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GRAVITY DRIVEN FLOWS THROUGH OPEN DOORS

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SYNOPSIS

Occupants can significantly influence both the heating energy requirements and the indoor air quality of a building by opening and closing doors and windows. If the effects of these actions are to be accurately estimated, both the quantity and character of these exchange flows must be determined. In this paper, data on gravity-driven exchange rates through open doors obtained from field experiments at the Alberta Home Heating Research Facility are compared with laboratory model simulations and theoretical predictions. Experimental results are presented which show that simple theoretical models provide both physical insight and an accurate estimate of air flow through doorways.

Tracer gas techniques and thermocouple arrays were utilized in full scale experiments to determine air exchange rates and gravity current frontal velocities. These tests were conducted over a range of indoor-outdoor temperature differences from 3°C to 45°C. Experiments were also performed using a 1:20 scale model with salt water mixtures to simulate indoor-outdoor temperature differences. In spite of a Reynolds number mismatch of a factor of 7, the model and full scale exchange flow rates and gravity current frontal velocities were in very good agreement when opening times were adjusted using a buoyancy time scale based on Froude number similarity.

NOMENCLATURE

Fr_f	frontal Froude number
g	local gravitational acceleration, m/s^2
g'	effective gravitational acceleration, m/s^2
H	opening height, m
K	door orifice coefficient
L	hallway length, m
Q_n	net flow rate, m^3/s
T_i	indoor temperature, °C
T_o	outdoor temperature, °C
t	time, s
t_{cr}	critical time at which steady flow begins to diminish, s
t_c	closing time from 90° to 0°, s
t_d	duration of decreasing flow, s
t_{eq}	equivalent opening or closing time, s
t_h	fully open hold time, s
t_o	opening time from 0° to 90°
t_s	duration of steady flow, s
U_f	frontal velocity, m/s
U_o	average inflow velocity at doorway, m/s
V	net volume exchange during one opening/closing cycle, m^3
V_c	net volume exchange during the closing period, m^3
V_{cr}	net volume exchange at time t_{cr}, m^3
V_d	net volume exchange during decreasing flow period, m^3
V_h	net volume exchange during the fully open period, m^3
V_H	room volume beneath a horizontal plane at height H, m
V_{max}	maximum net volume exchange, m^3
V_o	net volume exchange during the opening period, m^3
V_s	net volume exchange during the steady flow period, m^3
W	opening width, m

W_c	hallway width, m
ΔT	indoor-outdoor temperature difference, °C
$\Delta \rho$	indoor-outdoor air density difference, kg/m^3
Δ	fractional density difference
ρ	average indoor-outdoor density, kg/m^3
ρ_i	indoor air density, kg/m^3
ρ_o	outdoor air density, kg/m^3

1.0 INTRODUCTION

If you live in a northern climate you have probably been told at some time to shut the door because someone's feet were getting cold. Or, perhaps you have felt cool air-conditioned air flowing from open shop doors in a tropical location. In either case, a significant energy cost is associated with these flows. The distribution of indoor air contaminants can also be influenced by air flow through doorways, with important implications for clean room areas, hospital operating theatres and other similar applications. The advent of airtight residential construction methods has caused concern about maintaining adequate indoor air quality, a condition which is partially ameliorated by air flow through open doors and windows.

An understanding of both the quantity and characteristics of exchange flows is essential if proper energy estimates are to be made and if effective designs are to implemented. The long term goal is the developement of a comprehensive model for the prediction of air exchange. Toward this end, the authors conducted both full scale experiments and scale model simulations of air exchange flows through doorways. The primary objectives were to determine the essential information necessary for the construction of an air exchange prediction model, and to evaluate the accuracy and usefulness of scale modelling techniques.

In this report, our attention will be focused on the most important cause of air exchange through large openings in buildings, namely gravity-driven flow. Several simple models will be developed to predict gravity flows through doors and experimental methods will then be briefly described. Finally, some of the experimental data will be used to evaluate the proposed models.

2.0 AIR EXCHANGE THROUGH DOORWAYS

The transport of air through doorways can be caused by a number of different mechanisms. These include indoor-outdoor temperature difference, occupant motion, pumping action of the door, interior air circulation and wind generated turbulence. The total exchange depends on the magnitude of these various driving mechanisms and to some degree their interaction with one another.

Experimental results showed that gravity-driven air flow, caused by an indoor-outdoor temperature difference, is the dominant source of air exchange except at very small temperature differences. Gravity-driven flow is characterized by the flow of warm buoyant interior air out the top of the opening and flow of cold heavier exterior air in through the bottom. The flow rate depends on the height, width and thickness of the opening, and on the indoor-outdoor temperature difference. The total air exchange that occurs for a single door opening-closing cycle will depend on the flow rate, the amount of time the door is open, and in some cases the shape and volume of the interior space.

