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Air exchange through revolving doors during operation

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E2B2

Förord

E2B2s vision är en resurs- och energieffektiv byggd miljö.

Bebyggelsesektorn svarar för cirka en tredjedel av Sveriges totala energianvändning och en effektivare energianvändning är en viktig del av utvecklingen av energisystemet. I E2B2 arbetar forskare och andra aktörer tillsammans för att utveckla samhällets byggande och boende och effektivisera energianvändningen.

E2B2 är ett forsknings- och innovationsprogram från Energimyndigheten där IQ Samhällsbyggnad är koordinator. Programmets andra programperiod pågår mellan 2018 och 2021.

Syftet med E2B2 är att ta fram ny kunskap, teknik, tjänster och metoder som bidrar till en hållbar energi- och resursanvändning i bebyggelsen. Det läggs därför stor vikt vid samverkan mellan näringsliv, samhälle och akademi och programmet ska bidra till och vara ett verktyg för att länka samman behovsägare med projektutförare.

Beräkning av luftutbyte genom karuselldörrar är ett av projekten som har genomförts i programmet med hjälp av statligt stöd från Energimyndigheten. Det har letts av RISE Research Institutes of Sweden och har genomförts i samverkan med ASSA ABLOY Entrance Systems AB.

Projektet har undersökt hur karuselldörrar påverkar byggnadens uppvärmningsbehov. Projektet bidrar till att tillverkare av karuselldörrar kan verifiera och uppdatera sina beräkningsverktyg.

Stockholm, 15 september 2021

Rapporten redovisar projektets resultat och slutsatser. Publicering innebär inte att E2B2 har tagit ställning till innehållet.

Sammanfattning

Karuselldörrar används ofta för att minska infiltration och energiförluster genom byggnaders entréer. Tidigare studier har visat på metoder för att uppskatta infiltrationen genom karuselldörrar men dessa studier var huvudsakligen baserade på dörrar som tillverkats på 60- och 70-talen, därför behöver fler studier på moderna karuselldörrar genomföras.

Detta projekt fokuserar på att uppskatta luftutbytet som orsakas på grund av karuselldörrens rotation. Fullskaliga mätningar utfördes för att undersöka effekterna av olika parametrar, dvs dörrens storlek, temperaturskillnad och dörrens hastighet, och hur dessa påverkar luftutbytet. Luftutbytet uppskattas baserat på värmebalansmetoden som appliceras på luften inuti rummet. Flera mätningar utfördes och det uppmätta luftutbytet visades påverkas av den kombinerade effekten av dessa tre parametrar. För den största dörren är lufthastigheten inte känslig för dörrens rotationshastighet där dörren roterar med en hastighet högre än 2 rpm, vilket troligen beror på fördröjningseffekten av att tömma rummet. Empiriska ekvationer härleddes för varje dörr baserat på mätresultaten. Jämförelser mellan de empiriska ekvationerna med den tidigare studien visar en liknande trend för luftutbytet som varierar med temperaturskillnader med olika dörrhastigheter.

Dessutom gjordes fallstudier för att visa ett tillvägagångsätt för att jämföra prestanda mellan en karuselldörr och en skjutdörr med användning av befintliga metoder och ekvationer. Karuselldörren visade sig ha en stor potential att minska infiltrationen genom skjutdörren, vilket kan minska infiltrationshastigheten minst cirka 6 gånger (motsvarande energibesparing på 8800 kWh/år,) baserat på fallstudiens resultat.

nyckelord: experimentell undersökning, luftutbyte, infiltration, svängdörr, skjutdörr, fallstudie

Summary

Revolving doors are widely used to reduce infiltration and energy losses through building entrances. Previous studies have shown methods for estimating infiltration through revolving doors which were mainly based on doors made 60s-70s, therefore more studies need to be performed for modern revolving doors.

This project focuses on estimating the air exchange rate caused by door movement through a revolving door. Full-scale measurements were performed to investigate the impact of different parameters, i.e., door size, temperature difference and door rotation speed, on the air exchange rate. The air exchange rate was estimated based on the heat balance method applied to the air inside the test room. Several measurements were performed, and the measured air exchange rate was shown to be affected by the combined effect of those three parameters. For the largest door, the air exchange rate is not sensitive to door rotation speed when the door rotates with a speed higher than 2 rpm, which is most likely due to the delay effect of emptying the compartment. Empirical equations were derived for each door based on the measurement results. Comparisons between the empirical equations with the previous study show a similar trend of the air exchange rate varying with temperature differences with different door rotation speeds.

Moreover, case studies were made to demonstrate the approach for comparing the performance between a revolving and a sliding door with use of the existing methods and equations. The revolving door was shown to have a great potential to reduce infiltration compared to the sliding door, which can reduce the infiltration rate at least about 6 times, corresponding to the energy saving of about 8800 kWh/year, based on the case study results.

key words: experimental investigations, air exchange rate, infiltration, revolving door, sliding door, case study

INNEHÅLL

1 Introduction and background

The building sector (residential, commercial, and institutional) is considered as a main contributor to the global energy consumption and greenhouse gas emissions [1]. In EU, this sector accounts for 40% of the primary energy use and 36% of the greenhouse gas emissions. [2]. Reducing energy use is important for the transition to low carbon buildings.

