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Experimental study of buoyancy driven natural ventilation through horizontal openings

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SUMMARY

An experimental study of buoyancy driven natural ventilation through single-sided horizontal openings was performed in a full-scale laboratory test rig. Measurements were made for opening ratios L/D range from 0.027 to 4.455, where L and D are the length and the diameter of the opening, respectively. The bidirectional air flow rate was measured using constant injection tracer gas technique. Smoke visualizations showed that the air flow patterns are highly transient, unstable and complex, and that air flow rates oscillate with time. Correlations between the Froude number Fr and the L/D ratio were in reasonable agreement with result in literature obtained from brine-water measurements, but the obtained Fr values show considerable deviations for a range of L/D ratios. The measurement results can be used in both simple calculation tools to give a rough estimate of the capacity for design of a ventilation system, but also be implemented in more detailed models, especially multi-zone models, for simulation of the performance of natural ventilation systems

INTRODUCTION

Air flow through horizontal openings is an important issue of mass and energy transfer between different zones in buildings. Horizontal openings occur in staircases, stairwells, ventilation shafts, service shafts and chimneys. Hence mass and energy transfer through them have important implications regarding energy saving, thermal comfort, control of contaminants, micro-organisms and spread of fire and smoke. Air flow through vertical openings has been widely investigated but little is known about the flow in the horizontal openings, especially when they are driven by buoyancy.

A literature survey shows that the brine-water system in scale models is normally used for the research of flow through horizontal openings, Blay and Gautier [1], Mercer and Thompson [2], Reynolds et al. [3], Tan and Jaluria [4]. The earliest experimental work dealing with buoyancy driven flow through single openings in horizontal partitions was made by Brown [5]. Using air as the working fluid, it was shown that exchange flow rates increased with the aspect ratios of opening length (or partition thickness) to the side length of the square opening L/D , in the range of $0.0825 \leq L/D \leq 0.66$. Brown interpreted the countercurrent flow as a heat transfer phenomenon and expressed his results a correlation in terms of a Nusselt number Nu , versus Grashof number Gr .

In Epstein's [6] work, he performed a detailed experimental study for the exchange flow for a single horizontal opening over a large range of aspect ratios $0.01 \leq L/D \leq 10$. He defined correlations between the Froude number Fr and L/D and identified four distinct flow regimes as a function of vent aspect ratio which were named oscillatory exchange flow (Regime I,

$L/D < 0.15$), Bernoulli flow (Regime II, $0.15 \leq L/D \leq 0.4$), Combined turbulent diffusion and Bernoulli flow (Regime III, $0.4 \leq L/D \leq 3.25$), and Turbulent diffusion (Regime IV, $L/D > 3.25$). At very small opening heights ($L/D < 0.15$) the pressure level on both sides of the opening is essentially the same and an oscillatory exchange flow regime will be established (Regime I). For larger values of L/D the flow regime changes from an countercurrent orifice flow regime (Regime II, $0.15 \leq L/D \leq 0.4$) to a turbulent diffusion flow regime for very large values (Regime IV, $L/D > 3.25$). In the turbulent diffusion flow regime the air exchange was much slower and the countercurrent flow within the tube appeared to comprise of packets of warm and cold air with a chaotic and random motion. For intermediate values ($0.4 \leq L/D \leq 3.25$) the flow will be a combination of an orifice flow and turbulent diffusion flow regime (Regime III). According to the four flow regimes, Epstein gave the following relations of Froude numbers and L/D :

$$Fr = \frac{q}{\sqrt{\frac{g(T_i - T_u)L^5}{T_i}}} \quad (1)$$

$$Fr = 0.055 \quad \frac{L}{D} < 0.15 \quad (2)$$

$$Fr = 0.147 \left(\frac{L}{D} \right)^{\frac{1}{2}} \quad 0.15 < \frac{L}{D} < 0.4 \quad (3)$$

$$Fr = 0.093 \frac{1}{\sqrt{1 + 0.084 \left(\frac{L}{D} - 0.4 \right)^3}} \quad 0.4 < \frac{L}{D} < 3.25 \quad (4)$$

$$Fr = 0.32 \left(\frac{L}{D} \right)^{\frac{3}{2}} \quad 3.25 < \frac{L}{D} < 10 \quad (5)$$

Where q is the exchange air flow rate [m^3/s], g is the gravitational acceleration [m/s^2], T_i is the inside temperature [K], T_u is the outside temperature [K], L is the length (or height) of opening [m] and D is the diameter of the opening [m].

