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# Mass flow through a horizontal vent in an enclosure due to pressure and density differences

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**Abstract**

A detailed experimental study is undertaken to understand the basic nature of the mass flow through a horizontal vent in an enclosure due to differences in pressure and density across the vent. This flow is of particular interest in enclosed regions with a heat source such as fire, whose growth and development depend on the flow of oxygen through the vent. In this study, fresh and saline water are employed to simulate the density differences that arise due to temperature rise in the enclosure. An externally imposed pressure difference is also exerted and the flow rates resulting from the combined effect of pressure and buoyancy are measured. In the absence of a pressure difference, but with heavier fluid overlying lighter fluid, a bidirectional flow arises across the vent, between the two regions, due to buoyancy effects. As the pressure in the lower region increases, the flow gradually shifts to a unidirectional flow. The critical pressure, at which transition from bidirectional to unidirectional flow arises, is determined for a range of density differences. The flow rates at relatively large pressure differences can be obtained from existing vent flow models that are based on Bernoulli's equation. However, typical fire conditions lie in the region where both buoyancy and pressure effects are important. Results on the measured flow rates in this region and also some correlations that consolidate the observed trends are presented. 

## 1. Introduction

The flow of air and combustion products across vents governs the growth and spread of fires in compartments and buildings. The rate of inflow of oxygen from the ambient determines the combustion process and the energy release rate in fires for many practical circumstances. Similarly, the spread of the fire to adjoining areas is strongly dependent on the resulting flow through vents. Horizontal vents are important in many situations, particularly in multi-room compartments, ships and containment buildings. This paper considers the flow through such vents for nonzero pressure and density differences that usually arise across the vent in typical fires.

Buoyancy-induced flows in enclosures and the associated transport due to fires in rooms and other compartments have received considerable attention in the literature [1–4]. However, not much work has been done on the flow through openings or vents such as those between connecting rooms in buildings and between quarters in ships. Vertical openings have received some attention because of their relevance to room fires and electronic and energy systems [5,6]. The flow through doors and windows has been studied in some detail and incorporated in mathematical models used to predict the growth of room fires [7–9]. The flow rate through the vertical opening is generally obtained by using Bernoulli's equation and a flow discharge coefficient to take into account the flow contraction and head losses at the vent.

The work done on the flow through horizontal vents, such as the one shown in Fig. 1 is very limited. The flow rate can be estimated, as done for vertical vents, by using Bernoulli's equation if a known pressure difference exists across the vent [9,10]. This approach has been used by

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**Nomenclature**

| | |
|---|---|
| $A$ | aspect ratio of the vent, $A = L/D$ |
| $A_v$ | area of cross-section of the vent |
| $B$ | buoyancy parameter, Eq. (8) |
| $C_D$ | discharge coefficient, Eq. (5) |
| $D$ | diameter of the vent |
| $g$ | magnitude of gravitational acceleration |
| $Gr$ | Grashof number, Eq. (9) |
| $L$ | height of the vent |
| $P$ | pressure |
| $\Delta p$ | pressure difference across the vent, $\Delta p = p_l - p_u$ |
| $\Delta p_c$ | critical, or purging, pressure difference |
| $Q$ | volume flow rate |
| $Q_{ex}$ | exchange-flow component |
| $Q_0$ | net flow rate through the vent |
| $Q_d$, $Q_u$ | downward and upward volume flow rates across the vent, respectively |
| $\hat{Q}$ | dimensionless flow rate, Eq. (1) |
| $Re$ | Reynolds number, Eq. (9) |
| $t$ | time |
| $V$ | volume of the flow region |
| $V_c$ | buoyancy-induced velocity, Eq. (3) |
| $V_p$ | pressure-induced velocity |

*Greek symbols*

| | |
|---|---|
| $\rho$ | density |
| $\bar{\rho}$ | average density |
| $\Delta\rho$ | density difference across the vent, $\Delta\rho = \rho_u - \rho_l$ |

*Subscripts*

| | |
|---|---|
| amb | ambient |
| l | lower region |
| 0 | initial |
| u | upper region |

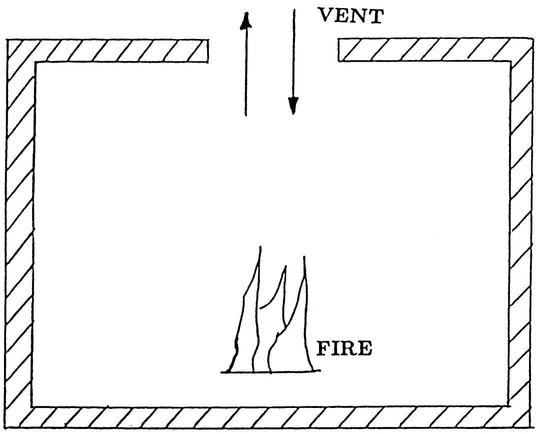


Fig. 1. Sketch of fire in a room with a ceiling vent.

Thomas et al. [11] and Hinkley [12] to obtain the effect of ceiling venting in various enclosure fire environments. However, this model breaks down, over certain ranges of the pressure and density differences, for problems such as the one sketched in Fig. 1, where both density and pressure differences exist across the vent and lead to significant buoyancy effects in addition to the pressure effect [13].

Some experimental work has been done on the buoyancy-driven flow through horizontal vents, particularly for the special circumstance of zero pressure difference across the vent, $\Delta p = 0$ [14,15]. The buoyancy effect is due to the unstably stratified circumstance caused by a heavier fluid lying above a lighter fluid. Air was used as the fluid in the former study and water/brine for the other. Epstein [15] studied in detail the effect of varying the aspect ratio *L*/*D* and identified different flow regimes. The dimensionless exchange flow rate is given in terms of a dimensionless flow rate $\hat{Q}$, which is correlated in terms of *L*/*D*. The correlating equation for $0.01 < L/D < 10.0$ was given as

$$\hat{Q} = \frac{Q}{\sqrt{g\Delta\rho D^5/\bar{\rho}}} = \frac{0.055[1+400A^4]^{1/6}}{[1+0.00527(1+400\,A^3)^{1/2}(A^6+117\,A^2)^{3/4}]^{1/3}}, \tag{1}$$

where $Q$ is the volume exchange flow rate, $A$ $(= L/D)$ the aspect ratio of the opening, $g$ the magnitude of gravitational acceleration, $\Delta\rho$ the density difference across the vent, and $\bar{\rho}$ is the mean density. Here

