Whole Building Annual Energy Analysis of Air Curtain Performance in Commercial Building

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Abstract

A common energy code solution to reducing energy loss from air infiltration through building entrance has been requiring a vestibule in climate zones 3 – 8. However, a vestibule is costly and takes extra building space. In comparison, air curtain is less expensive and designed to prevent outdoor air infiltration while permitting an unobstructed pedestrian entryway. This study investigated the impact of building entrance equipped with air curtain on whole building energy usage for the US DOE medium office reference building. 336 computational fluid dynamics simulations were conducted to characterize the infiltration characteristics of air curtain. The infiltration correlations were then applied for the prediction of annual whole building infiltrations and energy use. It is found that the whole building annual energy use for the air curtain door is less than the single door in the climate zone 1-3, and the vestibule door in the climate zone 3-8.

1 Introduction

The U.S. was reported to consume 19% of the global energy in 2011, and the building sector (residential, commercial and government buildings) accounted for about 41% of the primary energy usage. The top four end uses of the building sector are space heating (37%), space cooling (10%), water heating (12%), and lighting (9%), which sums up to about 70% of the buildings site energy consumption. For commercial buildings, air infiltrations can be as high as 18% of the total heat loss. Air infiltrations (or air leakages) are often caused by unintentional or accidental introduction of outside air into a building through cracks in the building envelope and/or entrance doors. Infiltrations through door openings become quite significant when the doors are used frequently such as in restaurants, retail stores, supermarkets, offices and hospitals (DOE, 2012).

A common energy code solution to reducing energy loss from air infiltration through open doors has been requiring a vestibule rather than having a single door. Currently based on the American Society of Heating, Refrigerating and Air-Conditioning Engineers Standard 90.1 – Energy Standard for Buildings Except Low-Rise Residential Buildings (ASHRAE, 2010a), and the International Energy Conservation Code (IECC), in most cases, vestibules are required in climate zones 3 – 8. However, vestibules seem not to cater to building owners' taste due to the concerns over space and construction cost. A vestibule could cost anywhere from $20,000 to $60,000. In addition, a vestibule becomes ineffective when both entrance doors open simultaneously during heavy traffic periods so as to allow cold outdoor air to penetrate.

Air curtains, which are typically mounted above doorways, separate indoor and outdoor temperatures with a stream of air strategically engineered to strike the floor with a particular velocity and position. The air prevents outdoor air infiltration while also permitting an unobstructed pedestrian entryway. An air curtain for a single six-foot-wide entrance/exit opening is often less than $6,000 plus installation costs. It also helps to block flying insects, dust, wind, cold/warm, and ambient moisture to achieve a better indoor comfort. Furthermore, building entrances equipped with air curtains are believed to be more energy efficient than the entrances with single doors and with vestibules as well. However, an exhaustive literature search reviewed that no previous studies to quantify the impact of building entrance equipped with air curtains on whole building energy usage. The details of the literature review can be found from one of our recent journal papers (Wang and Zhong, 2014).

