Investigation of the Impact of Building Entrance Air Curtain on Whole Building Energy Use

Short Summary

This study conducted the whole building energy analysis of the DOE medium office reference building for three different scenarios of building entrance:

1. single door without vestibule or air curtain (hereafter, a single door)
2. single door equipped with air curtain (hereafter, an air curtain door)
3. single door with vestibule (hereafter, a vestibule door)

For the modeled medium office building, the major conclusions were found as follows.

- The whole building annual energy use when the air curtain is installed is less in all the climate zones: 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.
- The modeled air curtain door is shown to reduce air infiltration significantly under the same conditions when compared to either the single door or the vestibule door.
- The predicted annual pressure difference across the envelope of the modeled building is mostly within -10 ~ 10 Pa.
- The modeled air curtain door is shown to provide comparable performance as the modeled vestibule door for the climate zone 3 – 8. Compared to the vestibule door, the air curtain door can save 0.3% ~ 2.2% energy for zone 3 ~ 8, corresponding to 1146 kWh ~ 18986 kWh. Better performance will be achieved for colder climate.
- The major saving of the air curtain door comes from the heating saving so, although there is saving, the air curtain total saving in zone 1 – 2 is marginal, which is 0.0% ~ 0.1% (81 kWh ~ 132 kWh) when compared to the single door.
- Building entrance orientation, building pressure, and door usage frequency all affect air infiltration/exfiltration and the resultant energy performance of the air curtain door. Particularly, the effects of building entrance orientation and the balance of the HVAC system cannot be overlooked and they were shown to be as important as door usage frequency.

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Executive Summary

BACKGROUND

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 2010), 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 air curtains on whole building energy usage.

OBJECTIVE

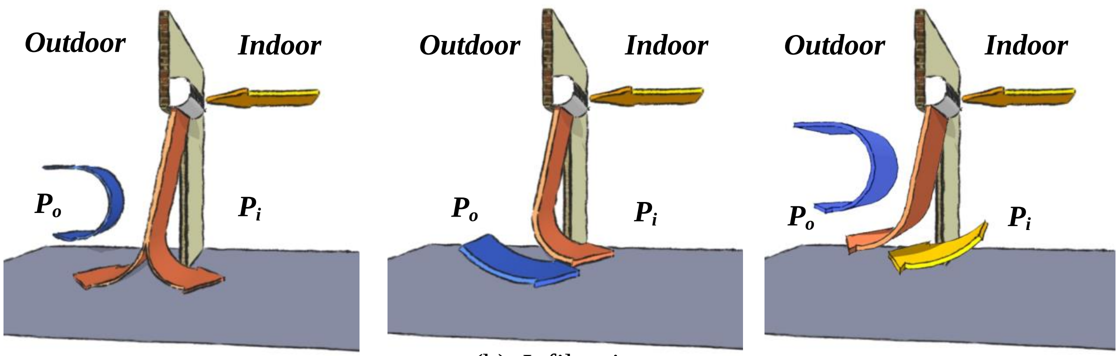
The objective of this study is to decide if air curtains can be considered comparable in energy performance to that of buildings with vestibules where they are required by building energy codes and standards in climate zones 3 – 8 by means of whole building annual energy simulations and computational 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.

METHODOLOGY

To achieve the objective, two major tasks were carried out:

- Determination of the amount of air infiltration through building entrance for different door setups: a single door with a vestibule (hereafter, a vestibule door), a single door with an air curtain (hereafter, an air curtain door or an air curtain means an air curtain applied to a single door), or a single door without either of them (a single door).
- Determination of the impact of infiltrations on the whole building annual energy use for different door setups.

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, C_d, and thus fewer infiltrations than a single door. As a constant in the orifice equation model, a higher C_d value 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 Pacific Northwest National Laboratory (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.



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

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

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

Fig. 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).