$$\Delta\rho = \rho_u - \rho_l, \tag{2}$$

where $\rho_u$ is the density of the fluid in the upper region and $\rho_l$ that of the fluid in the lower region, below the vent. Also, $\bar{\rho} = (\rho_u + \rho_l)/2$. Therefore, a positive $\Delta\rho$ leads to an unstable situation and generates a resulting exchange flow through the vent at zero imposed pressure difference $\Delta p$, with equal upward and downward flow rates due to continuity. The characteristic buoyancy-induced velocity $V_c$ is given by [5,16]:

$$V_c = \sqrt{\frac{g\Delta\rho D}{\bar{\rho}}}, \tag{3}$$

where $D$ is taken as the characteristic length dimension. Since the area $A_v$ of a circular vent is $\pi D^2/4$, the flow rate varies is $V_c(A_v)$ which varies $(g\Delta\rho D^5/\bar{\rho})^{1/2}$. This quantity is used to nondimensionalize $Q$, giving rise to

$\hat{Q} = Q/(g\Delta\rho D^5/\bar{\rho})^{1/2}$. The flow regimes that arose were termed oscillatory exchange flow, Bernoulli flow, combined turbulent diffusion and Bernoulli flow, and turbulent flow, by Epstein [15].

The effect of an externally induced flow was considered by Epstein and Kenton [17], who employed the same experimental arrangement as Epstein [15]. They introduced a fixed flow rate in the lower fluid region and studied the resulting flow across the opening. The forced flow required to purge the vent of the opposing flow of buoyancy-driven convection was determined. However, the resulting pressure and the flow mechanisms under an imposed pressure difference, which more correctly approximates the practical circumstance, were not investigated. Emmons [18] considered the results from several experimental studies on vertical, horizontal and inclined vents to estimate the effective flow coefficients to calculate the flow through fire vents of different shapes and orientations.

Mercer and Thompson [19] studied the flow between two fluid regions connected by an inclined circular pipe of diameter $D$. Fresh-water and salt-water were employed as the two fluids of different density. For small values of the velocity at the outlet of the upper tank, which contained brine, a wedge of length $W$ was observed in the pipe, indicating the flow of fresh-water back into the pipe and obstructing the flow into the lower tank. Thus, $W/D$ may be taken as a measure of the "purging" effectiveness. A total purging or flooding implies a unidirectional flow through the vent from one region to the other, depending on the sign of $\Delta p$, where

$$\Delta p = p_1 - p_u. \tag{4}$$

Here, $p_1$ and $p_u$ are the pressures at the vent elevation in the lower and upper environments, respectively. If $\Delta p$ exceeds some critical value, $\Delta p_c$, then the flow becomes unidirectional and the exchange-flow component, $Q_{ex}$, defined later, becomes zero [13]. A positive value of $\Delta p$ tends to curb the downward flow due to the density difference. The definitions of $\Delta p$ and $\Delta\rho$ are chosen so that positive values represent the usual conditions in a room fire.

The standard vent-flow model, based on Bernoulli's equation, assumes unidirectional flow and breaks down if a bidirectional flow exchange occurs under the combined effects of buoyancy and pressure. This model predicts zero flow when $\Delta p = 0$. The upward pressure-driven velocity $V_p$ is obtained as $V_p = \sqrt{2\Delta p/\rho_l}$. Thus, the volume flow rate $Q_u$ through the vent, into the upper region from the lower region, is given by the model, for $\Delta p > 0$, as

$$Q_u = C_D A_v \sqrt{2\Delta p/\rho_1}, \tag{5}$$

where $C_D$ is the flow discharge coefficient. Similarly, if $\Delta p < 0$, the flow $Q_d$ into the lower region is obtained, with $\Delta p$ in the preceding equation replaced by its absolute value $|\Delta p|$ and $Q_u$ by $Q_d$, as sketched in Fig. 2.

As mentioned earlier, there is a flow across the vent due to the density difference $\Delta\rho$, even if the pressure difference $\Delta p$ is zero, due to the unstable stratification resulting from the fluid in the upper region being heavier than that in the lower region. However, $Q_u = Q_d$ in this case. It is, therefore, important to determine the volume flow rates $Q_u$ and $Q_d$ at arbitrary values of $\Delta\rho, \Delta p$ and $L/D$. Copper [13] has developed an analytical model, employing an exchange-flow component, $Q_{ex}$. Thus, $Q_{ex}$ becomes zero if the density distribution across the vent is stable, i.e., $\Delta\rho \leqslant 0$, and also if $\Delta p > \Delta p_c$. Employing the results given by Epstein [15], and Mercer and Thompson [19], the model estimates $\Delta p_c$ and $Q_{ex}$ for arbitrary $\Delta\rho$ and $\Delta p$, with $L/D \to 0$. An algorithm was developed for use in zone models for compartment fires. Using this algorithm, the flow of oxygen into an enclosure through a horizontal vent was obtained. Assuming total consumption of the inflowing oxygen, Cooper [13] determined the steady-state rate of burning in a ceiling-vented room, such as the one sketched in Fig. 1, as a function of the vent area, oxygen concentration in the ambient medium and room temperature.

A few other studies have considered the buoyancy-induced flow through openings in enclosures. The work of Steward et al. [20] and Takeda [21] was largely directed at fires in ships. Experimental studies were carried out to determine the effect of vent flow on fire growth and spread. Heskestad and Spaulding [22] carried out an experimental study on the inflow of air into an enclosure

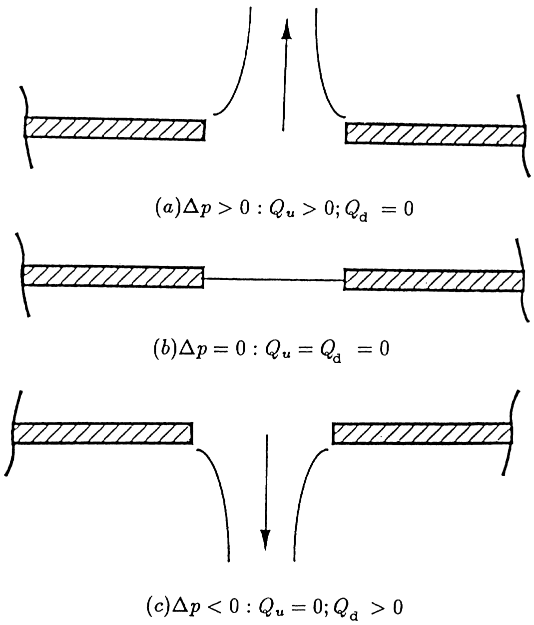


Fig. 2. The standard vent flow model for horizontal vents.

with a fire, through wall and ceiling apertures, in order to prevent escape of smoke. The fluid mechanics of natural ventilation has been considered experimentally and analytically by Linden et al. [23], to bring out the basic characteristics of the flow in stratified regions with openings. Jaluria et al. [24,25] carried out visualization and preliminary measurements in such enclosures, particularly for heated and cold air across the vent.