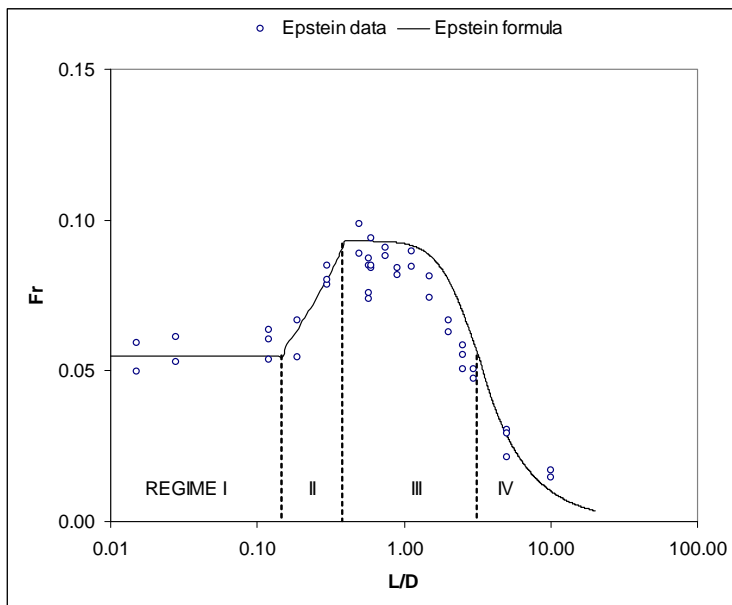


Figure 1. Experimental results for countercurrent exchange flow through a single opening, given by Epstein [6].

Figure 1 shows the experimental results used as basis for the developed relations by Epstein for the four different flow regimes.

This research work is focused on obtaining the air flow rate through the horizontal openings driven by buoyancy. The experimental analysis was carried out in a full-scale laboratory test rig. The basic nature of air flow through a single horizontal opening was measured. The measurement results can be used in both simple calculation tools to give a rough estimate of the capacity for design of a ventilation system, but also be implemented in more detailed models, especially multi-zone models, for simulation of the performance of natural ventilation systems.

METHODS

The experimental analysis of buoyancy driven natural ventilation through horizontal openings was performed in a laboratory of Indoor Environmental Engineering at Aalborg University. The essential features of the experimental system for the case of a single opening are schematized in Figure 2.

