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Assessing dynamic efficiency of air curtain in reducing whole building annual energy usage

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Abstract

The efficiency of air curtain in reducing infiltration and associated energy usage is currently evaluated statically by using an efficiency factor, η_{air}, based on single steady/static condition, which is often not the case for actual buildings under variable weather conditions and door usages. Based on a new method to consider these dynamic effects on air curtains, this study uses a dynamic efficiency factor η_B in terms of whole building site end-use energy to assess the efficiency of air curtains when compared to single doors (i.e. without air curtains) and vestibule doors. Annual energy simulations were conducted for two reference building models considering their specific door usage schedules in 16 climate zone locations in the North America. The variations of the proposed efficiency factor for different climate zones illustrated the dynamic impacts of weather, building, unit fan energy and door usage frequency on air curtain efficiency. A sensitivity study was also conducted for the operation temperature conditions of air curtain and showed that η_B also considers these operational conditions. It was thus concluded that using whole building site end-use energy to calculate the efficiency factor, η_B, can provide more realistic estimates of the performance of air curtains operations in buildings than the existing static efficiency factor.

Keywords

efficiency factor,
infiltration,
air curtain,
whole building energy simulation

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1 Introduction

Air curtains, which usually consist of a casement and fan with a jet outlet, have been in use for more than 50 years (Alamdari 1997; Van Belleghem et al. 2012; Chen 2009) in the HVAC industry. Air curtains are widely used to protect cold storage room and food cabinets, to control dust in the mining industry and also to control the propagation of smoke and fire in buildings (Alamdari 1997; Van Belleghem et al. 2012; Chen 2009; Johnson et al. 2008). In building applications, air curtains are usually mounted on top of openings (such as doors) to supply a continuous stream of air that is circulated across the doorway providing an aerodynamic seal (Costa et al. 2006). In order to correctly seal openings, air curtains are designed to supply jets (or one jet) of air that reach the floor at specific velocities and locations, so that any air that tries to penetrate the curtain is entrained (ASHRAE 2015). In buildings, air curtains are widely used in entrance doors to restrict air infiltration. Air infiltration is one of the leading causes of energy loss in building and can account for up to 25% of the total heat losses (Emmerich and Persily 1998). In modern well-insulated buildings, air infiltration through entrance doors, especially in commercial buildings with high door usage frequency, is one of the main sources of infiltration (Cho et al. 2010; Yuill 1996). Based on existing studies on air infiltration through automatic doors (Cho et al. 2010; Karlsson 2013; Yuill 1996), many current energy codes (such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 90.1—Energy Standard for Buildings Except Low-Rise Residential Buildings, as well as International Energy Conservation Code (ASHRAE 2010)) require the use of vestibules in commercial building entrances.

One of most prominent sources of literature regarding air curtains is the series of publication by Hayes (Hayes 1968; Hayes and Stoecker 1969a,b). Hayes was able to develop theoretical models that describe the airflow jet of vertically blowing air curtains under isothermal and non-isothermal

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Nomenclatures and abbreviations

A	area
b_0	width of the air curtain nozzle (air outlet width)
C	automatic door coefficient (for specific door size)
C_A	airflow coefficient
C_d	discharge coefficient
$C_{D,\ section}$	average discharge coefficient for each door operation section
C_{Dave}	average flow coefficient for a full door operation cycle
C_p	specific heat
D_d & D_{Dave}	discharge modifier (air curtains)
D_m	deflection modulus of air curtain jet
E_{AC}	end-use energy consumption of models with air curtain door (s)
F_u	air curtain infiltration usage correction factor
H	door height
P_h	people per hour (door usage)
Q	volume flow rate
q	heat transfer rate
R_p	pressure factor
T_h	usage per hour (doors)
u_0	air curtain discharge speed
ΔP_{lc}	lower critical pressure difference
ΔP_{uc}	upper critical pressure difference
ΔP_{oi}	pressure difference = outdoor pressure minus indoor pressure
η	efficiency factor for heat transfer reduction
η_{air}	efficiency factor for volume flow rate reduction
$\eta_{air\left(\frac{AC}{SD}\right)}$	efficiency factor of air curtain in reducing air infiltration in reference to the single door
$\eta_{air\left(\frac{VD}{SD}\right)}$	efficiency factor of vestibule door in reducing air infiltration in reference to the single door
$\eta_{air\left(\frac{AC}{VD}\right)}$	efficiency factor of air curtain in reducing air infiltration in reference to the vestibule door
η_B	efficiency factor for whole building end-use energy
$\eta_{B\left(\frac{AC}{SD}\right)}$	efficiency factor of air curtain in reducing whole building end-use energy in reference to the single door
$\eta_{B\left(\frac{VD}{SD}\right)}$	efficiency factor of vestibule door in reducing whole building end-use energy in reference to the single door
$\eta_{B\left(\frac{AC}{VD}\right)}$	efficiency factor of air curtain in reducing whole building end-use energy in reference to the vestibule door
ρ	air density

The following list is alphabetically ordered

AC	air curtain
air curtain door (AC)	double swing doors opening out with air curtain unit
CFD	computational fluid dynamics
CZ	climate zone
DOE	United States Department of Energy
fully open door	door open at 90°
LG	large store (in the strip mall reference building model)
PNNL	Pacific Northwest National Laboratory
SD	single door, double swing doors opening out (without vestibule or air curtain)
SM	small store (in the strip mall reference building model)
VD	vestibule door, vestibule with double swing doors opening out (2 sets of double swing doors)

conditions. Hayes developed the deflection modulus, D_m, which is indicative of the deflection of the air curtain jet and expresses the ratio of the outlet moment to the transverse forces on the jet (Hayes 1968). The D_m is still used by many for the design and sizing of air curtain units based on the minimum outlet velocities (Foster et al. 2006; Howell 2008). One of the most important findings that Hayes reported was that air curtains have an optimum flow condition where their jet reaches their floor and correctly seals the room, and that air curtains also can experience breakthrough conditions where they can cause excessive infiltration (more infiltration/exfiltration than if the door is unprotected) (Hayes and Stoecker 1969a).

