INFLOW OF AIR REQUIRED AT WALL AND CEILING APERTURES TO PREVENT ESCAPE OF FIRE SMOKE

GUNNAR HESKESTAD
ROBERT D. SPAULDING
Factory Mutual Research Corporation
1151 Boston-Providence Turnpike
Norwood, MA 02062, USA

ABSTRACT

Experiments have been conducted to determine critical Froude numbers associated with required inflow of air to a fire space through wall and ceiling apertures to prevent escape of smoke. The experiments were conducted mostly on reduced, model scale, with verification in a 2.4 m high test room. Critical Froude numbers, as formulated, were insensitive to aperture geometry. Those for wall apertures varied slowly and predictably with the vertical temperature distribution in the room, consistent with a discharge coefficient of 0.64 for the inflow. Those for ceiling apertures exhibited a dependence on an aperture Grashof number, with both a high-Grashof number asymptote and an <u>apparent</u> low-Grashof number asymptote. While discharge coefficients for wall apertures can be considered constant near 0.64 for aperture Froude numbers larger than critical, the discharge coefficient for ceiling apertures increased from 0.19 near the critical Froude number, toward the familiar isothermal value for sharp-edged orifices of 0.61 near a Froude number seven times larger than the critical.

1. INTRODUCTION

Smoke control may be practiced according to two different objectives. One objective might be to limit smoke to a fire zone, which always includes the compartment on fire, but may also include contiguous space on the same floor, even an entire floor or several floors of a building. The other objective might be to limit smoke to a fraction of the space of the fire compartment. Accordingly, one may speak of "zoned smoke control" and "compartment smoke control." The present investigation was undertaken to provide data for the design of zoned smoke control systems, addressing specifically the minimum flow rates needed at openings in a boundary to a fire zone from the surrounding space to prevent escape of smoke, i.e., contamination of the surrounding space.

The most relevant previous work is the investigation by Thomas[1] on the minimum air velocity necessary to prevent smoke flowing upstream in a horizontal passage. The critical average velocity in the passage, $\bar{u}_c$ can be expressed in terms of a critical Froude number (assuming 80 percent of the heat generated by the fire source was transferred to the air in the experiments):

$$\bar{u}_c/[2gH\Delta T_{ave}/T_{ave}]^{1/2} = 0.79 \ . \qquad (1)$$

Epstein[2] studied buoyancy induced exchange flows through openings in a horizontal partition of a constant-volume liquid system, with brine initially on top and fresh water initially below the partition. From experiments with two simultaneous circular openings, it was possible to determine a critical volumetric flow rate and associated Froude number for transition between unidirectional flow and bidirectional flow in a 0.045m diameter opening. An analogue critical Froude number exists for escape of smoke from an opening in the roof of a fire compartment:

$$\bar{u}_c/[2gD\Delta T/T]^{1/2} = 0.29 \qquad (2)$$

This result pertains to the specific Grashof number of the experiment, which was:

$$(\Delta\rho/\bar{\rho})gD^3/\nu^2 = 7.0 \cdot 10^5 \qquad (3)$$

2. THEORETICAL CONCEPTS

For an aperture in a vertical wall, a simple theory leads to a prediction for the critical inflow at the aperture which just prevents hot gases from escaping the fire space. The theory is most appropriate for the case where the aperture extends from the floor to the ceiling, Figure 1. Cold air from the surrounding space flows through the aperture of width W into the fire ("hot") space, forming a jet into the fire space which has a vena contracta considerably narrower than the width of the aperture. Since pressures increase more rapidly with depth in the cold space than in the hot space, the critical condition of zero, local velocity in the aperture is first reached at the top of the aperture as the overall throughflow is gradually reduced. Any further reduction in throughflow causes hot gases to back up into the cold space. Bernoulli's equation can be written for any elevation, y, between the quiescent cold space and the vena contracta, where the horizontal velocity profile is considered uniform, which provides an expression for u(y/H) in the vena contracta. At the critical condition, u(1) = 0, which fixes the vertical velocity profile in the vena contracta in terms of the temperature distribution in the hot space. The average (cold) velocity through the aperture at the critical condition, $\bar{u}_c$, can be defined from the total volumetric flow rate and the aperture area, whose nondimentional form,