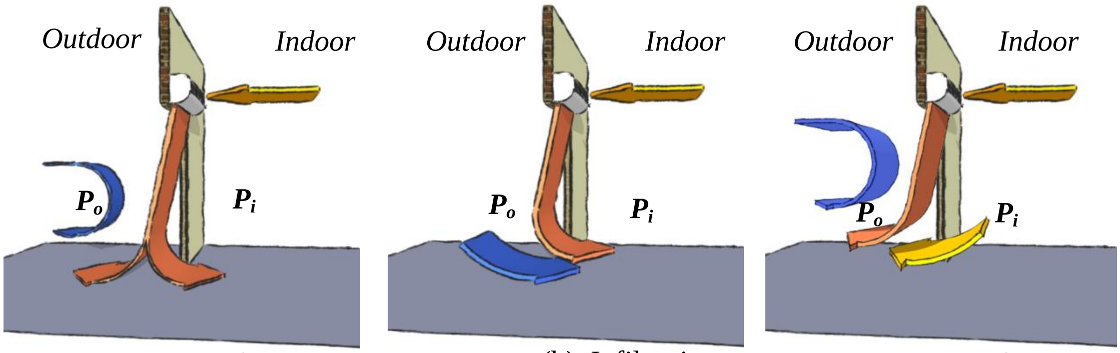
The objective of this study is to determine if air curtains can be considered comparable in energy performance to that of buildings with vestibules where they are required by building energy codes and standards in climate zones 3 – 8 by means of whole building annual energy simulations and computational fluid dynamics (CFD) modeling of air curtains. For the climate zones 1 and 2, where vestibules are not required by the codes, this study will also quantify the potential energy savings of air curtains compared to the baseline case of the building entrance without air curtain or vestibule. To achieve the objective, two major tasks were carried out in the following sections: 1). Determination of the amount of air infiltration through building entrance with an air curtain (hereafter, an air curtain door or an air curtain means an air curtain applied to a single door) by a series of CFD simulations. A commonly used commercial CFD software package, ANSYS FLUENT 14.0 (ANSYS, 2011), is selected in this study. 2). Determination of the impact of the infiltrations through air curtain on the whole building annual energy use. The whole building annual energy analysis is conducted by using TRNSYS 17.1 (TRNSYS, 2012) coupled with CONTAM 3.1 (Walton and Dols, 2008) through a data interface, TYPE 98, developed by the U.S. National Institute of Standards and Technology (NIST). TRNSYS is well-known building energy analysis software featuring flexible modular development. CONTAM is also known for the predictions of whole building air infiltrations and pressures. The whole building energy analysis was conducted for a three-story medium office building, which is the prototype building from the study of the Pacific Northwest National Laboratory (PNNL) (Cho et al., 2010).

2 Methodology

Infiltration models for air curtain door

Air infiltrations through a single door and a vestibule door can be determined by a commonly used orifice equation model, which considers the amount of infiltration to depend linearly on a power law function of the pressure difference across the door. Yuill (1996) conducted extensive experimental studies to provide the orifice equation models for both single and vestibule doors based on door usage frequency, geometry, and pressure difference across a door. The test chamber was an air tight box with the dimension of 2.44 m × 2.44 m × 1.30 m (L × W × H) and the door opening of 0.61 m × 0.71 m (W × H). The vestibule was a smaller box with the dimension of 0.91 m × 1.22 m × 0.94 m (L × W × H) attached to the test chamber. The whole setup was designed to be in the 1:3 scale of the real case so the real vestibule is with the size of 2.73 m × 3.66 m × 2.82 m (L × W × H). It was found that a vestibule door leads to smaller discharge coefficients and thus fewer infiltrations than a single door. As a constant in the orifice equation model, a higher discharge coefficient indicates more infiltration under a same pressure difference across a door. The vestibule model developed by Yuill was used to estimate air infiltrations in the study of "Energy Saving Impact of ASHRAE 90.1 Vestibule Requirements" by the PNNL (Cho et al., 2010). In this study, we used the orifice equation models from Yuill to find air infiltration rates of single and vestibule doors.

To determine the air infiltration characteristics of air curtains, this study used CFD to model an air curtain under different pressure differences and ambient conditions. The infiltration through an air curtain is not a simple orifice equation function of pressure difference but complicated by fluid dynamics features of the air curtain jet. The jet flow can be characterized by three cases as shown in Figure 1. In the first case (Figure 1a), when the outdoor & indoor pressure difference, ΔP, is mild, the jet reaches the floor and successfully blocks the outdoor air so the infiltration is zero. Here, the zero infiltration does not apply to the air recirculating through the air curtain. In this case, there is still a net outflow from the air curtain jet through the door as shown in Figure 1a. Infiltration will occur when ΔP rises above a threshold value (hereafter the upper critical pressure difference, ΔP_{uc}) as illustrated in Figure 1b. When ΔP_{uc} is reached, any increase of pressure difference will cause more infiltration. Figure 1c shows the third scenario when the indoor pressure is higher than the outdoor pressure ($\Delta P < 0$) and ΔP reaches another threshold value (hereafter the lower critical pressure difference, ΔP_{lc}) so exfiltration of indoor air occurs. In summary, three flow scenarios of an air curtain are considered: zero infiltration ($\Delta P_{lc} < \Delta P < \Delta P_{uc}$ in Figure 1a), infiltration ($\Delta P > \Delta P_{uc}$ in Figure 1b) and exfiltration ($\Delta P < \Delta P_{lc}$ in Figure 1c). Note here the amount of airflow through the door is determined by the net flow for both inflow (positive flow by default) and outflow (negative flow by default). For example, the total net flow in Figure 1c includes the air curtain jet flow plus the exfiltration of the indoor air.