Researchers have proposed assessing the performance of air curtains based on either the air infiltration or heat flux through the opening (Van Belleghem et al. 2012; Hayes and Stoecker 1969a; Sirén 2003). The airflow efficiency factor (Eq. (1)), $\eta_{air\left(\frac{AC}{SD}\right)}$, is one of the most commonly used methods (Costa et al. 2006; Verhaeghe and Van Belleghem 2010).

$$\eta_{air\left(\frac{AC}{SD}\right)} = 1 - \frac{Q_{AC}}{Q_{SD}} \quad (1)$$

where $\eta_{air\left(\frac{AC}{SD}\right)}$ is the efficiency factor of the air curtain in reducing the air infiltration through the door, Q_{AC} is the volumetric flow rate through the door with the air curtain used, e.g. m^3/s, and Q_{SD} is the flow rate through the door without air curtain, i.e. single door.

By applying the ASHRAE-suggested method to consider heat transfer rate through the door with an air curtain (ASHRAE 2015), we obtain another existing definition of efficiency factor (Eq. (2)).

$$\eta_{\left(\frac{AC}{SD}\right)} = 1 - \frac{q_{AC}}{q_{SD}} \tag{2}$$

where $\eta_{\left(\frac{AC}{SD}\right)}$ is the efficiency factor of the air curtain in reducing the heat losses through the door, q_{AC} is the heat transfer rate through the door with the air curtain used, e.g. kW, and q_{SD} is the heat transfer through the door without air curtain, i.e. single door. Assuming a constant air density and that all heat transfer is caused by airflow through the door, Eq. (3) can be used to calculate q (Van Belleghem et al. 2012; Costa et al. 2006). Such assumptions would result in both the airflow efficiency factor and the heat flow efficiency factor to be identical.

$$q = \rho C_p Q \Delta T \tag{3}$$

where q is the heat transfer rate through the opening, ρ is air density, C_p is the specific heat of air, Q is volumetric flow rate through the opening, and ΔT is the temperature difference across the opening.

Various studies have shown the relationship between the air curtain efficiency factor and the jet flow and speed: it was reported the efficiency factor can range from 30% up to 90% (Pappas and Tassou 2003). However, most air curtain studies dealt with close room applications for air curtain under steady/static state conditions (jet condition as well as pressure and temperature differences), and neglected the effect of door usage on the air infiltration (Alamdari 1997; Foster et al. 2006; Hayes 1968; Verhaeghe and Van Belleghem 2010). Meanwhile, both formulations in Eqs. (1) and (2) do not consider the electricity power (or energy usage) of air curtain fan itself so they are only an indicator of air curtain's "sealing effectiveness" to the doorway instead of the actual "energy performance". During the actual operation of air curtains, however, the steady state condition assumption is not valid since fluctuations in temperature, wind as well and the door usage are inevitable.

For entrance doors without air curtains, Yuill's study (Yuill 1996) provided one of the most frequently methods used to estimate the air infiltration through single and vestibule doors. Yuill calculated average discharge coefficients, C_{Dave}, which considers the full door opening cycle. Yuill then simplified his model (Eq. (4)) by suggesting airflow coefficients, C_A, for single and vestibules doors (which consider the presence of people in the doorway) that can be obtained directly from charts and that depend on the door usage rate (Yuill 1996). By setting a number of assumptions regarding weather and building[1], Yuill also suggested the use of the pressure factor, R_p, which represents a design value for the pressure difference across the door. R_p is dependent on the outdoor temperature and the height of the building (ASHRAE 2013; Yuill 1996).

$$Q_{SDorVD} = C_A A R_p \tag{4}$$

where Q_{SDorVD} is the air infiltration through the single or vestibule door, C_A is the overall airflow coefficient (single door or vestibule door), and R_p is the pressure factor obtained from ASHRAE and based on the outdoor temperature and building height (ASHRAE 2013).

Wang and Zhong (2014) conducted a numerical study to assess the infiltration characteristics of an air curtain door (without heating elements). In the study, ANSYS FLUENT 14.0 (ANSYS 2011) was used to model and simulate a 2 m × 2.4 m ($W \times H$) door with an air curtain supplying air at 15 m/s at 20° outwards from a slot of 0.08 m × 2 m. The pressure difference across the door was set across a larger domain and stack effect was considered by varying the temperatures across the door. In order to account for the door opening and closing cycles, the door opening angles were varied from 10° to 90° (fully open). Following the methods proposed by Yuill (1996), Wang and Zhong (2014) developed a model (Eq. (5)) which can estimate the air infiltration through the air curtain door (Q_{AC}) which included a flow modifier. The results of the study confirmed the findings of Hayes regarding the operation conditions of air curtains and identified them as (a) optimum condition, (b) outflow breakthrough condition after reaching the lower critical pressure (ΔP_{lc}) and (c) inflow breakthrough condition after reaching the upper critical pressure (ΔP_{uc}) (Wang and Zhong 2014).

$$Q_{AC} = (-1)^i C_{Dave} A T_h \sqrt{\frac{2\,|\,\Delta P_{oi}\,|}{\rho}} + D_{Dave} T_h \sqrt{\frac{2}{\rho}} \tag{5}$$

where

$$D_{Dave} = \frac{D_{Da}a + D_{Db}b + D_{Dc}c + D_{Dd}d}{a+b+c+d}$$

$i = 0$ when $\Delta P_{oi} \geq 0$ and $i = 1$ when $\Delta P_{oi} < 0$.