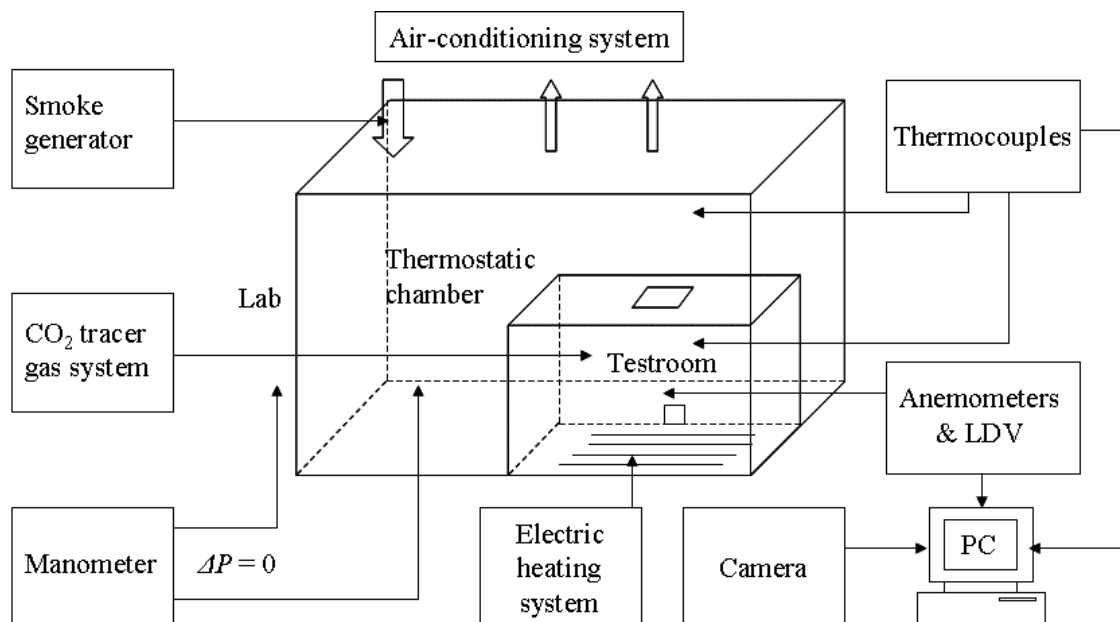


Figure 2. Schematic representation of system and measurement equipments.

The experiments were carried out in a full-scale test cell which was divided into two rooms, namely the “thermostatic chamber” and the “testroom”. The thermostatic chamber was 8 m length, 6 m width and 4.7 m height; and the testroom was 4.1m length, 3.2 m width and 2.7 m height, respectively. The thermostatic chamber simulated the environmental conditions controlled accurately by an air conditioner. Only one square horizontal opening was located on the roof center of the test room. The higher indoor temperature was produced by heating cables uniformly distributed on the floor inside the testroom. CO₂ constant injection tracer gas system, thermocouples, anemometers and Laser Doppler Velocimetry (LDV) were used to measure the air flow rate, air temperatures and air velocities respectively. Special attention was paid to ensure the pressure difference to be zero between the chamber and the laboratory hall in order to avoid unnecessary errors of infiltration and exfiltration. Different cases were examined by varying the temperature differences of inside and outside of the test room, the

opening area and the opening ratio L/D . The measurements were carried out with a single square opening of side length 0.2 m, 0.4 m, 0.6 m, 0.8 m and 1.0 m, so the opening area varied from 0.04 m² to 1.0 m².

The roof thickness of the test room is 0.13 m, and the opening height varied from 0.13 m to 1.0 m, thus the opening ratios L/D might vary in the range from 0.115 to 4.455. In order to measure the L/D ratios in the flow regime I, an insulated metal plate with thin thickness 0.012 m and side length 1.0 m was used and located on the test room roof center. A square hole was opened with different side length 0.1m, 0.2m, 0.3m and 0.4m, therefore the L/D ratios from 0.027 to 0.106 could be obtained for flow regime I.

In this study only square openings were used. For a square opening with a side length S , D should be viewed as the diameter of a round opening that has the same area as the square opening described by the following relation:

$$D = \sqrt{\frac{4}{\pi} S^2} = 1.128 \cdot S \quad (6)$$

The tracer gas system included injection and distribution devices, a flow meter and tracer gas sampling apparatuses. Six monitor points for CO₂ concentrations was used to determine whether the equilibrium state was reached or not. When the equilibrium steady state was reached, a couple of fans were used to maintain homogenous mixing of the tracer gas in the room air and to measure the $C(\infty)$ after the opening was closed and the tracer gas supply stopped. According to the constant injection tracer gas theory, the constant air flow rate at steady state can be obtained by the equilibrium concentration:

$$q = \frac{q_{\text{tracer}}}{C(\infty) - C(0)} \quad (7)$$

Where q is the air flow rate [m³/s], q_{tracer} is the tracer gas constant injection flow rate [m³/s], $C(\infty)$ is the equilibrium concentration of the CO₂ tracer gas, $C(0)$ is the CO₂ concentration of the atmospheric air about 390 ppm.

RESULTS

Smoke visualization

The air above the opening has a lower temperature and a higher density and the air below the opening. This density difference creates a buoyancy driven down flow of more heavy air from the upper thermostatic chamber to the lower test room. Since the test room is sealed, mass conservation dictates up flow of the lighter air. In the case of a single opening, this situation gives rise to bidirectional exchange flow across the horizontal opening. In order to get a better understanding of this bidirectional flow, smoke visualizations were carried out. The air flow pattern in steady state conditions near the opening was observed during the experiment. The smoke was introduced in the thermostatic chamber or in the test room, thus the down flow or up flow was observed. The smoke visualizations showed that the bidirectional air flow is highly transient, unstable and complex. In the full-scale airflow measurements, it is difficult to observe the flow pattern differences for different flow regimes by means of smoke visualization.