(a). Zero infiltration when $\Delta P_{lc} < \Delta P < \Delta P_{uc}$

(b). Infiltration when $\Delta P > \Delta P_{uc}$

(c). Exfiltration when $\Delta P < \Delta P_{lc}$

Figure 1: Infiltration/exfiltration characteristics of an air curtain jet under different pressure differences, $\Delta P = P_o - P_i$ (note that the zero infiltration does not apply to the air recirculating through the air curtain)

A series of CFD simulations were conducted to determine the infiltration/exfiltration models of air curtain. The modeled building section is with the size of 20 m × 24 m ×10 m (L × W × H), which is within a CFD domain of 50 m × 24 m × 10 m (L × W × H) as shown in Figure 2. The door of interest is an automatic double swing door at the building main entrance, the size of which is selected as 2 m × 2.4 m (W × H) according to the Automatic Door Selection Guide from the American Association of Automatic Door Manufacturers (AAADM, 2007). The door open/closing angles are considered from the gap at 10° to the fully open position at 90°. An air curtain is mounted horizontally over the door with a supply slot of 0.08 m × 2 m (W × L) and a return of 0.2 m × 2 m (W × L). The supply velocity and temperature is 21 °C for the winter mode and 24 °C for the summer at 15 m/s with an angle of 20° outwards (Figure 2). The pressure difference across the door was considered by the pressure boundary conditions prescribed at the inlet and the outlet to account for ambient wind effect and by the outdoor/indoor temperature differences for stack effect. The prescribed pressure difference, $\Delta P_{oi} = P_o - P_i$ in Figure 2, ranges from 40 to -20 Pa. The outdoor temperature is selected on the basis of the design day temperatures of the climate zones one to eight (ASHRAE, 2010b). The range of outdoor temperature is thus found to be between -40 ºC and 40 ºC. The selected outdoor temperatures for the modeling are -40 ºC, -20 ºC and 10 ºC for the winter mode and 25 ºC, 30 ºC and 40 ºC for the summer mode. The indoor temperature was set to be 24 °C for the summer and 21 °C for the winter. The CFD simulation is considered at steady state based on the standard k-ε model, the theoretical details of which can be found in the reference (ANSYS, 2011). The k-ε model is used here because it is one of mostly common used models for indoor environmental modeling. Table 1 summarizes the details of the simulation settings. A total of 336 CFD simulations are conducted for different parameters as shown in Table 2. Note that the pressure difference used for the regression analysis includes the prescribed values in Table 1 to account for the wind pressure, and the stack pressure difference caused by the outdoor and indoor temperature difference. We extract the actual pressure difference for the regression analysis from the CFD simulations at the middle sections as shown in Figure 2.

