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Experimental study on the flow characteristics of air curtains at building entrances

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ABSTRACT

Air infiltration through building entrances is one of the main sources of energy loss in modern buildings. Previous studies have shown that air curtains, when used at building entrances, can reduce infiltration-related energy loss significantly. A recent computational fluid dynamics (CFD) study proposed a new empirical model to capture air curtain door infiltration/exfiltration characteristics under varying operation conditions and pressure differences. Extending the recent CFD study, this paper presents an experimental study to verify and further investigate the flow characteristics of building entrances equipped with air curtains. A small scale chamber of 2.44 m × 2.44 m × 1.3 m (L × W × H) was constructed and used for the measurements of infiltration/exfiltration and pressure differentials, which were then used for developing the empirical model across the operating air curtain. A 2-D particle image velocimetry (PIV) system with helium filled soap bubbles as seeds was used to visualize the airflow fields captured at the doorway. Both the PIV and the measurement-based correlations were also compared to CFD simulations. The flow/pressure measurements confirmed that, for the tested pressure difference range, air curtains can significantly reduce infiltration. The PIV results confirmed the existence of multiple flow characteristics subject to pressure differences across the air curtain. The experimental results also validated the CFD modeling methods for air curtain, and verified that the empirical model of air curtain from the literature is valid in estimating infiltration through building entrances equipped with air curtains.

1. Introduction

Air infiltration is the uncontrolled inward leakage of outdoor air into buildings through cracks in the envelope or through large openings such as doors [1]. Air leakage, movement of air in or out of buildings, is mainly caused by pressure difference across the various building enclosure elements. These differences in pressure can be caused by many factors such as wind, stack effect, and/or HVAC system operations [1]. In modern well constructed and insulated buildings, it is estimated that air infiltration can be responsible for up to 25% of the building heating loads and it can mainly be due to entrance doors and their use [2]. Based on the available research and standards [3,4], many building energy codes[1] require vestibule doors in commercial buildings to reduce the infiltration through entrance doors. Another solution, which has been in use for more than 50 years and offers cost and space savings for building owners, is the use of air curtains [5–7]. Air curtain units, typically made of a fan and casement with a jet outlet, are used as to create an air barriers in various applications: they have become a standard in cold storages and food cabinets, they are used in buildings to block smoke in the event of fires, as well as to control dust in the mining industry [5–8]. For entrance doorways, the units are most commonly mounted above the doorway/opening and are designed to supply one (or more) jet(s) of air that are engineered to reach the floor at a particular velocity and position in order to seal openings aerodynamically [9]. Air curtains are defined by the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) as a continuous broad stream of air circulated across a doorway of a conditioned space which reduces penetration of unconditioned air into conditioned spaces by forcing an air stream over the entire entrance [10]. The air stream layer moves with a velocity and angle such that any air that tries to penetrate the

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[1] 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 [1].

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Nomenclatures and abbreviations

η_{air}	Efficiency factor for infiltration reduction (air curtain)
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
D_d & D_{Dave}	Discharge modifier (air curtains)
D_m	Deflection modulus of air curtain jet
F_u	Air curtain infiltration usage correction factor
H	Door height
η	Efficiency factor for heat transfer reduction (air curtain)
P_h	People per hour (door usage)
Q	Volume flow rate
R_p	Pressure factor
T_h	Usage per hour (doors)
u_0	Air curtain discharge speed
V_0	Air curtain volume supply rate
α_0	Air curtain discharge angle
ΔP	Pressure difference across the air curtain door
ΔP_{lc}	Lower critical pressure difference
ΔP_{uc}	Upper critical pressure difference

Abbreviations

AC	Air curtain
Air curtain door	Double swing doors opening out with air curtain unit
AMCA	Air Movement and Control Association (International)
Door mid-plane	Vertical plane 30.5 cm away from the left side of the chamber door edge (middle of the door opening)
Door side-plane	Vertical plane 8.5 cm away from the left side of the chamber door edge – in the experimental chamber
Fully open door	Door open at 90°
HFSB	Helium filled soap bubbles
PIV	Particle Image Velocimetry
RMS	Root mean square values (PIV velocity fields)
Single door	Double swing doors opening out (without vestibule or air curtain)
Vestibule door	Vestibule with double swing doors opening out (2 set of double swing doors)

curtain is entrained [10]. Besides restricting air infiltration into buildings, air curtain doors (single doors equipped with air curtain units) can also provide building users with un-obstructed entranceways, blocking outdoor pollutants, respirable dust, insects, and moisture [11]. Manufacturers of the units claim that air curtain doors can reduce the energy losses from entrance doors by 70% compared to building entrance doors without air curtains [8,11,12].

Hayes [13] was able to develop theoretical models that describe the airflow and jet of vertically downwards blowing air curtains for isothermal and non-isothermal cases. Hayes [13] proposed the deflection modulus of air curtains to be used in the design and selection of the units. The deflection modulus, D_m, which is indicative of the deflection of the air curtain, is the ratio of the air curtain jet momentum to transverse forces due to the stack effect on the jet [13]. Hayes and Stoecker then developed, based on the "deflection modulus", widely used design charts for air curtains that provide the minimum jet outlets momentum needed for the jet to reach the floor [14]. In their work, Hayes and Stoecker defined the operation condition where the air curtain jet reaches the floor as the "optimum condition" and other operation conditions where the air curtain jet does not reach the floor as "break-through condition" [14]. They also proposed evaluating the performance of air curtains by calculating the air infiltration efficiency factor, η_{air}, which evaluates the ability of the air curtain to limit the air infiltration in reference to the unprotected opening. This measure has been widely used by researchers in the industry up till this day [14]. Pappas and Tassou have extended this concept to measure the efficiency of air curtains in reducing heat losses by proposing the heat transfer efficiency factor, η [15]. However, the work of Hayes and Stoecker was limited to fully sealed rooms under constant and steady conditions of pressure and temperature differences; the models developed were only applicable for air curtains operating under optimum conditions [14]. This resulted in other design guides[2] to conclude that air curtains were not suitable for leaky buildings under windy conditions [5]. However, other research has shown that even when operating in a breakthrough condition, air curtains can still provide better protection than single or vestibule doors [16]. What is most important to note is that most of the studies dealing with air curtains infiltration have focused on single or steady condition analysis (usually with the door fully open) to evaluate the performance of air curtain doors, neglecting the variable conditions, varying usage and the door opening cycles that entrance doors experience during their normal operation.

In contrast, when it comes to doors not equipped with air curtains (i.e. single doors and vestibule doors), the model developed by Yuill [3] is widely used in predicting air infiltration through doors. Yuill's model (presented in Eq. (1)) uses the well known orifice equation and presents average discharge coefficients for the door, C_{Dave}, based on the usage frequency and considers the full door opening cycle [3]: during one operation cycle of a single door, the door opens from the shut-off position (0°) to the fully open position (90°) (i.e. the opening section a), stays fully open (i.e. the section b), shuts off (i.e. the section c), and finally closes completely (i.e. the section d).

$$Q = C_{Dave} A T_h \sqrt{\frac{2\Delta P}{\rho}} \tag{1}$$

where C_{Dave} is the overall average discharge coefficient,

$$C_{Dave} = \frac{C_{D\ a}a + C_{D\ b}b + C_{D\ c}c + C_{D\ d}d}{a+b+c+d}$$

$C_{D,\ section\ (a,b,c,d)}$ is the average discharge coefficient for each door operation section,

[2] Such as the Building Services Research and Information Association (BSRIA) Application Guide 2/97 Air Curtains – Commercial Applications for the design of air curtains [5].