The model indicates that the infiltration through air curtain doors depended both on the pressure difference and the air curtain jet. The flow coefficient, C_{Dave}, and the flow modifier, D_{Dave}, are not universal but rather are used to describe the flow of the simulated air curtain under one of the three flow conditions (i.e. a coefficient and modifier for each flow condition was calculated) (Wang and Zhong 2014). It was then found that the relationship between the air infiltration and the door usage could be expressed in ratios

[1] Assumptions: steady winds of 6.7 m/s (15 mph) with no correction for terrain, the location of the neutral pressure plane at the building's mid-height, and that the draft coefficient to be 0.9 (Yuill 1996).

(from the infiltration at door usage rate of 100 P_h—people per hour) that are applicable for all three flow conditions (Goubran et al. 2015). Based on the results, it was found that air curtain doors can significantly reduce infiltration in comparison to the vestibule and single doors. Using the same CFD model and methods, a study by Qi et al. (2015) carried out similar analysis for an air curtain door with a supply speed of 20 m/s at 20° that also considers the presence of people under the air curtain's jet during the fully open section of the door. Figure 1 shows the air infiltration and exfiltration characteristic of the 2 m × 2.4 m air curtain door modeled (20 m/s supply at 20° outwards) in comparison single and vestibule doors of the same size and door usage frequency (Wang and Zhong 2014). It also shows the three operation conditions of the air curtain door (Wang and Zhong 2014).

Based on the review of previous studies, it was concluded that the existing methods of static efficiency factors for air curtains are based on single steady condition assessments which do not reflect the actual operation conditions of the units. This paper aims to propose a dynamic efficiency factor of air curtains in terms of their ability to reduce whole building annual site end-use energy in buildings. Unlike the existing efficiency factor method, which focuses on the door related heat losses, the proposed calculation considers other factors such as outdoor temperature, door usage factor, energy losses related to the air curtain energy consumption as well as operation temperature controls of air curtain door. The proposed whole building dynamic efficiency factor is crucial in understanding the impact of using air curtains on the energy performance of buildings. The study uses the ASHRAE 90.1-2013 strip mall and outpatient healthcare reference building models developed by PNNL ("Commercial Prototype Building Models | Building Energy Codes Program" 2016; Deru et al. 2011) to assess the efficiency of the air curtains in reducing site end-use energy consumption in 16 climate zone locations of the North America by using whole building energy simulations on EnergyPlus.

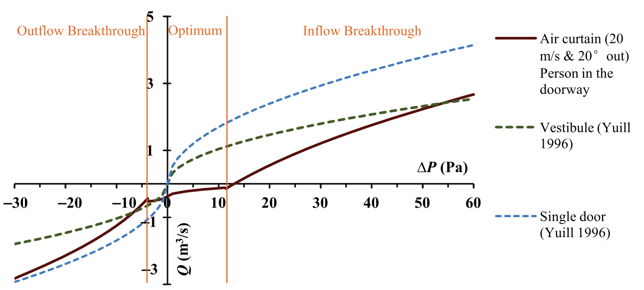

Fig. 1 An example of plotting Eq. (5) for the infiltration and exfiltration characteristic (Q_{AC}) of a 2 m × 2.4 m air curtain door modeled (20 m/s supply at 20° outwards) in comparison single and vestibule doors of the same size (100 P_h) (Qi et al. 2015)

2 Methodology

2.1 Air curtain efficiency factors

For this study, the efficiency factor of the air curtain, $\eta_{\text{air}\left(\frac{\text{AC}}{\text{SD}}\right)}$, will be calculated in comparison to the performance of the single door (a door without air curtain) using Eq. (1) and based on the results in Fig. 1. In addition, the efficiency of the air curtain, in reducing air infiltration will also be calculated with door usage rate varying from 0 P_h to 200 P_h by using Eq. (1). In order to put the factors calculated in context and for the purpose of comparison, the efficiency of the vestibule doors will also be assessed in reference to single door ($\eta_{\text{air}\left(\frac{\text{VD}}{\text{SD}}\right)}$) based on the following equation:

$$\eta_{\text{air}\left(\frac{\text{VD}}{\text{SD}}\right)} = 1 - \frac{Q_{\text{VD}}}{Q_{\text{SD}}} \tag{6}$$

Considering the vestibule code requirements, it is also worthwhile to compare air curtains and vestibules. So the efficiency of the air curtain door to reduce air infiltration in reference to the vestibule door is also calculated here using Eq. (7).

$$\eta_{\text{air}\left(\frac{\text{AC}}{\text{VD}}\right)} = 1 - \frac{Q_{\text{AC}}}{Q_{\text{VD}}} \tag{7}$$

where $\eta_{\text{air}\left(\frac{\text{AC}}{\text{VD}}\right)}$ is the efficiency factor of the air curtain in reducing the infiltration through the door in reference to the vestibule door, Q_{AC} is the volumetric flow rate through the door with the air curtain used, e.g. m^3/s, and Q_{VD} is the flow rate through the vestibule door.

To calculate the efficiency of air curtain door in reducing the whole building site end-use energy, the results of energy simulations that are conducted for the strip mall and outpatient healthcare buildings will be used as inputs in Eq. (8).

$$\eta_{\text{B}\left(\frac{\text{AC}}{\text{SD}}\right)} = 1 - \frac{E_{\text{AC}}}{E_{\text{SD}}} \tag{8}$$

where $\eta_{\text{B}\left(\frac{\text{AC}}{\text{SD}}\right)}$ is the efficiency factor of the air curtain in reducing whole building site end-use energy in reference to the single door, E_{SD} is the annual site end-use energy of the model simulated with the single door (or baseline case) in MJ/m^2, and E_{AC} is the annual site end-use energy of the model simulated with the air curtain door in MJ/m^2 (which includes the air curtain fan energy).

