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Restriction of Air Infiltration by an Air Curtain Optimized with Secondary Jets—A Numerical Investigation

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ABSTRACT

Infiltration of unconditioned air through access openings and entrance doors with high recurrence can cause detrimental impacts to the energy performance, air quality and thermal comfort of buildings. Air curtains are of strategic importance to attenuate these negative impacts. In addition, air curtains are relevant in specialized HVAC applications for which the impediment of infiltration is also essential (e.g., reduction of smoke propagation in fire events, decrease of contamination hazard in clean rooms, preservation of refrigeration properties in cold rooms). A common performance indicator of an air-curtain system is the separation efficiency, which relates to the rate of heat or mass transfer between the two environments that are separated by the air curtain. The jet parameters have a large influence on the momentum and mixing/entrainment processes that take place in the jet, ultimately affecting the separation efficiency of air curtains. However, to the best of our knowledge, information in the scientific literature is focusing mostly on the analysis of air curtains with single jets. Therefore, this study addresses a preliminary investigation of the implementation of secondary co-flowing jets in air curtains as an approach to modify the jet characteristics to restrict jet entrainment and improve the separation efficiency of air curtains. Reynolds-averaged Navier-Stokes (RANS) simulations are performed to analyze the effect of modifying one of the major parameters of secondary jets (i.e., velocity ratio R) on the air-curtain separation efficiency. The simulation results indicate that reasonable improvements of 4.3% in the air-curtain separation efficiency based on infiltration can be obtained with the incorporation of secondary jets under certain jet discharge conditions.

INTRODUCTION

The health and wellbeing of building users rely on the preservation of indoor environments that are controlled in terms of temperature, humidity, concentration of gas species and particles, odors, lighting, noise and other physical, chemical and biological parameters. The unwanted introduction of unconditioned air (i.e., infiltration) into these controlled environments can result in complications that are detrimental for thermal comfort and indoor air quality

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(Mitchell et al. 2007; Toyinbo 2019). Moreover, unrestrained air infiltration can increase heat losses and thus undermine energy conservation efforts (Younes et al. 2012; Brinks et al. 2015). Entrance doors and access openings with high recurrence contribute significantly to air infiltration. A widespread strategy to reduce infiltration through open doors and openings without restricting transit of people and goods is the use of air curtains. Building entrances are locations where air curtains are often implemented; however, there are various other specialized HVAC applications that take place within buildings for which the restriction of local air infiltration by means of air curtains is also relevant. A few examples of the latter are the confinement of smoke in designated smoking areas or during fire events (Krajewski and Sztarbala 2011; Luo et al. 2013), the decrease of pollutant transport into clean rooms of industrial or healthcare facilities (Shih et al. 2011), the preservation of refrigeration properties in cold storage rooms (Gil-Lopez et al. 2014; Giraldéz et al. 2016), and the impediment of contaminant dispersion in industrial process rooms (Popendorf 2006).

An air curtain is fundamentally a jet of air expelled from a thin nozzle at high velocity which impinges on a surface, thus generating an aerodynamic barrier that seals the opening or door at hand. The most typical configuration of an air curtain consists of a single jet stream of air issued downwards, and therefore the great majority of scientific literature on the topic focuses on such configuration (see e.g., Costa et al. 2006; Frank and Linden 2014; Wang and Zhong 2014; Yang et al. 2019; Khayrullina et al. 2020; Razeghi et al. 2021). Nonetheless, basic research shows that several jet parameters at the discharge can have a paramount influence on the momentum distribution, the development of turbulence, and the entrainment and transport processes that occur in jet flows (Crow and Champagne 1971; Reynolds et al. 2003; Ghadi et al. 2016). This potentially includes jet parameters that could deviate from a single jet stream configuration. To the best of our knowledge, research in this area is scarce and literature addressing air curtains with multiple jets is very limited in number.

The purpose of this study is to provide a first investigation on the performance of air curtains that incorporate secondary co-flowing jets. A direct performance comparison is presented between air curtains with secondary jets subjected to variable velocity parameters and a baseline air curtain with a single jet operating under optimal performance conditions. Two distinct definitions of the separation efficiency are adopted as performance indicators. The study is performed numerically using computational fluid dynamics (CFD) models based on Reynolds-averaged Navier-Stokes (RANS) approximations of the governing flow equations.