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 Fig. 1. In the first case (Fig. 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 Fig. 1a. Infiltration will occur when ΔP rises above a threshold value (hereafter the upper critical pressure difference, ΔP_{uc}) as illustrated in Fig. 1b. When ΔP_{uc} is reached, any increase of pressure difference will cause more infiltration. Fig. 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 observed: zero infiltration ($\Delta P_{lc} < \Delta P < \Delta P_{uc}$ in Fig. 1a), infiltration ($\Delta P > \Delta P_{uc}$ in Fig. 1b) and exfiltration ($\Delta P < \Delta P_{lc}$ in Fig. 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 Fig. 1c includes the air curtain jet flow plus the exfiltration of the indoor air. In this study, 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. The air curtain will be mounted horizontally over the door and are expected to operate when the door is opened.

In the second task, 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) on medium office buildings. The total floor area is 4,982 m^2 (53,626 ft^2) with 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 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 total energy saving 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

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

This study modeled the air curtain by CFD, a commonly used numerical method to solve conservation laws of mass, momentum and energy for the predictions of air velocity, temperature and thus flow rate and energy consumption. A commonly used commercial CFD software package, ANSYS FLUENT 14.0 (ANSYS 2011), is selected in this study. 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.

RESULTS

The two tasks were divided into the following five sub-tasks.

Task 1 – Air Curtain Infiltration and Exfiltration

The determination of infiltration & exfiltration characteristics of air curtain is the key task. About 350 CFD simulations were conducted to model an air curtain under different settings of outdoor and indoor pressure and temperature differences by using the standard k-ε turbulence model. Both winter and summer operational modes of air curtain were considered. The air curtain jet is supplied with a 20˚ angle (outwards as shown in Fig. 1) at 15 m/s and 21 ˚C for the winter mode, and 15 m/s and 24 ˚C for the summer mode. The indoor design temperatures are the same as the air curtain supply temperatures, and the outdoor temperatures varies among -40, -20 and 10 ˚C in the winter mode, and 25, 30, and 40 ˚C in the summer mode. Different door opening angles were also considered including 90˚ (fully open), 60˚, 30˚ and 10˚ under the pressure difference (ΔP) of -20, -10, -5, 0, 10, 20, 30, and 40 Pa for all the cases and -3.5, -2.5, -1.5, -1, and -0.5 Pa for some cases across the door. Fig.2 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. 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 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" (Fig. 1a) to "exfiltration" (Fig. 1c) because the indoor air starts to exfiltrate under the air curtain jet as shown in Fig. 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.

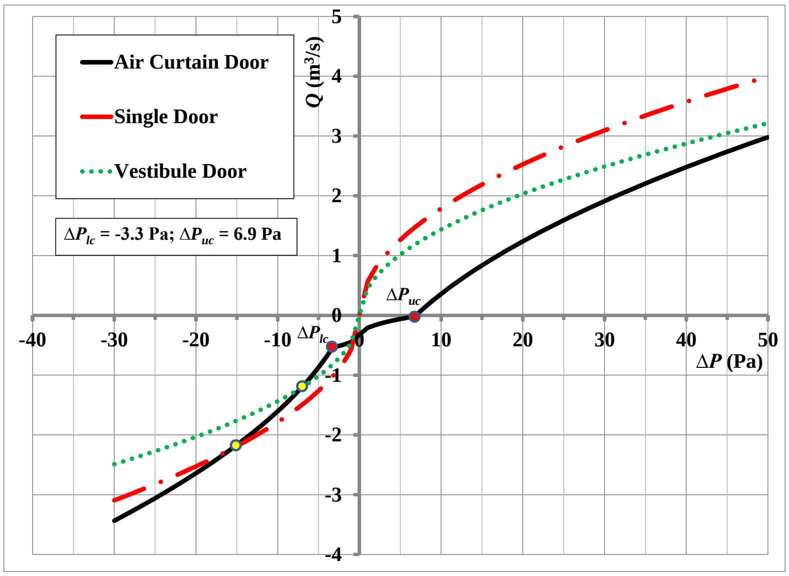


Fig. 2. Infiltration/Exfiltration characteristics of air curtain door when the air curtain is in operation when compared to single door and vestibule door.