This paper presents a detailed experimental study on the flow across a horizontal vent in an enclosed region for arbitrary values of the governing variables $\Delta\rho, \Delta p$ and $L/D$, using fresh and saline water to simulate the density difference. Visualization is used to determine whether the flow is unidirectional or bidirectional. The flow rates across the vent are determined and correlated in terms of the governing parameters. The relevance of these results to the study of fires in vented compartments is discussed.

## 2. Experimental arrangement

This study is directed at the flow through horizontal vents for nonzero pressure and density differences across the opening. An experimental system based on a fresh-water/salt-water flow arrangement is employed, as sketched in Fig. 3. The higher density brine is in the upper region and the lower density fresh water is in the lower region, yielding a positive value for the density difference $\Delta\rho = \rho_u - \rho_l$. Values of $\Delta\rho/\bar{\rho}$, where $\bar{\rho}$ is the average fluid density, up to around 0.2 have been employed. This is approximately the same density difference ratio that is generated by a temperature difference of 100 K in gases, with 500 K as the average temperature.

The experiments are carried out in a rectangular tank, which is made of plexiglass so as to allow flow visualization. The tank is 0.74 m long, 0.44 m wide and 0.62 m high. It is supported by a metal frame on all sides and at the bottom. A horizontal plexiglass partition is attached to a 1.0 cm wide ledge that is constructed all the way around in the tank interior. It is located at a height of 0.31 m from the bottom, separating the two fluid regions. Plexiglass tubes of different lengths and diameters, for a variety of $L/D$ ratios, were fabricated. These are attached to the partition by means of a support plate, which is located at the opening in the partition, as shown in the figure. The value of $L/D$ can be varied from close to 0, i.e., vents of very small thickness, to values of around 6.0.

The density difference $\Delta\rho$ between the fluids in the two regions is varied by changing the salinity level in the brine solution. The density difference ratio $\Delta\rho/\bar{\rho}$ is varied to cover the range encountered in typical vented-compartment fires. The salinity is measured by means of a hydrometer. Several hydrometers with different full-scale ranges are used to obtain accurate measurements, over these ranges of density. These hydrometers were tested over a wide range of salinity levels, indicating error of less than 5% in the density measurements.

The pressure difference $\Delta p$ across the vent is obtained by keeping the upper region open to the atmosphere and pressurizing the bottom region. Generally, the pressure differences that arise in compartments like the one shown in Fig. 1 are very small, with $\Delta p/\Delta p_c$ being of order unity [13]. A calculation for the critical, or purging, pressure difference $\Delta p_c$, over the range of vent diameter and density difference of interest, shows that the pressure difference $\Delta p_c$ is of the order of $(g\Delta\rho D)$, which yields a value of 39.2 N/m$^2$ for $D = 0.02$ m and

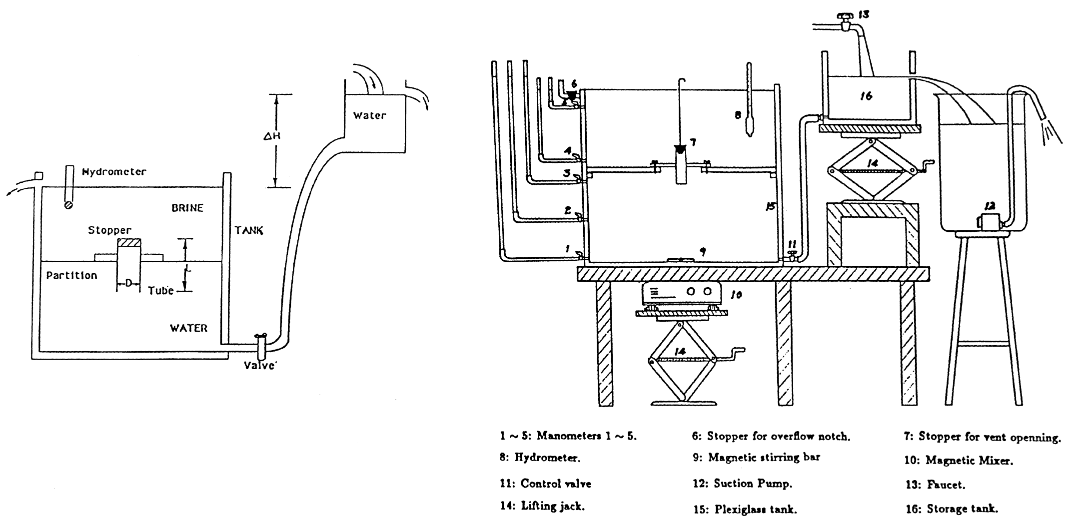


Fig. 3. Sketch and details of the experimental arrangement.

$\Delta\rho = 200\ \mathrm{kg/m^3}$. This is a relatively small value and is easily obtained by the simple arrangement shown in the figure. Higher pressure differences can also be imposed for studying the forced flow transport across the vent. The arrangement imparts the required pressure difference due to the gravitational head provided by a reservoir which can be moved vertically by means of a micrometer screw capable of providing elevation to an accuracy of 0.01 mm. The upper region is kept open to the atmosphere and the lower region is connected at the bottom of the tank to the reservoir, which contains fresh water. Adequate values of the pressure difference can easily be obtained by this arrangement to stop the bidirectional buoyancy-induced transport and to make the flow across the vent unidirectional. The uncertainty in the imposed pressure difference was estimated as 1%.