Similarly, the efficiency of the vestibule door in reducing whole building site end-use energy in reference to single door can be assessed using Eq. (9).

$$\eta_{\text{B}\left(\frac{\text{VD}}{\text{SD}}\right)} = 1 - \frac{E_{\text{VD}}}{E_{\text{SD}}} \tag{9}$$

where $\eta_{B\left(\frac{VD}{SD}\right)}$ is the efficiency factor of the air curtain in reducing whole building site end-use energy in reference to the single door, E_{SD} is the annual site end-use energy of the model simulated with the single door (or baseline case) in MJ/m^2, and E_{VD} is the annual site end-use energy of the model simulated with the vestibule door in MJ/m^2.

When assessing the efficiency of the air curtain in reducing whole building site end-use energy in reference to the vestibule door, Eq. (10) is used:

$$\eta_{B\left(\frac{AC}{VD}\right)} = 1 - \frac{E_{AC}}{E_{VD}} \quad (10)$$

where $\eta_{B\left(\frac{AC}{VD}\right)}$ is the efficiency factor of the air curtain in reducing whole building site end-use energy in reference to the vestibule door, E_{VD} is the annual site end-use energy of the model simulated with the vestibule door (or baseline case) in MJ/m^2, and E_{AC} is the annual site end-use energy of the model simulated with the air curtain door in MJ/m^2 (which includes the air curtain fan energy usage).

2.2 Building models and simulation parameters

For this study, the strip mall building and the outpatient healthcare reference building models (Fig. 2) will be used. These models (Deru et al. 2011), which were developed by the U.S. DOE, are used for the research and development as well as assessment of the new energy codes and standards ("Commercial Prototype Building Models | Building Energy Codes Program" 2016; Deru et al. 2011). The models are available as input files compatible with the energy simulation software EnergyPlus (DOE 2010). This study uses the ANSI/ ASHRAE/IES Standard 90.1 Prototype Building Models that are compliant with ASHRAE 90.1-2013 ("Commercial Prototype Building Models | Building Energy Codes Program" 2016). Distinct models, which are non-directional, are available as EnergyPlus input files for each climate zone location. Table 1 and Table 2 provide some relevant details about the models used and their schedules as reported by Pacific Northwest National Laboratory (PNNL) (Cho et al. 2010; Deru et al. 2011).

Based on the building parameters, the R_p factors of each of the buildings were obtained from ASHRAE (ASHRAE 2013). For the strip mall building R_p is calculated to be 4.49

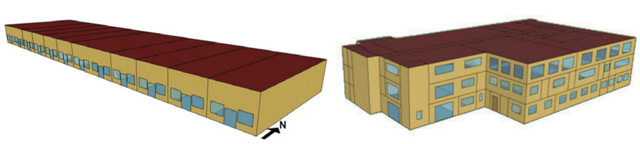

Fig. 2 Strip mall (left) and outpatient healthcare (right) reference building models (Deru et al. 2011)

(20.16 Pa) and 4.53 (20.52 Pa) for the outpatient healthcare building. Thus, the average pressure difference across the doors of both buildings is calculated to be 20.34 Pa. In addition, based on the doors operation schedule in Table 1 and Table 2, the weighted average door usage for the strip mall building was calculated to be 7 P_h and 38 P_h for the outpatient healthcare building. This study will investigate the effectiveness of air curtains in 16 locations (Table 3) which represent eight climate zones of US and Canada. TMY3 weather data files (Crawley 1998) for the 16 climate zone locations, which are compatible with EnergyPlus, are used in the simulations. EnergyPlus (ver. 8) (DOE 2010) was

Table 1 Schedule and description for strip mall building model ("Commercial Prototype Building Models | Building Energy Codes Program" 2016)

Category		Details
Building schedule	Operation time	All week
	Peak hours	10 AM to 6 PM
	Peak door usage (P_h)	34 (large store) 16 (small store)
	Off-peak hours	8 to 10 AM and 6 to 8 PM
	Off-peak door usage (P_h)	3 (large store) 2 (small store)
Building description	Number of entrances	10 doors (10 air curtains)
	Door opening zone/total area	100% (10/10 zones)

Table 2 Schedule and description for outpatient healthcare building model ("Commercial Prototype Building Models | Building Energy Codes Program" 2016)

Category		Details
Building schedule	Operation time	Weekdays
	Peak hours	7 AM to 5 PM
	Peak door usage (P_h)	123
	Off-peak hours	6 to 7 AM and 6 to 7 PM
	Off-peak door usage (P_h)	12
Building description	Number of entrances	1 door (1 air curtain)
	Door opening zone/total area	1.53% (1/118 zones)

Table 3 16 climate zone locations used and their representative cities

1A	Miami	4C	Salem
2A	Houston	5A	Chicago
2B	Phoenix	5B	Boise
3A	Memphis	5C	Vancouver
3B	El-Paso	6A	Burlington
3C	San-Francisco	6B	Helena
4A	Baltimore	7	Duluth
4B	Albuquerque	8	Fairbanks

used for this study and that all the simulations were conducted with the original north direction of the energy models. It is important to note that vestibule doors will only be simulated in climate zones 3A to 8 where they are required by the codes (ASHRAE 2010).