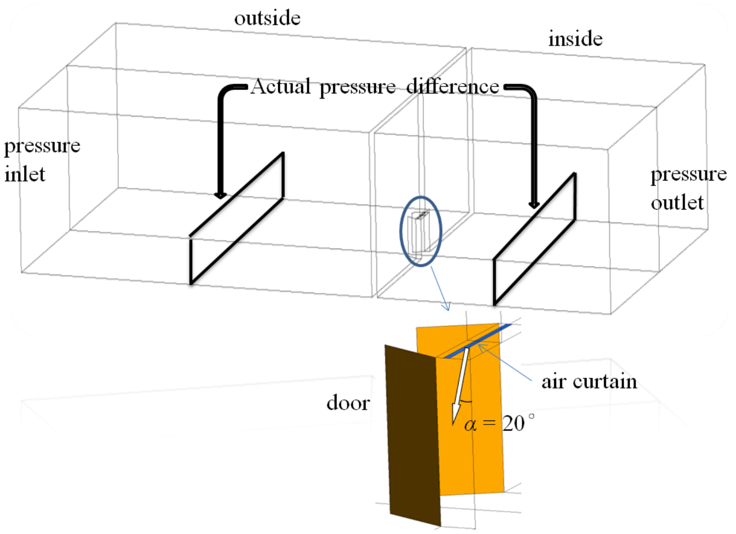


Figure 2: CFD model of the building section with the air curtain

Table 1: CFD simulation settings

	Categories	Settings
Building	Size	20 m × 24 m ×10 m (L × W × H)
	Indoor temperature	24 °C for the summer and 21 °C for the winter
Door	Door size	2 m × 2.4 m (W × H)
	Door open/closing angles	10°, 30°, 60°, 90° (fully open)
Air Curtain	Supply velocity/temperature	21 °C for the winter and 24 °C for the summer at 15 m/s with an angle of 20° outwards
	Supply slot size	0.08 m × 2 m (W × L)
	Return slot size	0.2 m × 2 m (W × L)
CFD	Domain size	50 m × 24 m × 10 m (L × W × H)
	Total grid number per case	1,260,000
	Transient/Steady simulation	Steady state
	Turbulence model	Standard k-ε

Boundary conditions	The prescribed outdoor and indoor pressure difference (pressure inlet and outlet) of 40, 30, 20, 10, 0, -0.5, -1, -1.5, -2.5, -3.5, -5, -10, -20 Pa
Outdoor temperature	-40 ºC, -20 ºC and 10 ºC for the winter and 25 ºC, 30 ºC and 40 ºC for the summer

Table 2: CFD simulation scenarios

Categories	Winter Mode	Summer Mode
Door Opening Angle (°)	10, 30, 45, 60, 90	
Outdoor Temperature (°C)	-40, - 20, 10	25, 30, 40
Indoor Temperature (°C)	21	24
Pressure Difference (Pa)	-20, -10, -5, -3.5, -2.5, -1.5, -1, -0.5, 0, 10, 20, 30, 40	
Air Curtain Velocity (m/s)	15	
Air Curtain Temperature (°C)	21	24
Total CFD Runs	336	

Whole building energy analysis

The predictions of whole building air infiltration/exfiltration and energy analysis are achieved by the coupled simulations of TRNSYS and CONTAM, in which CONTAM provides to TRNSYS air infiltration/exfiltration data and TRNSYS provides to CONTAM weather data and room temperature data. The integration of TRNSYS and CONTAM is based on a new TRNSYS TYPE, TYPE 98, a data interface developed by NIST to exchange information between TRNSYS and CONTAM in a "ping-pong" manner, where information is exchanged only one way at each time step. The details of the new coupled program can be found in the paper from Dols et al. (2013).

The US DOE medium office reference building is with a total floor area of 4,982 m^2 (53,626 ft^2) and a dimension of 49.9 (m) × 33.27 (m) × 12 (m) (L × W × H). The heating, ventilating and air-conditioning (HVAC) system is selected as the variable air volume (VAV) direct expansion (DX) system for cooling and a gas heating system for each floor without economizers. The return air is running through the plenum of each floor. The details of the reference building can be found from (Cho et al., 2010).