Air flow rate at different openings and L/D

Figure 3 to 7 compares the measured air flow rate as a function of temperature difference for different flow regimes with calculated data from Epstein's formula.

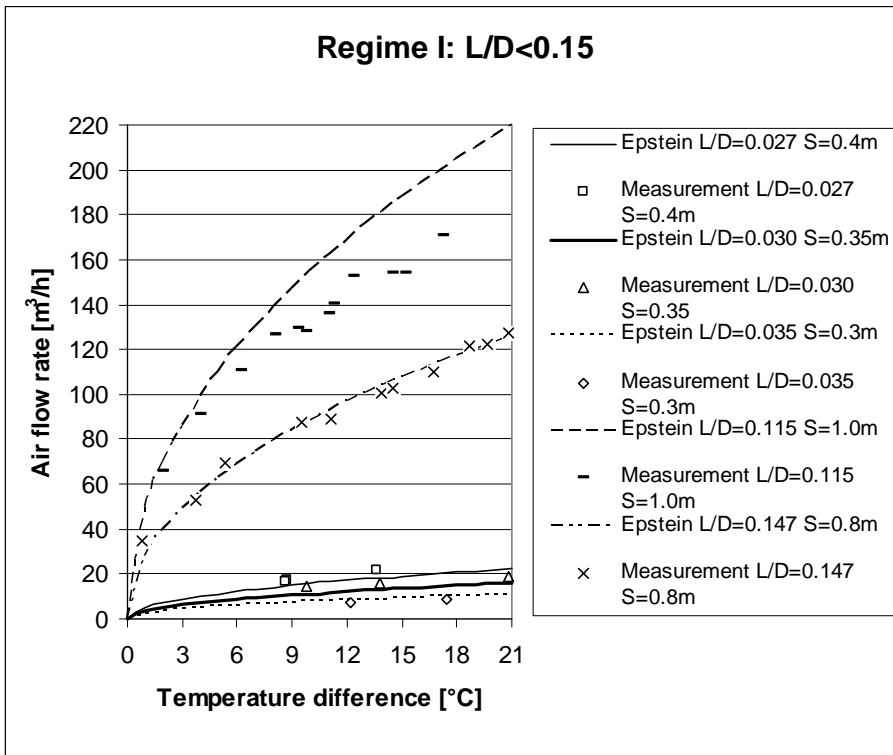


Figure 3. Comparisons of measured and predicted air flow rate as a function of temperature difference for flow regime I.