$$Fr_c = \bar{u}_c/(2gH\Theta_H)^{1/2}, \qquad (4)$$

is the critical Froude number. The following prediction is established for the critical Froude number:

$$Fr_c = CP. \qquad (5)$$

Here, C is the discharge coefficient or coefficient of contraction, often found to be near 0.6 for isothermal flows through sharp-edged circular and slot orifices. The quantity, P, is a temperature distibution parameter for the hot space, defined:

$$P = \int_o^1 [\int_{y/H}^1 (\Theta/\Theta_H)\, d(y'/H)]^{1/2} d(y/H)\ . \qquad (6)$$

For a uniform vertical temperature profile, P = 2/3 .

If the aperture does not extend from floor to ceiling, there are difficulties with the simple theory since it cannot be assumed that there is no contraction of the cold jet into the hot space in the vertical direction. One might still expect Eq. (5) to be applicable, with H (in definition of Fr_c and P) taken as the height of the aperture, but possibly with a different value for the coefficient, C.

Viscous effects on the aperture flow, if they exist, are expected to depend on the Grashof number:

$$Gr = g\rho_c^2\ \Theta_H\ (HW^2)/\mu^2, \qquad (7)$$

where μ is evaluated at the mean of the hot and cold temperatures.

Transitions between bidirectional and unidirectional flows, of the kind included in Epstein's studies[2] and the issue of concern in connection with ceiling apertures, are extremely complex and no theory is attempted for this case. In general, the state of the flow at a horizontal aperture, with a hot fire space below and cold ambient space above, will be governed by Froude and Grashof numbers akin to those defined for vertical openings in Eqs. (4) and (7), except H is replaced by the aperture width, W. The critical Froude number for ambient air flowing into the fire space, just sufficient to prevent escape of smoke, will be a function of the Grashof number, where the two nondimensional groups are defined:

$$\text{Critical Froude Number: } Fr_c = \bar{u}_c/(2gW\Theta_{c\ell})^{1/2} \qquad (8)$$

$$\text{Grashof Number: } Gr = g\rho_c^2\ \Theta_{c\ell}W^3/\mu^2\ . \qquad (9)$$

Here, $\Theta_{c\ell}$ is $\Delta T/T$ evaluated at the ceiling level (away from the thermal boundary layer).

3. EXPERIMENTAL ARRANGEMENT

Most of the experiments were conducted in a reduced scale facility having a ceiling height of 0.61 m. The facility consisted of a square fire compartment measuring 2.44 m on the side, with an air supply plenum attached to one side of the compartment, in which various wall apertures were mounted, and with two floor-to-ceiling ventilation openings for the fire in the opposite side. As fire source was used a 0.31 m diameter "sandbox" gas burner flush with the floor near the ventilation wall, burning propylene or propane at rates from 8 to 165 kW (corresponding to 270-5600 kW in a 2.5 m high room). Temperatures were measured at several elevations in the fire compartment and the air plenum, and the pressure differential between the plenum and fire compartment was monitored at midheight of the facility. Following ignition, temperatures in the fire compartment were allowed to approach a steady state. Then the flow rate of conditioned air from the plenum was decreased in 10 percent steps until the first indication of smoke by a photometer in the plenum. The critical flow rate was taken as the average of the first flow rate indicating presence of smoke and the immediately preceding flow rate. Figure 2 illustrates the wall apertures investigated, formed by 2.7 or 1.7 mm thick steel plating.

For investigation of ceiling apertures, the air plenum was positioned over apertures in the ceiling of the fire compartment near the wall of the compartment opposite the burner. Figure 3 shows the various ceiling apertures, cut in 1.7 mm steel plates.

A fire test room was available from a previous program to investigate door-size apertures (0.92 m x 2.03 m) in wall and ceiling. The fire test room, measuring 3.7 x 7.3 x 2.4 m high, was exhausted by a blower via 0.61 m diameter ducting attached to one of the walls of the test room and provided with flow metering. Vertical thermocouple traverses were provided in the room. As fire source was used heptane floated on water in a 0.5 m diameter container (approximate heat-release rate of 150 kW). The critical flow conditions for escape of smoke were determined by visual observation of the aperture flows, which were illuminated by flood light. Observations began after temperatures in the room had stabilized.