Task 2 – Building Pressure Difference

Pressure difference across building envelope is one of the major driving forces for infiltration/exfiltration. Nine CONTAM simulations were conducted to calculate the annual pressure differences and infiltration/exfiltration rates through the single door, the vestibule door, and the air curtain door for the medium office building with three scenarios of the HVAC system: a baseline supply and return system (hereafter, 100% supply system), a system with 5% less supply than return (95% supply system) or a system with 10% less supply than return (90% supply system). The 100% supply system is provided by NIST for the medium office building in the study of "Airflow and Indoor Air Quality Models of DOE Reference Commercial Buildings" (NIST Technical Note 1734) (Ng et al. 2012). The last two scenarios were created to consider the impact of the depressurization of the building by the HVAC system, which could cause more infiltrations than the baseline system. The door usage is the baseline case of 100 people/hr. The annual whole building analysis is conducted for 8760 hours including both occupied and unoccupied hours, and considering the on/off schedules of the HVAC system.

- For the 100% supply system,
  - the annually average building pressure difference across the entrance door is 0.8 Pa of a range of -9.5 ~ 27.4 Pa with a median value of 0.2 Pa. The pressure difference is mostly -10 ~ 10 Pa.
  - compared to the single door, the air curtain door reduces 62% of the annual total air infiltration and 3% of the total exfiltration, and the vestibule door reduces 23% infiltration and 25% exfiltration.

Table 1. Annual infiltration/exfiltration reductions in percentage and door pressure differences for the vestibule and air curtain doors compared to the single door.

Systems		100% Supply	95% Supply	90% Supply
Average/Min./Max. Pressure Difference, ΔP (Pa)		0.8/-9.5/27.4	1.3/-7.9/29.6	1.8/-6.5/31.5
Annual Infiltration Reduction (%)	Vestibule	23	23	24
	Air Curtain	62	65	67
Annual Exfiltration Reduction (%)	Vestibule	25	25	24
	Air Curtain	3.0	-3.0	-11

- For the 95% supply system,
  - the annually average building pressure difference across the entrance door is 1.3 Pa of a range of -7.9 ~ 29.6 Pa with a median value of 0.5 Pa.
  - compared to the single door, the air curtain door reduces 65% of the annual total air infiltration and increases 3% of the total exfiltration, and the vestibule door reduces 23% infiltration and 25% exfiltration;
- For the 90% supply system,
  - the annually average building pressure difference across the entrance door is 1.8 Pa of a range of -6.5 ~ 31.5 Pa with a median value of 0.9 Pa.
  - compared to the single door, the air curtain door reduces 67% of the annual total air infiltration and increases 11% of the total exfiltration, and the vestibule door reduces 24% infiltration and 24% exfiltration.

Task 3 – Whole Building Energy Simulation

The energy performance of air curtain is a combination effect of infiltration and exfiltration, which can be evaluated by whole building energy analysis. Nine whole building energy analyses were performed by the coupled TRNSYS and CONTAM model for the single door, the vestibule door, and the air curtain door for both summer and winter modes of Chicago, IL. The parameters in consideration include the baseline door usage frequency of 100 people/hr, the 100% supply, 95% supply and 90% supply systems. 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 ℃ for the winter mode, or increases above 30 ℃ for the summer mode. The major conclusions are as follows.

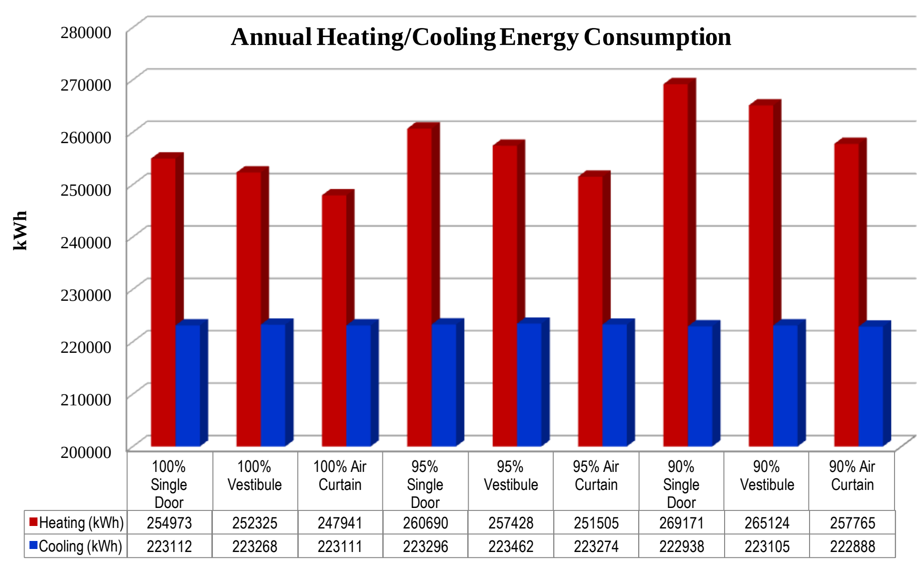


Fig. 3. The annual heating/cooling demand for different building entrance in Chicago.