Building energy efficiency is directly related to the heating and cooling demand that is affected by infiltration between a building and its surrounding. ASHRAE defines infiltration as the uncontrolled inward leakage of outdoor air into building caused by the existence of a pressure deferential across the various building enclosure elements [3]. Infiltration can be responsible for up to 30% of the building heating demand and 14% of the cooling demand [4-6], the impact on modern buildings can become quite significant as the buildings are airtight and well-insulated. Entrance doors can cause a major source of infiltration and energy loss in commercial and public buildings where the doors are used frequently [7-9]. Revolving doors have been shown more energy efficient than open types of doors such as sliding and swing door [10-13] and widely used in restaurants, retail stores, supermarkets, offices and hospitals etc.

Air infiltration through a revolving door occurs in two ways: (1) the air leakage through the seals and gaps between the door and its housing, which is related to the pressure difference across the door; (2) the air exchange rate due to door movement related to door speed, door usage and indoor-outdoor temperature difference [14].

Few studies are found regarding air exchange through revolving doors. The work conducted by Schutrum et al. in 1961 [15] is one of the most cited up to this day. Schutrum et al. [15] studied the impacts of several parameters on the air exchange rate through a revolving door by performing laboratory measurements on a full-size revolving door, and the measurement results were presented in a series of curves of the air exchange rate varying with the door speed and temperature difference. Those results were applied further in the field investigation and building energy simulation for estimating infiltration through revolving doors [11, 16]. Zmeureanu et al. [14] investigated the air leakage characteristics for four revolving doors of a large institutional buildings and presented the data of air leakage through door seals at different pressure differences. Allgayer [17] conducted in depth study about air and heat transfer mechanics including the motion of revolving door based on a 1:3 scale model. The results showed that the air transfer depends on the temperature difference, the geometry of the doorway and the door rotation speed. More recently, Du et al. [18] carried out an experimental study on a reduced scale method (1:10) of a revolving door, and proposed empirical models based on the measurement data. To be able to use those empirical equations from Ref. [18], one needs to provide air temperature measurements at several specific points. Du et al. [18] concluded that the door rotation speed has a small impact on the air exchange rate, which is contradictory to the findings from Schutrum et al. [15].

In the above-mentioned literature studies, only two were made based on full size revolving doors which were produced in 60s-70s. As the modern revolving doors are more energy efficient than the doors made 50-60 years ago due to a more sophisticated design, using old data for presenting the performance of the modern doors can be less appropriate. Therefore, data for the doors made today are needed. In addition, even though revolving doors have been shown to be more energy efficient than other open-type doors, it is still unclear exactly how efficient revolving doors are, and the door manufactures still have difficulties to provide scientific data to prove their products [10]. Therefore, full-scale measurements on new revolving doors were conducted and presented in this report.

Moreover, building energy simulation programs are commonly used for investigating different design solutions and their impacts on building energy use. In general, the current building simulation programs do not accurately address the uncontrolled infiltration effect due to simplifications and assumptions of the empirical models employed in the simulation programs. Thus, more studies are needed to provide more knowledge and data which can put forward a valid model to describe air infiltration through revolving doors.

The aim of the project was to investigate the air exchange rate through revolving doors with respect to the door size, door rotation speed and temperature difference, as well as to establish empirical correlations based on the data from the full-scale measurements. The equations derived from the present study are compared with the previous study. Case studies were performed to show a method for comparing the performance between a revolving and sliding door, as well as to present the potentials of infiltration reduction by the revolving door. Outputs from this project will provide more updated information about the performance of new revolving doors, which is beneficial to entrance solution developers and manufacturers, building or property owners, simulation program developers and researchers.

The project was carried out by RISE Research Institutes of Sweden and ASSA ABLOY Entrance Systems. RISE was responsible for the entire project, including project conceptualization, methodology, results analysis, and investigation. ASSA ABLOY was responsible for lab resources, including laboratory measurement, instrument, and test objects (i.e., revolving doors).

2 Implementation

2.1 Measurement set-up and procedure

In this project, full-scale measurements were performed at the laboratory of ASSA ABOLY Entrance Systems, Karlskrona, Sweden. Different size revolving doors, i.e., small, medium, and large, were used, which were with the diameter (D) of 1.8, 2.4 and 2.7 m. These revolving doors were 4-wing type, and the door wing height was 2.2 m. Photos of the large door are shown in Figure 1.

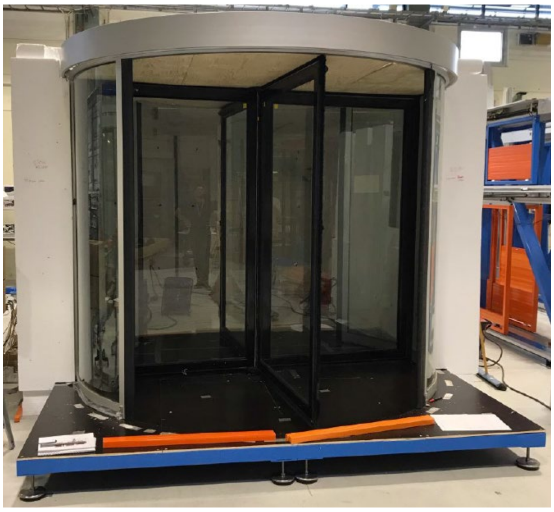

Figure 1. Photographs of the large door: front view (left) and back view (right)