The upward volume flow rate across the vent $Q_u$ is obtained by measuring the dilution of the brine solution contained in the upper region, as discussed by Epstein [15]. If the pressure difference $\Delta p = 0$, a bidirectional flow arises across the vent, with the upflow equal to the downflow. The flow rate $Q$ is obtained from the expression given by Epstein [15]

$$Q = \frac{-V_u(\mathrm{d}\rho_u/\mathrm{d}t)}{(\rho_u - \rho_{l,0}) - (V_u/V_l)(\rho_{u,0} - \rho_u)}, \tag{6}$$

where the subscripts u and l refer to the upper, heavier, and lower, lighter, fluids, respectively, subscript 0 to the values at the start of the experiment at time $t = 0$, and $V_u$ and $V_l$ to the volumes of the two regions. When $\Delta p \neq 0$, the expression becomes more complicated. If $Q_u$ is the volume flow rate from the lower, less dense, fluid to the upper, heavier one, $Q_d$ that from the upper to the lower region, and $Q_0 (= Q_u - Q_d)$ the volume overflow rate, i.e., the net flow across the vent which is also the flow rate of ambient water entering the lower region, we have

$$\begin{aligned} &Q_u - Q_d = Q_0, \\ &\frac{\mathrm{d}(\rho_u V_u)}{\mathrm{d}t} = Q_u\rho_l - Q_d\rho_u, \\ &\frac{\mathrm{d}(\rho_l V_l)}{\mathrm{d}t} = Q_d\rho_u - Q_u\rho_l + Q_0\rho_{amb}, \end{aligned} \tag{7}$$

where $\rho_{amb}$ is the density of the fluid entering the lower region.

Therefore, by measuring $Q_0$ and $\rho_u$, the flow rate $Q_u$ may be obtained from the above equations. Overflow arrangements are used to maintain the fluid levels in the reservoir and in the upper region constant. The net upward flow through the vent $Q_0$ is measured by collecting the overflowing fluid in the upper region. A hydrometer is employed to measure the density $\rho_u$ of the brine solution at various time intervals. However, this approach for measuring the flow rates assumes that the two regions are at uniform, though different, densities at any given time. This condition is accomplished by allowing the transport to occur over a finite period of time. The opening is then closed and the fluid regions are well mixed before the density is measured. From these measurements, the average flow rate across the vent over the given time interval is obtained. A magnetic mixer is used to ensure that the density is uniform.

The flow field near the vent is also observed during the experiment. Because of the density differences, a shadowgraph yields the flow pattern quite clearly. It allows the determination of the transition from a bidirectional to a unidirectional flow as $\Delta p$ is increased for a given density difference $\Delta\rho$. The flow patterns near the vent are also observed. A suitably calibrated hot film anemometer was also used for velocity measurements. The velocities were found to be of order 0.1 m/s. Further detailed measurements of the flow field can be used to provide important quantitative information on the transport across the vent [25].

The imposed pressure difference $\Delta p$ across the vent is measured by means of a manometer as well as a low pressure differential transducer made by Omega (Model PX-154-001D1) to confirm the accuracy and consistency of the measurements. The accuracy of the transducer was of order 0.1% of the full scale reading of 250 $\mathrm{N/m^2}$. Several pressure taps are located on the side of the tank and these may be attached to the manometer or the transducer to yield the pressure difference, employing appropriate taps for a given vent geometry. As expected, the pressure variation far from the flow region was found to be due to the hydrostatic variation. The values of $\Delta p$ given in this study represent the imposed pressure differences across the vent, excluding the hydrostatic variation. The pressure difference between any two points in the tank can be obtained by using the hydrostatic variations in the two regions at the different fluid density levels. The measured flow rates are also presented in terms of the pressure and density differences and the aspect ratio $L/D$ of the opening. Attempt is made to obtain correlating equations in terms of the flow rates and the pressure and density differences. The dimensionless flow rate $\hat{Q}$ and the buoyancy parameter $B$ may also be used to present the results, where $B$ is defined as

$$B = \frac{Gr}{Re^2} = \frac{g\Delta\rho D}{\Delta p}. \tag{8}$$

Therefore, $B$ is similar to the mixed convection parameter used in the literature [5,16]. Here, the Grashof number $Gr$ and the Reynolds number $Re$ are defined by using the buoyancy-induced velocity $V_c$ and the pressure-driven velocity $V_p$ as

$$Gr = \frac{g(\Delta\rho/\bar{\rho})D^3}{\nu^2}, \quad Re = \sqrt{\frac{\Delta\rho}{\bar{\rho}}}\frac{D}{\nu}. \tag{9}$$

As $B \to 0$, the forced flow circumstance, with negligible buoyancy effects, is obtained and as $B \to \infty$, the pure buoyancy-driven flow, with no externally imposed pressure difference $\Delta p$, is achieved. Therefore, the flow rate $Q$, where $Q$ represents $Q_u$, $Q_d$ or $Q_0$, is determined at different values of $L/D$ and $B$, particularly for the mixed convective circumstance where both the transport mechanisms are significant.

## 3. Experimental results

Several interesting and useful results have been obtained. Using the shadowgraph for flow visualization, a bidirectional flow was found to arise across the vent for $\Delta\rho > 0$, at $\Delta p = 0$. Several interesting flow patterns were observed, the most common one being denser fluid descending in the central portion of the opening and lighter fluid rising in the outer portion [24]. As the opposing pressure difference $\Delta p$ was increased, this downward flow was found to decrease, ultimately giving rise to a unidirectional upward flow, see Fig. 4. This purging, or flooding, pressure difference $\Delta p_c$ is of order $O(g\Delta\rho L)$ for a vent of height $L$. Therefore, for typical values of $L = 0.1$ m and $\Delta\rho = 100\ \mathrm{kg/m^3}$, $\Delta p_c = 98\ \mathrm{N/m^2}$. A differential transducer of around 250 $\mathrm{N/m^2}$ full scale was used for these pressure measurements.