From Fig. 3 and Table 2, the major conclusions can be drawn as follows.

- Annual energy saving mostly comes from heating saving.
- Small penalty may occur for the vestibule, since during shoulder seasons the vestibule may block the free cooling from the ambient.
- Air curtain leads to better energy performance than the single door and the vestibule door.
- The annual total heating saving of the air curtain varies 7031 kWh (2.8%) ~ 11406 kWh (4.2%) compared to the single door, and 4383 kWh (1.7%) ~ 7359 kWh (2.8%) compared to the vestibule door.
- The reduction of peak heating load by the air curtain varies 28 kW (5.6%) ~ 32 kW (6.2%) compared to the single door, and 18 kW (3.7%) ~ 19 kW (3.8%) compared to the vestibule.
- The reduction of peak cooling load by the air curtain varies 1 kW (0.3%) ~ 2.3 kW (0.8%) compared to the single door, and 0.3 kW (0.1%) ~ 1.3 kW (0.4%) compared to the vestibule.
- The annual air curtain fan energy is 371 kWh.
- Compared to the single door, the annual total energy saving of using air curtain varies 6660 kWh (1.4%) ~ 11085 kWh (2.3%).
- Compared to the vestibule door, the annual total energy saving of using air curtain varies 4169 kWh (0.9%) ~ 7205 kWh (1.5%).
- The variation of the savings depends on how well the HVAC system is balanced. When the HVAC system is less balanced thus tending to cause more infiltration, the energy saving of the air curtain becomes better.

Table 2. Annual heating demand saving, peak heating/cooling load reduction and total energy saving of the air curtain door compared to the single door and vestibule door for different systems.

Systems		100% Supply				95% Supply				90% Supply			
Basis for Comparison		Single Door		Vestibule		Single Door		Vestibule		Single Door		Vestibule	
Annual Heating Saving (kWh)	%	7031	2.8	4383	1.7	9186	3.5	5923	2.3	11406	4.2	7359	2.8
Annual Cooling Saving (kWh)	%	1.0	0.0	157	0.1	22	0.0	188	0.1	50	0.0	217	0.1
Peak Heating Reduction (kW)	%	28	5.6	18	3.7	31	6.1	19	3.8	32	6.2	18	3.5
Peak Cooling Reduction (kW)	%	1.0	0.3	0.3	0.1	1.8	0.6	0.9	0.3	2.3	0.8	1.3	0.4
Air Curtain Fan Energy (kWh)		371											
Total Saving, E_{saving}, (kWh)		6660		4169		8837		5740		11085		7205	
Total Percentage Saving, P_{saving} (%)		1.4		0.9		1.8		1.2		2.3		1.5	

Task 4 – Sensitivity analysis

A sensitivity analysis of 72 whole building energy simulations was performed for the single door and the air curtain door for different climates: climate zone 2 (for cooling dominant climate, e.g. Austin), zone 4 (for heating & cooling climate, e.g. Baltimore), and zone 6 (for heating dominant climate, e.g. Minneapolis). The following key parameters are considered: building entrance orientation, building pressures affected by the 100% supply/95% supply/90% supply HVAC systems, door usage frequencies.

- For climate zones 2,4 and 6, most of the saving comes from heating, and colder climate enjoys more saving from air curtain.
- All the parameters in the sensitivity analysis are important, the variation of which may cause at least 30% difference in terms of annual heating demand saving compared to the according sensitivity test components.

a. Entrance orientation

Building entrance orientation was evaluated for the north, south, east, and west directions. The door usage frequency is set to be 100 people/hr, and the building HVAC is the 100% supply system. The annual heating saving of the air curtain depends on the dominant wind direction for different cities.

