SIMULATION OF AIR INFILTRATION THROUGH REVOLVING DOORS

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ABSTRACT

Air infiltration through revolving doors may have significant impact on the heating load of commercial and institutional spaces, and may create discomfort to people. This paper modifies a 40-year old model by Schutrum et al. (1961), composed of two components: (1) estimation of air exchange between one segment of the revolving door and the indoor/outdoor, and (2) estimation of net air infiltration rate.

INTRODUCTION

Revolving doors are installed in commercial and institutional buildings to reduce the heat losses caused by the large circulation of people between inside and outside. Although the air infiltration is significantly reduced, if compared with the sliding or swinging doors, the amount of cold air brought into the building in the winter can still affect the heating load of adjacent spaces and the thermal comfort of people. From the designer's perspective, it is important to determine accurately the airflow rate through revolving doors and therefore to properly size the HVAC system.

The air infiltration through a revolving door is composed of two components: (1) the air leakage past door seals due to pressure differential between outside and inside, when the door is not revolving; and (2) the air exchange due to door movement. The magnitude of air leakage through the seals of the door is the result of the pressure differential across the building entrance and the size of cracks.

PREVIOUS STUDIES

Schutrum et al. (1961) performed experimental research on the air infiltration and air leakage through revolving doors, under heating and cooling conditions, using the tracer gas technique. For more than 40 years, this was the only source of information available for the estimation of heating load due to air infiltration through this type of doors. More recently, Zmeureanu et al. (2001) measured the air leakage of existing revolving doors of an institutional building.

Schutrum also developed an analytical model to estimate: (1) the air exchange between one segment of the revolving door and the indoor/outdoor, and (2) the net air infiltration rate through a revolving door. The model applies to both manually operated and motor driven revolving doors. A short summary of this original model for the air exchange is presented here.

A revolving door consists of four parts, called segments. When a segment is opened to the indoor space, the air displacement takes place as the result of the buoyancy forces due to cold air in the segment and warm air in the room, and the inertia due to the door movement. There are two cycles to be considered: (1) the opening cycle, when the exposure to indoors increases; and (2) the closing cycle, when the exposure to indoors decreases.

The opening cycle of one segment corresponds to the time interval between $t = 0$ and $t=1/4N$, where N is the revolving speed in rotations per minute (rpm) (Figure 1). The volumetric air exchange q^1 from one segment of the door (including inertia) during the opening cycle is expressed as follows:

$$\frac{dq^1}{dt} = Kt\left(\frac{V-q^1}{V}\right)\sqrt{\left(\frac{V-q^1}{V} - \frac{L^2}{2gVh_0}\frac{d^2q^1}{dt^2}\right)} \quad (1)$$

where:

$$K = CL\pi RN\sqrt{2gh_0} \quad (2)$$

$$h_0 = 0.5L\frac{\rho_{segment} - \rho_i}{\rho_{ref}} \quad (3)$$

C = flow coefficient, L = door height, R = door radius, V = volume of one segment, ρ = air density.

The closing cycle corresponds to the time interval between $t=1/4N$ and $t=1/2N$ (Figure 1).

The air exchange q^1 from one segment of the door (including inertia) during the closing cycle is expressed as follows:

$$\frac{dq^1}{dt} = K\left(\frac{1}{4N} - t\right)\left(\frac{V - q^1}{V}\right)\sqrt{\left(\frac{V - q^1}{V} - \frac{L^2}{2gVh_0}\frac{d^2q^1}{dt^2}\right)} \quad (4)$$

ANALYTICAL MODEL

Model of air exchange

According to the original model of the air exchange, a segment is partially or completely exposed to indoors/outdoors during one-half of the door rotation. For instance, at a revolving speed N = 10 rpm, with one rotation taking 6 seconds, the total opening and closing time of one segment is equal to three seconds. The total amount of air leaving one segment, i.e. the volumetric air flow (q_s), is given by $\int q^1 dt$ over a period of three seconds.