Fig. 5 shows the measured variation of the density $\rho_u$ of the upper region, heavier, fluid with time $t$, for $\Delta p = 0$. A smaller density difference gives rise to a smaller flow rate $Q$ across the vent. This flow rate $Q$ is proportional to the rate of decrease in $\rho_u$. The average

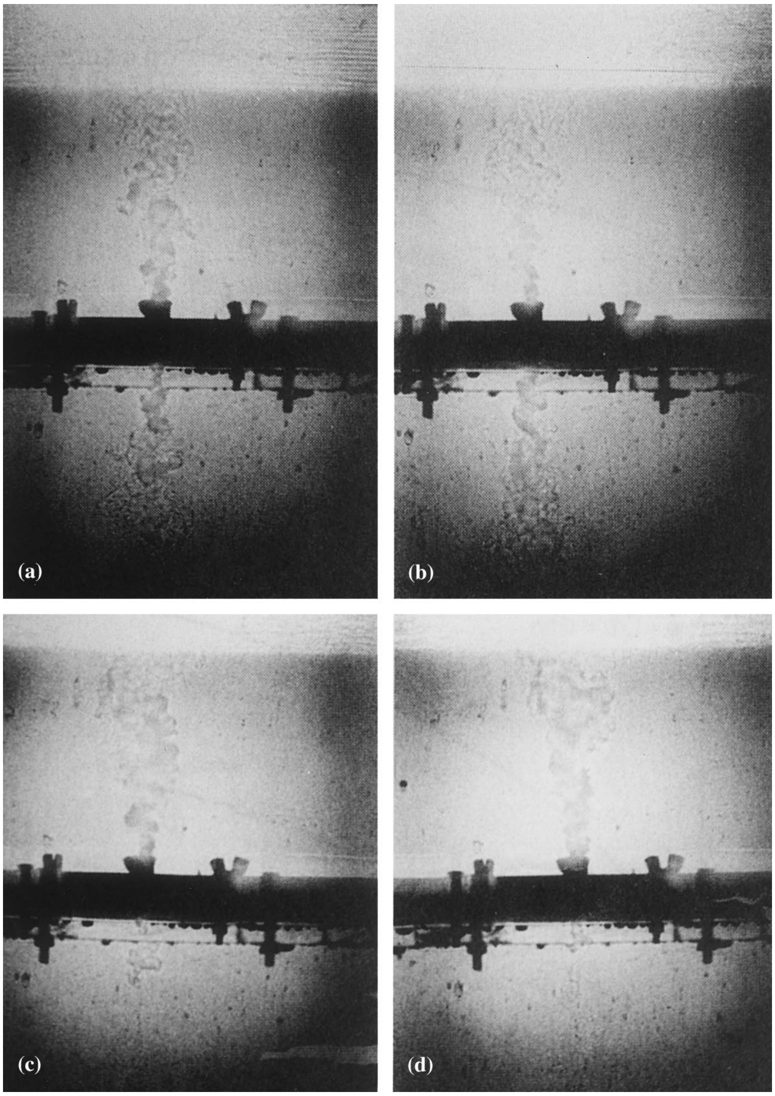


Fig. 4. Shadowgraph flow visualization results for flow across a horizontal vent with increasing $\Delta p$ at a fixed value of $\Delta\rho$.

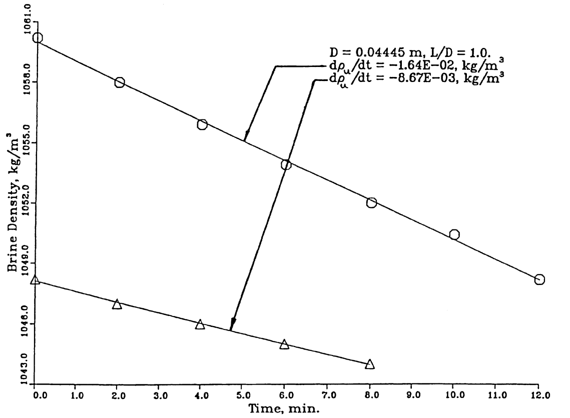


Fig. 5. The variation of the density $\rho_u$ of the heavier, upper region, fluid with time $t$ for $\Delta p = 0$ and $L/D = 1.0$, considering two different initial density differences.

values of the gradient over the duration of the experiment are given in the figure. A comparison with earlier work on this circumstance indicated good agreement. The dependence of $Q$ on $L/D$ follows the trends predicted by Epstein [15], lending support to these measurements. This comparison is shown in Fig. 6, which also indicates the accuracy of these flow rate measurements.

Results are shown for the unstratified, $\Delta\rho = 0$, circumstance in Fig. 7. The flow across the vent is unidirectional, upward or downward, depending on the pressure difference imposed across the vent. For the cases shown, the net flow $Q_0$ is upward. As seen in Fig. 7, the net upward flow $Q_0$ increases with $\Delta p$. Several such experiments were carried out to determine the effect of the pressure difference $\Delta p$ on the flow across the vent. A comparison between the measurements and the predictions from Bernoulli's equation is also shown. The trends are very similar and the flow discharge coefficient

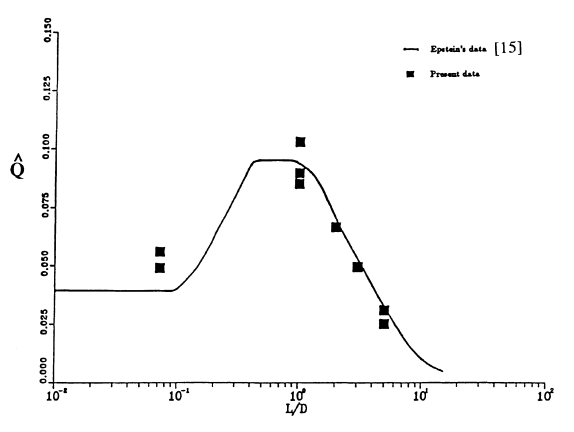


Fig. 6. Comparison between the current volume flow rate data for $\Delta p = 0$ with those of Epstein [15].

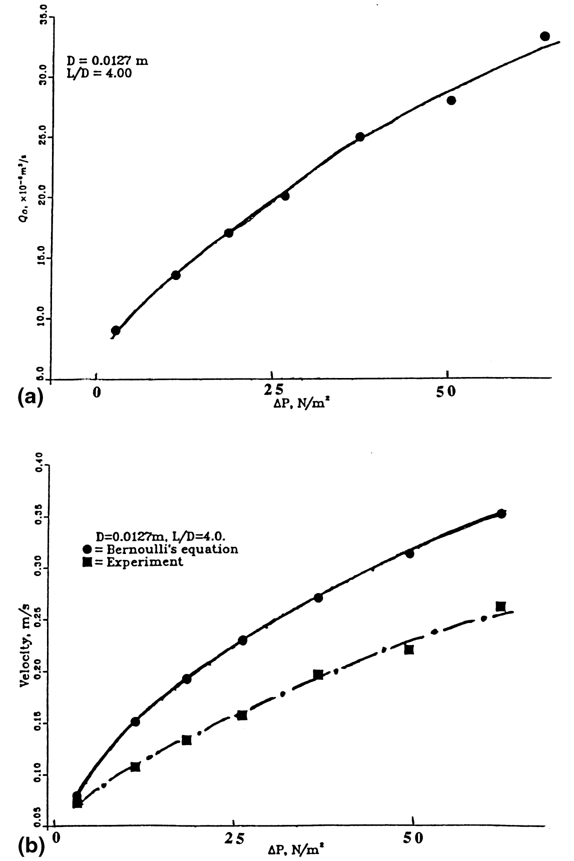


Fig. 7. Experimental results for the unstratified circumstance, $\Delta\rho = 0$: (a) volume flow rate $Q_0$ versus $\Delta p$; (b) average velocity versus $\Delta p$ from the experiment and from Bernoulli's equation.