A test room, 4 m in width and 4 m in depth, with the material of S100 EPS Styrofoam, was built to represent a building entrance space. Two layers of Styrofoam, each of them was 100 mm thick, were used for reducing heat losses through the walls. Inside the test room, two heating fans were used to keep the temperature difference between inside and outside (i.e., ambient environment) at desired values. The heating fans were with the maximum power of 6 kW and 9 kW, respectively. One heating fan was operated with the fixed power, and the other one was regulated by a temperature-based on-off controller. To provide a uniform temperature distribution inside the test room, two mixing fans were used, and were measured to consume 0.067 kWh electricity in total for an hour.

In total, 20 T-type (copper-constantan) thermocouples were used: 18 of them were used to measure air temperatures inside the test room and the rest 2 were placed outside for measuring the ambient temperature. Positions of the thermocouples are shown in Figure 2. The 18 thermocouples (inside the test room) were placed at three vertical planes located at the front, middle and back of the test room; at each plane, 6 thermocouples were used and placed at the floor and ceiling level. The average temperature measured by the 18 thermocouples was used as the mean room air temperature. The ambient temperature was the average temperature measured by thermocouple number 19 and 20 that were placed outside of the test room and with some distance to the revolving door. In addition, one extra thermocouple was placed at the center of the test room and connected to the controller for regulating the power for the heating fan. All temperature data was collected by 34972A Data Acquisition System. The uncertainty of the temperature measurement was ±0.2 °C. An energy meter was used to measure energy consumption by the heating fans. A control unit was used for controlling the door start, stop and rotation speed. The time for conducting each test was one hour.

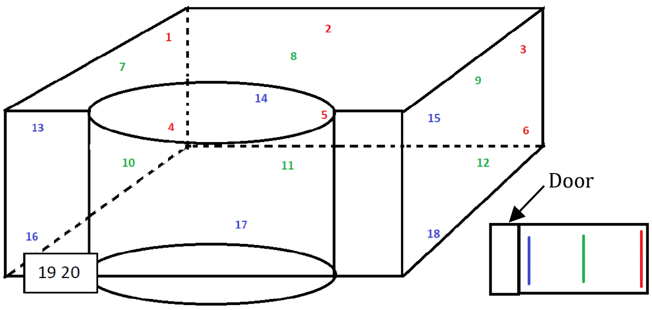

Figure 2. Positions of the thermocouples used for measurement.

Three temperature differences (ΔT) were measured, i.e., 10, 15 and 20 °C; for each ΔT, several tests were conducted which were with the door rotation speed (N) of 2, 3, 4 and 6 Revolutions Per Minute (rpm). As the measurement started in the middle of summer, the laboratory temperature was high, e.g., above 25 °C. To create a ΔT of 20 °C means that the test room needs to be heated at least up to 45 °C, which was already close to maximum limit we could reach, so that is why we chose 20 °C as the maximum ΔT in this project. If we have the possibility or better test facility, a larger ΔT was preferred. For each revolving door, measurements with door closed, i.e., N = 0 rpm, were performed to identify the transmission and leakage losses through the test room envelope. This is called offset measurement in this report and the results are used for the energy balance calculation. The measurement cases for the small door are shown in Table 1, and the same set-ups were made for the medium and large door. Some of the measurements were repeated due to the variation of the results.

Table 1. Measurement cases for the small door

Diameter of the revolving door (m)	**Temperature difference between inside and outside (°C)**	**Door rotation speed (rpm)**
1.8	10	0, 2, 3, 4 and 6
	15	0, 2, 3, 4 and 6
	20	0, 2, 3, 4 and 6

2.2 Heat balance method

The air exchange rate caused by door movement was calculated based on the heat balance method applied to the air inside test room over the measurement period. The total heat losses from the test room consists of (1) transmission loss through the test room envelope and the revolving door, (2) leakage loss through door seals and brushes and (3) air exchange related loss caused by door movement. Part (1) and (2) exists all the time regardless the door is revolving or not, which can be assumed to be the same as long as the pressure difference across the door is the same. In this work the pressure difference was mainly caused by the temperature difference. The sum of part (1) and (2) was determined by the offset measurement for each door at each specified ΔT. The air exchange rate associated heat loss, i.e., part (3), can then be determined by subtracting the offset measurement results, i.e., sum of part (1) and part (2), from the results of the door revolving measurement.

The air exchange rate related to the door movement, q, in m3/s, was calculated by:

$$q = Q_{door\ movement} / (\rho \times C_p \times \Delta T \times \Delta t_{measurement\ period}) \qquad (1)$$

where $Q_{door\ movement}$ is the heat loss caused by the door movement, i.e., corresponding to part (3) in the above mentioned heat balance method, ρ is air density, in kg/m³, C_p is the specific heat capacity, in kJ/(kg °C), ΔT is the temperature difference between inside and outside, in °C, and $\Delta t_{measurement\ period}$ is the measurement time step, in hours, which was 1 hour in this study. $Q_{door\ movement}$ was estimated by:

$$Q_{door\ movement} = Q_{revolving} - Q_{offset} \qquad (2)$$

where $Q_{revolving}$ is the total heat losses through the test room when the door is revolving, Q_{offset} is the heat loss through the test room when the door is closed, which consists of the transmission and leakage loss. $Q_{revolving}$ and Q_{offset} was assumed to equal to the energy consumption by the heating and the mixing fans during the measurement period.