METHODS

Performance indicators (definitions of separation efficiency)

A separation efficiency formulated based on mass transport is used to evaluate air-curtain performance, which has been introduced in (Alanis Ruiz et al. 2021). This is further divided into two indicators: the first one relates to only infiltration and is defined as the ratio of mass transfer of unconditioned air that infiltrates through the opening when the air curtain is in operation ($\dot{m}_{in,ac}$) to the mass transfer of unconditioned air that arises from the same opening when the air curtain is not operating (reference scenario) ($\dot{m}_{in,ref}$).

$$\eta_{s,inf} = 1 - \frac{\dot{m}_{in,ac}}{\dot{m}_{in,ref}} \tag{1}$$

Using a similar nomenclature, the second indicator takes into account the contributions of infiltration and exfiltration that simultaneously occur through the opening. It is quantified from the mass transfer of unconditioned air to the conditioned environment (i.e., infiltration; $\dot{m}_{in}$) in addition to the mass transfer of conditioned air to the unconditioned environment (i.e., exfiltration; $\dot{m}_{ex}$). As in the first indicator, the sum of both quantities is evaluated in a scenario where the air curtain is operating (subscript *ac*) against a reference scenario without air curtain (subscript *ref*).

$$\eta_{s,tot} = 1 - \frac{\dot{m}_{in,ac} + \dot{m}_{ex,ac}}{\dot{m}_{in,ref} + \dot{m}_{ex,ref}} \quad (2)$$

It is important to note that the appropriateness of these separation efficiencies depends on the specific intent of the air-curtain application under consideration. While some applications focus on the reduction of infiltration regardless of any exfiltration that the air curtain could generate—for instance, air curtains applied in clean rooms of industrial and healthcare premises, as well as those employed for fire safety applications—, for others it is important to keep both infiltration and exfiltration to a minimum (e.g. air-curtain systems at building entrances and cold rooms where exfiltration implies energy losses of already conditioned air).

Description of tests on air curtains with secondary jets

The situation considered in this investigation consists of a system where an air-curtain device is placed above an opening that is the interface between a conditioned and an unconditioned environment in order to restrict gas transport between these two environments. The device issues a main planar jet flow vertically downwards accompanied by a smaller secondary co-flowing jets at the lateral sides (illustrated in Figure 1b). The secondary jets are aligned with the streamwise direction of the main jet stream.

The primary intent of implementing secondary co-flowing jets in the air curtain is to “shield” the main jet and reduce both the spatial evolution of the shear layer of the main jet and the entrainment of surrounding air into it. The development of vorticity in the jet due to the evolution of the shear layer is associated with erosion of the jet's potential core that decreases its streamwise momentum. On the other hand, air entrainment into the jet translates into mixing between the two environments separated by the air curtain. Therefore, shielding the main jet via the implementation of secondary jets is expected to be advantageous to attain higher separation efficiencies in air curtains.

The velocity ratio between main and secondary jets is deemed to be a crucial parameter affecting performance of this air-curtain configuration, thus it is the subject of this parametric analysis. The velocity ratio *R* is provided in Eq. (3) and gives an indication of the intensity of the shear layer formed between the main and secondary jets:

$$R = \frac{V_0 - V_s}{V_0 + V_s} \quad (3)$$

where V_0 is the mean jet discharge velocity of the main jet and V_S the mean jet discharge velocity of the secondary jets.

Three cases for analysis are constructed as a function of the velocity ratio: $R =$ 0.60, 0.15 and -0.15. In every case the mean velocity of the main jet is kept constant with V_0 = 9 m/s. The width of the secondary jets (W_S = 20 mm) is constant and it is specified as a fraction of the width of the main jet (W_{jet}= 65 mm). The principal characteristics of the main jet (i.e., V_0 and W_{jet}) are consistent with that of a benchmark case. Whereas the influence of non-zero spacing between multiple jets on air-curtain efficiency has been investigated recently under idealized cross-jet conditions (i.e., no gradients of density or pressure), the present study centers on the jet velocity ratios of co-flowing jets assuming zero interjet spacing, meaning that jets are adjacent and separated by merely a thin (zero-thickness) wall.