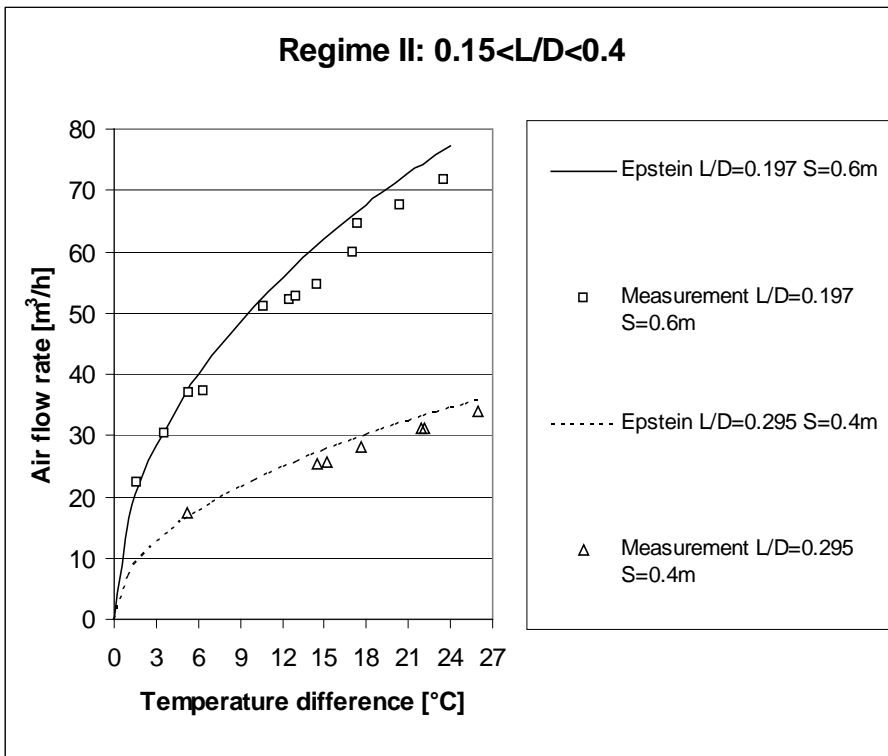


Figure 4. Comparisons of measured and predicted air flow rate as a function of temperature difference for flow regime II.

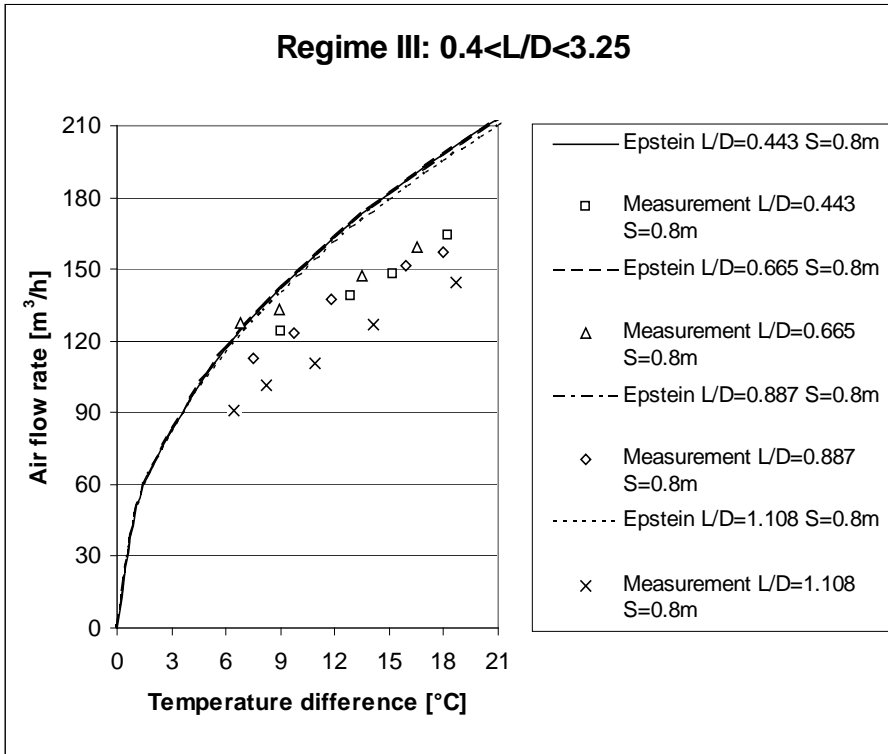


Figure 5. Comparisons of measured and predicted air flow rate as a function of temperature difference for flow regime III.