- For Austin (climate zone 2), the annual heating saving varies from 328 kWh (0.7%) for the north to 2514 kWh (4.9%) for the south; the annual cooling saving varies from 192 kWh (0%) for the south to 253 kWh (0.1%) for the north, when compared to the single door.
- For Baltimore (climate zone 4), the annual heating saving varies from 497 kWh (0.3%) for the north to 4933 kWh (3.1%) for the west; the annual cooling saving varies from -25 kWh (-0%) for the south to 217 kWh (0.1%) for the north compared to the vestibule.
- For Minneapolis (climate zone 6), the annual heating saving varies from 5788 kWh (1.6%) for the north to 9023 kWh (2.5%) for the west; the annual cooling saving varies from 134 kWh (0.1%) for the south to 292 kWh (0.2%) for the north compared to the vestibule.
- The annual air curtain fan energy is 256 kWh for Austin, 331 kWh for Baltimore and 385 kWh for Minneapolis.
- The annual total saving of using air curtain varies from 330 kWh to 2449 kWh when compared to the single door in Austin; from 383 kWh to 4709 kWh for Baltimore, and from 5695 kWh to 8822 kWh for Minneapolis when compared to the vestibule door.
- The annual total percentage saving of using air curtain varies from 0 to 0.4% when compared to the single door in Austin, from 0% to 1.1% for Baltimore when compared to the vestibule, and from 1% to 1.5% for Minneapolis when compared to the vestibule.

Table 3. Sensitivity study of building entrance orientation for climate zones 2, 4 and 6.

Climate Zones	Zone 2 (Austin)		Zone 4 (Baltimore)		Zone 6 (Minneapolis)	
Basis for Comparison	Single Door		Vestibule		Vestibule	
Orientation & Energy Saving	Orientation	kWh (%)	Orientation	kWh (%)	Orientation	kWh (%)
Annual Min. Heating Saving	North	328 (0.7)	North	497 (0.3)	North	5788 (1.6)
Annual Max. Heating Saving	South	2514 (4.9)	West	4933 (3.1)	West	9023 (2.5)
Annual Min. Cooling Saving	South	192 (0.0)	South	-25 (-0.0)	South	134 (0.1)
Annual Max. Cooling Saving	North	253 (0.1)	North	217 (0.1)	North	292 (0.2)
Air Curtain Fan Energy (kWh)	256		331		385	
Min. Total Saving, E_{saving}, (kWh)	North	330	North	383	North	5695
Min. Total Percent Saving, P_{saving} (%)		0.0		0.0		1.0
Max. Total Saving, E_{saving}, (kWh)	South	2449	West	4709	West	8822
Max. Total Percent Saving, P_{saving} (%)		0.4		1.1		1.5

b. Building pressure

Sensitivity analysis of building pressures was conducted by changing the supply air of the HVAC system to be either 5% or 10% less than the return air to depressurize the building so more infiltrations tend to occur. These simulations are based on the entrance orientation facing the south, and 100 people/hr door usage frequency.

- For Austin (climate zone 2), the annual heating saving varies from 328 kWh (0.7%) for the 100% supply system to 485 kWh (1.0%) for the 90% supply system; the annual cooling saving varies from 258 kWh (0.1%) for the 100% supply system to 714 kWh (0.1%) for the 90% supply system, when compared to the single door.
- For Baltimore (climate zone 4), the annual heating saving varies from 497 kWh (0.3%) for the 100% supply system to 1755 kWh (1.1%) for the 90% supply system; the annual cooling saving varies from 189 kWh (0.1%) for the 90% supply system to 217 kWh (0.1%) for the 100% supply system compared to the vestibule.
- For Minneapolis (climate zone 6), the annual heating saving varies from 5788 kWh (1.6%) for the 100% supply system to 9725 kWh (2.6%) for the 90% supply system; the annual cooling saving varies from 292 kWh (0.2%) for the 100% supply system to 367 kWh (0.2%) for the 90% supply system compared to the vestibule.
- The annual air curtain fan energy is 256 kWh for Austin, 331 kWh for Baltimore and 385 kWh for Minneapolis.