In a previous study by the present authors (Alanis Ruiz et al. 2018), the optimal performance, based on the indicators referred in previous subsection, of a commercial air curtain with a single jet subjected to cross-jet pressure gradients was determined. This is used as the baseline performance (benchmark) for the present analysis, wherein a comparison is made between the performance of the different air curtains with secondary jets and this benchmark air curtain.

Environmental conditions—i.e., wind, room/building pressurization, differences of temperature or concentration of species between environments separated by an air curtain—exert loads on the air-curtain jet(s), which are directly represented by a cross-jet gradient of pressure. In consistency with the baseline case, all parametric configurations and their reference scenarios undergo a pressure difference of ΔP = 2 Pa.

Computational settings and parameters

3D CFD simulations are performed of the air-curtain system. The geometry and relevant dimensions of the computational domain are shown in Figure 1. The computational grid is made in compliance with best practices. It is formed of 1,014,050 structured hexahedral cells and the resolution is based on a grid-sensitivity analysis. Refinement of the grid is particularly applied in the region where the jets develop, as visualized in Figure 1b. At the side of the domain where the environment is unconditioned, a boundary with a static gauge pressure P = 2 Pa and an unconditioned air concentration x_{uc} = 1 is implemented. On the other side, where the environment is conditioned, a boundary with zero static gauge pressure and a backflow concentration x_{uc} = 0 are enforced. No-slip wall boundaries partially enclose the space where the environment is conditioned, as well as the surfaces of the air curtain device that are not responsible for the flow discharge and extraction. Symmetry boundary conditions (i.e., zero normal velocity and zero normal gradients of all variables at the boundary) constrain the extension of the computational domain in the transversal (z) direction to 500 mm. The jets are issued as per the velocity conditions specified in previous section with a turbulence intensity I = 6% and a turbulence length scale l = 4.26 mm that are in line with the baseline air curtain. Mass conservation is enforced in the flow that is extracted and subsequently ejected by the air-curtain device (recirculation). Boundary conditions are also indicated in Figure 1.

Steady RANS simulations employing standard wall functions and the standard k-ε turbulence model (Jones and Launder 1972) are conducted for the analysis using the solver ANSYS Fluent 18.2. The semi-implicit method for pressure-linked equations (SIMPLE) is applied for the coupling of pressure and velocity. Pressure is interpolated with a second-order central differencing scheme while second-order upwind schemes are used for the discretization of all other flow variables. The computational settings are based on a prior validation study with dedicated experimental data of turbulent impinging jets, of which the results are outlined in Alanis Ruiz et al. (2018).