2.3 Whole building energy simulations

Using Yuill's model (Yuill 1996) and the calculated pressure factors, the infiltration rates of the single door and vestibule doors of the two models were calculate based on their door usage rates using Eq. (4). The air curtain infiltration rates (Q_{AC}) were also calculated using the pressure differences obtained from the R_p and the correction factors for the door usage by Eq. (11).

$$Q_{AC} = F_u Q_{100P_h} R_p \tag{11}$$

where, F_u is the door usage correction factor, and Q_{100P_h} is the infiltration rate through the air curtain door with 100 P_h door usage in Fig. 1.

In accordance to the parameters found in literature (Wang 2013), the air curtain unit is set to operate only when the doors are in use and when the ambient temperature is below 10 °C or above 30 °C. Since the air curtain units only operate when the doors are in use, Eq. (12) is used to calculated T_h (time of use of the door in hour/hour) based on the hourly door schedule (P_h) (Yuill et al. 2000). The results of the calculated T_h related to the door usage schedule for the two building can be found in Table 4 and are used as inputs in the energy simulations.

$$T_h = 1 - e^{-0.002233P_h} \tag{12}$$

To automatically control the air curtain unit's operation in EnergyPlus (and thus calculate the fan energy consumption within the energy simulation of the building), an EnergyPlus Runtime Language (ERL) program was developed as part of the Energy Management System (EMS) of each building. The air curtain unit control program automatically controls the units' operation based on the parameters presented and calculates the total energy consumption of air curtain units based on their operation schedule and parameter. Also, the control program considered that when the conditions of air curtain units operation are not met, the door experiences single door infiltration. It is important to note that the strip mall building has 10 doors each of which had an air curtain model while the outpatient healthcare building only has one entrance door equipped with air curtain. In order to calculate the air curtain units' energy usage (E_{AC}), the power rating of the unit (1.05 kW) (Wang 2013) is multiplied by the total number of air curtain operation hours and the number of air curtain units in the building, Eq. (13) (this operation is

Table 4 Infiltration rates calculated for the modeled reference buildings

Building		Door usage (P_h)		Q (m^3/s) at 16 °C: Single door	Vestibule door	Air curtain door	T_h (air curtain operation) (h/h)
Outpatient		Peak	123	2.938	1.815	0.646	0.240
		Off peak	12	0.300	0.177	0.066	0.026
Strip mall	Large store	Peak	34	0.853	0.508	0.196	0.073
		Off peak	3	0.076	0.045	0.018	0.007
	Small store	Peak	16	0.404	0.239	0.093	0.035
		Off Peak	2	0.051	0.030	0.012	0.004

achieved automatically by the ERL program).

$$E_{AC} = \text{Total hours of operation} \times 1.05\ \text{kW} \times \text{Number of units} \tag{13}$$

When the buildings were simulated with single or vestibule doors, the air curtain units were removed. In addition, a number of simulations have been conducted to assess the sensitivity of the air curtain control temperature on its efficiency. It is important to note that the buildings are simulated with single doors and air curtain doors in all 16 climate zones and they are simulated with vestibule in only 13 climate zones (CZ 3A to CZ 8). For this study, a total of 90 energy simulations were conducted to obtain the main results and an additional 6 simulations for the sensitivity study.

3 Results and discussion

3.1 Air curtain infiltration reduction efficiency, η_{air}

Based on the air curtain performance of the CFD simulations by Qi et al. (2015), the air curtain door efficiency was calculated in reference to the single door (Fig. 3). The results indicate that the vestibule door, at 100 P_h door usage, has a $\eta_{air\left(\frac{VD}{SD}\right)}$ of 0.39 consistently at different pressure differences. However, the air curtain $\eta_{air\left(\frac{AC}{SD}\right)}$ varies significantly depending on the operation condition of the unit. As indicated by Fig. 1, the air infiltration through the air curtain door is consistently lower than that through the single door except for a small portion from approximately −2 Pa to 0 Pa. This is reflected in Fig. 3 for a continuously positive $\eta_{air\left(\frac{AC}{SD}\right)}$ for all the range of pressure differences and the discontinuity in the curve is due to the its approach to ±∞ near the vertical axis. However, it is also seen that the vestibule door is more efficient in reducing air exfiltration (negative ΔP range). Based on the direct calculation for the data provided by Qi

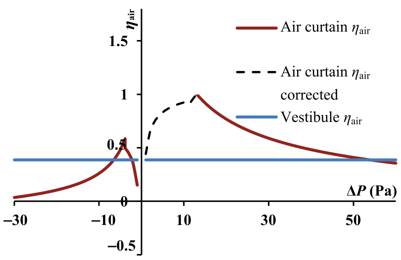

Fig. 3 η_{air} calculated for the air curtain ($\eta_{air\left(\frac{AC}{SD}\right)}$) and vestibule doors ($\eta_{air\left(\frac{VD}{SD}\right)}$) for a door usage of 100 P_h

et al. (2015), the air curtain door $\eta_{air\left(\frac{AC}{SD}\right)}$ peaks above the 1.0 in the optimum condition range (approximately between 0 Pa and 12.5 Pa). However, by examining Fig. 1 in the positive ΔP range, up to the ΔP_{uc}, the air curtain door is causing air exfiltration while the single door is causing infiltration. From considering a real-life scenario and mass balance, the exfiltration due to air curtain ought to be replaced from another source. With this concept, a correction to the $\eta_{air\left(\frac{AC}{SD}\right)}$ curve of the air curtain was made in Fig. 3.