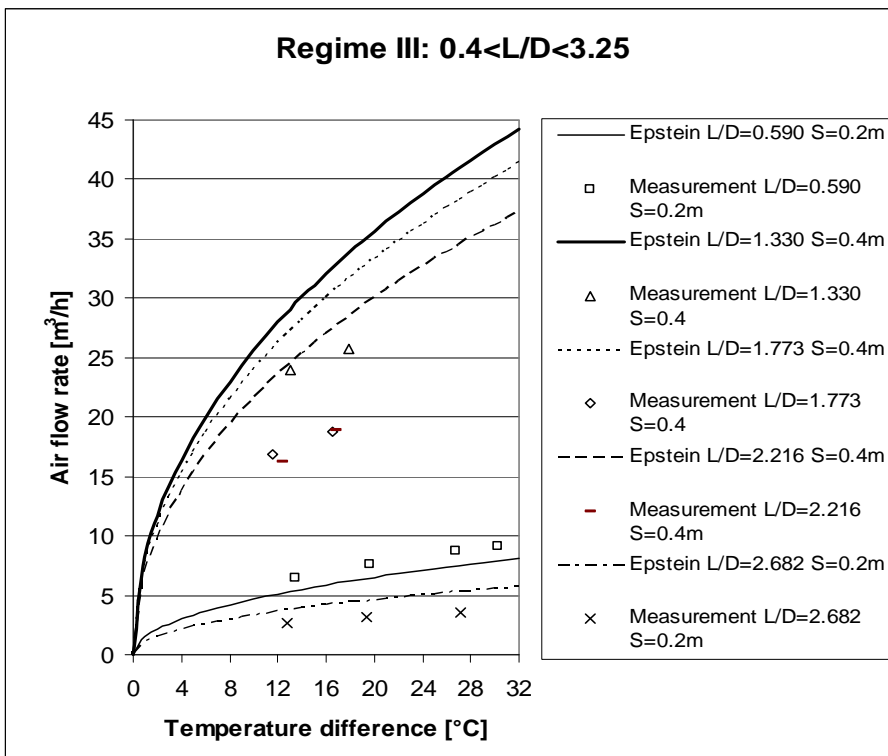


Figure 6. Comparisons of measured and predicted air flow rate as a function of temperature difference for flow regime III.

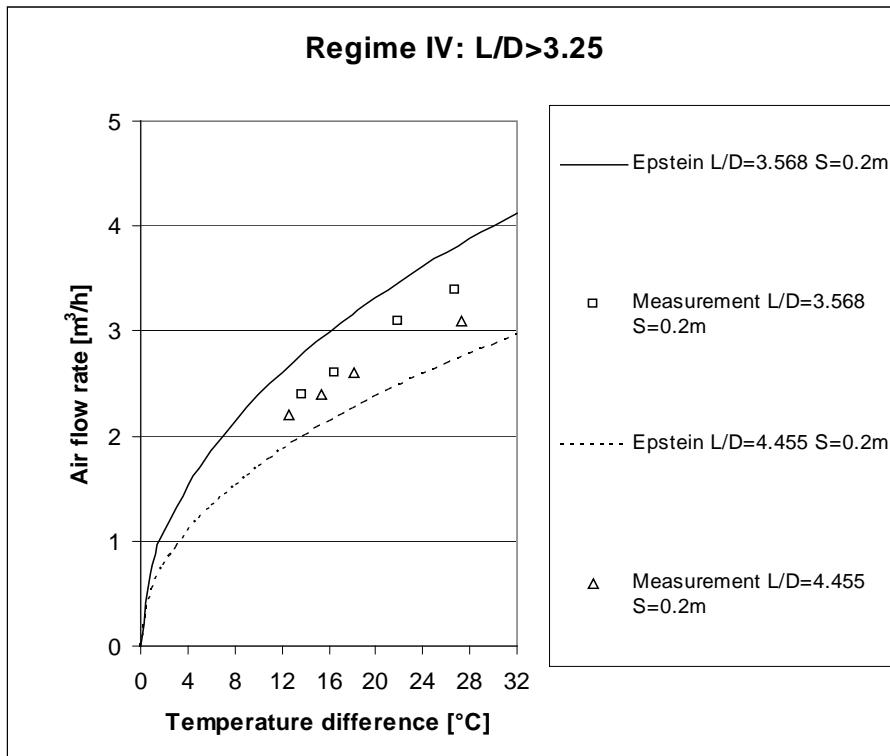


Figure 7. Comparisons of measured and predicted air flow rate as a function of temperature difference for flow regime IV.

Generally, the deviations between the measured data and predictions made with Epstein's formula increase when the temperature difference increases. The air flow rate also changes significantly in the horizontal openings with different L/D ratio. In some cases the measured air flow rate fit quite well with the Epstein's formula, such as the case of $L/D = 0.147$, $S = 0.8$ m in flow Regime I and the case of $L/D = 0.295$, $S = 0.4$ m in flow Regime II; but in some cases the measured data show clear deviations with the Epstein's formula, such as the case of $L/D = 1.108$, $S = 0.8$ m and the case of $L/D = 1.773$, $S = 0.4$ m in flow Regime III.

