Combined Buoyancy and Pressure-Driven Flow Through a Shallow, Horizontal, Circular Vent

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Combined buoyancy and pressure-driven (i.e., forced) flow through a horizontal vent is considered where the vent-connected spaces are filled with fluids of different density in an unstable configuration (density of the top is larger than that of the bottom). With zero-to-moderate cross-vent pressure difference, Δp, the instability leads to bidirectional exchange flow between the two spaces, e.g., as in the emptying from the bottom of a liquid-filled can with a single vent opening. For relatively large Δp, the flow through the vent is unidirectional, from the high to the low-pressure space, e.g., as is the case when the can has a large enough second vent at the top. Problems of a commonly used unidirectional orifice vent flow model, with Bernoulli's equation and a constant flow coefficient, C_D, are discussed. First, the orifice model does not predict bidirectional flows at zero-to-moderate Δp. Also, when Δp exceeds the critical value, Δp_{FL}, which defines the onset of unidirectional or "flooding" flow, there is a significant dependence of C_D on the relative buoyancy of the upper and lower fluids (i.e., C_D is not constant). Analysis of relevant boundary value problems and of available experimental data leads to a mathematical vent flow model, which removes the problems of the orifice flow model. The result is a general algorithm to calculate flow through shallow, horizontal, circular vents under high-Grashof-number conditions.

Introduction and Background

Consider the flow through a horizontal vent where the fluids in the vent-connected spaces near the elevation of the vent are of arbitrary density. Assume that in each space, away from the vent, the environment is relatively quiescent with pressure well approximated by the hydrostatic pressure. As in Fig. 1, designate the spaces as *T*op and *B*ottom and let the subscripts T and B, respectively, refer to conditions in these spaces near the vent elevation, but removed far enough laterally so that variations to the quiescent far-field environment, due to vent flows that may exist, are negligible. $\dot{V}_T$ and $\dot{V}_B$ are volume flow rates through the vent from top to bottom and bottom to top, respectively. The flow is determined by the vent design, i.e., shape and depth, L; densities, ρ_T and ρ_B; and cross-vent pressure difference

$$\Delta p = p_H - p_L \geq 0; \quad p_H = \max(p_T, p_B); \quad p_L = \min(p_T, p_B) \tag{1}$$

The subscripts H and L will always refer to the conditions on the *H*igh and *L*ow-pressure sides of the vent, respectively. When $\Delta p = 0$, the high/low-pressure designations are arbitrary. In cases where gas flows are involved, Δp is assumed to be small compared to p_B and p_T.

$$\Delta p/\bar{p} \ll 1; \quad \bar{p} = (p_H + p_L)/2 = (p_B + p_T)/2 \tag{2}$$

The objective of this work is to develop a mathematical model for predicting, for arbitrary specified p_T and p_B, the rates of flow through the vent under conditions involving unstable configurations, where

$$\Delta\rho = \rho_T - \rho_B > 0 \tag{3}$$

With zero-to-moderate Δp, the instability leads to bidirectional exchange flow between the two spaces (Taylor, 1950; Epstein, 1988; Brown, 1962; Epstein and Kenton, 1989; Tan and Jaluria, 1991). As flows enter the upper and lower spaces they are upward and downward-buoyant, respectively, and they rise and fall as plumes to the far field. For relatively large Δp, the vent flow is unidirectional, from high to low pressure. Sufficiently deep into the low-pressure space, the flow is dominated by buoyancy forces, continuing to the far field as a buoyant plume. Photographs of the far-field plume flows are presented by Tan and Jaluria (1991) for both the bidirectional and unidirectional flow regimes.

Only quasi-steady features of the flows being studied will be discussed and analyzed. Thus, even when the flows are fluctuating, it is assumed that time scales that characterize their fluctuations are small compared to characteristic times of a particular applications problem of interest, and that meaningful time-averaged flow characteristics can be established.

The Standard Vent Flow Model and its Shortcomings. There is a simple, effective model for estimating the flow through both horizontal and vertical vents, which is typically used in zone-type model simulations of compartment fire phenomena (see, e.g., Mitler and Emmons, 1981; Tanaka, 1983; Cooper and Forney, 1990; Cooper, 1990). The model, referred to here as the standard model, uses a unidirectional orifice-type flow assumption with Bernoulli's equation and a constant orifice flow coefficient, C_D, to compute the rate of flow through the vent (Emmons, 1988; Cooper, 1989). For a vertical vent, the cross-vent hydrostatic pressure difference (generated by stably stratified environments in the vent-joined spaces) and, therefore, the predicted cross-vent flow flux generally varies with eleva-

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