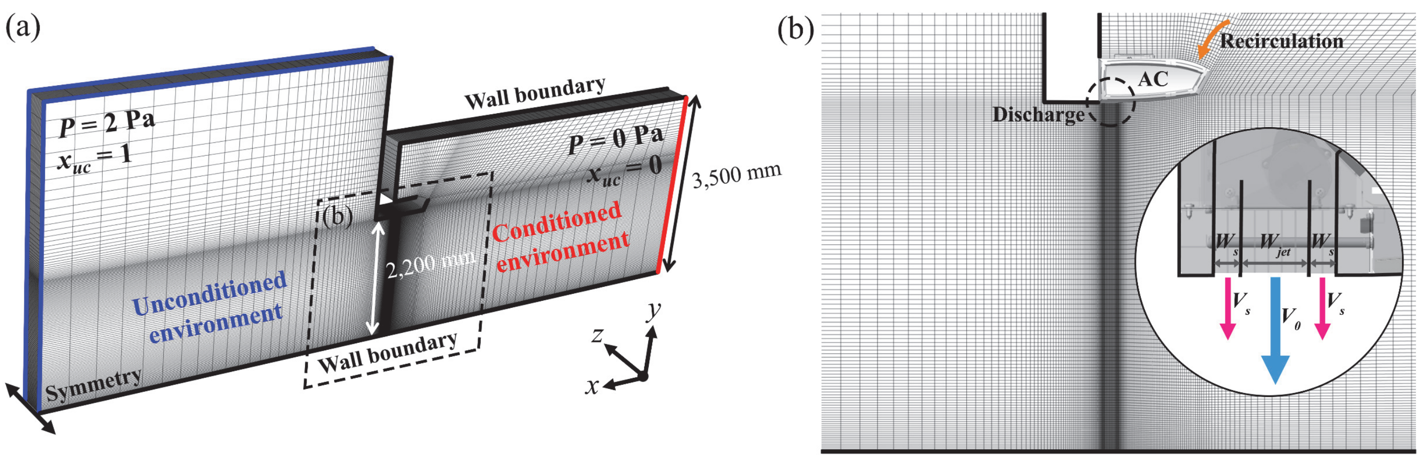

Figure 1 (a) Computational domain and grid visualization over the surfaces of the domain. (b) Enlarged section of the computational domain enclosing the air-curtain jet region and schematic illustration of secondary jets implemented in the air-curtain device (AC). Thick lines indicate distinct boundary conditions: blue lines are relative to the unconditioned environment, red lines are relative to the conditioned environment and black lines are wall boundaries.

RESULTS AND DISCUSSION

Figure 2 shows the performance of the test cases compared against the benchmark. An evident increase in the separation efficiency based on infiltration only ($\eta_{s,inf}$) over the benchmark is observed with an increase in the velocity of the secondary jets (V_S). Conversely, the separation efficiency based on simultaneous infiltration and exfiltration ($\eta_{s,tot}$) exhibits a decline in performance with increasing V_S (decreasing R). In spite of that, the air curtain with secondary jets under velocity ratios R = 0.60 and 0.15 displays an improved separation efficiency $\eta_{s,inf}$ (+1.5% and +4.3%, respectively) while maintaining virtually the same or slightly higher separation efficiency $\eta_{s,tot}$ (+0.9% and -0.1%, respectively) than that of the benchmark. It is considered that the best overall improvements are attained by R = 0.15 given that a meaningful increment of the separation efficiency based on infiltration is achieved at the same time that the separation efficiency based on combined infiltration and exfiltration is not compromised.

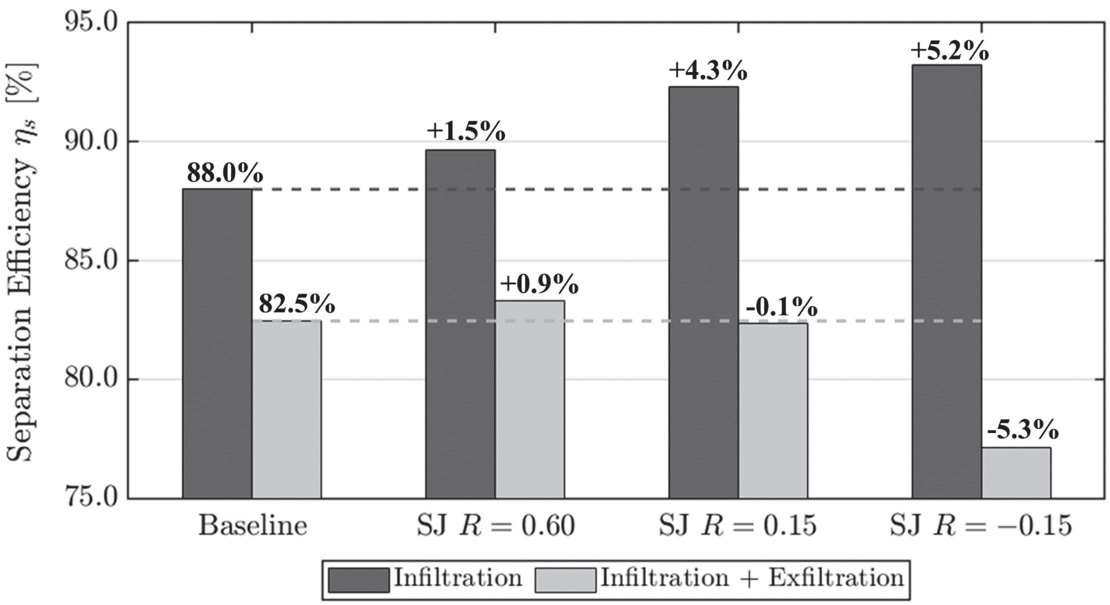

Figure 2 Comparison of performance (separation efficiency) between a baseline air curtain with a single jet stream (benchmark) and air curtains with secondary jets (SJ) under variable jet velocity ratios R.