For example in Figure 5, the flow rates estimated by Epstein formula have no significant differences when L/D ranged from 0.443 to 1.108, but the experimental measurement indicates that the air flow rates vary significantly at these L/D ratios. At a temperature difference of 10°C, the air flow rates are 127.5, 136.6, 125.4 and 107.3 m³/h for the experimental measurements corresponding to the L/D ratio of 0.443, 0.665, 0.887 and 1.108, but the air flow rates corresponding to these L/D ratios are 149.7, 149.6, 149.0 and 147.6 m³/h when predicted by Epstein formula. The Epstein formula overestimates the air flow rates for these L/D values at the opening size of $S = 0.8$ m.

In order to compare the full-scale air flow measurement data with the Epstein's brine-water scale measurement data, Figure 9 shows all data as Froude numbers versus the L/D ratio for both measurement series.

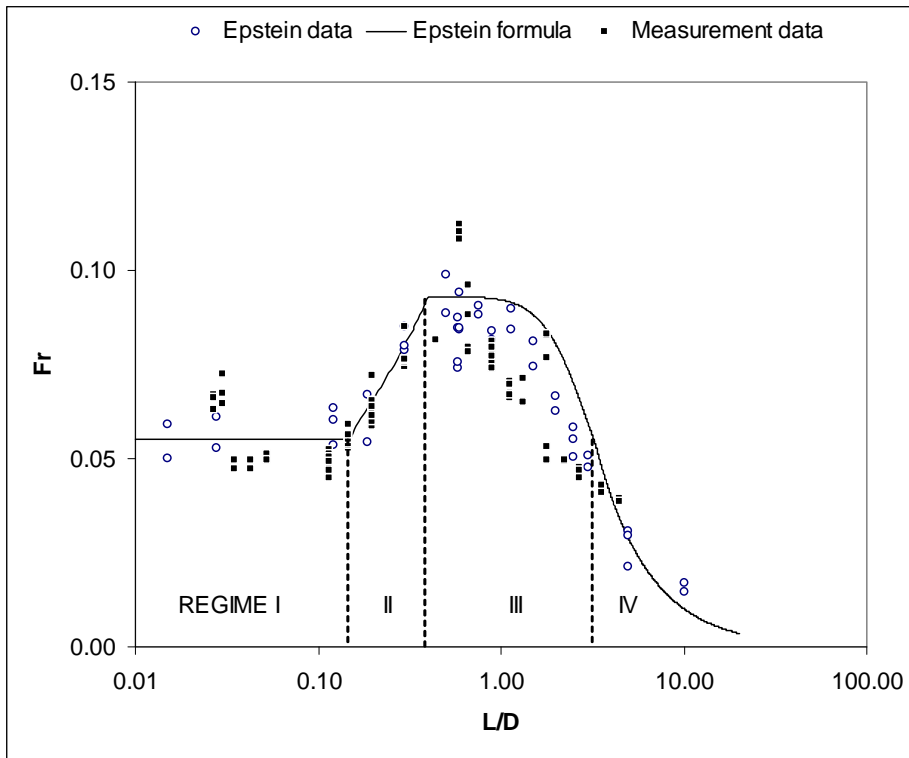


Figure 9. Comparison of full-scale air flow measurement and the Epstein brine-water scale measurement expressed by the Fr number as a function of the L/D ratio.

The full-scale measurement data fit reasonable well with the brine-water scale measurements, although significant differences exist between them for certain L/D ratios. For opening ratios L/D from 0.035 to 0.115, the dimensionless air flow rate, expressed by the Fr number, was found to be about 0.050, which is lower than the constant Fr value 0.055 given by Epstein. Conover et al. [7] as well as Sandberg and Blomqvist [8] also found these values lower than 0.055. Their values were between 0.035 and 0.047. When the L/D ratios are 0.027 and 0.03, the Fr number are about 0.067 which is much higher than 0.055. The large deviations at these two points probably take place because the influence of the test room roof thickness, since the opening side length are 0.4 m and 0.35m and not much smaller than the hole's side length of 1.0m. The maximum dimensionless air flow rate was found about 0.11 for L/D = 0.59 in stead of L/D = 0.4, and approximately 15% higher than the peak value 0.095 predicted by Epstein. It can also be seen from Figure 9, that only three different flow regimes can be distinguished in this experimental study: Oscillatory exchange flow (Regime I), Bernoulli flow (Regime II), and turbulent diffusion (Regime IV). The combined turbulent diffusion and Bernoulli flow (Regime III) cannot be identified in this figure.