The total volumetric air flow rate of a revolving door, with four segments, is calculated as follows:

$$q = 240\, q_s N \quad [m^3/h] \quad (5)$$

Model of net air infiltration

The analysis of the original mathematical model of the net air infiltration indicated that, although the predictions fit relatively well the experimental data presented by Schutrum et al. (1961), the model was based on some simplifications that are quite subjective, at the first look. For example, the outdoor air temperature T_o was set to 0°F for convenience in order to simplify the heat balance equation. In spite of this simplification, the model was recommended to be used for any value of outdoor air temperature. Moreover, the air density of cold outdoor air and warm indoor air are not used in the calculations.

In the original model, the net air infiltration through a revolving door, due to the air movement, is calculated as the difference between the quantities of outdoor air in the incoming segment (no. I) and the outgoing segment (no. II) (Figure 2).

A modified model of the net air infiltration is proposed in this paper. The calculations are performed in the following sequence:

1. Given are the door characteristics: height L, radius R, flow coefficient C, and rotation speed N; the indoor T_i and outdoor air temperature T_o.
2. Assume values for the air temperature in segment I and II (T_I and T_{II}). Calculate the air density in segment I (ρ_I) and segment II (ρ_{II}), and the corresponding specific heat of air: c_{pI} and c_{pII}. Calculate the air density ρ_o (outside air) and ρ_i (inside air).
3. Calculate the volumetric air flow rate $q_{I,i}$ between the segment I and indoors, and $q_{II,o}$ between segment II and outdoors, using equations (1) to (4), and then the corresponding air mass flow $m_{I,i}$ and $m_{II,o}$, using the air density ρ_I and ρ_{II}.
4. Calculate the air temperatures T_I and T_{II}, using the heat balance equations for segment I and segment II:

   Segment I:

   $$m_I T_I c_{pI} = m_{o,I} T_o c_{po} + m_{II,I} T_{II} c_{pII} \quad (6)$$

   Segment II:

   $$m_{II} T_{II} c_{pII} = m_{i,II} T_{II} c_{pII} + m_{I,II} T_I c_{pI} \quad (7)$$

5. Calculate the air density ρ_I and ρ_{II} in terms of T_I and T_{II}. Compare the new calculated values with those previously estimated. At the first iteration, the initial guess for ρ_I and ρ_{II} comes from step 2. If the difference exceeds 5%, then a new iteration is required: the air density ρ_I and ρ_{II} are re-calculated in terms of T_I and T_{II}. Since the temperature has a negligible impact on the specific heat of air at the atmospheric pressure (it varies by less than 1% between -100°C and +100°C), the specific heat values are not recalculated. Go to step 3. If the difference is less than 5% go to step 6.
6. Conservation of mass principle must be respected in each segment. For instance, for a segment opened to outside $m_{o,I} = m_{II,o}$, from which the volumetric air flow from outdoors into segment I is calculated as $q_{o,I} = m_{II,o}/\rho_o$. The percentage of cold air in segment I is then given by: $\alpha = q_{o,I} / V$.

The volumetric flow of cold air that goes from outside to inside is estimated as the product between the total volumetric rate of air that flows from segment I to indoors, $q_{I,i}$, and the percentage of cold air in segment I, α.

The net air infiltration rate (Q) due to the four segments of door rotated with speed N is calculated as follows:

$$Q = 240\ N\ \frac{q_{o,I} \cdot q_{I,i}}{V} \quad [\text{m}^3/\text{h}] \qquad (8)$$

$$m_{net} = Q\ \rho_I \quad [\text{kg/s}] \qquad (9)$$

Effect of wind and turbulence

In order to account for the effect of wind and indoor air movement, Schutrum et al. (1961) assumed that the average nondirectional air velocity head $v^2/2g$ is equivalent (in its effect on air infiltration) to a buoyancy head of equal magnitude. The velocity heads are converted to temperature difference heads: ΔT_T for indoor air movement and ΔT_W for outdoor wind. A trial and error approach was used to determine the effect of wind and indoor air movement on the net air infiltration.