The performance of the air curtain can be evaluated by the annual total saving of heating/cooling load in kWh and the peak heating/cooling demand in kW. If the operating cost of air curtain is considered, the final energy saving by using air curtain can be expressed by Eq. (1) when compared to the single door or the vestibule door.

$$E_{saving} = E_{base} - E_{ac} - E_{fe} \tag{1}$$

where

E_{saving} is the annual saving of the total energy of using air curtain, kWh;

E_{base} is the annual heating/cooling or both heating and cooling loads of the base for comparison: the single door or the vestibule door, kWh;

E_{ac} is the air curtain annual heating load for the regions using air curtain for heating only, or the cooling load for cooling only, or both heating and cooling loads for the regions using air curtain for both heating & cooling, kWh;

E_{fe} is the air curtain annual total fan energy, kWh, which is the air curtain fan power (kW) multiplied by the total operating time (hr).

Meanwhile, compared to the baseline, the total energy saving in percentage, P_{saving}, can be defined as

$$P_{saving} = \frac{E_{saving}}{E_{base}} \tag{2}$$

3 Results

CFD simulations of air curtain

A total number of 336 CFD simulation was conducted to model an air curtain under different settings of outdoor and indoor pressure and temperature differences. The details of regression analysis for all the cases can be found in one of our recent accepted papers (Wang and Zhong, 2014). We also validated our CFD models by comparing the calculated regression models of the single door from this study to those from Yuill (1996), which are not included here but can be found in the same paper. Figure 3 shows the three flow scenarios of the air curtain door when the air curtain is in operation compared to the single and vestibule doors during the occupied hours of the building. Many other simulation results can be found in the final report of this study (Wang, 2013). For the air curtain modeled in this study:

- The critical pressure is found to be ΔP_{lc} = -3.3 Pa and ΔP_{uc} = 6.9 Pa. The outflow (negative Q) occurs when $\Delta P < \Delta P_{uc}$, and the inflow (positive Q) occurs when $\Delta P > \Delta P_{uc}$.
- For the outflow section, there is a sharp increase of flow rate at ΔP_{lc} when the flow switches from "zero infiltration" (Figure 1a) to "exfiltration" (Figure 1c) because the indoor air starts to exfiltrate under the air curtain jet as shown in Figure 1c.
- Compared to both single door and vestibule door, air curtain reduces air infiltration significantly under the same pressure difference across the door, especially for mild ranges of pressure difference.
- Air curtain also causes less outflow than the vestibule door for the negative pressure difference of $-7.0 < \Delta P < 0$ Pa but creates more outflow when $\Delta P < -7.0$ Pa. When the pressure difference $\Delta P < -15$ Pa, air curtain could cause more outflow than the single door.

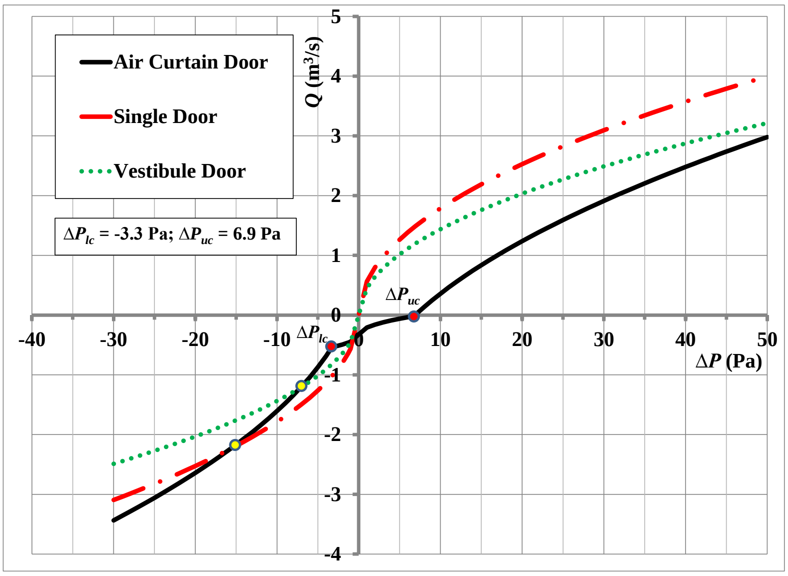


Figure 3: Infiltration/Exfiltration characteristics of air curtain door when the air curtain is in operation when compared to single door and vestibule door (Yuill, 1996)