At the extreme of small temperature differences, gravity-driven flow is small and inertia driven flows, such as the pumping action of a door or the motion of an occupant, become dominant. Under these circumstances, the air transfer will depend entirely on factors such as how quickly the door is opened or how fast the occupant passes through the opening. For a given inertia force, there will always be a range of temperature differences for which the buoyancy and inertial forces are of the same order of magnitude. The results of our study show that simple superposition is inappropriate under these circumstances. Discussion of inertia driven flows in this report will be limited to situations in which they significantly affect the buoyancy flow regime.

3.0 GRAVITY-DRIVEN FLOW MODELS

3.1 Gravity-Driven Air Exchange During a Typical Door Cycle

Figure 1 illustrates the exchanged air volume as a function of time for an idealized door cycle. The curve represents the exchange process that occurs when a residential door is swung open, left open for some time and then shut. The interior could be an entry vestibule or large room. Four time periods have been identified.

- Opening Period (t_o)- This period begins with the initial motion of the door and ends with its arrival at a 90° open position. The exchange rate increases as the opening width enlarges.

- Fully Open Steady Flow Period (t_s)- Steady state flow persists until the door begins to close or until a finite interior volume causes a reduction in flow rate.

- Decay Period (t_d)- This period exists only if the flow rate decreases because of a finite interior volume.

- Hold Period (t_h)- The hold period is the total time that the door is open 90° or more, and is equal to t_s+t_d. If the door is not open long enough for the decay period to exist, then $t_d=0$ and $t_s=t_h$.

- Closing Period (t_c)- This period begins when the opening width starts to decrease because the door is closing. This period is the reverse of the opening period, beginning as the door passes the 90° open position and ending when it is fully closed. The volume exchanged during this period depends on both the decreasing opening size and on the steady state flow rate that exists when the door begins to close.

3.2 Steady Gravity-Driven Flow

When an indoor-outdoor density difference $\Delta\rho$ exists, it is possible to define an effective gravitational acceleration in terms of the fractional density difference and the local gravitational acceleration as,

$$g' = g\ (\Delta\rho/\rho) \tag{1}$$

This effective gravitational force will cause steady counterflow through an open door or window at a rate of exchange given by Shaw[1] as,

$$Q_n = \frac{K\ W}{3}\ (g'H^3)^{1/2} \tag{2}$$

All viscous effects such as surface drag and interfacial mixing are included in the orifice coefficient, K. The effect of interfacial mixing is to cause some of the outgoing warm air to be entrained by the incoming cold air, reducing the net exchange rate. The amount of interfacial mixing between the incoming cold air and the exiting warm air may be affected by the turbulence levels in both the indoor and outdoor reservoirs, and by the Reynolds number which governs shear induced mixing at the cold air - warm air interface. Once the coefficient K is determined, Equation 2 can be used to find the air exchange V_s, that occurs during the steady flow period.

3.3 Flow During Door Opening and Closing

Often, the coming and going of occupants occurs so rapidly that the door spends very little time in the fully open position and most of the exchange occurs while the door opens and closes. Is it possible to approximate the gravity-driven exchange that occurs during the opening and closing period by assuming quasi-steady flow?

For a door swinging at a constant speed, it is easy to show that the average opening width is $W(2/\pi)$. Integrating Equation 2 over the opening time t_o, results in,

$$V_o = \frac{K\ W\ 2/\pi}{3}\ (g'H^3)^{1/2}\ t_o \tag{3}$$

Rather than thinking of this as flow through an average orifice of width $W(2/\pi)$ for a time t_o, it is more convenient to treat it as flow through an orifice of width W, for a reduced period of time, $t_o(2/\pi)$. With this in mind, Equation 3 is rewritten in terms of the net flow rate Q_n, and an equivalent time t_{eq}, which in this case is $t_o(2/\pi)$.

$$V_o = Q_n t_{eq} \quad (4)$$

The same approach can be applied to the closing period, so that $V_c = Q_n t_{eq}$, assuming that the opening and closing motions are identical, and that decreasing flow has not begun. It is important to take note of two assumptions made in the integration of Equation 2. First, that the fully open door orifice coefficient is the same for all door positions, and second that the startup time of the gravity flow is negligible. Experimental data will be used to assess the validity of these assumptions.

Often the opening and closing motions are similar, and the hold period is short enough that decreasing flow does not occur. In this case, the total gravity-driven exchange for the complete door cycle is given by

$$V = V_o + V_h + V_c = Q_n (t_h + 2t_{eq}) \quad (5)$$

If decreasing flow begins before the door starts to close, then the opening and closing exchange will not be the same and Equation 5 is not valid. In this case, the closing exchange must be determined independently from the opening exchange. The flow rate that is occurring at the moment the door begins close must be used rather than Q_n.