Although the same assumption is used in the present study, the approach used to estimate the impact of indoor and outdoor air movements is different. For a given air velocity (v), the equivalent velocity head, which creates the same volumetric air flow between the segment and indoors/outdoors, is calculated using an equivalent air density difference ($\Delta\rho$):

$$0.5\ \Delta\rho\ L/\rho_{ref} = v^2 / (2\ g) \qquad (10)$$

With this $\Delta\rho$, an equivalent air density can be calculated for indoors and outdoors:

$$\rho_{equiv,i} = \rho_i - \Delta\rho_{inside} \qquad (11)$$

$$\rho_{equiv,o} = \rho_o + \Delta\rho_{outside} \qquad (12)$$

The corresponding equivalent indoor air temperature $T_{equiv,i}$ and outdoor air temperature $T_{equiv,o}$ are calculated in terms of equivalent densities. The equivalent temperature differences ΔT_T and ΔT_W are then calculated as:

$$\Delta T_T = T_{equiv,i} - T_i \qquad (13)$$

$$\Delta T_W = T_o - T_{equiv,o} \qquad (14)$$

The total equivalent temperature difference between indoors and outdoors is calculated as $\Delta T = (T_i - T_o) + \Delta T_T + \Delta T_W$, and used to estimate the net air infiltration.

The results are presented, in the paper as well as in Schutrum's (1961), in terms of ΔT.

ANALYSIS

The model presented above was implemented in the MATLAB environment. The following door characteristics were used in this application: height of 2.08 m, radius 0.97 m, volume of one segment 1.53 m^3, and flow coefficient 0.5.

Volumetric air flow rate

The difference between the volumetric air flow rate estimated in (Schutrum, 1961) and that calculated in the presented study is about 6% at ΔT equal to 4°C, and becomes negligible at ΔT greater than 9°C. At smaller ΔT, the difference between the results is more significant. However, at small ΔT the air infiltration has a small impact on the building thermal loads. Since the same model was used in both estimations, without any change, the difference appears to be caused by the numerical solution of differential equations (1) and (4). In the present study, the solution was obtained in the MATLAB environment, while in 1961 the solution was obtained, most likely, by hand calculations.

Net air infiltration

The net infiltration rate at three different values of rotation speed (N=2, 5 and 10 rpm) versus the indoor-outdoor air temperature ΔT is shown in Figure 3, for the case of no air movement inside and outside (ΔT_T and ΔT_W equal to zero). When the door rotates with a speed of 2 rpm, the net air infiltration is about 600 m^3/h regardless of the total equivalent temperature difference, provided that ΔT is greater than about 16°C. If ΔT is less than about 9°C, two patterns are noticed: (1) higher is the rotation speed, smaller the net air infiltration, and (2) the increase of ΔT has a higher impact on the infiltration rate at smaller rotation speed.

The model predictions were compared with experimental data published by Schutrum. It is important to mention that the wind speed for the experimental data was not clearly identified. For this reason, two cases were considered, based on information presented in reference (Schutrum et al., 1961): wind speed of 0.89 m/s and 6.26 m/s.

In the case of indoor air velocity of 0.13 and 0.46 m/s with wind velocity is 6.26 m/s, the results show good agreement (Figure 4). The model slightly overpredicts the infiltration rate if the total equivalent temperature difference ΔT is greater than about 16°C. If the wind velocity is assumed to be 0.89 m/s, the measurements indicate a higher net infiltration rate than the predicted values, although the trend of variation with ΔT is similar.

The sensitivity analysis of the new model with respect to several parameters was made, using the following base case:

- R = 0.97 m
- L = 2.08 m

- $T_i = 22°C$
- $T_o = -23$ °C
- N = 10
- C = 0.5
- Wind velocity= 0.89 m/s; and
- Indoor air velocity= 0.13 m/s

Figure 5 shows the relative change of the net infiltration rate due to changes in value of each parameter. For example, by increasing the flow coefficient by 50%, the net infiltration will increase by about 45%, while by increasing the revolving speed by 40%, the net infiltration rate is expected to decrease by about 20%.

As shown, not every value has the same impact on the net air infiltration rate. For instance, the model is very sensitive to the flow coefficient C and the door dimensions R and L (as expected). At the other extreme, the change of equivalent temperature difference due to wind or indoor air velocity has little influence on the infiltration rate.

Total air infiltration

The air infiltration due to the door movement was compared with the infiltration through gaps and seals for the case of existing 30-year old doors (Zmeureanu et al., 2001) and a new door (Schutrum, 1961).

