TRANSITION FROM BI-DIRECTIONAL TO UNIDIRECTIONAL FLOW IN A DOORWAY

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1. ABSTRACT

The air flow in a doorway is governed by density difference caused by temperature difference and pressure difference caused by mechanical ventilation. Tests have been carried out in a unique indoor test house where the room to room to temperature difference could be controlled very accurately with a new control system. In addition to these tests some tests were carried out in a scale model with water as the operating fluid.
Two main criteria of unidirectional flow in a doorway have been explored:

1a. The recorded mean velocity is unidirectional
1b. The neutral height is equal to the height of the door
2. Unidirectional flow in the sense that there is no transfer of contaminant from one room to another.

To explore condition one the velocity profile in the doorway have been recorded by transversing the door opening. Condition two has been explored by using tracer gas technique.

2. KEYWORDS

Air flow pattern, Air velocity, Convection flows, Full-scale experiments, Tracer gas

3. INTRODUCTION

3.1 Theory

The flow in a door way can be caused by several mechanisms of which the two most important are:

- Density difference caused by temperature differences, ΔT
- Pressure differences caused by mechanical ventilation

In practice there is a combination of both. A flow driven by density difference, characterised by its reduced gravity $g'=g\Delta\rho/\rho=g\Delta T/T$, through an aperture with area A=hw and located in a partition wall with height H and width W can be written as:

$$q_e = f(\frac{w}{h},\frac{w}{W},\frac{h}{H},Gr)\cdot A\cdot(g'\cdot h)^{1/2} \quad (1)$$

Where the first three factors are aspect ratio of the door way, contraction in width and contraction in height. Gr is the densiometric Grashof number.
For a given geometry equation(1) can be cast into :

$$q_e = f(Gr)\cdot A\cdot(g'\cdot h)^{1/2} \quad (2)$$

For a fixed doorheight equation (2) implies the densiometric Grashof number is a function of the temperature (density) difference only. The presence of a temperature dependence has been observed by Kiel and Wilson (1989) and Fritsche and Lilienblum (1968).

The flow, q_s , required for transition from bi-directional to unidirectional flow can be parameterised as:

$$q_s = C(\Delta\rho)\cdot A(g'h)^{1/2} \quad (3)$$

The constant C(Δρ) is known for some types of flows (for a review, see Etheridge & Sandberg (1996)) Using the Bernoulli equation the constant becomes $\sqrt{8/3} \approx 0.94$. For a two layer hydraulics model the constant is equal to one. One aim of this project is to determine the constant experimentally.
An important circumstance is that the theory only predicts when transition from bi-directional to unidirectional flow occurs for the time averaged flow. There may still be time dependant flow (turbulent fluctuations) that transports contaminants between the rooms. In practise one wants to know when there is ***fully*** unidirectional flow in the sense there is no transport of contaminants in the direction opposite to the main direction flow.

3.2 Ongoing research

Results of measurements of air speed in doorways and contaminant spread within a building have been reported by Blomqvist, Sandberg (1996,1997) and numerical simulations on the same issue have been reported by Björsell (1996).

The aim of this paper is to report on full scale experiments carried out in order to find out the air flow that is needed to achieve fully unidirectional flow in a doorway. During the experiments extract air flow as well as temperature differences have been varied The work includes both tracer gas measurements and air velocity measurements.

4. METHODS

4.1 Test house

For the experimental work has been used a unique test house in the laboratory of the department. The house is built up to look like an ordinary Swedish apartment consisting of five rooms including hall, kitchen and bathroom (Figure 1). The height of the doors are 2.0m and the width 0.7m and 1.2m (living room door). The ceiling height is 2.5m. The mechanical ventilation system of the house can easily be changed so it is possible to obtain any system desired.

With a computer controlled system for release of tracer gas it is possible to use any type of tracer gas method. The pressure and temperature can be recorded in each room. To be able to measure the flows through the door ways there is a computer controlled traversing unit in each door way. Each of these traversing units is equipped with 10 thermistor anemometers mounted at different heights. The anemometer was developed in house by Lundström et al. (1990) and is of the omnidirectional type.