A side-by-side comparison of the baseline air curtain and the air curtain with secondary co-flowing jets under R = 0.15 is presented in Figure 3. Figure 3a compares the two cases with respect to the dimensionless mean z-vorticity ($\omega_Z W_{jet}/V_0$), which provides evidence of the formation of secondary potential cores (SPC) and secondary shear layers (SSL) associated to the additional co-flowing jets. In contrast, a single potential core (PC) and shear layer (SL) is formed with the baseline air curtain. The potential core of the main jet in the case with secondary jets extends further downstream (55% increase in length) as it is less affected by the generation of vorticity, resulting in a reduced decay of the main jet and preservation of streamwise momentum over a longer distance. A comparison based on the dimensionless mean velocity magnitude ($|V|/V_0$) in Figure 3b reinforces latter observations, and in addition reveals a decrease in the main jet spreading as a result of the implementation of secondary co-flowing jets. Lastly, the distribution of dimensionless mean unconditioned air concentration (x_{uc}/x_{tot}) shown in Figure 3c indicates a visible drop in the transfer of unconditioned air to the conditioned environment when secondary jets are implemented, culminating in lessened infiltration across the opening.

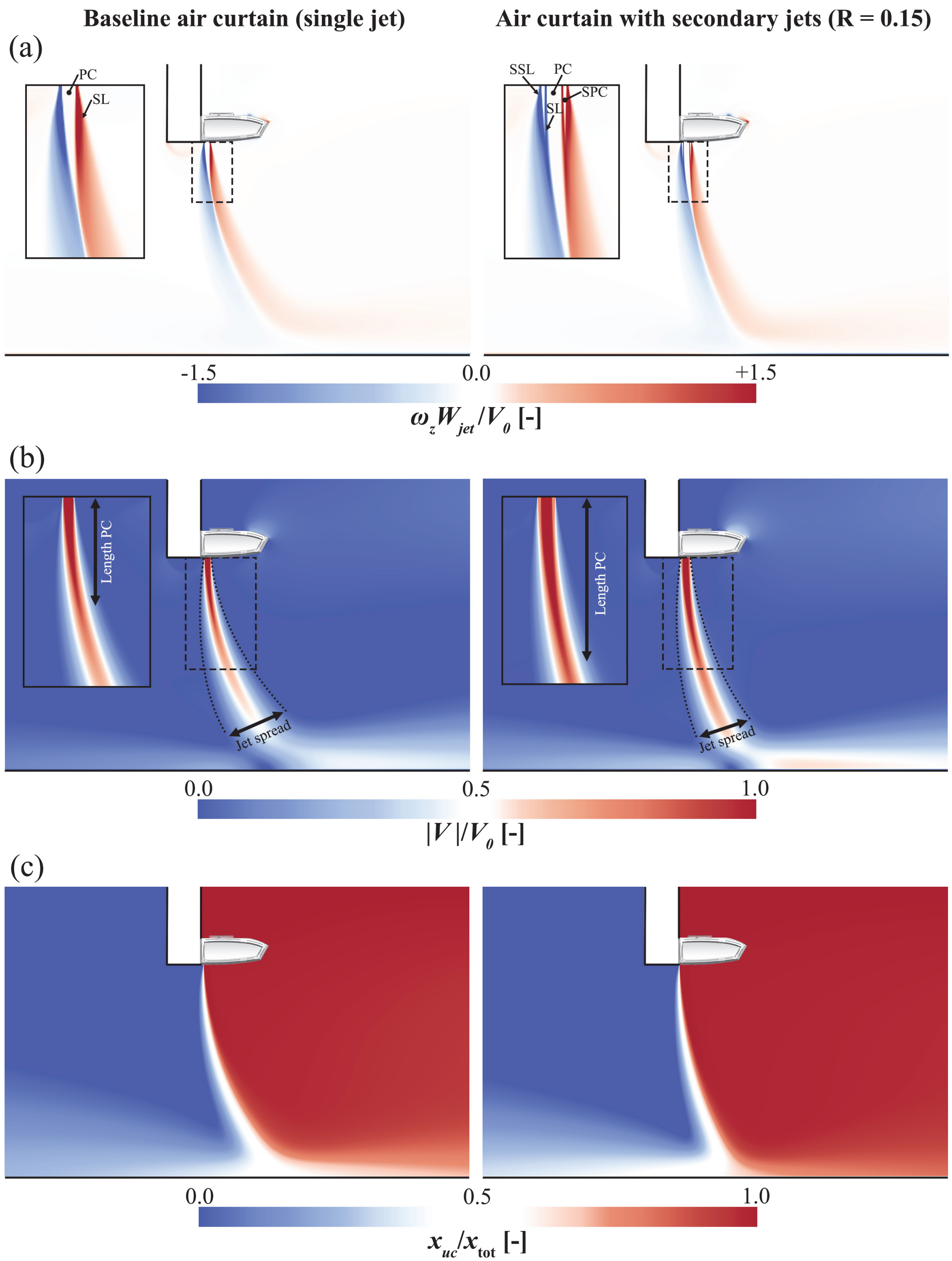

Figure 3 Comparison between the baseline air curtain and an air curtain with secondary co-flowing jets (R = 0.15) under cross-jet pressure difference ΔP = 2 Pa in terms of dimensionless mean (a) z-vorticity ($\omega_Z W_{jet}/V_0$), (b) velocity magnitude ($|V|/V_0$) and (c) concentration of unconditioned air (x_{uc}/x_{tot}).

CONCLUSIONS AND FUTURE WORK

In this study numerical simulations using CFD have been conducted to make quantitative predictions of the flow behavior in an air-curtain system and to facilitate a parametric evaluation of the air-curtain separation efficiency in a device that adopts secondary jets as a strategy to further restrict infiltration through an opening.

The results demonstrate the capability of air curtains with secondary jets in reducing the spatial development of the vorticity in the initial jet region, thereby extending the length of the potential core of the jet and reducing the overall decay and spread of the jet. Consequently, secondary co-flowing jets decrease entrainment of surrounding air into the main jet stream and thus reduce mixing. The largest overall improvements are found for the tested case with a velocity ratio $R = 0.15$, where