For instance, the air infiltration through gaps and seals accounts for about 30 % of the total infiltration in the case of old doors and for about 10 % for a new door, if the following conditions apply: $T_i = 22°C$, $T_0 = -23°C$, N = 10, C = 0.5, wind velocity (v_W) = 0.89 m/s, and indoor air velocity (v_T) = 0.13 m/s. The remaining 70% (old door) and 90% (new door), respectively, are due to the door movement.

The heat loss (E) due to the total air infiltration can be calculated as follows:

$$E = m_{net} c_p \left(T_i - T_o\right) \quad \text{[kJ/h]} \qquad (15)$$

Figure 6 shows the total heat loss, due to both air infiltration through gaps and seals and the door movement, estimated by the model presented in this paper, using the leakage values reported in references (Schutrum et al., 1961) and (Zmeureanu et al., 2001), and the following conditions: N = 10, C = 0.5, wind velocity (v_W) = 0.89 m/s, and indoor air velocity (v_T) = 0.13 m/s.

COMMENTS ON CURRENT STANDARDS

ASHRAE Standard 90.1 (1999) specifies that the air leakage shall not exceed 5.0 L/(s·m^2 of door area) for commercial entrance swinging doors or revolving doors, when tested at 75 Pa pressure difference. In the previous version of ASHRAE Standard, the maximum leakage area was set at 6.3 L/(s·m^2 of door area).

MNECCB (1997) specifies that the swinging, revolving and sliding doors shall be designed to limit the rate of air leakage to no more than 17 L/s for each metre of door crack, when leakage is measured at 75 Pa pressure difference.

The two standards do not indicate the basis of their recommendations, however, the comparison shows that the MNECCB (1997) is much less restrictive than ASHRAE (1999).

The current standards prescribe that maximum air infiltration through gaps and seals, when the door is not moving. Under these conditions, the air infiltration accounts only for 10-30% of the total infiltration rate. Therefore, it is important to develop new techniques and add recommendations to standards, which can help in reducing the air infiltration due to the door movement.

CONCLUDING REMARKS

A modified model for prediction of the air infiltration rate through revolving doors was presented using as starting point a 40-year old model. Although the model can presently be used for estimating the air infiltration, the authors are planning for a more comprehensive study in this area. On the research side, future work will cover the development of a detailed CFD model and validation with new experimental data. On the practical side, new approaches will be sought to reduce the air infiltration due to the door movement, and therefore the impact on the building energy usage.

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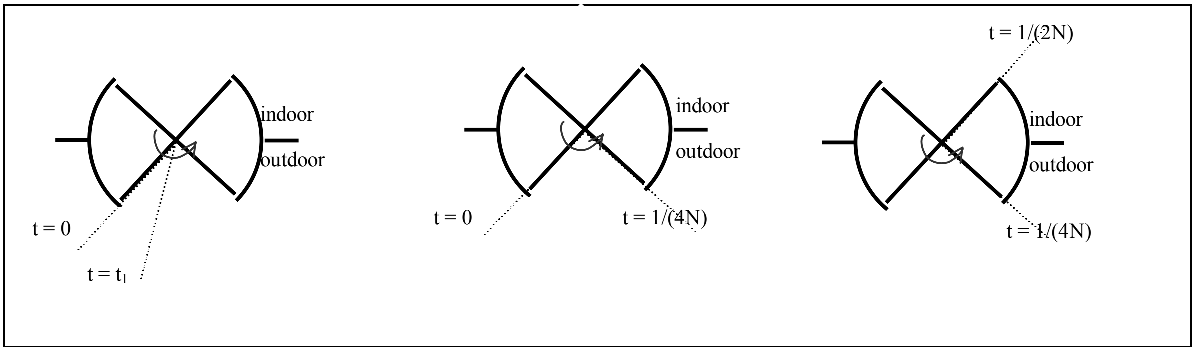

Figure 1: The opening cycle from t=0 to t=1/(4N) and the closing cycle from t=1/(4N) to t=1/(2N)

