Fire-Induced Mass Flow into a Reduced-Scale Enclosure

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Introduction

Enclosure fires are of great interest because of the resulting loss of life and property, yet the fluid dynamic and chemical behaviors of fires within enclosures are still not well understood. In recent decades, it has become clear that burning rates, fire growth and spread, production of toxic gases, and depletion of oxygen in room fires are very dependent on air supply and entrainment rates.

A recently developed procedure for calculating the mass flow rate into and out of a room has been applied to a reduced-scale enclosure having a single doorway. Both overventilated (preflashover) and underventilated (flashover) conditions have been studied for a series of natural-gas-fueled, quasi-steady-state fires. The new computational approach employs mass conservation to locate the neutral-plane height, z_N. Results using the new method are compared to results using an earlier method for estimating z_N based on a single static pressure measurement. Concentration measurements within the upper layer of the enclosure provided reliable estimates of the actual equivalence ratio within the enclosure which were related to the mass flow rates into and out of the doorway.

Background

Fire-induced flows through a doorway may be monitored using a grid of velocity probes and thermocouples to measure the velocities and estimate the densities necessary for calculating mass flow. While accurate, these measurements are expensive, tedious, and intrusive. Simpler approaches employing less instrumentation are clearly desirable.

A simple computation of flows models the vent such that a pressure gradient draws cool air into the enclosure through the lower region of the vent and hot, expanded combustion products exhaust through the upper region. At the vent, the boundary between the outgoing and incoming flows is referred to as the neutral plane and is required in order to determine mass flow rates through the vent. The equations necessary to calculate mass flow rates from quantities measured in an enclosure fire were derived beginning with Bernoulli's equation and assuming orifice flow. The instrumentation required for the practical use of the equations in experiments includes a thermocouple tree just inside the doorway of the enclosure, a thermocouple tree in the vent, and an ambient temperature measurement outside the enclosure.

Janssens and Tran[1] reviewed the necessary equations and gave descriptions of various approaches for locating z_N. To the same fires they applied and compared the z_N results for the single-pressure-probe approach, a mass-balance approach suggested by Nakaya et al.[2], and interpolation between multiple pressure probes. The mass-balance approach when applied to overventilated, full-scale enclosure fires was shown to be more accurate and consistent than that using a single pressure probe. The z_N location is obtained by solving the mass flow and mass balance equations iteratively. The mass flow rates into and out of the enclosure, $\dot{m}_i$ and $\dot{m}_o$, are then calculated by substituting the z_N height back into the mass flow expressions.

Experimental Apparatus and Procedure

Two vent-flow computation approaches, that using mass-balance by Janssens and Tran[1] and that using a single pressure probe, were applied to a series of fire tests performed at the National Institute of Standards and Technology. The experiments were conducted in the Reduced Scale Enclosure (RSE) test facility in the Fire Test Facility at NIST. A detailed description of the RSE and the experimental procedure will soon be available.[3] The RSE was instrumented with the required thermocouples and a pressure probe as well as front and rear combustion layer sampling probes for CO, CO_2, and O_2 concentration measurements. The front probe also supplied gases to an instrument referred to as a "phi-meter"[4], developed at NIST to measure the local equivalence ratio, ϕ_ℓ. A subroutine, "mass-flow-2", in the data reduction software RAPID[5] was modified to apply the new approach.

Results and Discussion

Figure 1 shows plots of z_N normalized by doorway height, $\dot{m}_i$, and $\dot{m}_o$ determined using the mass-balance approach as a function of heat release rate (HRR). The z_N values calculated using the mass-balance approach agree with visual observations of layer interface height and are generally located near the center of the doorway. z_N decreases somewhat as fire size increases and levels off for underventilated fires. The $\dot{m}_i$ rise sharply with increasing HRR until approximately 120 kW, at which point a maximum is reached. For HRRs > 160 kW there is only a slight decrease in $\dot{m}_i$ with increasing HRR.

The global equivalence ratio is the ratio of upper layer gases derived from fuel to those derived from air and normalized by the stoichiometric ratio. The phi-meter was used to measure values of ϕ_ℓ at the front probe location of the RSE. Figure 2 shows ϕ_ℓ plotted versus the calculated ϕ_g. The two equivalence ratios are in excellent agreement. The behaviors of upper-layer concentrations were also found to be consistent with the calculated gas flows when using the mass-balance approach. Values of mass flow rates derived using a single pressure probe gave poor estimates for z_N, did not obey mass balance, and were in poor agreement with the observed upper-layer concentrations.