DISCUSSION

According to the above data analyses, a revised formula can be developed. The value of the Fr number in the experimental study at L/D ratios below 0.115 can be expressed as:

$$Fr = 0.050 \quad \frac{L}{D} < 0.115, \quad (8)$$

Since the measurement data fit the Epstein's formula quite good in the opening ratio L/D range from 0.115 to 0.55, the value of the Fr number at L/D ratios from 0.115 to 0.55 can be expressed as:

$$Fr = 0.147 \left(\frac{L}{D} \right)^{0.5} \quad 0.115 < \frac{L}{D} < 0.55, \quad (9)$$

The major difference in the value of the Fr number was found when the L/D ratio varied from 0.4 to 2.7. The combined turbulent diffusion and Bernoulli flow (Regime III) and turbulent diffusion (Regime IV) could not be distinguished and may be defined by using only one formula as:

$$Fr = 0.077 \left(\frac{L}{D} \right)^{-0.5} \quad 0.55 < \frac{L}{D} < 4.455 \quad (10)$$

The comparison of the relation between the dimensionless number Fr as a function of L/D ratio developed in this work and the ones developed by Epstein can be seen in Figure 10.

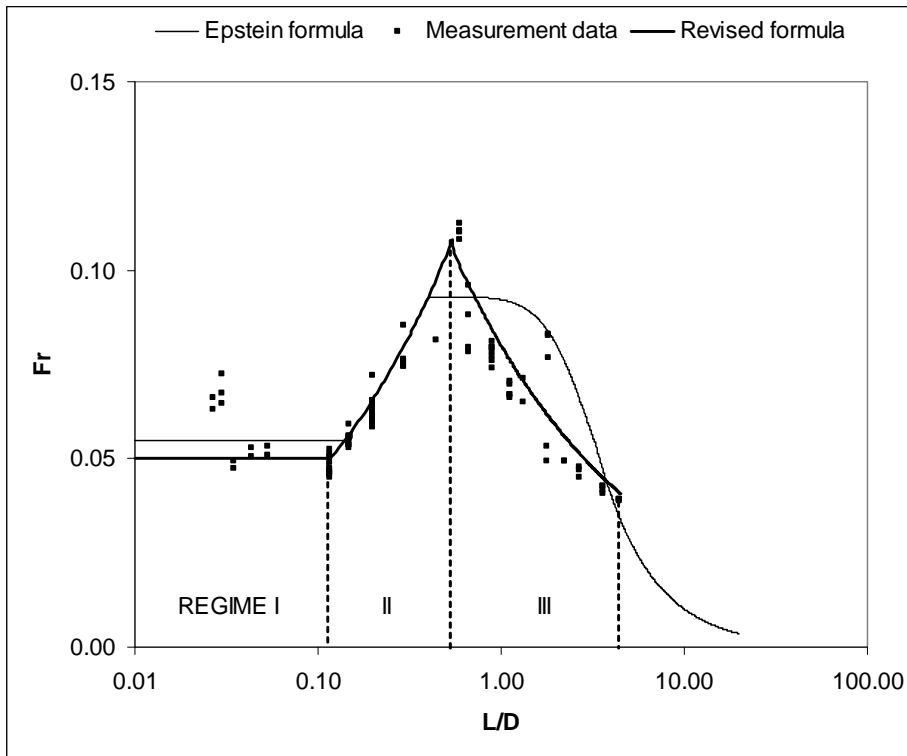


Figure 10. Comparison of the relation between the dimensionless number Fr and L/D ratio developed in this work and the relations developed by Epstein [6].

ACKNOWLEDGEMENT

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