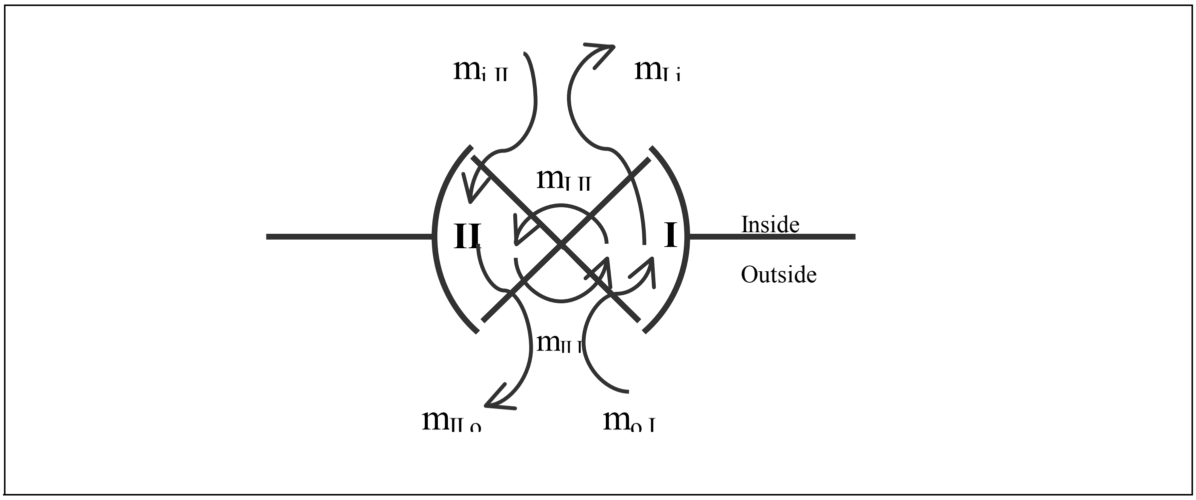

Figure 2: : Mass displacement as a result of the movement of the door (schematic)

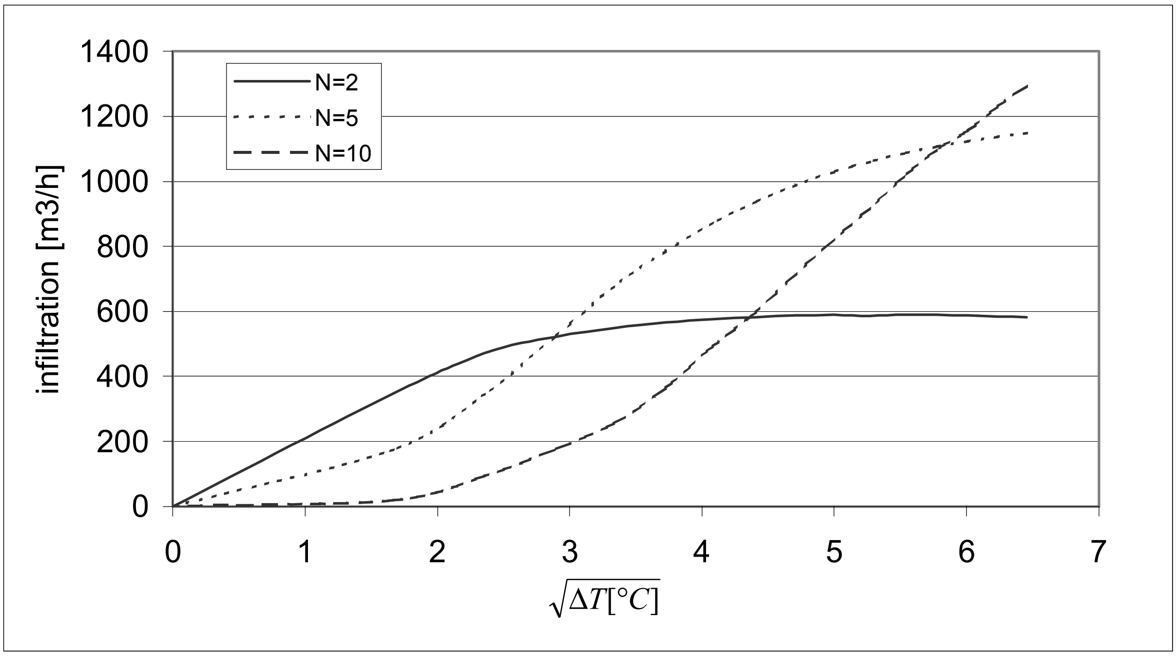

Figure 3: Net infiltration rate as a function of the temperature difference between indoor and outdoor