- The annual total saving of using air curtain varies from 330 kWh to 943 kWh when compared to the single door in Austin, from 383 kWh to 1613 kWh for Baltimore when compared to the vestibule, and from 5695 kWh to 9707 kWh for Minneapolis when compared to the vestibule.
- The annual total percentage saving of using air curtain varies from 0% to 0.2% when compared to the single door in Austin, from 0% to 0.4% for Baltimore when compared to the vestibule, and from 1.0% to 1.8% for Minneapolis when compared to the vestibule.

Table 4.Sensitivity study of building pressures caused by different HVAC systems for the climate zones of 2, 4 and 6.

Climate Zones	Zone 2 (Austin)		Zone 4 (Baltimore)		Zone 6 (Minneapolis)	
Basis for Comparison	Single Door		Vestibule		Vestibule	
System & Energy Saving	System Type	kWh (%)	System Type	kWh (%)	System Type	kWh (%)
Annual Min. Heating Saving	100% Supply	328 (0.7)	100% Supply	497 (0.3)	100% Supply	5788 (1.6)
Annual Max. Heating Saving	90% Supply	485 (1.0)	90% Supply	1755 (1.1)	90% Supply	9725 (2.6)
Annual Min. Cooling Saving	100% Supply	258 (0.1)	90% Supply	189 (0.1)	100% Supply	292 (0.2)
Annual Max. Cooling Saving	90% Supply	714 (0.1)	100% Supply	217 (0.1)	90% Supply	367 (0.2)
Air Curtain Fan Energy (kWh)	256		331		385	
Min. Total Saving, E_{saving}, (kWh)	100% Supply	330	100% Supply	383	100% Supply	5695
Min. Total Percent Saving, P_{saving} (%)		0.0		0.0		1.0
Max. Total Saving, E_{saving}, (kWh)	90% Supply	943	90% Supply	1613	90% Supply	9707
Max. Total Percent Saving, P_{saving}(%)		0.2		0.4		1.8

c. Frequency of the door usage

Door usage frequencies were considered for 20, 50, 100 (baseline), 200, and 400 people/hr. The simulations are based on entrance orientation facing the south, and a 100% supply HVAC system.

Table 5. Sensitivity study of door usages for the climate zones of 2, 4 and 6.

Climate Zones	Zone 2 (Austin)		Zone 4 (Baltimore)		Zone 6 (Minneapolis)	
Basis for Comparison	Single Door		Vestibule		Vestibule	
Door Usage & Energy Saving	People/hr	kWh (%)	People/hr	kWh (%)	People/hr	kWh (%)
Annual Min. Heating Saving	400	-52 (-0.1)	400	-215 (-0.1)	20	1222 (0.4)
Annual Max. Heating Saving	100	328 (0.7)	200	560 (0.4)	400	9441 (2.6)
Annual Min. Cooling Saving	20	64 (0.0)	20	78 (0.0)	20	106 (0.1)
Annual Max. Cooling Saving	200	363 (0.1)	400	290 (0.1)	200	319 (0.2)
Min. Air Curtain Fan Energy (kWh)	20	56	20	72	20	84
Max. Air Curtain Fan Energy (kWh)	400	756	400	978	400	1137
Min. Total Saving, E_{saving}, (kWh)	400	-455	400	-903	20	1244
Min. Total Percent Saving, P_{saving} (%)		-0.0		-0.2		0.2
Max. Total Saving, E_{saving}, (kWh)	100	330	100	383	400	8595
Max. Total Percent Saving, P_{saving} (%)		0.0		0.0		1.5

- No obvious relation is observed between people per hour and the total saving for different cities. For example, the maximum saving occurs at 100 ppl/hr for Austin and Baltimore but at 400 ppl/hr for Minneapolis. This is caused by that the simulations are based on one building orientation so the results depend on the combined effect of door usage, building orientation and dominant wind direction of the specific city. This shows again the importance of building orientation and dominant wind direction.