Conclusions

A new approach for calculating the z_N in an enclosure with a vertical opening using mass balance has been applied to a series of reduced-scale enclosure fires for a wide range of natural-gas fire sizes. The z_N results and calculated $\dot{m}_i$ values are validated by measurements of upper-layer chemical species and local equivalence ratios.

The mass-balance approach has been shown to be valid for a wide range of fire regimes including underventilated burning and flashover conditions. The mass balance approach of Janssens and Tran[1] is recommended for the whole range of fire conditions as a method for calculating z_N, $\dot{m}_i$, and $\dot{m}_o$ in vertical vents of enclosures. The approach is easily implemented and is considerably more accurate than a previously used single-pressure-probe approach.

References

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2. Nakaya, I., Tanaka, T., Yoshida, M., & Steckler, K. D., Doorway Flow Induced by a Propane Fire. *Fire Safety Journal*, **10** (1986) 185-195.
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4. Babrauskas, V., Parker, W. J., Mulholland, G. W., & Twilley, W. H., *The Phi-meter: A Simple, Fuel-independent Instrument for Monitoring Combustion Equivalence Ratio*, to appear in Reviews of Scientific Instruments.
5. Peacock, R. D., Breese, J. N., & Forney, C. L., *A User's Guide for RAPID, Reduction Algorithms for the Presentation of Incremental Fire Data V.2.3.* National Bureau of Standards, Gaithersburg, MD, 1991, Special Publication 798, 112 p.

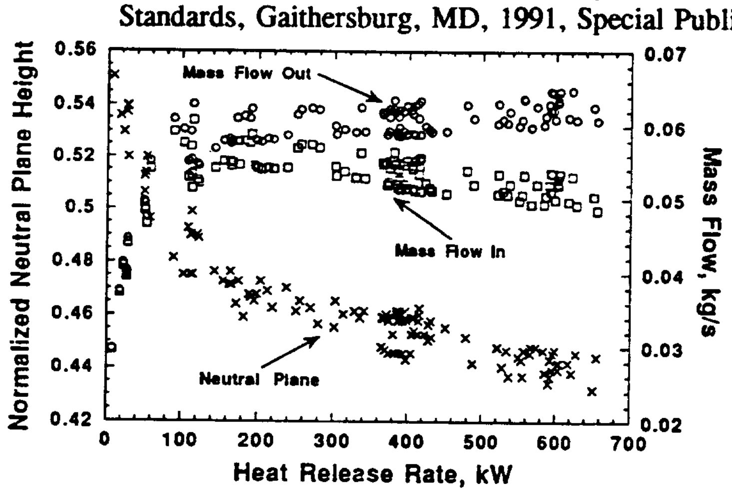

Figure 1: Neutral plane height normalized by doorway height and mass flow rates plotted versus heat release rate, Janssens and Tran approach.

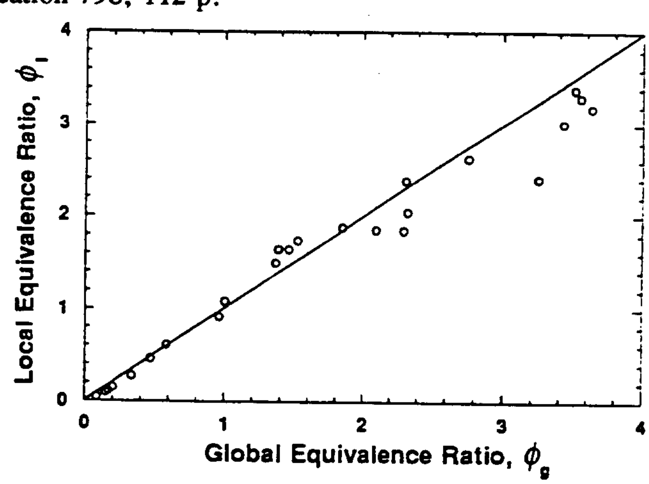

Figure 2: Local equivalence ratio plotted versus global equivalence ratio calculated using the Janssens and Tran approach