the separation efficiency based on infiltration increases 4.3% over a benchmark performance while equivalent separation properties are retained when considering the efficiency based on simultaneous infiltration and exfiltration. Such an improvement is especially favorable for air-curtain applications that aim foremostly to restrict infiltration. For instance, the preservation of thermal comfort and air quality at the entrance of commercial and public buildings, the conservation of controlled environmental conditions in industrial clean rooms and healthcare operating theaters, the smoke transport suppression in fire safety systems and various other applications.

Ongoing work focuses on detailed research on the flow behavior and vortex dynamics of air curtains with single and multiple jets and their influence on the separation efficiency using experimental and more advanced numerical techniques. The study of a wide range of jet and environmental parameters will be incorporated. Furthermore, the impact of air-curtain performance on energy use, indoor air quality and thermal comfort will be considered.

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NOMENCLATURE

ΔP = static cross-jet pressure difference [Pa]
η_s = air-curtain separation efficiency [%]
ω_z = z component of the vorticity [s^{-1}]
I = turbulence intensity [%]
l = turbulence length scale [m]
$\dot{m}$ = rate of mass transfer [kg/s]
R = velocity ratio between main and secondary jets [-]
$|V|$ = mean velocity magnitude [m/s]
V_0 = mean jet discharge velocity [m/s]
V_S = discharge velocity of secondary jet [m/s]
W_{jet} = jet width [m]
W_S = secondary jet width [m]
x_{tot} = sum of the mass fractions of all species in the air mixture [-]
x_{uc} = mass fraction of unconditioned air [-]

Subscripts

ac = related to an entrance or opening with an air curtain
inf = related to infiltration only

ref = related to a reference scenario of an entrance or opening without an air curtain

s = related to secondary jet

tot = related to combined infiltration and exfiltration

REFERENCES

Alanis Ruiz, C., van Hooff, T., Blocken, B., and van Heijst, G. 2021. Air curtain performance: Introducing the adapted separation efficiency. *Building and Environment 188*: Article nr. 107468. https://doi.org/10.1016/j.buildenv.2020.107468

Alanis Ruiz, C., van Hooff, T., Blocken, B., and van Heijst, G. 2018. CFD analysis of the effect of pressure gradients on the separation efficiency of a generic air curtain. *Proceedings of Roomvent&Ventilation 2018* (pp. 241-246). Helsinki, Finland: REHVA.