3.4 The Start Of Decreasing Flow Due To A Finite Interior Volume

Steady flow into a room of finite volume cannot last forever, and there must be some critical point at which the flow begins to decrease. The mechanism which determines when flow reduction begins is the return of a reflected gravity wave to the entry. Consider the simple, but none the less important case of flow into a long narrow room or hall from a door located at one end. The gravity current will flow down the length of the hall at a uniform velocity, strike the end wall and reflect back to the doorway. It is the arrival of this reflected wave at the doorway that signals the chocked flow condition that a limited interior volume exists.

The onset of decreasing flow is important because the justification for building a small enclosed entry is the potential energy savings associated with limiting the total possible amount of air transfer. The smaller the entry, the sooner the gravity wave returns to the door and the sooner the flow starts to diminish.

An estimate of gravity current frontal velocity in a long hallway can be made from classical lock exchange experiments by Benjamin[2]. For steady flow through an opening, given by Equation 2, the density current draft will advance along the floor of a long hallway of width W_c, at a frontal velocity of,

$$U_f = Fr_f^{2/3} \left[\frac{K}{3}\right]^{1/3} \left[\frac{W}{W_c}\right]^{1/3} (g'H)^{1/2} \qquad (6)$$

It is reasonable to expect the frontal Froude number to lie near the counterflow critical value of $2^{-1/2}$ derived by Benjamin. For a hall of length L, the critical time t_{cr}, at which decreasing flow begins is simply determined as $2L/U_f$. This concept will be evaluated using the full scale and model frontal velocities, and exchange flow information determined experimentally. First, the measured frontal velocities will be compared to Equation 6, and then exchange data will be examined to determine if in fact, decreasing flow begins at a time equal to $2L/U_f$.

If the gravity current flows into an open room, the flow rate will probably not exhibit the sudden decrease in flow expected in the long hall case. Instead, it is likely that a smooth departure from steady flow occurs because a series of gravity waves return to the door as the gravity front reflects off numerous interior surfaces.

3.5 Predicting The Decreasing Flow Rate

The following assumptions are used to develop a simple expression for decreasing flow rate as the room fills with outside air.

- o The flow rate smoothly departs from steady flow at some critical time t_{cr}, and critical volume V_{cr}.
- o The ratio of steady state to actual flow is exponential in form.
- o The exchange volume approaches a maximum value V_{max}, at an infinite time.

Equation 7 satisfies these assumptions and boundary conditions.

$$V = V_{max} \, (1 - e^{-A(t-B)}) \qquad (7)$$

$$\text{for} \quad t > t_{eq} + t_s$$

where

$$A = \frac{Q_n}{V_{max} - V_{cr}}$$

$$B = \frac{V_{cr}}{Q_n} + \frac{\ln(1 - V_{cr} / V_{max})}{A}$$

It is obvious that the maximum exchange V_{max}, must be related to the room volume. Warm interior air is effectively trapped in the space between the top of the door and the ceiling. Therefore it is reasonable to expect that the maximum exchange will be approximately equal to the volume beneath this height H, defined as V_H. Experimental results will be examined to determine if in fact, the measured value of V_{max} is close to V_H, and how well Equation 7 predicts the decreasing flow process.

4.0 MEASURING AIR EXCHANGE FLOWS IN HOUSES

Air exchange through an exterior doorway was studied experimentally at the Alberta Home Heating Research Facility. The test house used in this study was a detached single storey wood frame structure with overall interior floor dimensions of 6.5 m x 7.1 m and an interior wall height of 2.4 m. Plastic sheets were used to seal the basement from the main floor to simplify the interior geometry. For some tests, a partition was erected to make the room into a closed hallway, 1 m wide and 7.1 m long, with the exterior door located at one end.

Air exchange through the 2.05 m high and 0.89 m wide exterior door was measured using SF_6 as a tracer gas. With the door closed, tracer gas was added to the room and mixed with fans until a uniform concentration was established. The mixing fans were then turned off and interior turbulence allowed to dissipate. Following this, the exterior door was opened at a selected swing speed, held open for a time and closed at the same swing speed. The door was driven by a electric door actuator and controlled by a computer, producing an accurate and repeatable door motion. The fans were then turned on again to mix the air. Knowing the interior volume, initial concentration and final concentration, it was possible to determine the net exchange. For a constant indoor-outdoor temperature difference, tests were repeated for varying door opening durations. The volume exchanged verses opening time curve was then constructed and its slope used to determine the steady state flow rate through the door. For all of the tests, the door swing speed was maintained constant and only the fully open time was varied.

Fast response thermocouples were also employed during these exchange tests to determine information about the flow structure. Two types of measurements were made. First, a horizontal line of thermocouples was located on the centerline of the hall configuration, 15 cm above the floor. Monitoring these thermocouples with a computer allowed the frontal velocity of the cold incoming air to be determined. Second, thermocouples were spaced 10 cm apart on the vertical centerline of the door opening to determine temperature profiles during the exchange.