Using Yuill's model for the single and vestibule doors (Yuill 1996) and the infiltration data provided by Qi et al. (2015) for the air curtain door, an analysis of the infiltration rates through the 2 m × 2.4 m door (i.e. the door size for both buildings in the EnergyPlus simulations) was conducted for different door usage rates at the average pressure difference calculated based on R_p for the two building models (20.34 Pa) (Fig. 4). The efficiency factor of the vestibule and air curtain doors is based on the infiltration data. The efficiency factor data indicate that air curtain doors are much more efficient in reducing air infiltration than vestibules for door usages even up to 200 P_h. In addition, the data indicates that, with the increase of door usages, the efficiency of the vestibule declined by 11.5% while the efficiency of the air curtain increased by approximately 2%. This suggests that, not only do air curtains perform better than vestibules in reducing air infiltration, but that their efficiency actually improves at higher door usage rates.

Based on the weighted average door usage rates calculated for the two buildings, the efficiency of the vestibule and air curtain doors were calculated for the design pressure conditions (Table 5).

3.2 Air curtain whole building energy reduction efficiency, η_B

The detailed results of the simulations are presented in Fig. 5 and Table 6, and the averaged results of the energy simulations are presented in Table 7. It is important to note that the average η_B values in Table 7 are the mean values of η_B for all the climate zones considered. Also note that the vestibule door is only considered for where it is required by ASHRAE 90.1: 13 out of 16 climate zones so $\eta_{B\left(\frac{VD}{SD}\right)}$ and $\eta_{B\left(\frac{AC}{VD}\right)}$ are only available for these 13 climate zones. Even though the strip mall building has 10 air curtain units, which reflects in the air curtain fan energy in Table 7, and much lower door usage rates, the air curtain door was significantly more efficient than in the outpatient healthcare building. In the strip mall building, air infiltration affects all the 10 zones with air curtains and thus, any reduction in infiltration is directly reflected in site end-use energy. In the outpatient healthcare building, only 1.5% of the building area (1 of 118 energy zones) is affected by infiltration, which has a less significant effect on the end use energy. Air curtains are much more efficient in reducing building energy consumption than in the outpatient healthcare where a small portion is directly affected by door infiltration. The results also

Table 5 Weighted average η_{air} for the two buildings at design pressure condition

	Strip mall building	Outpatient healthcare building
Weighted average P_h	7	38
$\eta_{air\left(\frac{AC}{SD}\right)}$	0.78	0.783
$\eta_{air\left(\frac{VD}{SD}\right)}$	0.412	0.403
$\eta_{air\left(\frac{AC}{VD}\right)}$	0.626	0.636

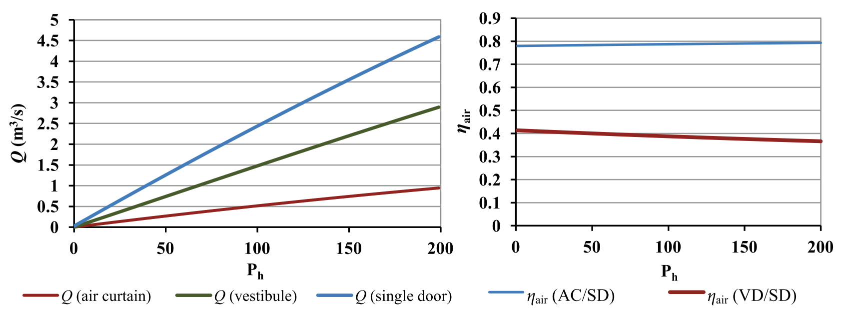

Fig. 4 Air infiltration through the three door types (left) and $\eta_{air\left(\frac{AC}{SD}\right)}$ and $\eta_{air\left(\frac{VD}{SD}\right)}$ (right) for door usage up to 200 P_h at the average pressure difference across the door

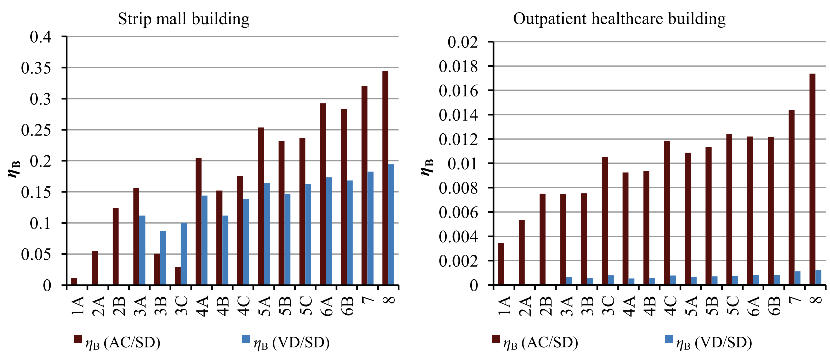

Fig. 5 Air curtain $\eta_{B\left(\frac{AC}{SD}\right)}$ and vestibule doors $\eta_{B\left(\frac{VD}{SD}\right)}$ efficiency in reducing whole building energy usages

Table 6 Climate zones' η_B and calculated average η_B for the two buildings

	Strip mall building			Outpatient healthcare building		
	$\eta_{B\left(\frac{VD}{SD}\right)}$	$\eta_{B\left(\frac{AC}{SD}\right)}$	$\eta_{B\left(\frac{AC}{VD}\right)}$	$\eta_{B\left(\frac{VD}{SD}\right)}$	$\eta_{B\left(\frac{AC}{SD}\right)}$	$\eta_{B\left(\frac{AC}{VD}\right)}$
1A	—	0.012	—	—	0.003	—
2A	—	0.055	—	—	0.005	—
2B	—	0.124	—	—	0.008	—
3A	0.112	0.157	0.050	0.001	0.007	0.007
3B	0.087	0.051	−0.040	0.001	0.008	0.007
3C	0.100	0.029	−0.078	0.001	0.011	0.010
4A	0.144	0.204	0.070	0.001	0.009	0.009
4B	0.112	0.152	0.045	0.001	0.009	0.009
4C	0.139	0.176	0.043	0.001	0.012	0.011
5A	0.164	0.254	0.107	0.001	0.011	0.010
5B	0.147	0.231	0.099	0.001	0.011	0.011
5C	0.162	0.236	0.088	0.001	0.012	0.012
6A	0.174	0.293	0.144	0.001	0.012	0.011
6B	0.168	0.284	0.139	0.001	0.012	0.011
7	0.182	0.320	0.169	0.001	0.014	0.013
8	0.194	0.345	0.187	0.001	0.017	0.016
Average	0.145	0.183	0.079	0.001	0.010	0.011