2.3 Case studies

Case studies for a simple office building were made with the purpose to show how to use the available methods to estimate infiltration through a sliding and revolving door, as well as to investigate the potentials of infiltration reduction by the revolving door. In the comparison study, the sliding door was assumed to be used/installed alone (for separating indoor and outdoor) and not in combination with vestibule. Considering the approach used for developing the infiltration prediction for the open-type door (including the sliding door) and the revolving door are different, the former was based on pressure measurement (Yuill, 2005), while the later (i.e., this study) was based on the temperature measurement, it might lead to different predictions. A simple case study, i.e., sliding door, was therefore chosen, with the purpose for illustrating the energy saving potential of a revolving door.

Infiltration was focused on the airflow through the door opening, while leakage through the door seals and gaps was not included considering that they are much smaller than the infiltration through doorway and can be relatively easy determined by using existing equations based on the pressure difference across the door.

The infiltration rate through the entrance door depends on the size of the door, door usage frequency, people flow rate (i.e., the number of people entering the building per hour), and indoor and outdoor temperature difference etc. The set-ups for the case studies are given in Table 2. For the revolving door, the door rotation speed of 2 and 4 rpm were chosen. For the number of people passing per hour, the peak was set to be 160 people/hour. The hourly profile for the number people passing was generated based on Ref. [10] for the Swedish office- time and behavior, but with a reduced number of people per hour to fit this study; the profile is shown in Figure 3.

Table 2. Set-ups for the case studies.

Term	**Set-ups**
Type of building	Office
Building height (m)	4
Location	Stockholm, Sweden
Yearly average outdoor temperature (°C)	6.6
Yearly average indoor temperature (°C)	21
Yearly average temperature difference (°C)	14.4
Revolving door: type, diameter (m) × height (m)	4-wing, 2.4 × 2.2
Sliding door: type, total width (m) × height (m)	Double door, 2.0 × 2.2
Rotation speed for the revolving door (rpm)	2 and 4
Peak number of people passing per hour	160
Opening hours of the office building	7:00-20:00 from Monday to Friday

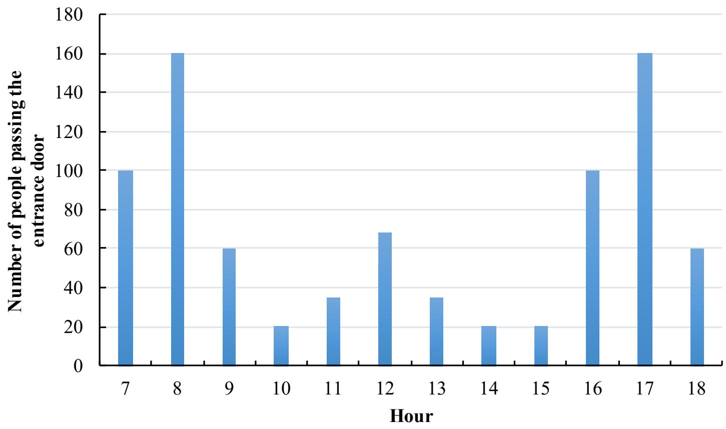

Figure 3. The profile of the number of people passing per hour during the office opening hours.

The method developed by Yuill et al. [19], demonstrated further by Mahajan et al. [16], was used to estimate infiltration through the sliding door. Yuill et al. [19] developed a method in the form of orifice equation for estimating the infiltration rate through automatic doors, which was based on the laboratory measurements and field observations. For the revolving door, the equations derived from the current measurement results were used. Moreover, as entrance doors are not opening or revolving all the time, methods for estimating the amount of the time the door is in use during the opening hours of the building are needed. The methods and equations used for the case studies are provided below.

2.3.1 Sliding door

Yuill et al. [19] introduced a new term, named airflow coefficient, to account for the changes in openness of the door. The airflow coefficient is related to the discharge coefficient and door usage frequency. Further simplifications were made by Yuill et al. [19] and a chart was proposed for determining the airflow coefficient based on the number of people passing per hour. For the sliding door, the airflow coefficient was determined by:

$$C_a = -6E\text{-}07(P_h)^2 + 0.0011P_h - 0.0006 \quad (3)$$

where C_a is the airflow coefficient, in $m^3/[m^2 \cdot second \cdot (P_a)^{\wedge}0.5]$, P_h is the number of people per hour. Equation (3) was generated based on data from Ref. [19] and with P_h up to 250.