5.0 LABORATORY MEASUREMENTS

The 1:20 scale model of the house was inverted and suspended from a load cell in a reservoir of fresh water. A computer controlled stepping motor drove a small door at varying door swing rates and fully open time intervals. With the door closed, the model was filled with a salt water solution. The density of the saline solution was selected to match the desired indoor-outdoor temperature difference to be simulated. When the door was opened, the denser saline solution poured from the model and was replaced by lighter fresh water, resulting in a weight variation throughout the exchange. This change in weight was monitored by rapidly sampling the load cell with a computer. The slope of the weight-time curve gave the net flow rate of the fresh water through the door into the model house.

The water filled model with its 15 times smaller kinematic viscosity had a Reynolds number 7 times smaller than the full scale flow. However, the use of water rather than air as the working fluid reduces the Reynolds number mismatch considerably. If the experiments had been done using air, the difference would have been a factor of 100.

A model of the hallway partition used in the full scale tests to measure density front velocities was constructed in the model. Fast response electrical conductivity detectors were used instead of the thermocouples employed in full scale, to measure the time dependent position of the density front as it passed along the floor of the model house.

6.0 TEST RESULTS

Selected full scale and model results will now be used to evaluate the flow models discussed in the previous sections. Our attention will be focused on answering the following important questions.

- What orifice coefficient should be used for an open door?
- Can a quasi-steady flow approximation be used during door opening and closing?
- Is it the return of a reflected gravity wave that informs the flow through an open door that a finite interior volume exists?
- If decreasing flow starts, does it decay exponentially and what is the maximum volume that can be exchanged assuming that interior circulation fans are not operating?

6.1 Steady State Gravity-Driven Flow

Some of the steady flow data from both full scale and model tests are shown in Figure 2. The theoretical curve given by Equation 2, using a door orifice coefficient of $K=0.6$, is also shown. With this orifice coefficient, the model data is in very good agreement with the theoretical prediction. Because the full scale flow rates were computed from a series of tests at varying opening times, the larger scatter in the full scale measurements is not surprising.

It is apparent from Figure 2 that the full scale results are consistently lower than the model predictions for a given temperature difference. If the orifice coefficient is correlated with temperature difference as shown in Figure 3, we find that the model value is $K=0.6$ for the entire test range, compared to the full scale results which correlate well with,

$$K = 0.40 + 0.0045\ \Delta T \tag{8}$$

A comparison of full scale temperature profiles measured at the opening, with model salinity profiles at the same location reveals an important fact. At large density differences both the full scale and model flows exhibit relatively little interfacial mixing across the counterflow interface. This is indicated by a steep gradient in temperature and salinity at the respective interfaces. At smaller density differences, the full scale flow showed increased interfacial mixing, as indicated by a more gradual variation in temperature. The model however, showed no significant increase in mixing at smaller density differences. Interfacial mixing causes transfer of inbound outdoor air into the outflow stream and a corresponding transfer of outbound indoor air into the inflow stream, thereby reducing the net exchange rate. The decrease in magnitude of the full scale orifice coefficient is therefore a direct result of an increasing level of interfacial mixing. This is why K depends on temperature difference.

Why is there less interfacial mixing in the model compared to the full scale case? One possible answer to this question is the Reynolds number mismatch. The lower Reynolds number in the model suggests that its flow regime is more stable, implying reduced interfacial mixing.

6.2 Gravity-Driven Exchange During Door Opening and Closing

It is possible to evaluate the assumption of quasi-steady flow while the door is opening and closing by examining data obtained with a very short hold time. Figure 4 shows full scale exchange volumes for a hold time of 0.5 s and a swing time of 3.75 s. Equation 5, which was developed on the basis of quasi-steady flow, is also shown. The agreement is very good down to about 4°C, at which point pumping exchange caused by the swinging door begins to make a small contribution to the total exchange volume. Clearly, pumping exchange can be neglected for all but the smallest temperature differences.

Model data similarly confirmed the accuracy of the quasi-steady flow assumption for the opening and closing period. It should be noted that the factor of $2/\pi$ is specific to the case of a constant swing speed door and can be derived for other swing motions or other types of doors.

6.3 Wave Return Time

If the door is open for a short period of time, or if the flow is entering into a very large room, the flow rate will probably not begin to diminish before the door closes. However, long durations and small rooms are often involved, and determining the time at which decreasing flow begins becomes important. In this section it will be shown that this critical time is dependent on gravity wave return time.

Figure 5 illustrates some hallway frontal velocities from both model and full scale experiments. The agreement between the model and full scale data is remarkably good and strongly supports the $20^{1/2}$ time scale obtained from Froude number similarity scaling. Unlike net flow rate, which has been shown to depend on mixing and entrainment, gravity current frontal velocity is unaffected by its entrainment rate as shown by Simpson and Britter[3]. This explains how it is possible for the model and full scale flow rates to differ at small temperature differences, while their frontal velocities agree so well.

A frontal Froude number of 0.75 provides that best theoretical fit to the data over the entire range, this is close to the expected value of 0.71 for pure counterflow. It is particularly interesting to note the excellent agreement between the model and full scale results at the small temperature differences. Here the scale model tests do better at predicting full scale frontal velocities than the inviscid theoretical prediction.

