OVERVIEW OF A THEORY FOR SIMULATING SMOKE MOVEMENT THROUGH LONG VERTICAL SHAFTS IN ZONE-TYPE FIRE MODELS

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INTRODUCTION

A Limitation of the Two-Layer Quasi-Steady-Buoyant-Plume Approach to Modeling Compartment Fires. The modeling strategy which uses the concepts of one-to-two uniform layers per room, room-to-room mass exchanges by vent flows, and layer-to-layer mass exchange by quasi-steady buoyant plumes has proven to be very robust. However, there are important practical room configurations and associated fire scenarios where these basic concepts are inadequate. If the basic concepts are not applicable to a particular room configuration, then, to the extent that room plays a significant role in the spread of fire and smoke throughout the facility (e.g., the room is the connecting flow path between the room of fire origin and a threatened space), the inadequacy of the simulation in that room can render inadequate the entire simulation.

Let L and d, be the height and horizontal span, respectively, of a room configuration. Then, for rooms with $L/d >> 1$ it is not reasonable to expect a two-layer, zone-type, modeling approach to lead to a successful simulation of fire environments if such spaces are described and treated in the manner of a standard, two-layer, room element, with plumes, etc. For such room configurations, some of the previously mentioned basic modeling assumptions become invalid, e.g. as the plume rises and spreads, its volume eventually becomes significant and it starts to fill a large fraction of the section of the shaft/duct; it is not reasonable to expect that characteristic times of mixing in the shaft will generally be small compared to times of interest; and there is no basis for support for a uniform, two-layer approximation to the density/temperature distribution. An illustration of a generic problematic facility and room configuration is presented in Fig. 1. In this facility, traditional modeling concepts would typically be applicable in the small-L/d room of fire origin, the upper floors, etc., but they would not be applicable in the large-L/d shaft.

A Strategy for Modeling Flow Through Shaft-Like Spaces in Zone-Type Compartment Fire Models; Objective of This Work. For the traditional two-layer, etc., zone-type modeling approach to be valid, large-L/d spaces in a multi-room facility need to be treated as a special class of room configuration. Fire-generated environments there need to be simulated with a method of analysis that 1) uses a valid intra-room fire dynamics modeling approach and 2) can be implemented in the compartment fire model to study fire scenarios in facilities which include other "standard," i.e., small-to-moderate-L/d, room elements.

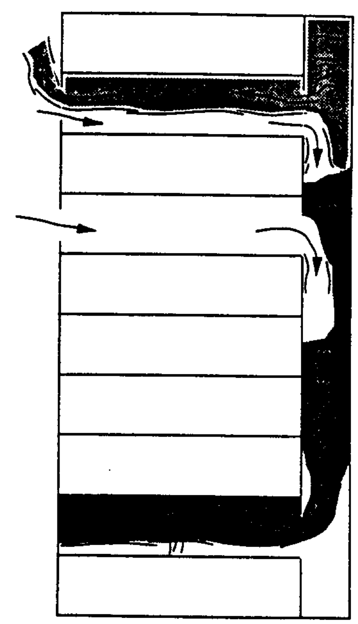

Fig. 1. **Sketch of a facility where traditional, two-layer, zone-type, modeling concepts are not uniformly applicable.**

Once a method of analyzing large-L/d spaces is developed and validated, it would be incorporated into an existing multi-room fire model. The revised model would then be capable of describing smoke movement through shaft-like spaces in a particular facility of interest. The strategy for carrying out simulations with the revised fire model would require the user of the model to characterize each room of a modeled facility as either a small-to-moderate-L/d space or a large-L/d space. When carrying out a simulation the model equations would invoke the traditional, two-layer, isolated-plume, etc. model equations for the small-to-moderate-L/d spaces and the new model equations for large-L/d spaces.

In carrying out the above strategy, a reasonable rule for distinguishing between the two types of spaces is to designate spaces as small-to-moderate-L/d when $L/d \leq 5$ and as large-L/d when $L/d > 5$. Note that an even more advanced strategy might eventually consider an additional, third class of facility space, designated as a "moderate-L/d" space. The analysis of the fire environment in the "moderate-L/d" space would be designed to bridge the gap between small- and large-L/d spaces by including important modeling features of both.