In analogy with the reduced-scale tests, the exhaust flow was reduced in small steps until smoke puffs were first observed to escape into the laboratory (at the top of the door, or above central regions of the ceiling aperture). It was possible to determine rather narrow flow brackets, no smoke versus smoke into the laboratory, for both apertures.

4. CRITICAL FROUDE NUMBERS

Figure 4 presents critical Froude numbers for the wall apertures, defined in Eq. (4), as a function of the temperature distribution parameter, P, defined in Eq. (6). (Some of the tests had to be discarded, because unacceptable density variations built up in the air plenum due to heat transfer from the fire compartment to the plenum through the common wall.) The straight, dashed line is a fair representation of the data, drawn to satisfy Eq. (5). This line corresponds to a discharge coefficient, $C = 0.64$. Note that most of the data are well represented by this line, i.e., the floor-to-ceiling apertures, high rectangular apertures, low rectangular apertures, central rectangular apertures, central circular aperture, and the normal-size doorway. The range in P from 0.53 to 0.67 may cover most practical cases, from highly non-uniform vertical temperature profiles at low heat release rates to nearly uniform profiles at high heat release rates. The accompanying variation in Fr_c is seen to be 0.32 to 0.43. No effect of the Grashof number (Eq.(7)) has been seen in the data of Figure 4.

Critical Froude numbers for ceiling apertures, defined in Eq. (8), are presented in Figure 5 as a function of the Grashof number, defined in Eq. (9). Here there is a definite effect of the Grashof number, with a high-Grashof number asymptote near $Fr_c = 0.23$ and an apparent low Grashof number asymptote near $Fr_c = 0.38$, separated by a transition range. There is no apparent effect of aspect ratio. Nor is there an effect of the orientation of a rectangular aperture. This latter finding, together with the small effect observed of a partial partition for Aperture I (partial wall between aperture and fire source), imply that gas motion in the ceiling gas layer had little effect on the critical conditions for escape of smoke.

5. PRESSURE DIFFERENTIALS AND DISCHARGE COEFFICIENTS

Pressure differentials measured across the floor-to-ceiling wall aperture at the critical Froude numbers, adjusted to the top of the aperture by hydrostatic corrections using the vertical temperature profiles, were verified to be close to zero, as assumed in the theory. The discharge coefficient best fitting the theory to the experiments for critical conditions in apertures of vertical walls, $C = 0.64$, is close to the value 0.61 often found to represent isothermal forced flows through sharp-edged orifices and slots. Consequently, it appears safe to assume a discharge coefficient of comparable magnitude for calculation of all supercritical flows through wall apertures.

For the ceiling apertures, the measured pressure differentials were converted, using hydro-static corrections, to pressure differentials across the ceiling, at the level of the ceiling. Most of the data pertained to the critical Froude numbers and slightly larger, but limited data were also obtained at considerably larger Froude numbers. Discharge coefficients, C, were calculated from:

$$\dot{m} = CA\,(2\rho_c \Delta p)^{1/2}\,, \qquad (10)$$

where $\dot{m}$ is the mass flow rate through the aperture for a given pressure differential across the ceiling, Δp. The discharge coefficients are plotted as a function of Froude number in Figure 6. For the high asymptotic range ($Gr \geq 2 \cdot 10^7$), the familiar isothermal flow limit, 0.61, appears to be approached at a Froude number of 1.5. The pressure differential across the ceiling can be calculated from:

$$\Delta p = (Fr/C)^2 \rho_c g W \Theta_{c\ell} \; . \qquad (11)$$

6. COMPARISON WITH PREVIOUS WORK

The critical Froude number derived from Thomas' work to prevent smoke from backing up in a horizontal passage[1], Eq.(2), can be converted to the form adopted in the present study:

$$Fr_c = 0.79 \left[(\Delta T_{ave}/T_{ave})/(\Delta T_H/T_H)\right]^{1/2} \qquad (12)$$