indicated in the outpatient healthcare, a building with high door usage, the air curtain is on average approximately 10 times more efficient than the vestibule door in reducing the building site end-use energy. Figure 5 shows that the air curtain door generally increases in its efficiency in reducing whole building energy in colder climates. The air curtain door was consistently more efficient in all climate zones for the outpatient healthcare building. The data presented confirm the ability of the suggested efficiency measure, η_B, to quantify the performance of air curtain doors while considering the effects of weather, door usage frequency, building related parameters and the unit's fan energy usage.

Table 7 Summary of simulation results and calculated averages for the two buildings

	Strip mall building		Outpatient healthcare building	
	CZ 1A to 8	CZ 3A to 8	CZ 1A to 8	CZ 3A to 8
Average end-use energy single door (MJ/m^2)	883.41	937.98	1314.42	1298.36
Average end-use energy vestibule (MJ/m^2)	—	793.51	—	1297.33
Average end-use energy air curtain (MJ/m^2)	695.76	716.82	1300.97	1283.52
Average $\eta_{B\left(\frac{VD}{SD}\right)}$	—	0.145	—	0.001
Average $\eta_{B\left(\frac{AC}{SD}\right)}$	0.183	—	0.010	—
Average $\eta_{B\left(\frac{AC}{VD}\right)}$	—	0.079	—	0.011
Average air curtain fans energy consumption (kWh)	605.9 (10 units)		308.3 (1 unit)	

3.3 Air curtain efficiency in comparison to ASHRAE 90.1 Requirements

Since ASHRAE 90.1-2010 (ASHRAE 2010) requires vestibules in climate zones 3 to 8 for most commercial buildings, a comparison between the air curtain door's performance and that of the vestibule is conducted for the air infiltration and energy consumption data. Figure 6 shows the $\eta_{air\left(\frac{AC}{VD}\right)}$ calculated based on the data of Qi et al. (2015). The data indicates that air curtains would result in more infiltration when compared to the vestibule in the negative ΔP range except for the pressure difference range from −8 Pa to −2 Pa. By assuming that in the positive ΔP range, the air exfiltrated by the air curtain is replaced, the corrected $\eta_{air\left(\frac{AC}{VD}\right)}$ of the air curtain, in comparison to the vestibule door, indicates that the air curtain door would result in worse performance for pressures up to 12.5 Pa and in pressures above 52 Pa. In the

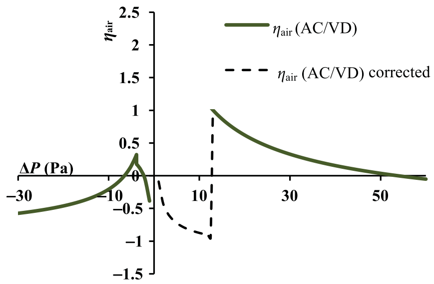

Fig. 6 $\eta_{air\left(\frac{AC}{VD}\right)}$ calculated for a door usage of 100 P_h

case of the strip mall and outpatient healthcare buildings, the design pressure difference is within the positive $\eta_{air\left(\frac{AC}{VD}\right)}$ range, which explains the efficiency of the air curtain door seen in the energy results. The $\eta_{B\left(\frac{AC}{VD}\right)}$ data in Table 7 indicates that air curtains are more efficient in reducing vestibule door infiltration in the outpatient healthcare building than in the strip mall building. Figure 7 shows the efficiency factor, $\eta_{B\left(\frac{AC}{VD}\right)}$, calculated for air curtain door in reference to the vestibule door performance in CZ 3A to 8 in accordance with ASHRAE 90.1-2010 requirements (Cho et al. 2010). Air curtains are shown to outperform vestibules ($\eta_{B\left(\frac{AC}{VD}\right)} > 0$) in most climate zones except for CZ 3B and 3C for the strip mall building. In Fig. 5, the air curtain door's efficiency ($\eta_{B\left(\frac{AC}{SD}\right)}$) was lower in CZ 3B and 3C for the strip mall building than the vestibule door's ($\eta_{B\left(\frac{VD}{SD}\right)}$), indicating that a vestibule door would save more energy in these warm climate zones. The comparison of the air curtain door performance to the vestibule door indicates that the efficiency factor proposed is able to accommodate for changes in the baseline cases for comparison.

3.4 Sensitivity study of air curtain temperature control

One of the aspects of modern air curtains is the use of temperature control that helps to optimize its operation. The air curtain in the baseline cases presented was set, based on the parameters found in literature (Goubran et al. 2015; Wang 2013), to operate if the temperature is above 30 °C or lower than 10 °C and when the doors are opening. Since the air curtain operation time, fan energy consumption and whole building energy performance can be effected by the temperature control, a number of simulations have been conducted to assess the sensitivity of the efficiency factors, $\eta_{B\left(\frac{AC}{SD}\right)}$ and $\eta_{B\left(\frac{AC}{VD}\right)}$, to the temperature controls of the unit in climate zone 3C (Fig. 8), where air curtain was shown to perform most poorly in the preceding analysis. Figure 8 shows that in the strip mall building, reducing the idle range (increasing the operation time) of the unit improved the air curtain doors' efficiency whereas in the outpatient healthcare building it reduced the efficiency. Such observation could be due to the different building schedules, different door usages or even building system related parameters. However, the data presented in Fig. 8 indicate that the proposed efficiency factor, η_B, is able to capture the effects of the unit-related controls on the efficiency of the air curtain door.

