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An approach to determine infiltration characteristics of building entrance equipped with air curtains

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ABSTRACT

Air curtains have been widely used as a barrier against infiltrations and associated energy losses through building entrances while still permitting an unobstructed pedestrian entryway. However, the evaluation of the energy performance of an air curtain often needs to quantify the infiltration rates under variable ambient conditions and door usage patterns. This study develops an approach to determine the infiltration and the exfiltration characteristics of building entrance equipped with an air curtain. A detailed parametric study for different ambient temperatures, pressure differences across the air curtain and different door usage frequencies was conducted by using computational fluid dynamics simulations. The calculated air infiltration rates were then correlated to the pressure differences across the air curtain. The numerical approach was first verified by comparing the obtained correlations for the building entrance without the air curtain to the published data in the literature. New infiltration/exfiltration correlations of the modeled air curtain were then developed as the functions of pressure difference, flow coefficient, and flow modifier. Compared to the single door without air curtain and the door with vestibule, the air curtain was found to reduce the infiltration significantly, especially for the mild ranges of pressure differences.

1. Introduction

Air infiltrations are often caused by accidental introduction of outside air into a building through cracks in the building envelope and/or entrance doors. For commercial buildings in North America, 18% of the total heat loss is caused by air infiltrations. Infiltrations through building entrance door become quite significant when the doors are used frequently such as in restaurants, retail stores, supermarkets, offices and hospitals [1]. Therefore, how to limit undesirable air infiltrations is critical for whole building energy savings. One of the methods is the use of air curtains. Originally invented by Van Kennel in 1904, air curtains have been widely used for about 50 years in many applications [2]. Air curtains have been used as a barrier to reduce fuel consumption in disposal burners [3], to control respirable dusts in the mining industry [4], to preserve low temperatures in the cold storage rooms and food display cabinets [5], and to block smoke dispersion during fires in buildings [6] and transportation tunnels [7,8]. Consisting of a fan unit, air curtains are typically mounted above doorways to separate two spaces with different temperatures with a stream of air strategically engineered to strike the floor with a particular velocity and position. For the application to building entrance, the air prevents outdoor air infiltration while also permitting an unobstructed pedestrian entryway. It also helps to block flying insects, dusts, wind, cold/warm air, and ambient moisture to achieve better indoor comfort. An air curtain offers a cost effective solution: for a single six-foot-wide entrance/exit opening the cost can be less than $6000 plus installation fees. 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. Some manufacturers claimed that the energy saving by installing an air curtain can cut the energy loss through a double doorway by 70% [9,10]. However, no details were provided to support the claim.

The study by Hayes and Stoecker [11] is probably one of the mostly cited design methods for air curtains. An analytical model was proposed in terms of "deflection modulus", a ratio of air curtain jet momentum to transverse forces due to the stack effect of the jet. A design chart was also provided to determine the minimum jet outlet momentum necessary to ensure the jet to reach the floor. When the air curtain jet can reach the floor, Hayes and Stoecker

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Nomenclature

a	door open time for section a, 3.27 s for the double swing door
A	area of the door (m^2)
b	T_u–a–c–d for the fully open section b
c	closing time for the section c, 1.03 s for the double swing door
C	flow coefficient ($m^3/(s\,Pa^{0.5})$)
C_{Da}	discharge coefficient for section a
C_{Db}	discharge coefficient for section b
C_{Dc}	discharge coefficient for section c
C_{Dd}	discharge coefficient for section d
$C_{D,angle}$	discharge coefficient for a specific door open angle
C_{Dave}	time averaged discharge coefficient for one door open cycle
d	closing time for the section d (3.12 s)
D	flow modifier (m^3/s)
D_{Da}	discharge modifier for section a
D_{Db}	discharge modifier for section b
D_{Dc}	discharge modifier for section c
D_{Dd}	discharge modifier for section d
$D_{D,angle}$	discharge modifier for a specific door open angle ($Pa^{0.5}$)
D_{Dave}	time averaged discharge modifier for one door open cycle ($Pa^{0.5}$)
P	pressure (Pa)
P_h	total number of people passing through the door per hour (people/h)
P_i	indoor pressure (Pa)
P_o	outdoor pressure (Pa)
P_u	number of people pasting the door per every door usage, people/usage
Q	volumetric flow rate for one door open cycle (m^3/s)
Q_{angle}	volumetric flow rate for a specific door open angle (m^3/s)
T_h	door total open time per hour (h/h)
T_u	total time of one door operation cycle (s)
U_h	hourly door usages (usages/h)