- For Austin (climate zone 2), the annual heating saving varies from -52 kWh (-0.1%) at 400 ppl/hr to 328 kWh (0.7%) at 100 ppl/hr; the annual cooling saving varies from 64 kWh (0%) at 20 ppl/hr to 363 kWh (0.1%) at 200 ppl/hr, when compared to the single door.
- For Baltimore (climate zone 4), the annual heating saving varies from -215 kWh (-0.1%) at 400 ppl/hr to 560 kWh (0.4%) as 200 ppl/hr; the annual cooling saving varies from 78 kWh (0%) at 20 ppl/hr to 290 kWh (0.1%) at 400 ppl/hr, compared the vestibule.
- For Minneapolis (climate zone 6), the annual heating saving varies from 1222 kWh (0.4%) at 20 ppl/hr to 9441 kWh (2.6%) at 400 ppl/hr; the annual cooling saving varies from 106 kWh (0.1%) at 20 ppl/hr to 319 kWh (0.2%) at 200 ppl/hr, compared the vestibule.
- The annual air curtain fan energy varies from 56 kWh to 756 kWh for Austin, from 72 kWh to 978 kWh for Baltimore, and from 84 kWh to 1137 kWh for Minneapolis. More door usage causes higher usage of fan energy.
- The annual total saving of using air curtain varies from -455 kWh to 330 kWh when compared to the single door in Austin; from -903 kWh to 383 kWh for Baltimore when compared to the vestibule, and from 1244 kWh to 8595 kWh for Minneapolis when compared to the vestibule door.
- The annual total percentage saving of using air curtain varies from -0% to 0% kWh when compared to the single door in Austin; from -0.2% to 0% for Baltimore when compared to the vestibule, and from 0.2% to 1.5% for Minneapolis when compared to the vestibule.

Task 5 – Impact of climate zones

The study of the impact of climate zones on the energy performance of the air curtain was conducted for zone 1-3 compared to the single door and for zone 3-8 compared to the vestibule door. A total of 27 whole building energy simulations was performance with the following settings: 100% supply HVAC system and door usage frequency of 100 people/hr.

Table 6. 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 door.

Climate Zone	City	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	Miami	Cooling	94	175 (0.0)	81	0.0	-		
2	Austin	Cooling	158	290 (0.1)	132	0.0			
3	Atlanta	Heating	200	2003 (2.9)	1757	0.4	1172 (1.7)	1146	0.3
		Cooling		-46 (-0.0)			174 (0.1)		
4	Baltimore	Heating	331	-			2425 (1.6)	2217	0.5
		Cooling					123 (0.1)		
5	Chicago	Heating	371				4383 (1.7)	4169	0.9
		Cooling					157 (0.1)		
6	Minneapolis	Heating	372				7379 (2.0)	7007	1.2
7	Fargo	Heating	415				9152 (2.0)	8737	1.4
8	Fairbanks	Heating	529				19515 (2.5)	18986	2.2
For selected zones, when the operation of air curtain is not controlled by outdoor temperature									
3	Atlanta	Heating	786	2161 (3.2)	911	0.2	1330 (2.0)	300	0.0
		Cooling		-464 (-0.1)			-244 (-0.1)		
4	Baltimore	Heating	786	-			2695 (1.7)	1620	0.4
		Cooling					-289 (-0.1)		
5	Chicago	Heating	786				4694 (1.9)	3721	0.8
		Cooling					-187 (-0.1)		

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.

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.

The annual total savings in kWh and in percentage in Table 6 are plotted in Fig. 4 and Fig. 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 Fig. 5.