The infiltration rate through a sliding door per hour was calculated by:

$$q_{sliding} = C_a \times A \times (\Delta P)^{0.5} \times 1000 \quad (4)$$

where $q_{sliding}$ is the infiltration rate through a sliding door, in l/s. A is the doorway area, in m^2, ΔP is the pressure difference, in P_a. 1000 is unit conversion factor from m^3/s to l/s. In this study, ΔP was only caused by the stack effect due to different temperatures between indoors and outdoors, determined by equation [3]:

$$\Delta P = \rho_o (\Delta T/T_i)\, g\, (H_{NPL}-H) \quad (5)$$

where ρ_o is outdoor air density, in kg/m^3, T_i is indoor temperature, in K, H_{NPL} is the height of neutral pressure level above reference plane, in m, which can be assumed to be at the mid-point of the building's height when the actual value of NPL is unknow, and H is the height above the reference plane, in m, which was assume to be one-half of the door height.

2.3.2 Revolving door

The equations used for estimating infiltration through the revolving door are presented in the section of Results and Discussion, as they are part of measurement results.

Estimating the degree of door usage for a specific hour is a complex probability problem, which depends not only on people flow and door capacity but also sensors and the shape of the flow [10]. The method used in Ref. [10] was adopted in this report:

$$DR_{usage} = P_h/\text{Door capacity} \quad (6)$$

where DR_{usage} is the door usage frequency. The door capacity was calculated by:

$$\text{Door capacity} = N_c \times N_{ppc} \times N \times 60 \quad (7)$$

where Nc is the number of segments. For a 4-wing door, Nc = 4. N_{ppc} is the number of people per segment. For a revolving door up to 3 meters in diameter it is common that every segment/compartment can hold one person, based on assumptions made through consulting the manufacture specifications [10], which means that in this case N_{ppc} = 1. N is the door rotation speed in rpm. Based on equation (7), for a 4-wing revolving door, with N = 2 rpm, the door capacity will be 480; with N = 4 rpm, the door capacity will be 960.

The final infiltration rate due to door movement through a revolving door each hour was determined by:

$$q_{revolving} = q_{present} \times DR_{usage} \quad (8)$$

where $q_{present}$ is infiltration caused by door movement based on the present work, in l/s. The sum of the infiltration rates each hour during the office opening hours will be the total infiltration rate through the entrance door for a day cycle.

3 Results and Discussion

3.1 Measurement results of the air exchange rates

The air exchange rates measured at different temperature differences and door rotation speeds for the small, medium, and large revolving door are shown in Figure 4-6. Empirical equations for each door were derived from the data shown in Figure 4-6. The equations can be used to predict how the air exchange rate, *y,* varies with temperature difference, *x,* with certain door rotation speed. Take the small door as an example, see results in Figure 4: with N = 6 rpm, the air exchange rate at different temperature differences in the range of 10-20 °C can be calculated by equation $y = 9.3311x+138.0$.

The air exchange rate is increased by increasing the temperature difference and the door rotation speed, according to the results from Figure 4-6. The trend of how the air exchange rate varying with ΔT and N is somewhat different for different sizes of the revolving doors. For the small door, the air exchange rate seems to vary with ΔT linearly, while for the medium and large door, the variation is likely to follow a polynomial relation.

Regarding the effect of the door rotation speed, the air exchange rate for the large door seems to be less affected compared to that for the small and medium door, when the door rotates with a speed higher than 2 rpm. As shown in Figure 6, the air exchange rate through the large door measured at different N (i.e., N = 3, 4, 6 rpm) are intended to merge to each other, and ΔT seems to be the only parameter affecting the air exchange rate. This is most likely to be explained by the delay that it takes longer time to empty the large compartment in the large door, so that the large compartment is emptied to a lower extent with a higher speed, which results in a similar energy losses as the door rotating with a lower speed where the compartment is emptied to larger extent. Other factors, such as indoor air movement and turbulence might influence the results which have not been investigated in this report.

When the door rotates with a low speed, i.e., N = 2 rpm, ΔT does not seem to have a noticeable impact on the air exchange rate. In Figure 4, the air exchange rate for the small door measured at different ΔT with N = 2 rpm seem to be maintained stably. This has also been observed from the study by Schutrum et al. [15] and that by Schijndel et al. [20]. The small variation for the medium door with N = 2 rpm (see Figure 5) is probably due to measuring errors. The air exchange rate through the revolving door is determined by the combined effect of the temperature difference, rotation speed and size of the door.

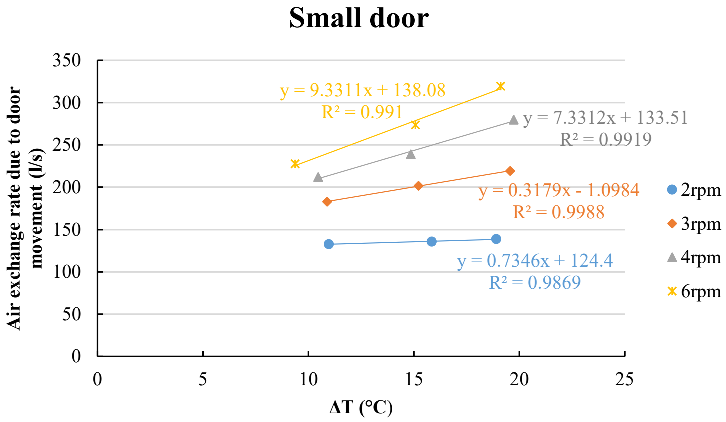

Figure 4. Air exchange rate for the small door (D = 1.8m) at different temperature differences and door rotation speeds.