We now turn our attention to the question of wave return time and decreasing flow. Figure 6 shows some of the exchange volume data as a function of time for the long room geometry. This data is plotted so that results from a wide range of temperature differences collapse onto the same curve. Using Equation 6, a frontal Froude number of 0.75, and the assumption that the critical time equals $2L/U_f$, allows an estimate to be made of the critical time when departure from steady flow will occur. Substituting the physical dimensions of L=7.1 m and W_c=1 m, results in the predicted departure point indicated on Figure 6. A more accurate prediction of the departure point could not be hoped for. This result strongly confirms that the flow rate begins to decrease when the gravity wave has traveled down the length of the hall and back to the door at frontal speed U_f. The data also exhibits the rather sudden change in slope expected a the return wave uniformly at the door.

6.4 Predicting Decreasing Flow

From Figure 6 it is apparent that the exchanged volume does approach a maximum value as expected. Equation 7 was proposed to describe the volume exchange between the time of departure from steady flow until a maximum exchange has occurred or until the door begins to shut. Equation 7 is shown in Figure 6 with best fit values of $V_{cr}=8.0\ m^3$ and $V_{max}=19.2\ m^3$. This function underpredicts the departure point slightly because of the forced boundary condition of smooth transition from steady flow, however it still provides a good fit to the data. The best fit value of $V_{max}=19.2\ m^3$, is slightly larger than the theoretical maximum value of $V_H=17.8\ m^3$. This is reasonable, because it is likely that entrainment causes some of the buoyantly trapped air above height H to be mixed down to participate in the exchange.

From these results we see that the flow begins to decrease when about half of the theoretical volume is exchanged and continues until the entire amount is replaced with exterior air. This estimate can be used for most interior geometries with reasonable accuracy.

7.0 A COMPLETE GRAVITY-DRIVEN FLOW MODEL

We are now in a position to estimate the gravity-driven exchange given the house dimensions, temperature difference and the door motion.

First it must be determined if departure will occur before the door closes. If so, Equation 7 can be used with the generalized results from the last section to determine the total exchange, including opening and closing contributions. If departure does not occur then Equation 5 applies.

Combining the information obtained in these experiments, the following simplified calculation for estimating gravity-driven exchange volumes for simple interiors is given. For a given problem the following must be provided;

$$T_i,\ T_o,\ W,\ H,\ t_o\ (=t_c),\ t_h,\ V_H$$

Then calculate;

$$\Delta = \Delta\rho/\rho = 2\ (T_i - T_o)\ /\ (T_i + T_o) \qquad \text{(T in degrees kelvin)}$$

$$\Delta T = 295\Delta\ /\ (1 + \Delta/2) \qquad \text{(22°C indoor reference temperature)}$$

$$K = 0.4 + 0.0045\Delta T$$

$$t_{eq} = (2/\pi)\ t_o \qquad \text{(only for constant swing speed)}$$

$$Q_n = K\ (gW^2H^3/9)^{1/2}\ \Delta^{1/2}$$

$$t = 2t_{eq} + t_h$$

The gravity-driven exchange is found using;

If $Q_n\ t\ /\ V_H > 0.5$ then $V = V_H\ (1 - e^{-A(t-B)})$

where $A = 2Q_n\ /\ V_H$

$B = (0.5\ V_H/Q_n) - 0.69/A$

If $Q_n\ t\ /\ V_H < 0.5$ then $V = Q_n\ t$

CONCLUSIONS

Some of the questions concerning the nature of gravity-driven flow through doorways have been answered in this report. Experimental data obtained at the Alberta Home Heating Research Facility and from laboratory simulations, supports the proposed theoretical models designed to estimate gravity-driven air exchange through doorways.

The reader should however be cautioned, the model can only be expected to provide reasonable estimates of air exchange if conditions are similar to those tested here. For example, inertial effects, which are of particular importance at small temperature differences, have not yet been accounted for in the model. Increased interior or exterior turbulence levels may cause substantially increased interfacial mixing, dramatically altering the door orifice coefficient and net flow rate. The presence of an occupant in the opening causes a blockage, reducing gravity-driven flow, an effect totally unaccounted for as of yet. Fortunately, in many applications these effects will be small and the proposed model will produce a good estimate.