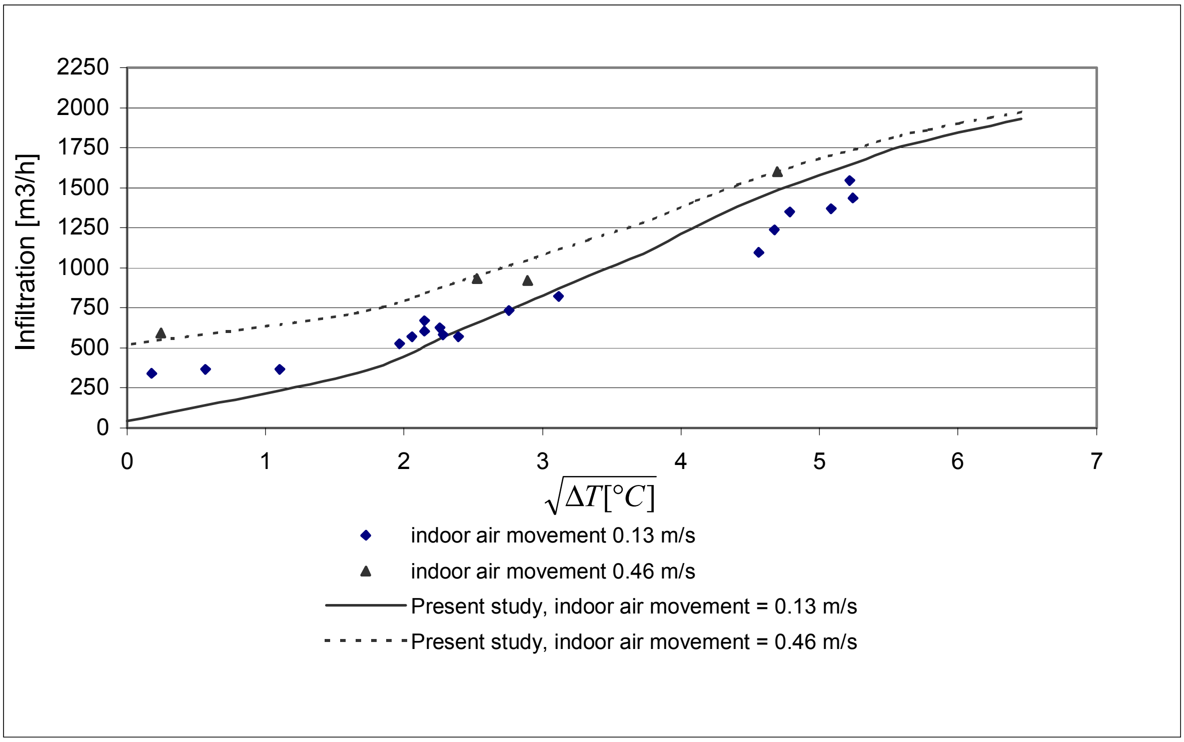

Figure 4: Net infiltration rate due to door movement, present study versus experimental data from Schutrum et al. (1961) at wind speed of 6.26 m/s.