Greek letters

Δ	difference
θ	door open angle
ρ	density of the air, kg/m^3

Subscripts

sim	simulation
exp	experiment
ave	average
lc	lower critical
uc	upper critical
oi	outdoor and indoor

called this situation as the "optimum condition", the details of which can be found from their report [11]. To be consistent with their study, this paper used the term of "optimum condition" to represent those situations where air curtain jet reaches the floor to block any incoming infiltration from the outdoor environment. The proposed design method however is limited to a fully sealed space without infiltrations other than the entrance where an air curtain is installed. Other studies proposed to use the Richardson number [12], which is similar to the deflection modulus, for the design of air curtains. Based on the work of Hayes and Stoecker, and computational fluid dynamics (CFD) simulations, the Building Services Research and Information Association (BSRIA) at the UK developed a comprehensive guideline, Application Guide 2/97 Air Curtains – Commercial Applications for the design of air curtains [13]. The design methods from the guide cover both fully-sealed buildings and buildings with air leakages for specific indoor and outdoor design temperatures, and building tightness specifications. However, the guide shows that air curtain jet will not reach the floor (so-called the "break-through" condition by Hayes and Stoecker) under certain pressure differences across the air curtain especially under windy conditions for buildings with leakages. As a result, it was suggested that air curtains are inappropriate for the building leakage level higher than 5 $m^3/(h\,m^2)$, evaluated by the hourly infiltration rate per unit floor area. Otherwise, the break-through of the air curtain cannot be avoided. However, a break-through air curtain may still cause lower infiltration and thus reduce energy loss through the doorway than an open door or even a vestibule. The BSRIA air curtain guideline did not provide a method to determine the infiltration across a break-through air curtain under such circumstances.

There have been limited studies to determine infiltration characteristics of air curtain, especially when the break-through occurs. On the other hand, there have been many studies on the infiltration through open doorway without air curtains in the past years. Many analytical models to predict air infiltration through open doors have been proposed [14]. Brown and Solvason [15] assumed the neutral plan across an open door is half of the door height and provided the infiltration as a function of density difference of indoor and outdoor. The model was improved by later studies of Tamm [16], Gosney and Olama [17], and Pham and Oliver [18]. However, it was noted that when air curtains are used, these models are apparently inapplicable [14]. The Handbook of American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) [19] is probably one of the authority references for the predictions of infiltrations. However, no information of the amount of infiltrations or the method to determine infiltrations is provided for air curtains. Limited information on air curtain operations can be found in the ASHRAE Applications Handbook [20], which is however less detailed than the BSRIA air curtain guide [13]. The handbooks only point out that the performance of air curtain depends on many factors such as ambient weather conditions, building pressurization, jet characteristics, and door usage frequencies [19] without further details.

Instead of focusing on infiltrations, some researchers evaluated air curtain performance in terms of the efficiency and/or the effectiveness. The air curtain efficiency is often defined as one minus the ratio of the energy loss through the entrance door with the air curtain to that without it. Quite a few experimental studies as reviewed by Pappas and Tassou [21] determined the efficiencies ranging from 60% to 90% in general. Although the efficiency factor provides a general and single criterion on air curtain performance, many of these experimental studies had to limit the test conditions to specific ambient conditions. The previous studies did not consider the effects of variable ambient conditions, especially pressure differences, and different door usage frequency on the performance of an air curtain.

The literature search also found that numerical simulations using CFD are able to investigate many cases and parameters, and have been widely used in the study of air curtains. Foster et al. [22] simulated a 1.0 m wide air curtain by a 2-D CFD model and noted that the jet velocity and door open duration are directly related to the air curtain performance. Pappas and Tassou [21] conducted a 3-D CFD simulation of an air curtain and found that the optimum performance can be achieved when the air curtain jet reaches and maintains contact with the floor. Costa et al. [23] modeled an air curtain by a 2-D CFD model and found that under the optimum condition the modeled air curtain can provide an energy saving