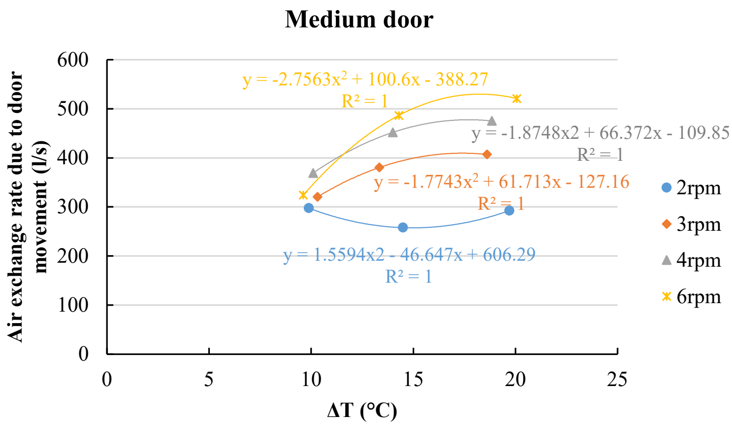

Figure 5. Air exchange rate for the medium door (D = 2.4m) at different temperature differences and door rotation speeds.

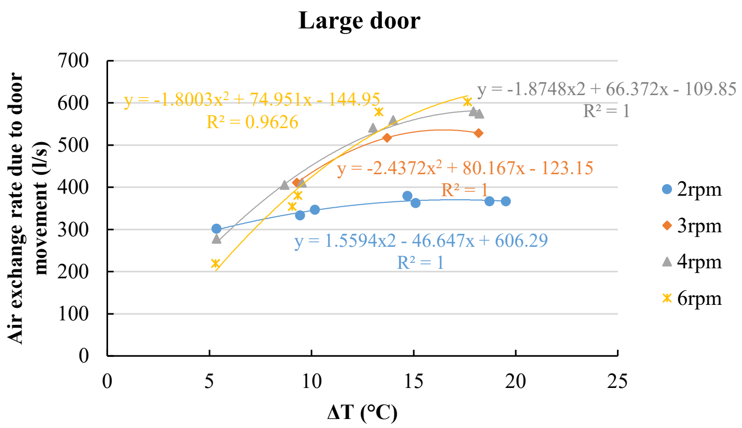

Figure 6. Air exchange rate for the large door (D = 2.7m) at different temperature differences and door rotation speeds.

3.2 Equations used for the revolving door for case studies

The small revolving door was used for the case studies for comparing with a sliding door, and the equations with N = 2 and 4 rpm (shown in Figure 4) were used and are shown below:

With N = 2 rpm

$$q_{present} = 1.5594\Delta T^2 - 46.647\Delta T + 606.29 \quad (9)$$

With N = 4 rpm

$$q_{present} = -1.7743\Delta T^2 + 61.713\Delta T - 127.16 \quad (10)$$

3.3 Comparison with the previous study

Predictions by the equations developed from this report were compared with the data published by Schutrum et al. [15], and the comparison results are shown in Figure 7. Considering the revolving door used in Ref. [15] has the size of 1.93 m in diameter and 2.1 m in height, the small door used in this study has the closest size and therefore chosen for the comparison. In Figure 7, the dots are the air exchange rate predicted based on the current work, and the curves are based on the data published in Ref. [15].

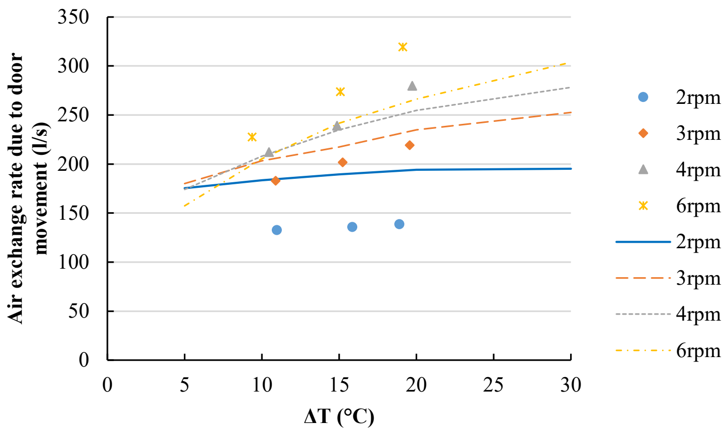

Figure 7. Comparison of the air exchange rate between the current study and Schutrum et al. (1961) [15]. Dots are the predicted results by the present study and the line curves are from Ref. [15].

Figure 7 shows some similarities between the current work and Schutrum et al. [15] in the trend of how the air exchange rate varying with ΔT at different N, though some discrepancies were observed. Comparing to the data by Schutrum et al. [15], the current model over-predicts the air exchange rate at a low door speed, i.e., N = 2 rpm, while under-predicts the results at a high door speed, i.e., N = 6 rpm. The comparisons at N = 3 and 4 rpm seem to correspond to each other well. The data from Ref. [15] was based on the settings of indoor air movement of 0.18 m/s and the average outdoor wind speed of 0.9 m/s. However, no other data or studies concerning this issue have been found. The deviations could be due to different measurement set-ups, conditions inside the test room and the revolving door itself etc.