Whole building energy simulation

The correlations, e.g. those in Figure 3, were input in CONTAM by using customized air infiltration models based on discrete values of flow rates and pressure differences, and combined with CONTAM sensor controls. In this section, the whole building energy simulations were conducted for eight representative cities in different climate zones as shown in Table 3. The key input parameters were set up as follows. The simulations were conducted for the building orientations of the north, south, east and west and the energy usage data were averaged over the four directions. The air curtain fan power is 1.05 kW. The air curtain is equipped with temperature control and expected to operate only during the occupied hours, when the door is opened and at the same time the ambient air temperature drops below 10 °C for the winter mode, or increases above 30 °C for the summer mode. When the air curtain is not in operation during occupied hours, the air curtain door was modeled as a single door by using CONTAM's control nodes and schedules. When the building is unoccupied, the building door was assumed to be completely closed and the leakages were zero for the single door, the air curtain door and the vestibule door. The door usage frequency is 100 people per hour and the air curtain operation season include both summer and winter.

Table 3: Whole building energy analysis for different climate zones

Climate Zone (CZ)	Representative City	Single Door (baseline)	Air Curtain	Vestibule (baseline)	Air Curtain Season Schedule
1	Miami	X	X	-	Summer only
2	Austin	X	X	-	Summer only
3	Atlanta	X	X	X	Summer & Winter
4	Baltimore	-	X	X	Summer & Winter
5	Chicago	-	X	X	Summer & Winter
6	Minneapolis	-	X	X	Winter only
7	Fargo	-	X	X	Winter only
8	Fairbanks	-	X	X	Winter only

The energy performance of the air curtain was evaluated for zone 1-3 compared to the single door and for zone 3-8 compared to the vestibule door as shown in Table 4.

If the air curtain is equipped with temperature control, i.e. “on” when the door is opened and at the same time the outdoor temperature is over 30 ˚C or under 10 ˚C, and “off” in other cases during the business hours.

- In the hot climate, when compared to the single door, the annual total energy saving of the air curtain is 81 kWh for Miami (zone 1) and 132 kWh for Austin (zone 2). The total percentage saving is +0% for Miami and +0% for Austin.
- In the mild climate, when compared to the single door, the annual total energy saving is 1757 kWh and the percentage saving is 0.4% for Atlanta (zone 3); when compared to the vestibule, the annual total energy saving is 1146 kWh for Atlanta (zone 3) and 2217 kWh for Baltimore (zone 4) and the percentage saving is 0.3% for Atlanta and 0.5% for Baltimore.
- In the cold climate, when compared to the vestibule, the annual total energy saving is 4169 kWh for Chicago (zone 5), 7007 kWh for Minneapolis (zone 6), 8737 kWh for Fargo (zone 7), and 18986 kWh for Fairbanks (zone 8). The percentage saving is 0.9% for Chicago, 1.2% for Minneapolis, 1.4% for Fargo, and 2.2% for Fairbanks.
- The most cost effective saving for the typical climates of the U.S. comes from annual heating. The colder the climate is, the better annual saving: up to 18986 kWh for Fairbanks in zone 8 compared to the vestibule in the cases studied.
- For the mild and cold climates (climate zone 3-8), the use of vestibule may result in some annual cooling demand penalty because of the vestibule may block the ambient free cooling in summer whereas air curtain is more manageable and seems to perform better.

Table 4: Impact of climate zones on the annual heating/cooling saving and total energy savings of air curtain compared to the single door and/or the vestibule