The vertical temperature distributions in Thomas' experiments are not known. It will be assumed they were rather steep, with a representative value of 0.5 for the temperature ratio within brackets in Eq. (12), as for the lowest heat release rate experiments in the current study. Then Thomas' result corresponds to $Fr_c = 0.56$. For a flow passage, having a discharge coefficient of 1, the present results correspond to (cfr. Eq. (5)):

$$Fr_c = P \qquad (13)$$

The experiments indicated a close correlation between P and the temperature ratio in Eq. (12); for a temperature ratio of 0.5, the value $P = 0.55$ was indicated. Hence the present experiments imply the value $Fr_c = 0.55$ for a horizontal passage, in good agreement with the value deduced from Thomas' experiments, $Fr_c = 0.56$.

Eq. (2) was inferred from Epstein's work for the critical Froude nmber to prevent escape of smoke from a ceiling vent, i.e., $Fr_c = 0.29$, associated with a Grashof number of $7 \cdot 10^5$. According to Figure 5, the present study indicates $Fr_c = 0.38$ at the same Grashof number, a somewhat higher value.

7. CONCLUSIONS

1. Critical Froude numbers of air inflow to prevent escape of smoke from <u>wall apertures</u>, Fr_c (Eq. (4)), were found to be insensitive to aperture geometry, consistent with simple theory and an experimental discharge coefficient of 0.64. Values of Fr_c varied from 0.32 to 0.43 in the tested range of vertical room temperature distributions (Figure 4).

2. Critical Froude numbers of air inflow to prevent escape of smoke from <u>ceiling apertures</u>, Fr_c (Eq. (8)), were also insensitive to aperture geometry and approached an asymptotic value $Fr_c = 0.23$ at Grashof numbers (Eq. (9)) greater than $2 \cdot 10^7$. An <u>apparent</u> asymptote was also reached at Grashof numbers smaller than $5 \cdot 10^6$, $Fr_c = 0.38$.

3. Discharge coefficients for ceiling apertures were found to increase with the Froude number (Figure 6), starting near 0.19 at $Fr = Fr_c = 0.23$ and approaching 0.61, the familiar isothermal value for sharp-edge orifice flows, near $Fr = 1.5$ (high Grashof number range). Discharge coefficients for wall apertures can be assumed to remain near 0.64 (Conclusion 1) as Froude numbers increase above Fr_c.

SYMBOLS

A	area of aperture
C	discharge coefficient
D	diameter
Fr	Froude number, $\bar{u}/(2gH\Theta_H)^{1/2}$ for wall apertures and $\bar{u}/(2gW\Theta_{c\ell})^{1/2}$ for ceiling apertures
Fr_c	critical value of Fr to prevent escape of smoke from aperture
Gr	Grashof number, Eq. (7) for wall apertures and Eq. (9) for ceiling apertures
g	acceleration of gravity
H	height of aperture or passage
$\dot{m}$	mass flow rate
P	temperature distribution parameter, Eq. (6)
Δp	pressure differential across aperture
T	compartment temperature
T_{ave}	average dowmstream temperature in passage
T_c	temperature in quiescent cold space
T_H	temperature at top level of aperture
T_∞	ambient temperature
ΔT	$T-T_c$
ΔT_{ave}	$T_{ave}-T_\infty$
ΔT_H	T_H-T_c
u	velocity
$\bar{u}$	average velocity in aperture or passage (volumetric flow rate in ratio to flow area)
$\bar{u}_c$	critical $\bar{u}$ to prevent escape of smoke from aperture
W	aperture width (being smaller dimension of a recentangular ceiling aperture)
y	height above bottom of aperture
Θ	$\Delta T/T$
$\Theta_{c\ell}$	Θ just under ceiling
Θ_H	Θ at top level of aperture
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density in quiescent hot space
ρ_c	density in quiescent cold space
$\bar{\rho}$	mean density of two liquids
$\Delta\rho$	density difference between heavier and lighter fluid ($(\rho_c-\rho)$ in fire applications)

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2. Epstein, M., "Buoyancy-Driven Exchange Flow Through Small Openings in Horizontal Partitions," ASME Journal of Heat Transfer, Vol. 110, 1988, pp. 885-893.

