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Oscillating behaviour of fire-induced air flow through a ceiling vent

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ABSTRACT

Oscillations of fire-induced air flow through a ceiling vent in a compartment will be studied in this paper. The equations describing the oscillations of air flow induced will be discussed first. Air flow through the vent is found to be induced by buoyancy or by pressure. A wave function was introduced as a perturbation to a control volume concerned. Oscillation growth, amplification, response and frequency will then be studied by solving these key equations under practical conditions. Useful semi-empirical formula on those parameters is derived for fire safety engineering design. The predicted results will be discussed and compared with experimental data available in the literature.

1. Introduction

Buoyancy-induced flow due to a thermal object in an enclosure had been studied extensively in the literature [4,19]. Many work had been done on air flow through vertical vents as the results would be useful for modeling room fires and energy systems [1,12]. However, air flow through horizontal vents with configuration as shown in Fig. 1 was not so clearly understood.

Horizontal ceiling vents are commonly installed in atria for smoke exhaust. It is classified as static smoke extract system in the local codes on fire service installation [11]. Also, many horizontal fire vents are installed in underground spaces. Workable design guides on horizontal vents cannot be developed without in-depth studies. There are not yet design data specified in the code [11], and even the fire safety objectives are not spelled out clearly. Only a better understanding of the fire-induced air flow through a horizontal vent can give proper design of those smoke management systems [16,18]. Air flow across the horizontal vent might oscillate under some conditions. It would affect the performance of the static smoke exhaust systems. Therefore, when oscillation will occur and the factors determining the oscillation frequency should be clearly identified.

For a compartment of space volume V_g with an opening of area A_o and discharge coefficient C_d, the pressure variations resulted from a fire with heat release rate Q_o to give hot gas of temperature T_g and density ρ_g are due to:

- Expansion giving a pressure difference ΔP_p:

$$\Delta P_p = \frac{1}{2\rho_g}\left(\frac{Q_o}{C_p T_g A_o C_d}\right)^2$$

- Buoyancy at height y above a reference level would give a pressure difference ΔP_b in terms of the ambient air density ρ_∞:

$$\Delta P_b = y(\rho_\infty - \rho_g)g$$

- Pressure fluctuation ΔP due to differences in mass flow rates $\Delta\dot{m}$ passing through the vent:

$$\Delta P = \frac{\Delta\dot{m}^2}{2\rho(C_d A_o)^2}$$

Mass flowing in and out of the compartment would give a pressure difference. The difference in mass flow rates $\Delta\dot{m}$ is zero under equilibrium. Perturbations to give $\Delta\dot{m}$, or other changes on heat release rate would change the density and hence ΔP to give air flow oscillations. As far as energy is continuously supplied, the oscillations can be sustained or even grow up. In fact, low-frequency oscillation flow had been investigated for combustion in solid rockets [2,17,29]. Flow instability was resulted as the burning-rate response lagged behind the pressure fluctuation. The ratio of pressure fluctuation to burning rate fluctuation was used to describe the response function in oscillation amplification in a combustion chamber. This concept will be applied to study air flow oscillation through a horizontal vent in a fire compartment.

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Nomenclature

A_o	flow area of opening
B	buoyancy parameter
B_w	width of the compartment
C_d	discharge factor
C_p	specific heat at constant pressure
C_v	specific heat at constant volume
D	characteristic scale
f	frequency of oscillations
g	magnitude of gravitational acceleration
Gr	Grashof number
H	height of the compartment (or vent)
m	mass flux
P	pressure
R	gas constant
Re	Reynolds number
Ri	Richardson number
Rm	ratio of amplitudes for fluctuation of mass flow rate and temperature, $\mathrm{Rm} = \mathrm{Rm}^{(r)} + i\mathrm{Rm}^{(i)}$
T	temperature
t	time
V	space volume of the compartment
v	velocity
W	length of the compartment
ω	angular frequency
ρ	density
γ	ratio of specific heat capacity of the fire gas or heated air
α	exponential growth rate constant for amplitude of oscillations
τ	lead time of mass oscillations relative to temperature oscillations
τ_f	characteristic time for the compartment
ν	kinematic viscosity
β	m_f/m_∞