$C_D$ may be determined from these results. The range of values is consistent with the value of 0.61 given in the literature [9,10].

Some typical results on the critical, or flooding, pressure difference $\Delta p_c$ for different values of $g\Delta\rho D$ and $L/D$ are shown in Fig. 8. The measured values are in the range that may be obtained by considering the magnitudes of the pressure and buoyancy effects, as outlined earlier. The results were found to be repeatable, within a few percent, of the measured values. However, the transition from bidirectional to unidirectional flow was found to be a fairly gradual one, indicating the downflow $Q_d$ to gradually reduce to zero as the pressure difference $\Delta p$ is increased. With increasing values of $g\Delta\rho D$, at a given $L/D$, the purging pressure difference $\Delta p_c$ was found to increase, as expected. Also, if $L/D$, increases for a given diameter $D$, the purging pressure is expected to increase because of the larger vertical distance $L$ which results in a greater buoyancy effect. This is the trend seen in Fig. 8(b). However, a more complicated dependence on $L/D$ is observed in Fig. 8(a), where a wider range of

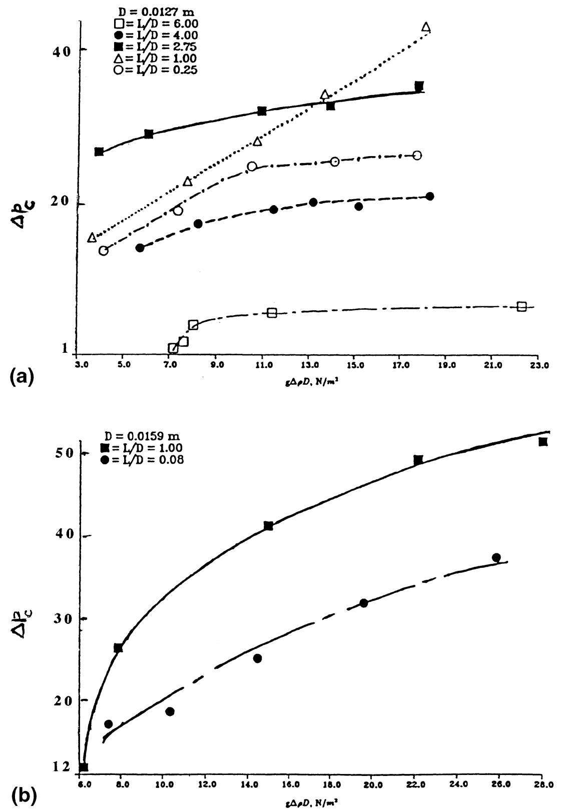


Fig. 8. Measured purging pressure difference $\Delta p_c$ in N/m$^2$ as a function of the buoyancy effect, characterized by $g\Delta\rho D$.

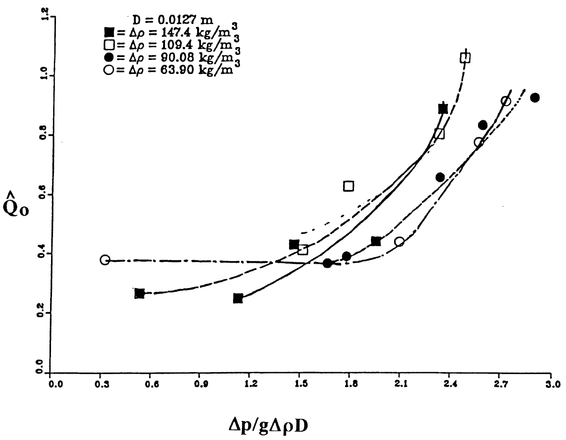


Fig. 9. The dependence of the dimensionless net flow rate $\hat{Q}_0$ near purging conditions on the dimensionless parameter $\Delta p/(g\Delta\rho D)$ at $L/D = 4.0$.

values is presented. This is similar to the results of Epstein [15] for zero $\Delta p$ and suggests different flow regimes over the given range of $L/D$. Several other results were obtained and this figure shows the characteristic behavior.

The dependence of the dimensionless flow rate $\hat{Q}_0$ at purging on the dimensionless buoyancy parameter $B$ was also investigated. Fig. 9 shows $\hat{Q}_0$ as a function of $B$ for a given diameter $D$ and different values of $\Delta\rho$, at $L/D = 4.0$. The flow rate is found to increase with the pressure difference $\Delta p$, at given $\Delta\rho$. As discussed earlier, the flooding pressure is of the same order as the buoyancy effect $g\Delta\rho D$, and, therefore, $B$ is expected to be of order unity, as seen in the figure. However, the purging condition is not very sharply defined and the transition from bidirectional to unidirectional flow is a gradual one. Therefore, an increase in the flow rate with the pressure in the vicinity of the purging condition is physically expected.

The net upward flow rate $Q_0$ was also measured and the other flow rates $Q_u$ and $Q_d$ determined from the measurements of density and net fluid flow in the upper region. Fig. 10 shows some of the characteristic results obtained at different values of the density difference $\Delta\rho$, for fixed values of the pressure difference $\Delta p$. As mentioned earlier, at zero $\Delta p$, the upward and downward flow rates are equal, yielding a zero net upward flow $Q_0$. This trend is confirmed by the observation that the upward and the downward flow rates approach each other as the density difference increases or as the pressure difference decreases. As the pressure difference increases, the flow rate $Q_0$ increases, with the effect of the density difference $\Delta\rho$ diminishing. Also, $Q_0$ decreases with increasing $\Delta\rho$, indicating the effect of increasing buoyancy that tends to curb the net upward flow. At very low pressure differences, the density difference effects dominate the flow across the vent. The results are obtained for a wide range of $L/D$ ratios. The trends are found to be quite sensitive to the value of $L/D$, as observed by Epstein [15] for the pure buoyancy case. Thus, the $L/D$ ratio is found to be an important parameter and $(g\Delta\rho L)$ indicates the buoyancy effect more appropriately than $(g\Delta\rho D)$, which applies for $L/D \to 0$.