Brinks, P., Kornadt, O., and Oly, R. 2015. Air infiltration assessment for industrial buildings. *Energy and Buildings*, 663-676.

Costa, J., Oliveira, L., and Silva, M. 2006. Energy savings by aerodynamic sealing with a downward-blowing plane air curtain - A numerical approach. *Energy and Buildings*, 1182-1193.

Crow, S., and Champagne, F. 1971. Orderly structure in jet turbulence. *Journal of Fluid Mechanics*, 547-591.

Frank, D., and Linden, P. 2014. The effectiveness of an air curtain in the doorway of a ventilated building. *Journal of Fluid Mechanics*, 130-164.

Ghadi, S., Esmailpour, K., Hosseinalipour, S., and Mujumdar, A. 2016. Experimental study of formation and development of coherent vortical structures in pulsed turbulent impinging jet. *Experimental Thermal and Fluid Science*, 382-389.

Gil-Lopez, T., Castejon-Navas, J., Galvez-Huerta, M., and O'Donohoe, P. 2014. Energetic, environmental and economic analysis of climatic separation by means of air curtains in cold storage rooms. *Energy and Buildings*, 74, 8-16.

Giraldéz, H., Pérez Segarra, C., Oliet, C., and Oliva, A. 2016. Heat and moisture insulation by means of air curtains: Application to refrigerated chambers. *International Journal of Refrigeration*, 1-14.

Jones, W., and Launder, B. 1972. The prediction of laminarization with a two-equation model of turbulence. International *Journal of Heat and Mass Transfer*, 301-314.

Khayrullina, A., van Hooff, T., Alanis Ruiz, C., Blocken, B., van Heijst, G. 2020. Minimum momentum flux ratio required to prevent air curtain breakthrough in case of cross-jet pressure gradients: CFD versus analytical equation. *Building Simulation 13*, 943-960.

Krajewski, G., and Sztarbala, G. 2011. Air curtains used for separating smoke free zones in case of fire. *Proceedings of Building Simulation 2011* (pp. 2773-2777). Sydney, Australia: IBPSA.

Luo, N., Li, A., Gao, R., Zhang, W., and Tian, Z. 2013. An experiment and simulation of smoke confinement utilizing an air curtain. *Safety Science*, 59, 10-18.

Mitchell, C., Zhang, J., Sigsgaard, T., Jantunen, M., Lioy, P., Samson, R., and Karol, M. 2007. Current State of the Science: Health Effects and Indoor Environmental Quality. *Environmental Health Perspectives*, 958-964.

Popendorf, W. 2006. Industrial Hygiene Control of Airborne Chemical Hazards. Taylor & Francis.

Razeghi, S., Safarzadeh, M., Pasdarshahri, H. 2021. Evaluation of air curtain and emergency exhaust system for smoke confinement of an enclosure. *Journal of Building Engineering 33*: Article nr. 101650.

Reynolds, W., Parkeh, D., and Juvet, P. 2003. Bifurcating and blooming jets. *Annual Review of Fluid Mechanics*, 295-315.

Shih, Y., Yang, A., and Lu, C. 2011. Using air curtain to control pollutant spreading for emergency management in a cleanroom. *Building and Environment*, 1101-1114.

Toyinbo, O. 2019. Indoor Environmental Quality. In V. Tam, and K. Le, Sustainable Construction Technologies: Life-Cycle Assessment (pp. 107-122). Sydney: Butterworth-Heinemann.

Wang, L., and Zhong, Z. 2014. An approach to determine infiltration characteristics of building entrance equipped with air curtains. *Energy and Buildings*, 312-320.

Yang, S., Alrawashdeh, H., Zhang, C., Qi, D., Wang, L., and Stathopoulos, T. 2019. Wind effects on air curtain performance at building entrances. *Building and Environment*, 75 - 87.

Younes, C., Abi-Shdid, C., and Bitsuamlak, G. 2012. Air infiltration through building envelopes: A review. *Journal of Building Physics*, 267-302.