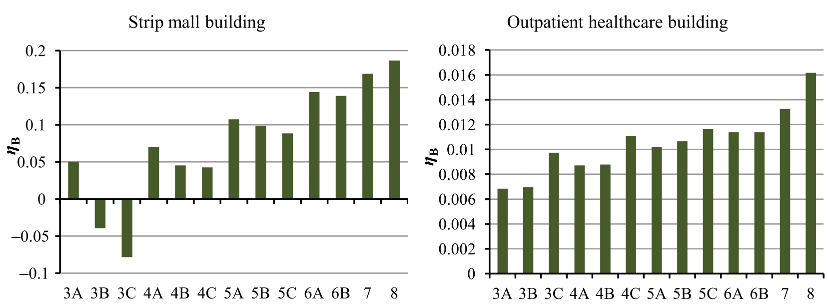

Fig. 7 Air curtain door efficiency $\eta_{B\left(\frac{AC}{VD}\right)}$ in reducing whole building energy use in zones 3A to 8

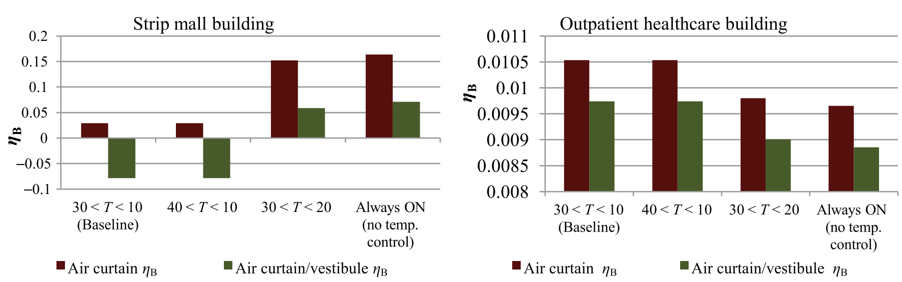

Fig. 8 Sensitivity of air curtain $\eta_{B\left(\frac{AC}{SD}\right)}$ and air curtain/vestibule $\eta_{B\left(\frac{AC}{VD}\right)}$ to the air curtain temperature control in zone 3C

4 Conclusions

The review of literature indicated that the existing efficiency factors used to assess air curtains' performance focus on door related infiltration and heat losses under steady/static conditions. However, in real buildings applications, air curtain doors experience fluctuations in temperature difference and door usage. The existing efficiency factors can hardly estimate the performance of the units under these changing conditions. This paper proposes to assess the efficiency of air curtains based on their ability to reduce site end-use energy consumption in buildings using η_B, which considers these dynamic factors.

Based on the infiltration characteristics of air curtain doors in operation with a person in the doorway, the study calculates and analyses the existing static airflow efficiency factor for air curtain and vestibule doors in comparison to single doors. The data indicated that, while vestibules have a steady efficiency for all pressure differences, the air curtain door's dynamic efficiency fluctuates depending on its operation condition. However, it was observed that in some cases, when the air curtain exfiltrates air and the single or vestibule door infiltrates air, the air curtain door's efficiency has to be corrected to account for air loss from its jet. It is concluded that, in the negative pressure range, vestibules are more efficient in reducing air exfiltration. However, the positive pressure range, air curtain doors can significantly reduce air infiltration. Calculating the air curtain doors' efficiency factor in comparison to vestibule doors indicated that they are mostly efficient in positive pressure difference range.

The study used the infiltration data for the three door types to conduct whole building annual energy simulations for the strip mall and outpatient healthcare reference building models in 16 climate zone locations of the North America. The results of the simulations were used to measure the whole building air curtain efficiency factor in comparison to single doors and vestibules. The results of calculations for the two buildings indicated that air curtain doors are efficient in reducing whole building site end-use energy consumption across all climate zones while outperforming the efficiency of vestibule. The fluctuations and differences in the air curtain efficiency factor η_B across the climate zones confirmed its ability to estimate the air curtain's whole building dynamic efficiency while considering building and weather related parameters. Calculating the η_B of air curtains in comparison to vestibules indicated that air curtains can consume more energy in certain warm climate zones. However, the negative η_B values obtained confirmed the ability of the proposed efficiency factor to consider different baselines for comparisons. A sensitivity study that varied the air curtain unit's operation condition also showed different trends in each building. This confirmed that the proposed efficiency measure, η_B, considers unit related parameters in its assessment of the air curtain doors' performance.

Finally, it is concluded that, the proposed efficiency factor, η_B, which uses whole building energy performance to assess the efficiency of air curtain doors can provide more realistic estimates that are applicable to buildings. As opposed to existing assessments, η_B is able to consider building and weather parameters, door usage frequency, the unit fan energy consumption as well as the unit operation control parameters. This study used the pressure factor, R_p, to calculate the pressure differences across doors assuming steady conditions. Future studies should aim to consider methods that provide more accurate estimates of pressure differences across the building envelope such as field measurements or airflow simulations. Using these more accurate estimates of pressure differences can enable η_B to also consider building orientation and wind related parameters in its assessment of air curtains. The efficiency factor, η_B, proposed in this study can be used by engineers in the design phase (with the aid of simulation tools) and in the operation phase (using field testing) to compare and select different entrance door configuration for buildings. The factor can also be used to aid in the selection of air curtain units for entrances.

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