Subscripts

b	buoyancy-driven
c	across the vent
f	flame
g	hot gases
in	entering
out	exiting
p	pressure-driven
∞, a	ambient

Superscripts

i	imaginary part
r	real part
$\bar{}$	steady state
$'$	perturbation
$*$	critical value

2. Literature review

Experiments had been conducted on the buoyancy-driven flow through horizontal vents for zero pressure difference across the vent [9]. Later, density difference across the vent was found to give strong enough buoyancy as the driving force [4]. Air flow through a horizontal vent was later studied by varying the pressure difference across the vent [5,6]. Spaces connected by vents were filled with fluids of different densities, with denser fluid placed above the vent. Perturbations would give a bi-directional flow across the vent. But if large pressure difference was applied across the vent, there would only be unidirectional flow from top to bottom.

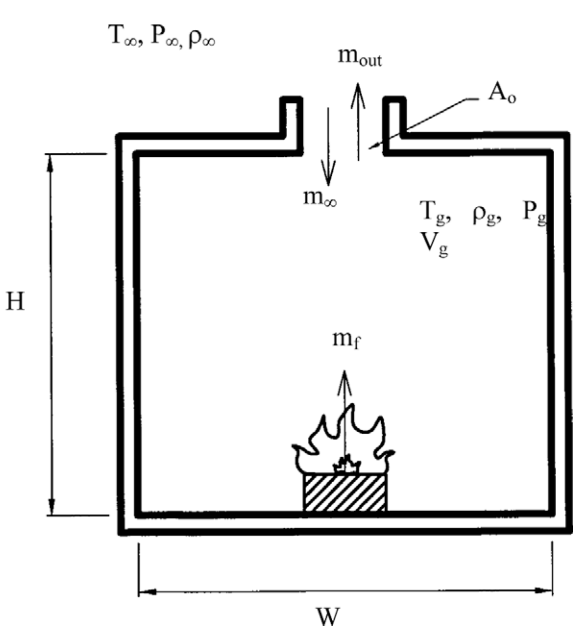

Fig. 1. Geometry concerned.

Flow visualization in salt-water models was reported by Tan and Jaluria [24,25]. Pressure and density differences were applied across horizontal vents. By studying the transient flow patterns, the conditions to give unidirectional or bi-directional flows were investigated. The results are useful in studying the oscillation of air flow as illustrated in this paper.

In a compartment fire, whether the air flow is induced by buoyancy or pressure should be clarified. The buoyancy parameter B, a ratio of density difference $\Delta\rho$ to pressure difference ΔP, was introduced by Tan and Jaluria [25] for studying that:

$$B = \frac{Gr}{\mathrm{Re}^2} = \frac{g\Delta\rho D}{\Delta P} \tag{1}$$

Note that B is the same as the Richardson number Ri in the fluid mechanics literature. The Grashof number Gr and the Reynolds number Re are defined in terms of the buoyancy-induced velocity v_{cb}, the pressure-driven velocity v_{cp}, the density difference across the vent $\Delta\rho$, and the mean density $\bar{\rho}$ given by:

$$\bar{\rho} = (\rho_\infty + \rho_g)/2 \tag{2}$$

At zero imposed pressure difference ΔP, the characteristic buoyancy-induced velocity v_{cb} is given by Gebbart et al. [12]:

$$v_{cb} = \sqrt{\frac{g\Delta\rho D}{\bar{\rho}}} \tag{3}$$

$$\mathrm{Gr} = \frac{g(\Delta\rho/\bar{\rho})D^3}{\nu^2} \tag{4}$$

$$\mathrm{Re} = \frac{D}{\nu}\sqrt{\frac{\Delta P}{\bar{\rho}}} \tag{5}$$

For forced-flow driven by pressure with negligible buoyancy effects, $g\Delta\rho\, D \ll \Delta P$, B (or Ri) approaches zero. For buoyancy-driven flow without applying any external pressure difference, $g\Delta\rho$