ACKNOWLEDGEMENTS

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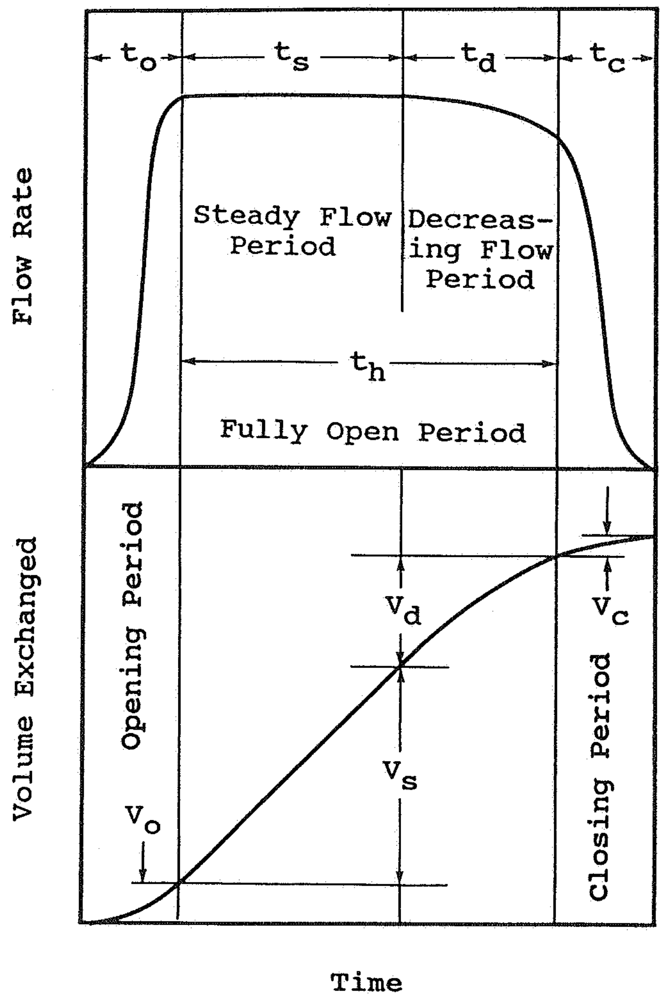

Figure 1: Idealized flow rate and volume exchange for a typical door cycle.

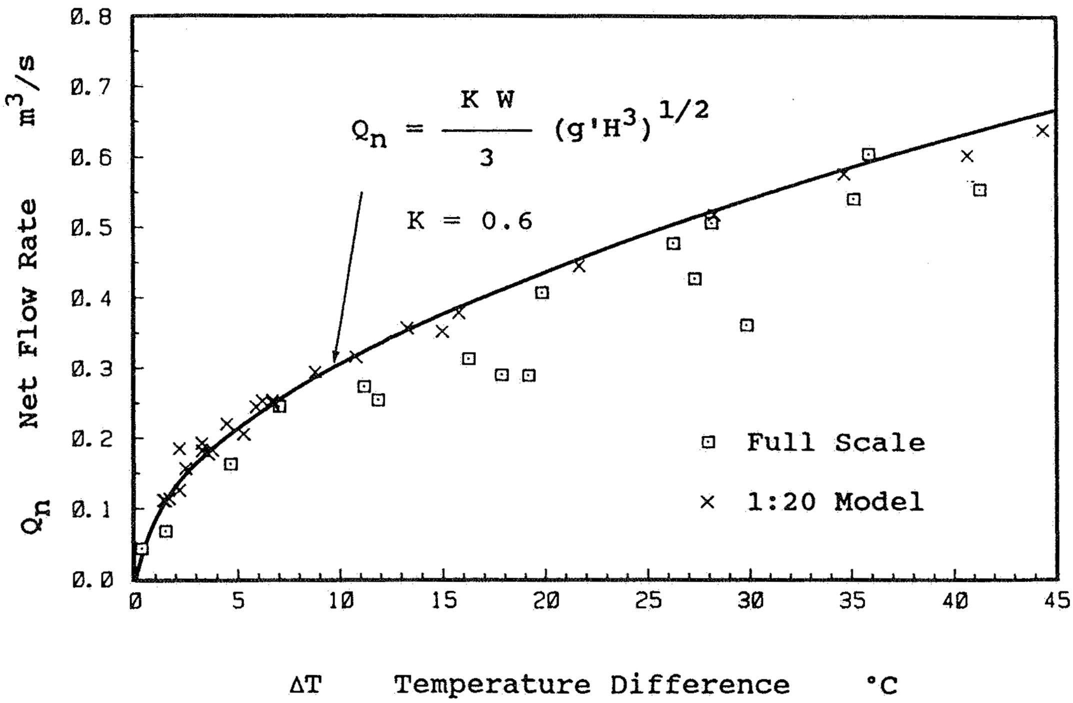

Figure 2: Comparison of model and full scale steady state flow rate variation with temperature difference.