3.4 Case study results

The comparison results between a sliding and revolving door for a simple office building are presented in this part. Figure 8 shows the hourly values of the airflow coefficient for the sliding door as a function of the number of people passing per hour for a day cycle. For the revolving door, the degree of the door usage when the door rotates with 2 and 4 rpm during a day is shown in Figure 9. The estimated infiltration rate through each door for an hour is presented in Figure 10, and the total infiltration rate during the office opening hours for a day is displayed in Figure 11.

It was observed from Figure 8 -11 that the infiltration rate through the entrance door is increased with increasing the number of people passing the building, which reaches to the maximum at the peak of the people flow rate i.e., at 8:00 and 17:00 o'clock during a working day. For the same people flow rate, the infiltration rate through the revolving door is higher when the door rotates with a lower speed because the more frequent use of the door. Based on the estimated results, with use of the methods and equations from Ref. [19] and that from the present experimental results, the revolving door can reduce the infiltration rate compared to the sliding one about 6 to 8 times, depending on the rotation speed. With the rotation speed of 2 rpm, the reduction factor of revolving door is about 6; with the rotation speed of 4 rpm, the reduction factor is about 8. The reduction factor was defined as the ratio between the infiltration rate through the sliding door and that through the revolving one. This means that, with 6-8 times infiltration rate reduction, i.e., corresponding to 2282-2388 l/s airflow rate (calculated based on Figure 4), for a "normal" door with daily usage presented in this report, with the yearly average temperature difference of 14.4 °C and with assumption of 224 working days, the energy saving for a year would be 8800-9200 kWh.

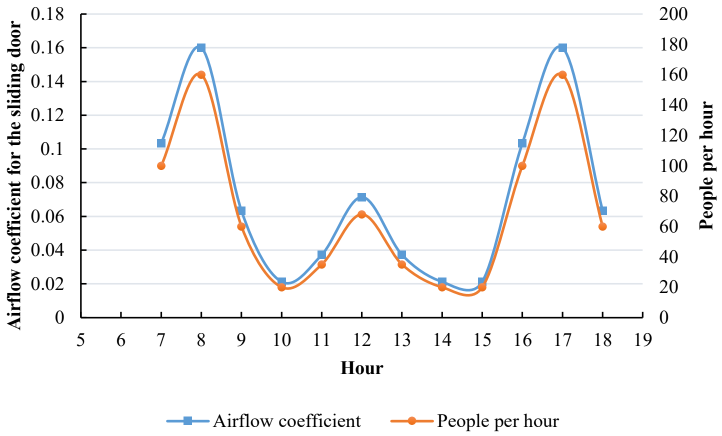

Figure 8. Airflow coefficient for the sliding door as a function of people passing per hour during the office opening hours.

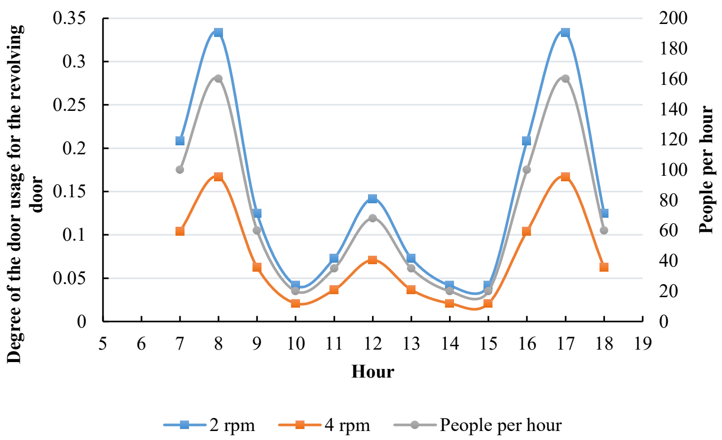

Figure 9. Degree of the door usage for the revolving door with the rotation speed of 2 and 4 rpm during the office opening hours.

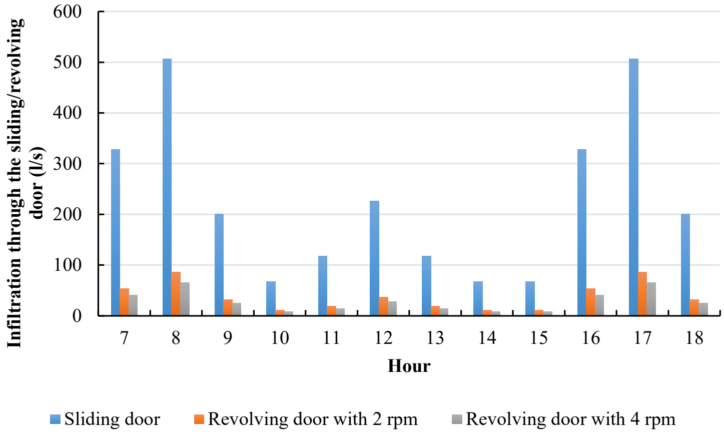

Figure 10. The hourly infiltration rate through the sliding/revolving door for a day cycle.