Fig. 11 shows the corresponding results for varying $\Delta p$ at fixed values of the density difference $\Delta\rho$. The net flow rate $Q_0$ increases with $\Delta p$, as expected. A larger density difference $\Delta\rho$ results in smaller net flow rate $Q_0$, as seen earlier. At large pressure differences, the upward and net flow rates approach each other. Thus, these results indicate the basic characteristics and complexity of this flow in vented enclosure fires.

Several such experiments have been carried out and effort was also directed at the interpretation of the data and at obtaining appropriate equations to correlate the data. For $0.25 < L/D < 6.08$, $0.043 < \Delta\rho/\bar{\rho} < 0.13$, and $30 \leqslant \Delta p \leqslant 100$ N/m$^2$, the correlating equations for $Q_0$ and $Q_u$ (m$^3$/s) were obtained for a circular vent as

$$Q_0 = 2.313 \times 10^{-7}(\Delta p + 30.12)^{0.914}(\Delta\rho)^{-0.157}(L/D)^{0.037}, \quad (10a)$$

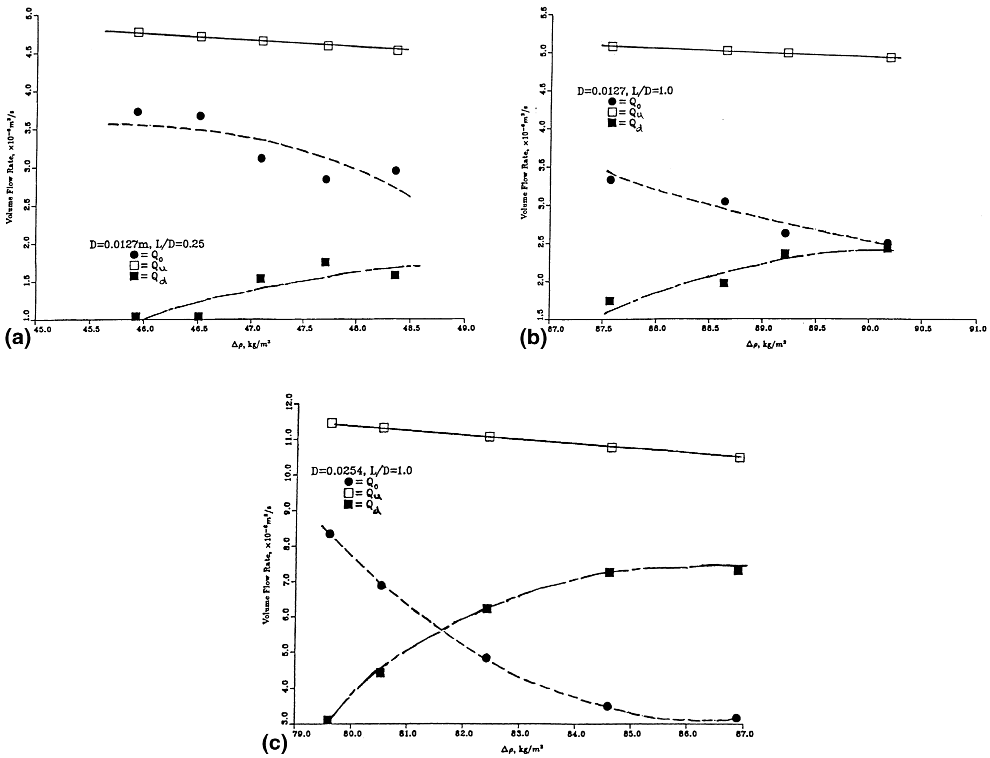


Fig. 10. Measured volume flow rates for varying $\Delta\rho$ at fixed $\Delta p$: (a) $\Delta p = 11.75\ \mathrm{N/m^2}$, $D = 0.0127$ m, $L/D = 0.25$; (b) $\Delta p = 26.18\ \mathrm{N/m^2}$, $D = 0.0127$ m, $L/D = 1.0$; (c) $\Delta p = 49.20\ \mathrm{N/m^2}$, $D = 0.0254$ m, $L/D = 1.0$.

$$Q_u = 5.048 \times 10^{-7}(\Delta p + 30.12)^{0.871}(\Delta\rho)^{-0.239}(L/D)^{0.030} \tag{10b}$$

with correlation coefficients of order 0.9. The repeatability of the flow rate results was in the order of 10% of the measured values and around 40 experiments were used in deriving these equations. The constant in the parentheses with $\Delta p$ is due to reference conditions in the experiment. Thus, from these equations, the net volume flow rate across the vent, as well as flow rate of fluid entering the upper compartment, may be determined for given values of $\Delta\rho, \Delta p$ and $L/D$. The flow $Q_d$ into the lower compartment may also be obtained using mass conservation. From the ambient concentration of oxygen, this estimate would yield the amount of oxygen entering the enclosure and the resulting energy release rate of the fire [13]. The fire in a chamber with a small opening was found to give rise to a periodically growing and decaying fire due this effect [20]. As the pressure builds up, unidirectional flow may arise, as shown here, resulting in zero oxygen flow into the chamber across the vent and consequent decay of the fire. This, in turn, causes the pressure difference to decrease and the inflow of oxygen to occur again, resulting in a growing fire. Thus, a periodic increase and decrease in the energy release rate arises. For other typical conditions, the actual flow rates across the vent may be determined for predicting the growth of the fire and the outflow of the combustion products.