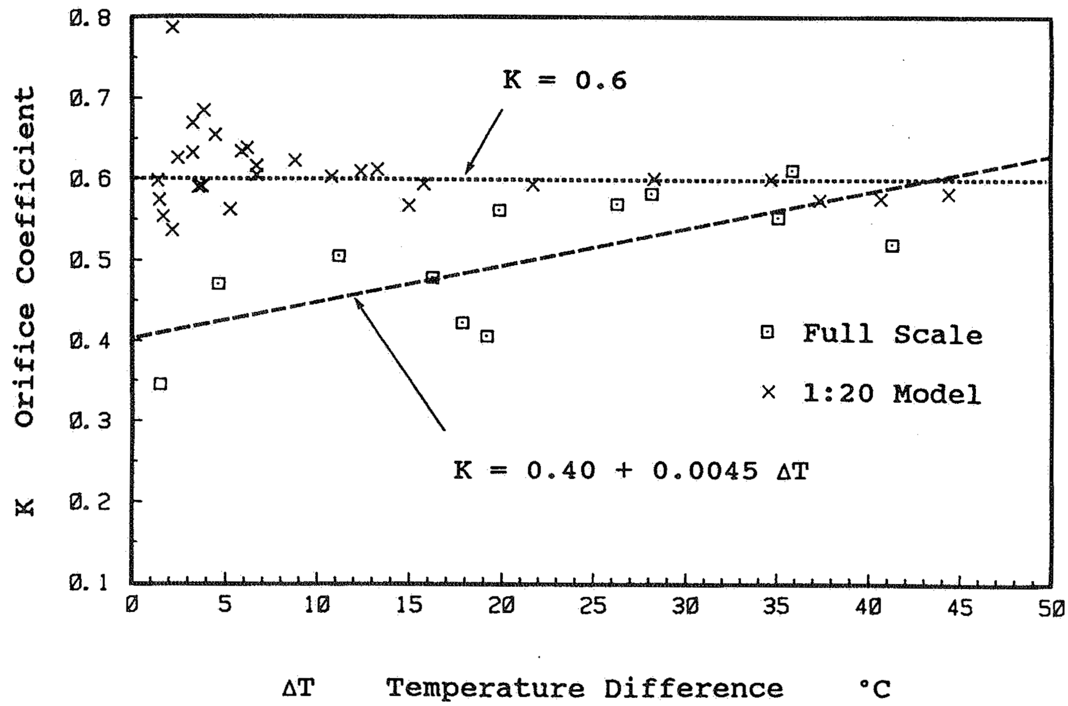

Figure 3: Comparison of model and full scale door orifice coefficient variation with temperature difference.

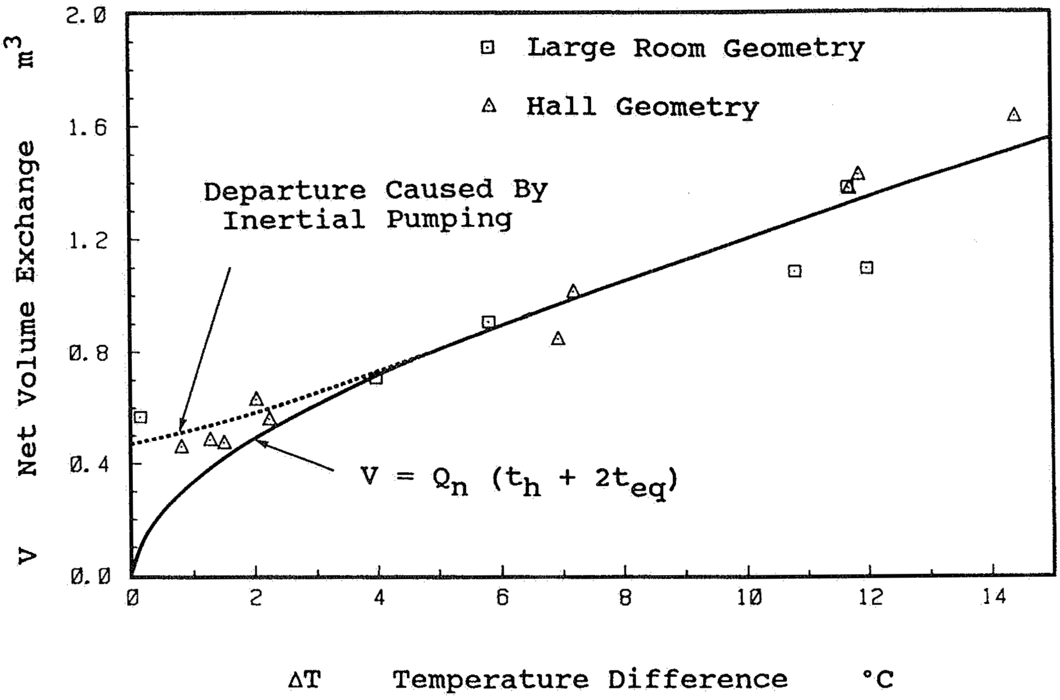

Figure 4: Correlation of short duration exchanges with temperature difference to test quasi-steady flow assumption, t_o = 3.75 s, t_c = 3.75 s and t_h = 0.5 s.