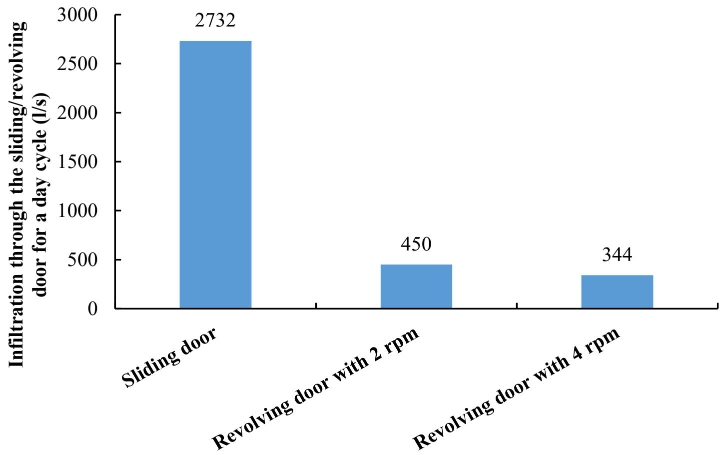

Figure 11. The total infiltration rate through the sliding, revolving door for a day cycle.

An extra figure, i.e., Figure 12, was made to show the impact of the number of people passing per hour on the reduction factor of the revolving door, which was based on the results from Figure 10. According to Figure 12, the reduction factor of the revolving door is maintained nearly the same regardless of the variations of the number of people passing per hour, and only small variations are observed when there is a big change of the number of people passing per hour, which occurs during 07:00-9:00 and 16:00-18:00 with the increase/decrease of 100 people per hour. This observation is only valid for this study with the current settings of the door size, number of people passing per hour profile, building height etc. The results or findings could be different if other set-ups are used. For example, the study by Karlsson [11] shows that the reduction is large when the people flow rate is low based on their simulation results for a large office building.

Figure 1. The total infiltration rate through the sliding, revolving door for a day cycle.

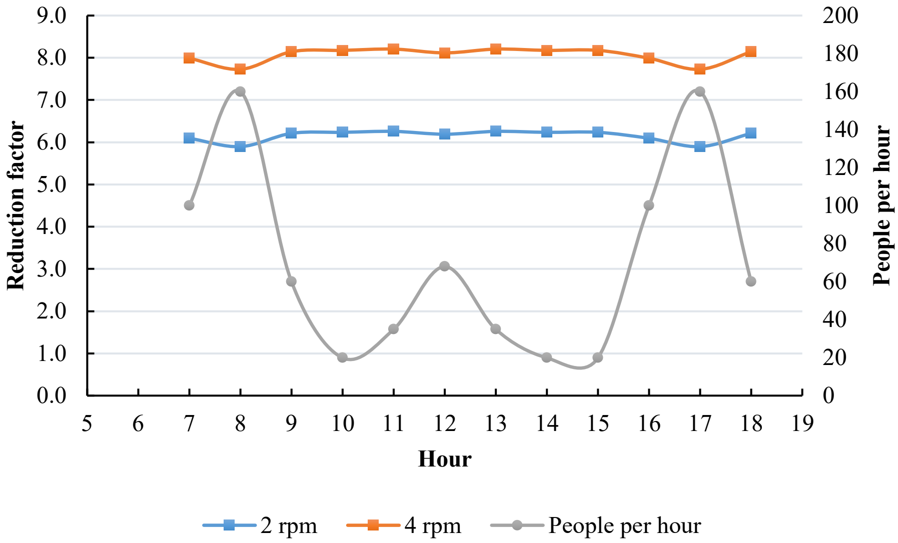

Figure 12. The reduction factor of the revolving door varying with the people flow rate.

The case studies were made for low-rise buildings and focused on the effect of the temperature difference, other factors such as wind effect, mechanical ventilation, building tightness were not considered. The method for predicting the fraction of open time for the sliding door is based on statistical data from field observations [19]. While the method used for the revolving door for predicting the degree of door usage is greatly simplified and needs to be improved [10], which can affect the infiltration rate through the revolving door as well as the associated reduction factor.

4 Conclusions

The air exchange rate through the revolving door is affected by the combined effect of the temperature difference, door rotation speed and door size, based on the measurement results. For the large door, the air exchange rate is not sensitive to door rotation speed when the door rotates with a speed higher than 2 rpm, which is most likely due to the delay effect of emptying the compartment. For the small door, both the temperature difference and door rotation speed are important to the air exchange rate. The effect for the medium door is in between of that for the small and large door.

A set of empirical equations were generated from the measurement results for each door, which can be used to predict the air exchange rate as a function of the temperature difference with a certain door rotation speed. Predictions by the equations show similar trend to the previous study on the air exchange rate varying with the temperature difference with a specified door rotation speed.

An approach was shown for comparing the infiltration rate through the sliding and revolving door in case studies, by implementing the methods for predicting infiltration through doorway as well as that for estimation of the door usage related to the people flow rate. The revolving door is shown to be more energy efficient than the sliding door, which has the potential to reduce the infiltration rate at least about 6 times based on the results from the case studies, corresponding to energy saving of about 8800 kWh per year. The method for estimating the degree of the door usage for the revolving door is greatly simplified, which can affect the case study results. Furthermore, the wind effect has not been included in this report which needs to be investigated in future studies.

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