COMBINED BUOYANCY- AND VENTILATION-DRIVEN FLOW THROUGH A LONG VERTICAL SHAFT; TURBULENT FLUCTUATIONS IN THE SHAFT FLOW

The Turbulence Equations. Consider perfect gas flow through a shaft of length L, and characteristic section dimension, d. Consider long shafts ($L/d >> 1$), where ρ and T, the gas density and temperature averaged across the section, vary along the shaft. In general, the shaft is ventilated; gas inflow or outflow can occur at vents in the shaft walls, or at its ends. Inflowing gas has specified density and temperature, ρ_{VENT} and T_{VENT}, which can vary along the shaft. Outflowing gas has density and temperature, ρ and T. The rate of mass addition due to ventilation is $\dot{m}'''_{VENT}$ (rate of mass added to the shaft per unit volume). Heat is transferred to the gas from the shaft surface at the rate $\dot{q}'''_{HT}$ (rate of heat transfer to the gas per unit volume). Assume that the only significant component of flow is along z, the shaft axis, with average velocity, V_z, across a section. Also, account for possible turbulent shaft flow fluctuations by introducing time-averaged ("barred") and fluctuating ("primed") components of the variables, e.g., $\rho = \bar{\rho} + \rho'$. Then, in was found in [1] that conservation of mass and energy, and the equation of state, with Reynolds averaging and neglect of heat conduction through the gas, and other assumptions outlined in [1] lead to the following equation set:

$$\partial\bar{\rho}/\partial t + \bar{V}_z\partial\bar{\rho}/\partial z + \partial(\overline{V_z'\rho'})/\partial z = \dot{m}'''_{VENT}(1 - \bar{\rho}/\rho_{VENT}) - (\bar{\rho}/\rho_{AMB})\dot{q}'''_{HT}/(T_{AMB}C_p);$$
$$\partial\bar{V}_z/\partial z = (C_p T_{VENT}\dot{m}'''_{VENT} + \dot{q}'''_{HT})/(\rho_{AMB}T_{AMB}C_p); \quad \bar{\rho}\bar{T} = \rho_{AMB}T_{AMB} = constant \qquad (1)$$

where C_p is the specific heat at constant pressure, and ρ_{AMB} and T_{AMB} are the density and temperature at an ambient reference state.

Turbulent fluctuations leading to significant values of $\overline{V_z'\rho'}$ will occur along the shaft where there are buoyancy-generated instabilities in the vertical density distribution, i.e., where, locally, the density is increasing with elevation, $\partial\bar{\rho}/\partial z > 0$. Indeed, such instabilities are the driving force for the turbulent-like mixing phenomenon which is of particular interest here. Also, shaft flow scenarios of present interest are such that $\bar{V}_z$ is small enough as never to lead to turbulent fluctuation enhancements that would significantly affect the value of $\overline{V_z'\rho'}$. For example, at elevations along the shaft where the gas is stably stratified, i.e., where $\partial\bar{\rho}/\partial z \le 0$, there will be no buoyancy-driven turbulence and it is reasonable to assume that $\partial(\overline{V_z'\rho'})/\partial z$ can be neglected completely.

Solutions to Eqs. (1) with initial and boundary conditions would provide a description of the fire environment that develops in ventilated, shaft-like, room configurations. However, to actually implement Eqs. (1) it is necessary to develop supplementary model equations to represent $\overline{V_z'\rho'}$ and the source terms, $\dot{m}'''_{VENT}$ and $\dot{q}'''_{HT}$. ($\dot{m}'''_{VENT}$ can be established from known vent-flow considerations.)

The task of establishing a representation for $\overline{V_z'\rho'}$ was a major result of [1]. Following ideas in [2], [3], and [4], the following representation was adopted in [1]

$$\overline{V_z'\rho'} = -D\partial\bar{\rho}/\partial z; \quad D = \begin{cases} Kd^2[(g/\bar{\rho})\partial\bar{\rho}/\partial z]^{1/2} \text{ if } \partial\bar{\rho}/\partial z > 0 \\ 0 \text{ if } \partial\bar{\rho}/\partial z \le 0 \end{cases} \qquad (2)$$

Then, it was determined in [1], that solutions to Eqs. (1) and (2) correlate well with all relevant data from the experiments of [2] (unsteady vertical-tube experiments with both salt-water/fresh-water and heavy-gas/light-gas systems) when $K = 0.44$.

CONCLUSIONS

Eqs. (1) and (2), with $K = 0.44$, should be used to describe time-dependent fire environments in ventilated, shaft-like, room configurations. This requires development of general representations for the $\dot{m}'''_{VENT}$ and $\dot{q}'''_{HT}$ terms of Eqs. (1). Also, confidence in the equations will be subject to validation with data from experiments on hot-air/cold-air systems involving gas-to-surface heat transfer exchanges. Finally, it is noted that the proposed equation set can be used to advance traditional, zone-type compartment fire models. This will require development of an efficient and robust method for solving the new equation set together with (i.e., coupled to) an existing, multi-room, zone-type model equation set. The advance would result in a compartment fire modeling capability that does not now exist; namely, the capability to simulate with confidence fire scenarios in facilities with shaft-like compartment elements.

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