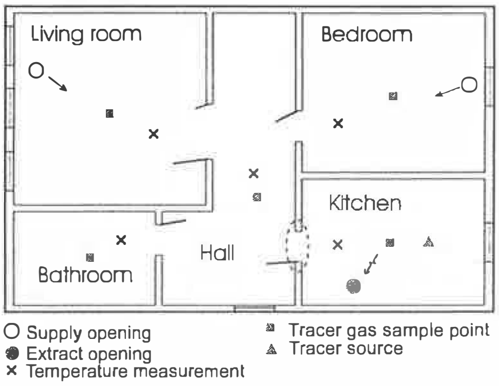

Figure 1 Test house

4.2 Test conditions

In the test apartment was installed mechanical extract ventilation with one exhaust opening in the kitchen. The supply air was taken from the laboratory hall through two openings in the ceiling of the living room and bedroom. The exhaust air flow rate was measured by means of orifice plates. To obtain a suitable temperature difference between the rooms electrically heated radiators were installed in all rooms. The electrical power of the heaters was 1000W each. The apartment was originally equipped with ordinary commercial temperature regulators. The performance of those regulators has shown to cause temperature oscillations in the rooms. Because of the fact that even very small temperature differences between the rooms cause large bi-directional air flows in the door ways (see figure 5), it has been necessary to improve the temperature control in the test apartment in order to get steady state conditions. To solve the

problem the regulators have been replaced by a computer based control system.
Table 1 shows the conditions for the 18 test cases. The table shows that for most of the cases the actual temperature differences have not differed more than 0.1°C from the desired(target) value.

Temperature differences between rooms		
Flow rate [l/s]	Set value [°C]	Actual value [°C]
25	0.0	0.08
25	0.3	0.31
25	0.6	0.46
37.5	0.0	0.09
37.5	0.3	0.26
37.5	0.6	0.57
50	0.0	0.09
50	0.3	0.36
50	0.6	0.62
60	0.0	0.08
60	0.0	0.10
60	0.3	0.32
60	0.6	0.62
75	0.0	0.09
75	0.3	0.35
75	0.6	0.60
100	0.3	0.41
100	0.6	0.62

Table 1. Test conditions for the 18 cases

4.3 Measurements

A computer controlled unit equipped with thermistor anemometers at 10 different heights was installed in the door opening. The air speed was measured at the ten heights and at seven horizontal positions in the door opening. At each position the velocity was recorded and averaged over a time period of ten minutes. The flow was visualised by smoke to determine the direction of the flow and the flow rate was calculated by integration over the door aperture.

Temperatures were measured by means of thermocouples at four different heights in each room at the cross marks in figure 1. The values in table 1 are calculated from those thermocouples

To detect any transport of contaminant from the kitchen to the neighbouring hall a constant flow of tracer gas was released in the kitchen at the triangle mark (figure 1). A small fan was used to mix the tracer into the ambient air. The concentration of the tracer was then recorded in each room until steady state conditions were reached.

5. RESULTS

5.1 Tests in scale model

Figure 2 shows the establishment of the bi-directional flow when tests were carried out in a model with water as operating fluid. The relative density difference corresponds to a room to room temperature difference of 1°C. One can observe that the outflowing heavy dark fluid flows as a density current along the floor whereas the lighter fluid exhibits a plume like flow.

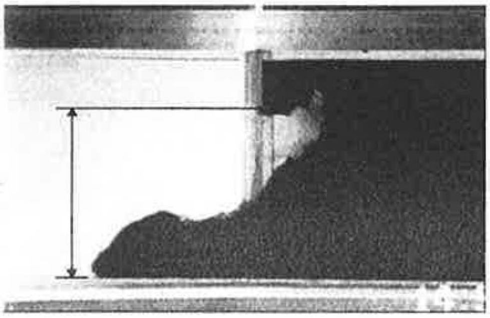

Figure 2. Scale model (water). Visualisation of bi-directional flow in a doorway. The arrow indicates the height of the doorway.