Climate Zone (CZ)	Heating/Cooling	Air Curtain Fan Energy kWh	Air Curtain Annual Performance					
			Basis for Comparison: Single Door			Basis for Comparison: Vestibule		
			Heating/Cooling Saving, kWh (%)	Total Saving		Heating/Cooling Saving, kWh (%)	Total Saving	
				E_{saving} kWh	P_{saving} %		E_{saving} kWh	P_{saving} %
1	Cooling	94	175 (0.0)	81	0.0	-		
2	Cooling	158	290 (0.1)	132	0.0			
3	Heating Cooling	200	2003 (2.9) -46 (-0.0)	1757	0.4	1172 (1.7) 174 (0.1)	1146	0.3
4	Heating Cooling	331	-			2425 (1.6) 123 (0.1)	2217	0.5
5	Heating Cooling	371				4383 (1.7) 157 (0.1)	4169	0.9
6	Heating	372				7379 (2.0)	7007	1.2
7	Heating	415				9152 (2.0)	8737	1.4
8	Heating	529				19515 (2.5)	18986	2.2
3	Heating Cooling	786	2161 (3.2) -464 (-0.1)	911	0.2	1330 (2.0) -244 (-0.1)	300	0.0
4	Heating Cooling	786	-			2695 (1.7) -289 (-0.1)	1620	0.4
5	Heating Cooling	786				4694 (1.9) -187 (-0.1)	3721	0.8

If the air curtain is not equipped with temperature control, zone 3, 4 and 5 were selected in this case.

- When compared to the single door, the annual total saving is 911 kWh and the percentage saving is 0.2% for Atlanta (zone 3).
- When compared to the vestibule door, the annual total saving is 300 kWh for Atlanta, 1620 kWh for Baltimore (zone 4) and 3721 kWh for Chicago (zone 5). The percentage saving is +0% for Atlanta, 0.4% for Baltimore and 0.8% for Chicago.

In general, the temperature control in this study can reduce the fan energy. The detailed simulation results for each floor of the building can be found in the final report of this study (Wang, 2013). The annual total savings in kWh and in percentage in Table 4 are plotted in Figures 4 and 5. It is shown that with or without temperature control, the modeled air curtain in this study provides comparable performance as the modeled vestibule. Compared to the vestibule, the air curtain saves 0.3% ~ 2.2% energy with temperature control for zone 3 ~ 8 and up to 0.8% without temperature control for zone 3 ~ 5 as shown in Figure 5.

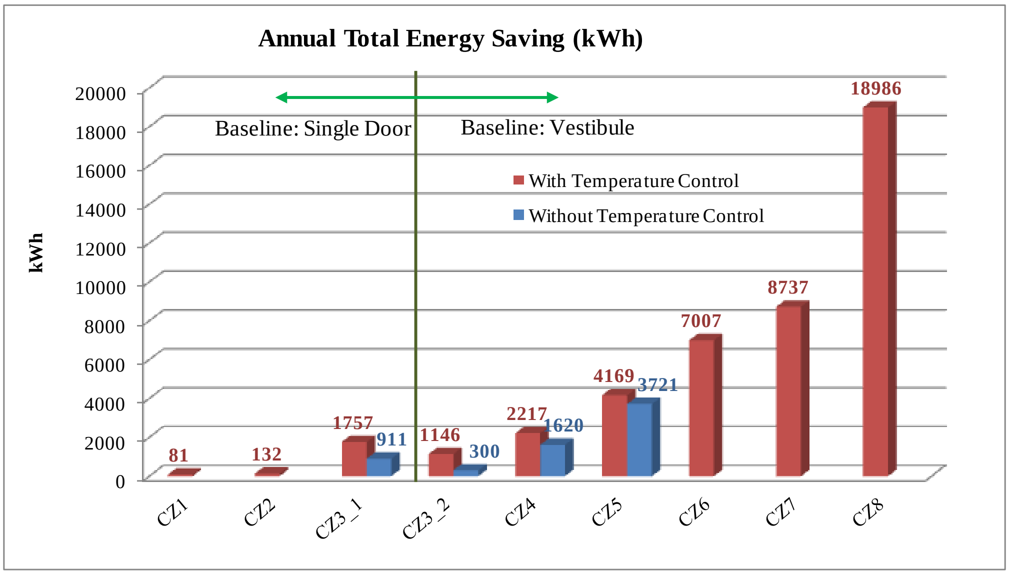


Figure 4: The national annual total saving of air curtain in kWh when compared to the single door and/or the vestibule