The results may also be given in terms of the dimensionless parameters $\hat{Q}_0$ and $B$. Fig. 12 shows the typical trends observed in these results. The physical behavior is as expected, with the net flow rate increasing with increasing pressure difference $\Delta p$ and/or decreasing density difference $\Delta\rho$. On the basis of such results, the flow discharge coefficient $C_D$, as defined in Eq. (5) may be determined. This discharge coefficient is given as around 0.61 for an orifice, if buoyancy effects are neglected [9,10]. However, as seen in this work, the net flow rate decreases if the opposing buoyancy effects are increased. Therefore, the discharge coefficient may be correlated in terms of the buoyancy parameter $B$ and $L/D$. A correlation obtained from the data over the parametric ranges considered is of the form

$$C_D = 0.61 - 0.0797B^a(L/D)^b, \tag{11}$$

where the constants $a$ and $b$ are obtained as 0.225 and 0.028, respectively, for $0.2 \leqslant B \leqslant 2.0$, with a correlation coefficient of around 0.8. This indicates the greater inaccuracy and uncertainty of correlating the data in terms

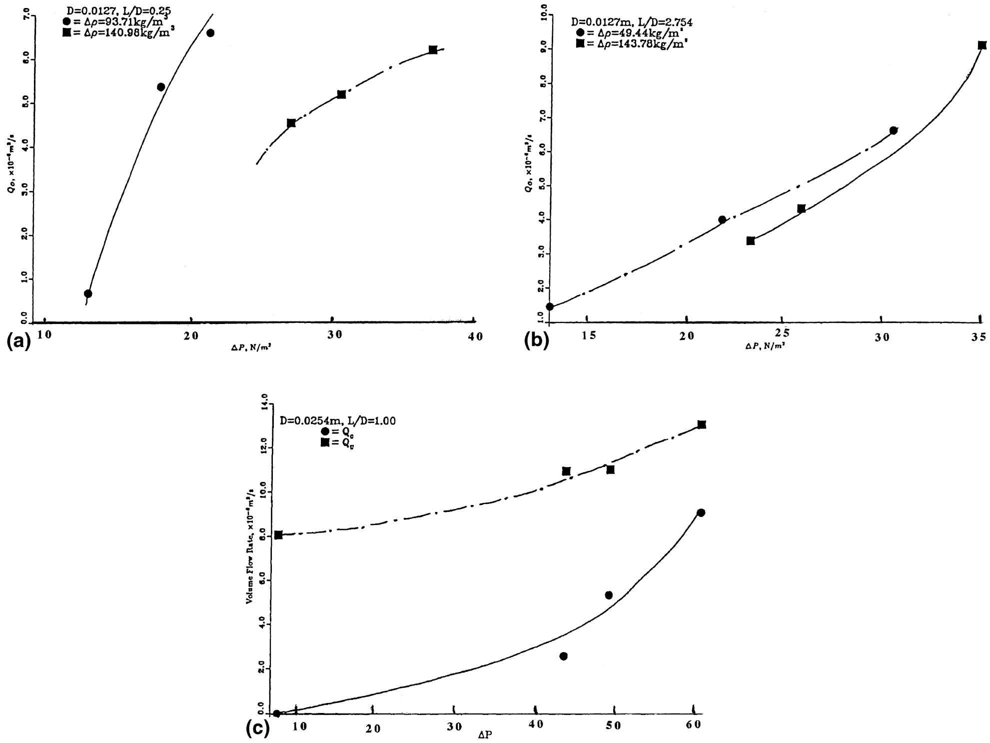


Fig. 11. Measured volume flow rates versus the pressure difference $\Delta p$ at fixed $\Delta\rho$: (a) $D = 0.0127$ m, and $L/D = 0.25$; (b) $D = 0.0127$ m, and $L/D = 2.75$; (c) $\Delta\rho = 84.42$ kg/m$^3$, $D = 0.0254$ m, and $L/D = 1.0$.

of $C_D$ and $B$. However, this equation allows the flow rates across the vent to be easily estimated for typical vented-compartment fires. As $B$ approaches zero, the value of $C_D$ approaches 0.61, as expected. Also, the net flow rate decreases as $B$ increases. This result applies as long as the buoyancy effect is not predominant, or the pressure difference is not close to zero. For that case, the earlier results at $\Delta p = 0$ may be employed.

## 4. Conclusions

This paper presents a detailed experimental study on the flow across a horizontal vent in a compartment, with nonzero pressure and density differences across the vent. This flow circumstance is of interest in the prediction of the growth and spread of fires in vented compartments and in multi-room enclosures. It is shown that the use of Bernoulli's equation, with a discharge coefficient, is appropriate only at pressure differences that are much larger than a critical value. This critical, or flooding, pressure difference is determined for a range of density differences and vent aspect ratios. For pressure differences less than the critical value, the buoyancy effects are comparable to the pressure effect and the resulting flow rate is a consequence of the two opposing effects. The flow rates that arise for a fairly wide range of these parameters are determined experimentally and correlated in terms of the governing variables. These correlating equations may be employed to obtain the outflow of the combustion products and the inflow of ambient air across the vent, thus allowing a prediction of fire growth in the compartment. A discharge coefficient $C_D$ is also defined in terms of the flow rates predicted by Bernoulli's equation and the dependence of $C_D$ on the buoyancy parameter $B$, that represents the buoyancy effect as compared to the pressure effect, is also investigated. The results would be valuable in the study and prediction of fire growth and spread in enclosures with horizontal openings and vents.

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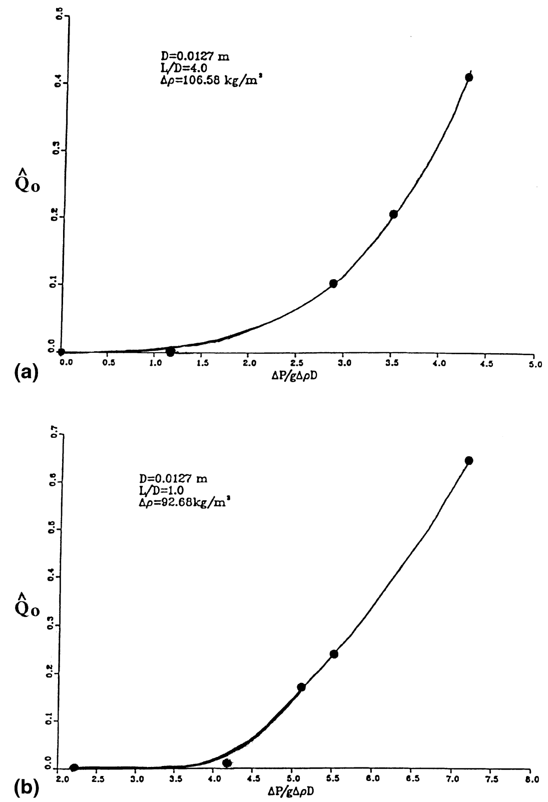


Fig. 12. The dimensionless net flow rate $\hat{Q}_0$ versus the dimensionless buoyancy parameter $B$ for: (a) $\Delta\rho = 106.58$ kg/m$^3$, $D = 0.0127$ m, $L/D = 4.0$; (b) $\Delta\rho = 92.68$ kg/m$^3$, $D = 0.0127$ m, $L/D = 1.0$.

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