5.2 Air flow measurements

Figure 3 shows the result from air speed and temperature measurements in the door way for two air flow rates (37.5 l/s and 50 l/s). The target temperature difference has been 0.0°C and the actual difference can be read out in the figure. For extract air flows greater than or equal to 50 l/s unidirectional flow has been detected in the doorway when the temperature difference has been 0.1°C. When the temperature difference was increased unidirectional flow could not be established even at the maximum possible flow (100 l/s).

The direction of the flow was detected by manual smoke visualisation and the values in the figure represent the speed of air rather than the component perpendicular to the plane of the doorway. The smoke tests showed that the air velocities were strongly dependant of time both in speed and direction. At levels about half of the total height of the doorway vertical air movements were common. Because of these difficulties to determine the direction of the air movements the accuracy of the flow rate calculated from the velocity measurements is expected to be rather poor.

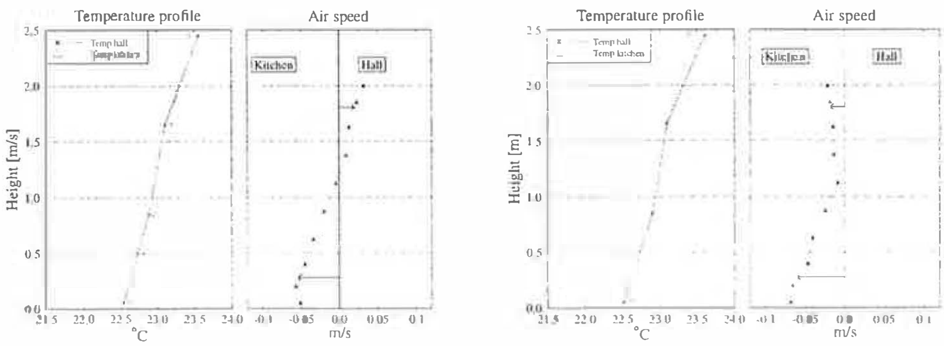

Figure 3. Temperature and air velocity profiles in the doorway at 37.5 l/s (left) and 50 l/s (right) extract air flow rate. h_n is the neutral height.

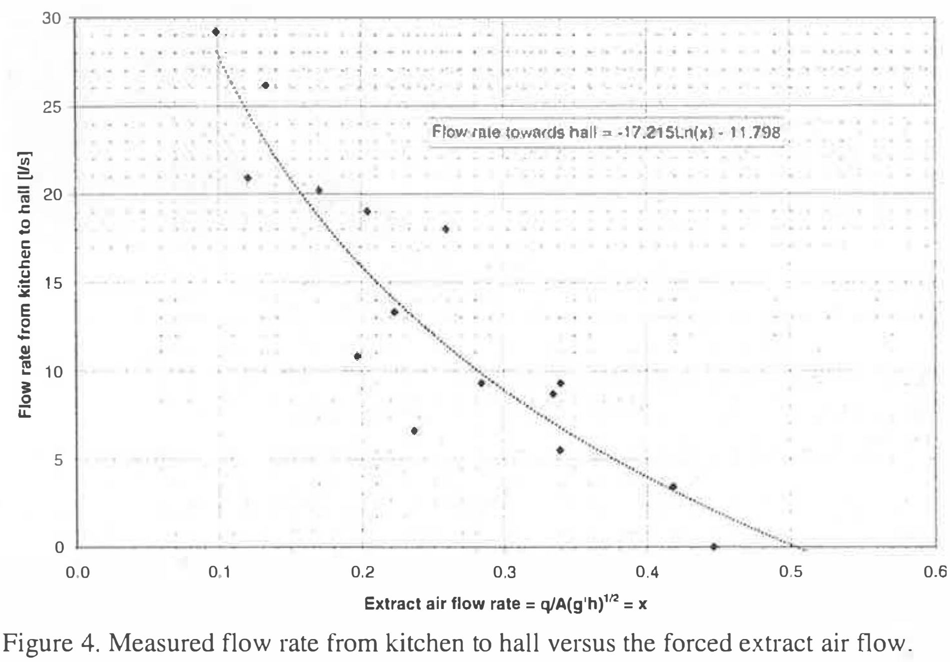

Figure 4. Measured flow rate from kitchen to hall versus the forced extract air flow.