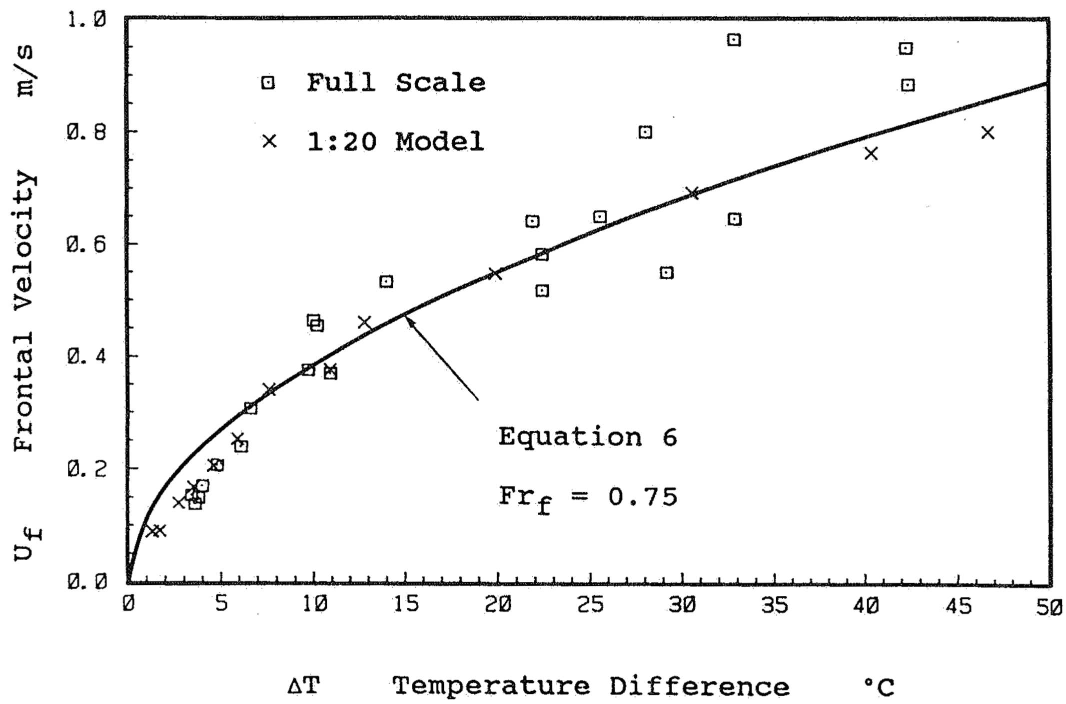

Figure 5: Comparison of model and full scale hall frontal velocity variation with temperature difference.

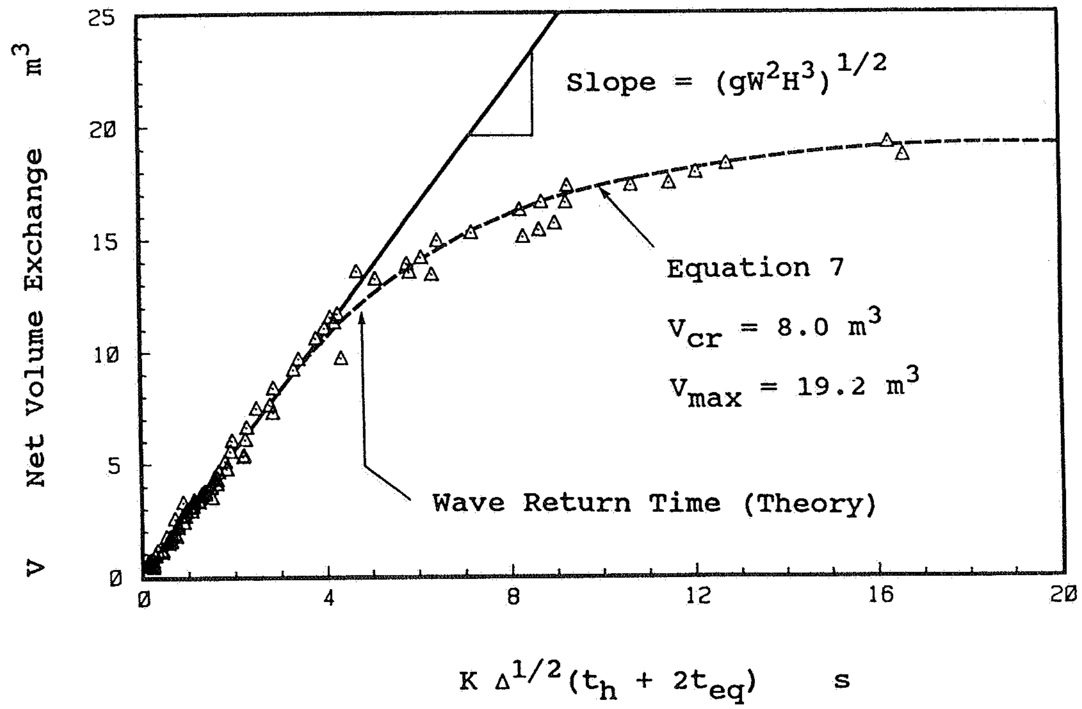

Figure 6: Critical departure time and decreasing flow for the hall geometry.