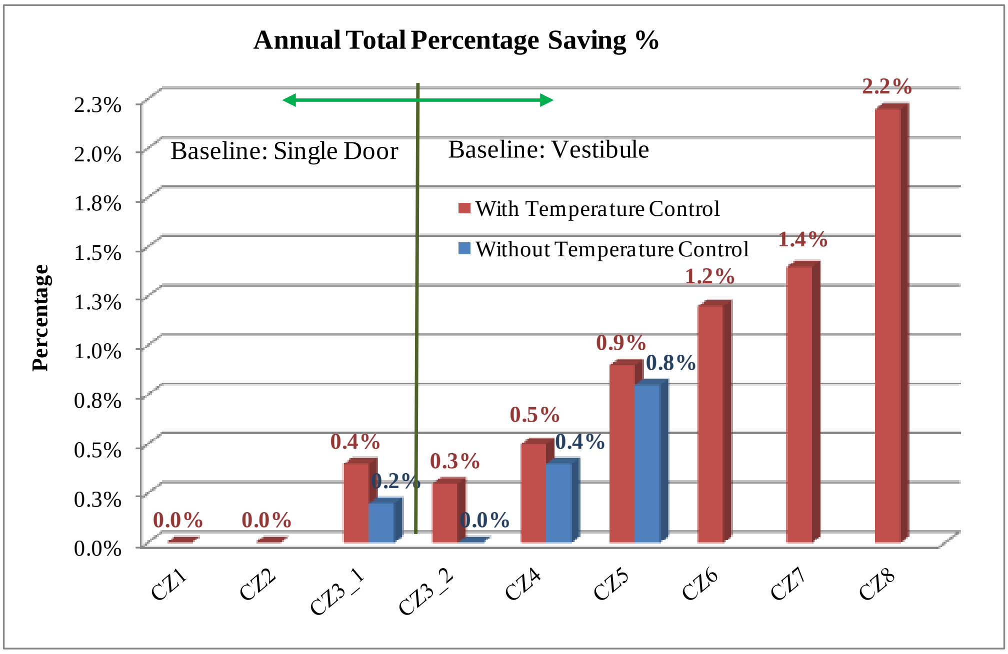


Figure 5: The national annual total saving of air curtain in percentage when compared to the single door and/or the vestibule

4 Conclusions

In this study, CFD simulations of air infiltration/exfiltration through the air curtain were conducted to obtain the corresponding correlations to be used in the whole building energy analysis of the medium office reference building by the coupled simulation of TRNSYS and CONTAM.

For the modeled medium office building, the whole building annual energy use when the air curtain is installed is less in all the climate zones modeled: it is less than the single door in the climate zone 1-3, and less than the vestibule door in the climate zone 3-8.

Specifically, the following key conclusions are found.

- The airflow rate through the air curtain can be characterized as the function of pressure difference across the door in three sections: zero infiltration, infiltration and exfiltration.
- Based on the obtained air curtain correlations, the air curtain is shown to reduce air infiltration significantly under the same conditions when compared to either the single door or the vestibule, whereas it may cause higher exfiltration when the indoor pressure is higher enough than the outdoor pressure (e.g. $\Delta P < -15$ Pa) when compared to the single door.
- The modeled air curtain is shown to provide comparable performance as the modeled vestibule for the climate zone 3 – 8. Compared to the vestibule, the air curtain can save 0.3% ~ 2.2% energy for zone 3 – 8, which corresponds to 1146 kWh ~ 18986 kWh. Better performance will be achieved for colder climate.
- The major saving of the air curtain comes from the heating saving so, although there is saving, the air curtain total saving in zone 1 – 2 is marginal, which is 0% (81 kWh ~ 132 kWh) when compared to the single door.

Based on the results of the modeled building and the air curtain in this study, considering its lower initial cost and space saving benefit, air curtain should be a good alternative to the vestibule for the climate zones of 3 – 8. Note that the results from this study are based on the specific building, the specific parameters and the modeling method of air curtains. Generalization of the conclusions to other cases may need further confirmations.

5 Acknowledgements

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