements are in reasonable agreement with those obtained using a collection hood at a single location.
2. The rate of entrainment of air into the visible flame surface is substantially lower than the rate of entrainment based on the fluid mechanical definition of the mass flow set in motion in the axial direction. The existing correlations and experimental data appear to be closer to the measured rate of entrainment into the visible flame surface. A clear definition of the flow that is being counted as entrained is necessary when comparing data from different experiments and different correlations.
3. The fire-induced flow field is highly transient and involves instantaneous entrainment as well as extrainment processes. The new transient information can be used in the development of accurate analyses of fire processes.

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REFERENCES

1. McCaffrey, B. J., National Bureau of Standards (currently N.I.S.T.) Report No. NBSIR 79-1910, 1979.

2. McCaffrey, B. J., and Cox, G., National Bureau of Standards (currently N.I.S.T.) Report No. NBSIR 82-2473, 1982.
3. Cetegen, B. M., Zukoski, E. E., and Kubota, T., *Combust. Sci. Technol.* 39:305 (1984).
4. Toner, S. J., Zukoski, E. E., and Kubota, T., NBS-GCR-87-528, California Institute of Technology, 1987.
5. Delichatsios, M. A., and Orloff, L., *Twentieth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, 1984, pp. 367–375.
6. Weckman, E. J., and Sobiesiak, A., *Twenty-Second Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, 1988, pp. 1299–1310.
7. Thomas, P. H., Baldwin, R., and Heselden, A. J. M., *Tenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, 1984, pp. 983–996.
8. Beyler, C. L., Ph.D. thesis, Harvard University, 1983.
9. Ricou, F. P., and Spalding, D. B., *J. Fluid Mech.* 11:21–32 (1961).
10. Liepmann, D., and Gharib, M., *J. Fluid Mech.* 245:643–668 (1992).
11. Delichatsios, M. A., *Combust. Flame* 70:33–46 (1987).
12. Baum, H. R., and McCaffrey, B. J., *Fire Safety Science: Proceedings of the Second International Symposium*, Hemisphere, New York, 1989, pp. 129–148.
13. Gore, J. P., Klassen, M., Hamins, A., and Kashiwagi, T., *Fire Safety Science: Proceedings of the Third International Symposium*, Elsevier, London, 1991, pp. 395–404.
14. Adrian, R. J., *TSI Q.* 4:3–10 (1978).

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Comments

D. Milov, RRA, USA. This paper is incomplete. The definition of turbulent boundary (not flame boundary) is vague, transient effects are not clearly described, and potential flow is not delineated. It is a great effort to a new approach, nevertheless. Comments of the author are appreciated.

Authors' Reply. The comments suggest that the main points of the paper were missed by the commenter.

The entrainment rate into free jets and plumes is defined by equation (1) based on pioneering and recent literature (see Refs. 9 and 10). As per this classical definition, there is no need for identifying either a turbulent flow boundary or a potential flow boundary (see comment by Prof. Kanury).

If the mass flow rate across a particular interface is required then its position and orientation must be clearly defined. One of the main points of the paper is that part of the discrepancy in the entrainment data for pool fires originates in: (1) deviation from the classical definition, and (2) the differences in the alternate definitions. We have selected a surface corresponding to the maximum extent of the visible flame boundary, which happens to be in the vicinity of the location at which the azimuthal vorticity component increases rapidly, as one of the interfaces of interest. We have not attempted to identify a turbulent boundary because it may not exist in the present flame (7.1 cm diameter pool fire). One of the simple yet significant contributions of our work is that it shows that the entrainment rate as per the classical definition [9, 10] is much greater than the mass flow rates across vorticity, turbulent, potential flow, and visible flame interfaces. It is also noted that only detailed spatially resolved velocity vector measurements such as those obtained in the present work allow definition of interfaces associated with the velocity field.

The fluctuating (may not be turbulent) nature of the entrainment flow field even around a small fire is experimentally demonstrated by presenting the PDFs of both velocity components. Our current work [1] utilizes particle imaging velocimetry (PIV) which sheds further light on the transient effects.

REFERENCE

1. Zhou, X. C. and Gore, J. P., "Particle Imaging Velocimetry (PIV) Measurements of the Fire Induced Flow Field Around a Small Pool Flame," *Comb. Flame*, submitted.

A. M. Kanury, Oregon State University, USA. The discussion related to the definition of the entrainment appear to unnecessarily distract attention from the important contributions of this paper. Why can we not similarly go back to the clear original fluid mechanical definition? "Entrainment of a jet (or plume) is the rate (with respect to the axial distance) of increase of total mass flow rate in the jet (or plumes.)" That there exists a flame within the plume to provide the driving buoyancy calls for no change in this definition. That the plume discharges into the ceiling layer is also of no concern in this definition. Or, is it that I am missing something else important in this discussion?

Authors' Reply. We do recognize and emphasize the classical definition of entrainment rate. Models that separate the fire induced flow field into different zones require specification of the interfaces and the flow rates across these. As discussed above one of the conclusions of our paper is that the mass flow rate across the visible flame interface is substantially lower than the entrainment rate defined by Eq. 1.

P. J. Pagni, University of California—Berkeley, USA. Your time dependent velocity field data might be used to estimate the circulation and the size of the toroidal vortices which are known [1] to be shed by a pool fire at the frequency

$$f = 1.5D^{-1/2}$$

where f is in Hz and D is in m. If the shedding frequency, circulation, and diameter of these toroidal vortices were known, the entrainment could be calculated directly.

REFERENCE

1. Pagni, P. J., in *Some Unanswered Questions in Fluid Mechanics*, Trefethen, L. M., et al., eds. *Appl. Mech. Rev. 43*, 8, 166–167, 1990.

Authors' Reply. We agree that the transient velocity data can be used for obtaining additional insight and as input to models of the entrainment process including the one that Professor Pagni suggests.

B. Cetegen, University of Connecticut, USA. In determining the entrainment rate into pool fires using time-averaged LDV measurements, how do you distinguish the portion of the flow which enters the plume up to a certain height, z, from that which is entrained below height z, but enter the plume at distances greater than z? Is the overprediction of entrainment rate a consequence of including this latter contribution? For example, can you make a mass balance by measuring velocities at the downstream cross-section?

Although the measurements of this kind are valuable to refine entrainment rate estimates of pool fires, a much better understanding of plume entrainment will be obtained with combined particle image velocimetry/scalar measurements in pulsating buoyant plumes behaving more or less like pool fires.

Authors' Reply. The mass flow rate entering the visible flame surface below a height "z" is calculated by integrating the mass flux obtained using the mean velocity component normal to the visible interface and the ambient density. It is noted that entrainment rate is much larger than the mass flow rate entering the visible interface. Except for the approximation of ambient density, there is no overprediction of entrainment rate and mass flow rate entering the visible flame surface. Yes, we can make a mass balance check as discussed in the paper.

We agree that particle imaging velocimetry (PIV) measurements are valuable and are systematically progressing in the completion of these as discussed above.