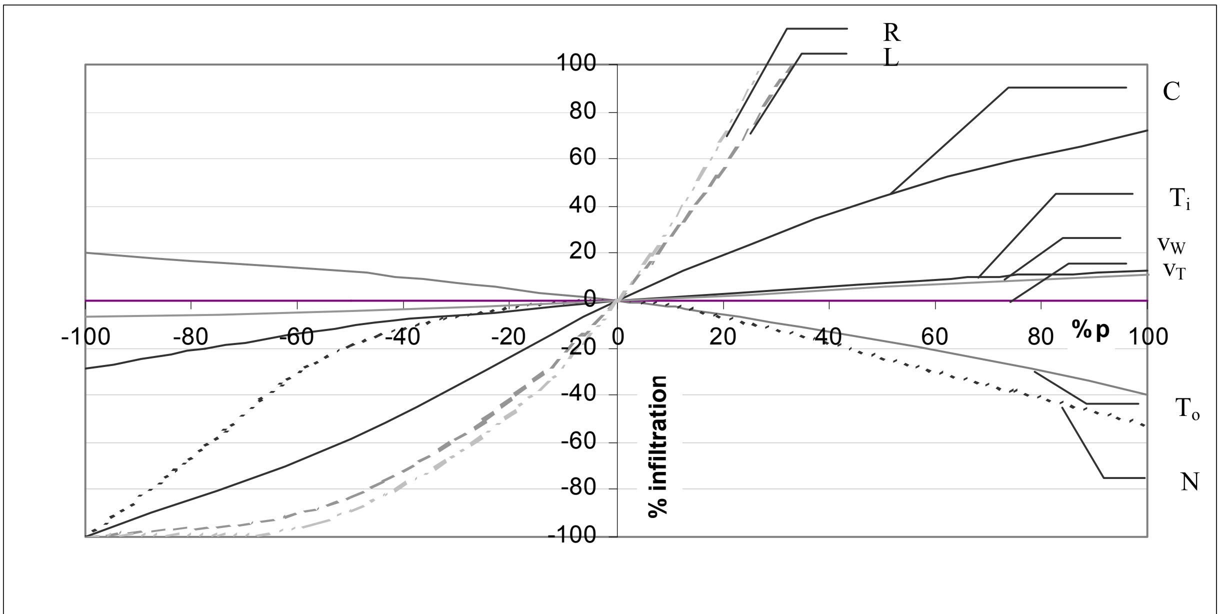

Figure 5: Sensitivity Analysis. Relative change of infiltration rates for selected percentage changes of the various variables from a reference case.

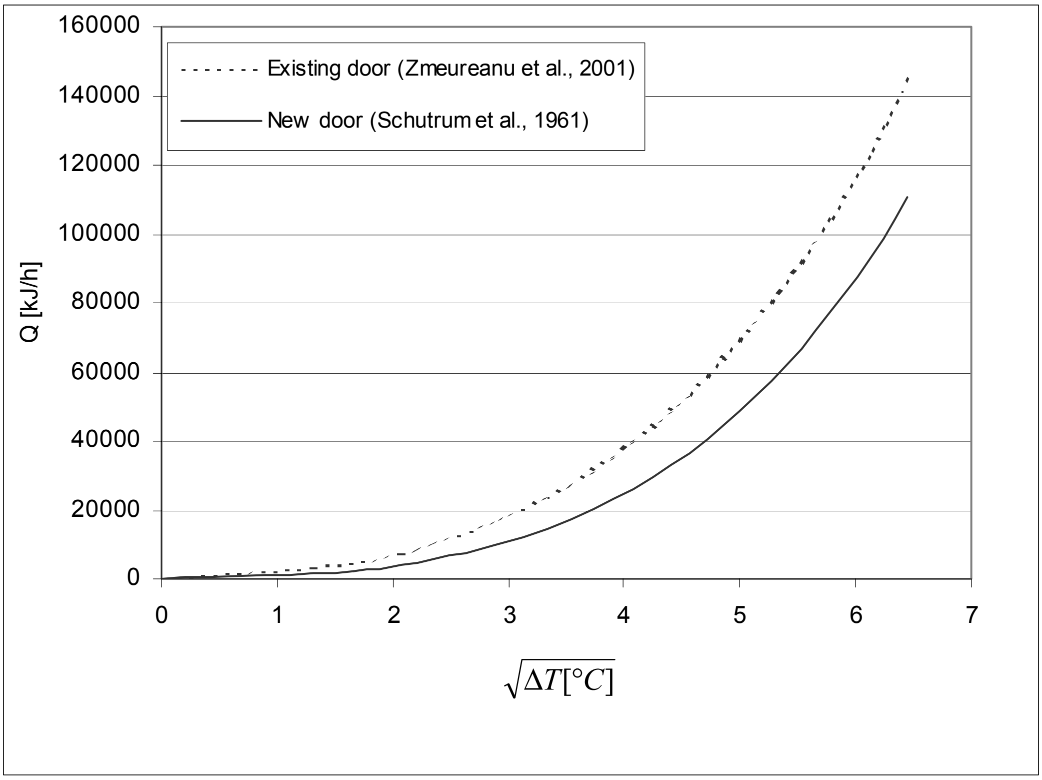

Figure 6: Estimated heat loss due to air infiltration versus temperature difference. Comparison between an existing door (Zmeureanu et al., 2001) and a new door (Schutrum et al., 1961).