Figure 4 shows the air flow calculated from the velocity measurements. The logarithmic curved fitted to the measured values can be extrapolated to zero where unidirectional flow is achieved.

Figure 5 shows the neutral level in the doorway. The neutral level is defined as the level in the doorway where the air velocity changes direction. When there is no forced flow and the density difference between the rooms is small one should expect the neutral height to be located at about half the height of the doorway.

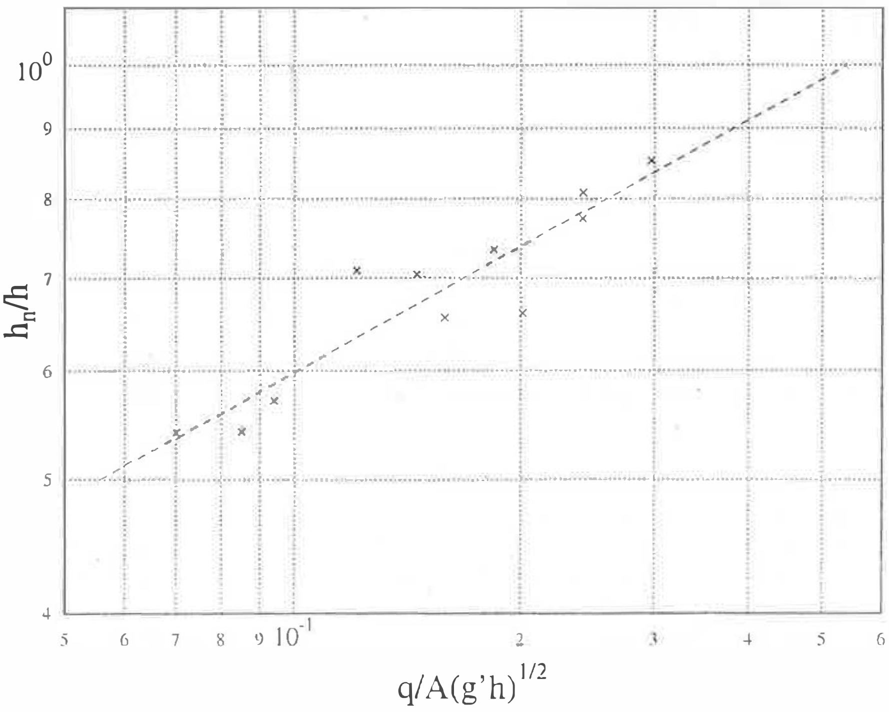

Figure 5 The neutral height in the doorway versus flow rate (non-dimensional)

The curve in figure 5 describing the shift in the location of the neutral height follows the relation:

$$\frac{h_n}{h} = 1.206 \cdot \left(\frac{q}{A(g'h)^{1/2}} \right)^{0.305} \tag{4}$$

For a Bernoulli type of flow model the exponent is 2/3.

5.3 Tracer gas measurements

The results of the tracer gas measurements for all cases are shown on non-dimensional form in figure 6. The concentration is shown in percentage of the concentration in the kitchen. The curve in figure 6 follows approximately the relation:

Fraction of concentration =

$$= 0.0022 \cdot \left(\frac{q}{A(g'h)^{1/2}} \right)^{-3.0044} \tag{5}$$

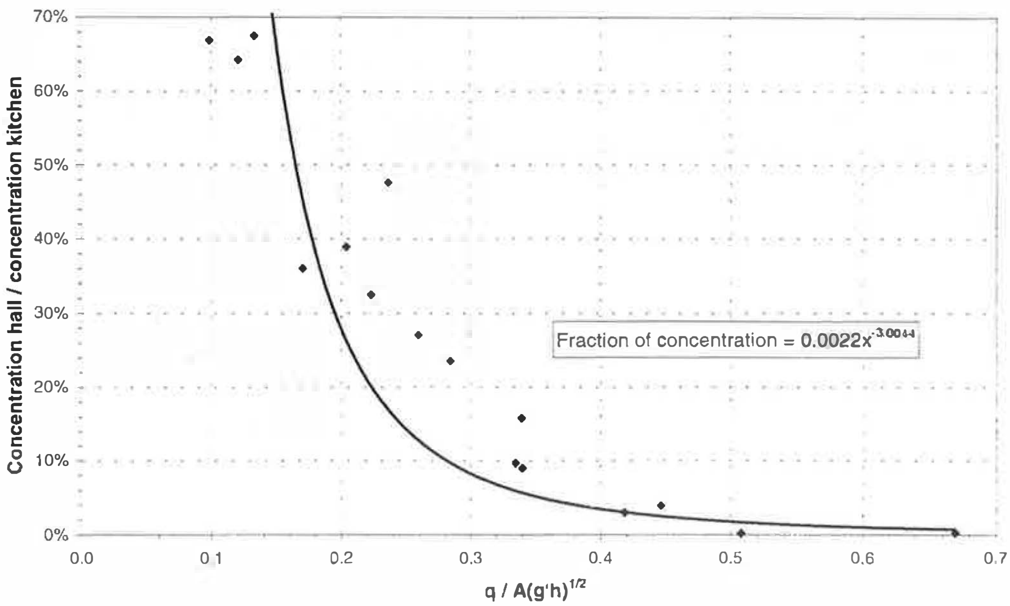

Figure 6. Leakage of tracer gas from the kitchen to the hall

6. DISCUSSION

Using the criteria that the recorded mean velocity in unidirectional the constant in relation (3) becomes C=0.50. The value can be read out of the relation that is described in figure 4. According to relation (5) the fraction of concentration is then 1.8 %

When the neutral level is equal to the height of the door the flow can be assumed to be uni-directional. According to figure 5 this occurs for C=0.54. According to relation (5) the fraction of concentration is then 1.4 %.

Figure 7 summaries the result. The flow rate, q_s , required according to the theory (equation (3)) to get unidirectional flow is presented for the constants set equal to C= 0.50 and C = 0.54 respectively.

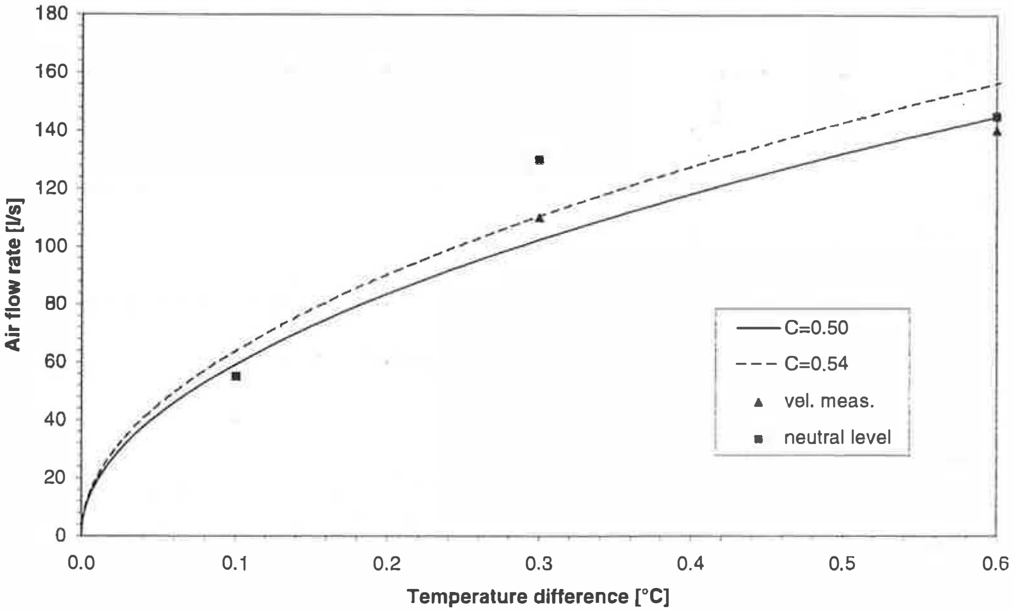

Figure 7. Predicted and measured flow rate needed to get transition to unidirectional flow as a function of the temperature difference (Equation (3) with C=0.50, resp 0.54).

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