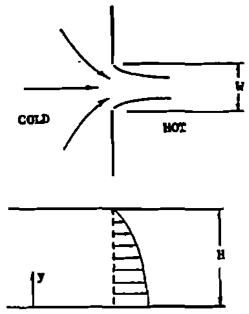

Figure 1 Critical flow conditions at a wall aperture extending from floor to ceiling.

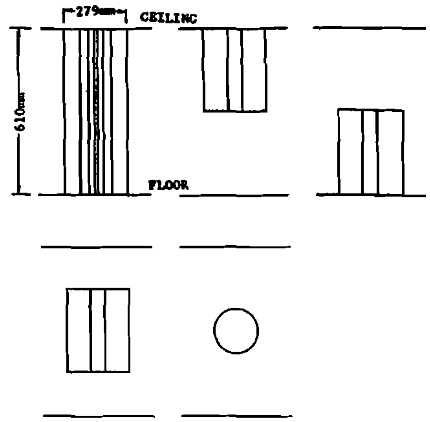

Figure 2 Wall apertures

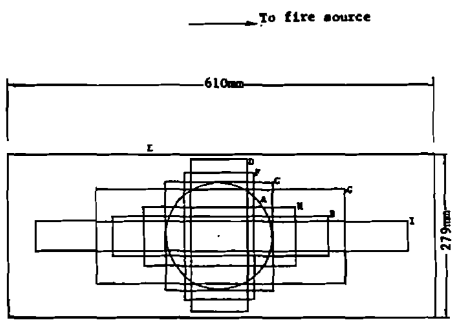

Figure 3 Ceiling apertures

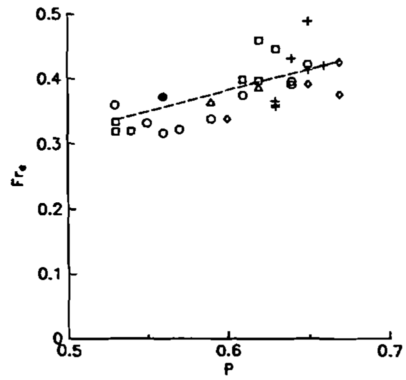

Figure 4 Critical Froude number for wall apertures; ○ floor-to-ceiling apertures; + high apertures; △ low apertures; □ central apertures; ◇ central circular aperture; ● doorway, larger-scale.

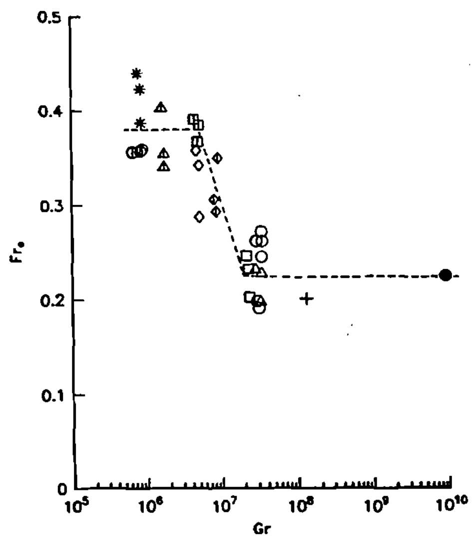

Figure 5 Critical Froude numbers for ceiling apertures: Except for ● (normal doorway), the symbols represent apertures identified with corresponding letters in Figure 3 according to ○(A), △(B), △(C), ⊞(D), +(E), ⌽(F), □(G), ◇(H), ✱(I), Φ(I with partition).

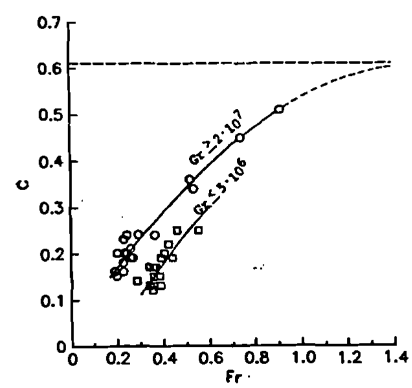

Figure 6 Discharge coefficients for ceiling apertures.