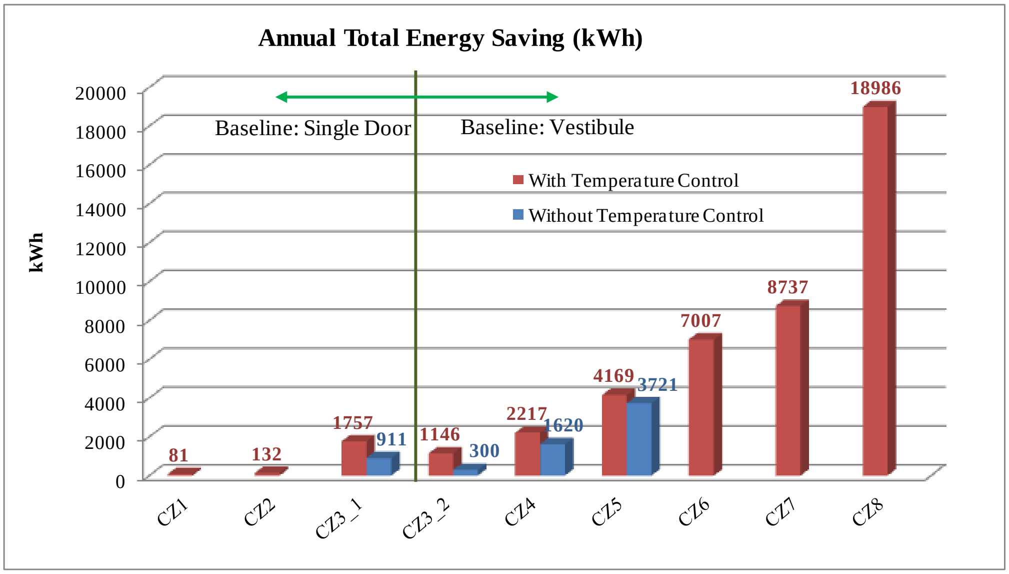


Fig. 4. The national annual total saving of air curtain in kWh when compared to the single door and/or the vestibule.

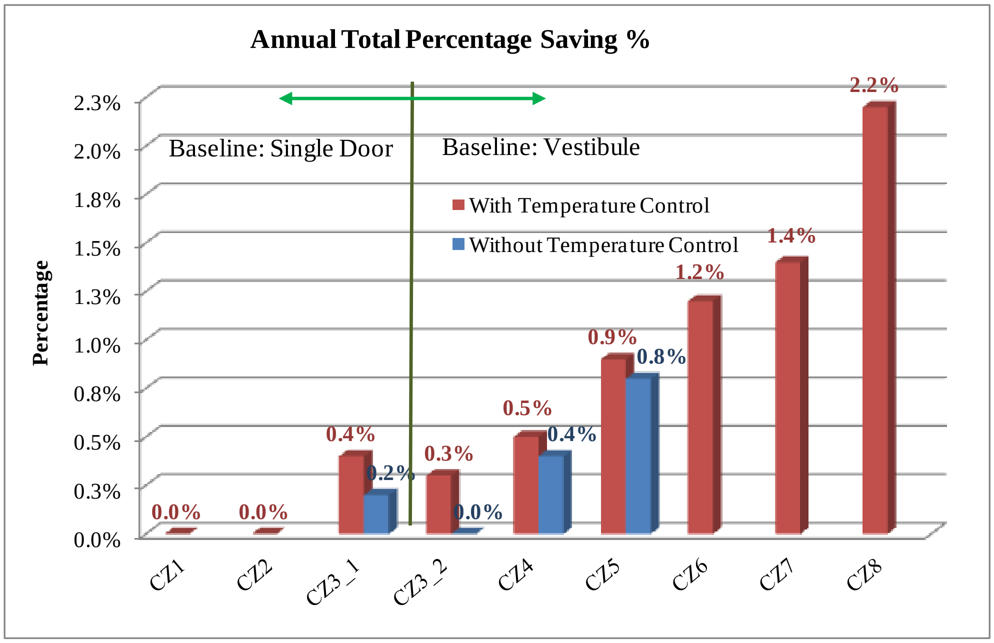


Fig. 5. The national annual total saving of air curtain in percentage when compared to the single door and/or the vestibule.

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 with the 100% supply HVAC system and the door usage frequency of 100 people/hr, 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. Following Yuill's method for the single door and the vestibule, the air curtain correlations can be obtained as the function of door usage frequency in people per hour in terms of the discharge coefficients and discharge modifiers, or the flow coefficients and flow modifiers.
- 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. ΔP < -15 Pa) when compared to the single door.
- The predicted annual pressure difference across the envelope of the modeled building is mostly within -10 ~ 10 Pa with the maximum of about 30 Pa and the minimum of -10 Pa for the case of Chicago, IL.
- 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.

- Building entrance orientation, building pressure, and door usage frequency all affect air infiltration/exfiltration and the resultant energy performance of the air curtain when compared to the single door and the vestibule. Particularly, the effects of building entrance orientation and the balance of the HVAC system cannot be overlooked and they were shown to be as important as door usage frequency.

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.

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