CFD MODELLING OF AERODYNAMIC SEALING BY VERTICAL AIR CURTAINS

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Abstract

This work presents a comparative study of the sealing effect of doorways of air-conditioned or refrigerated spaces, obtained by vertical air curtain devices (ACD). An analysis is made of the effect of installing the device(s) inside, outside or both sides of the door, considering both winter and summer operation conditions.

For this purpose, a numerical model was developed aiming the simulation of the turbulent non-isothermal 3D airflow generated by the air curtain after the door opening. The flow field induced by the opening of the door with the ACD turned off was also simulated and taken as a reference to assess the efficiency of the aerodynamic sealing process.

The numerical simulations have shown plausible results which comply with the physical interpretation of the convective phenomena involved. In line with previous investigations on air curtains, an optimum velocity of the air jet was found, that corresponds to the highest sealing effect. According to the simulations results, downward blowing air curtains can present high sealing efficiencies (over 70%). Although the direct air recirculation provides a better sealing performance (over 80%), the complexity, acquisition and maintenance costs inhibit its common use in ACD installations.

Keywords: Air Curtain, CFD, Heat Transfer, Thermal Comfort, Energy Consumption

1 Introduction

There are several situations configuring real physical spaces that, for various reasons, need to be isolated from the outside environment. Aerodynamic sealing by an air curtain consists of a air jet developed by a fan, which guarantees to a certain extent the preservation of the temperature and/or of the chemical properties of a closed space, allowing at the same time free access to it. Air curtains are widely used in: thermal comfort control (Howell and Shibata (1980), Silva *et al* (2002) and Neto *et al* (2006)); sealing entrances of cold rooms (Takahashi and Inoh (1963), Longdill and Wyborn (1979), and Hendrix *et al* (1989)); protection openings of refrigerated food display cabinets (Gaspar *et al* (2003) and D'Agaro *et al* (2006)); control of dust and thermal/humidity industrial environment (Valkeapää (2002)); sealing the access sections of industrial chemical treatment furnaces (Oliveira *et al* (1991)), etc.

Due to their multiple applications, air curtain equipments can present different configurations. Some typical characteristics can distinguish an air curtain, namely: main air jet direction (downward or horizontal); existence of a return grill for immediate air recirculation; number of injection nozzles (single or twin-jet air curtain); fan type; inclusion of heaters and/or cooling air equipment, etc.

Besides the experimental studies, computational fluid dynamics (CFD) has been commonly used, adopting a two dimensional (2D) approach (Tang (1998); Costa *et al* (2006)) or, more recently, through a three-dimensional (3D) perspective (Foster *et al* (2007), Gonçalves *et al* (2009[a,b]) and Jaramillo *et al* (2009)).

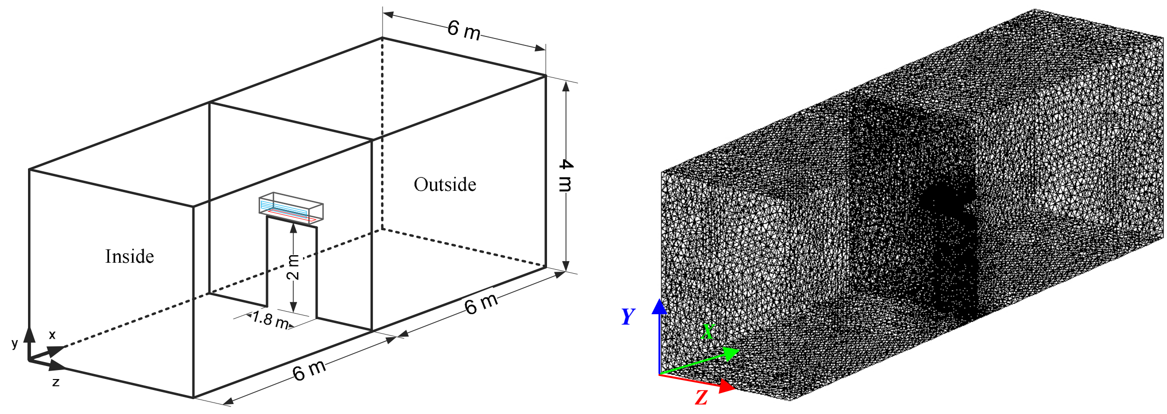
This work presents a 3D numerical study comparing the sealing efficiency of doorways connecting two rooms, initially at different temperatures, obtained by air curtains with different configurations.

2 Numerical model

2.1 Domain Geometry

The geometry of the physical domain consists of two adjacent rooms with similar dimensions, 6×6×4 m^3, connected by a door featuring 1.8 m width and 2 m height (figure 1(a)), with a ACD installed on the top. One of the rooms represents the indoor climate space to maintain sealed, and the other represents the outdoor environment.

The air curtain equipment is represented by a parallelepiped shape solid (0.4 m wide, 0.3 m high and 2 m long). The discharge nozzle, on the lower face of the ACD, has a width of 10 cm, and the return air section is 15 cm wide. A length of 1.9 m was considered for the discharge nozzle to ensure that the jet covers the whole door width.



(a) *(b)*

Figure 1: (a) Geometry of the calculation domain and (b) sketch of the numerical grid (half of the physical domain).

2.2 Numerical method and solution procedure

A 3D numerical model was implemented using the commercial code ANSYS CFX®. The calculation domain has a symmetry plane at half-width, therefore only half of the physical domain was simulated. The methodology consisted basically on the numerical simulation of the transient, three-dimensional turbulent airflow originated by the curtain jet. The calculations are based on the solution of the Reynolds averaged equations for conservation of mass, momentum and energy. The turbulence effects were modelled using the k-ω *SST* model. The advection and transient terms were discretized with the High Resolution and the Second-Order Backward Euler schemes, respectively. The iterative calculation procedure was assumed close enough to convergence when all residuals became lower than 10^{-4}.

2.3 Tests for grid independence

An unstructured grid was adopted for the spatial discretization of the domain, ensuring a better refinement in zones where higher gradients were expected (v. figure 1(b)). Tests were conducted to verify the independence of the results on the numerical grid.

The influence of the temporal discretization was also verified, considering different time steps: 0.2 s, 0.1 s and 0.05 s. Since results with time steps of 0.1 s and 0.05 s were very similar, the former was adopted.

2.4 Boundary and initial conditions

The envelope of the calculation domain was considered as impermeable, air changes being allowed only through the doorway between the two rooms. As initial conditions, the air was assumed stagnant all over the domain, at uniform temperatures of 20 ºC and -5 ºC, respectively, in the inside and outside spaces. All surfaces were considered as adiabatic, smooth and non-slipping. The airflow field inside the air curtain device was not simulated. The downwards jet exit section is considered as an inlet section to the calculation domain, where both temperature and velocity are assigned. On the other hand, the air return frame is the only flow exit (from the domain), where relative pressure is specified. During the calculations, the estimated average value of temperature in the return section is assigned to the downward injected airflow. A 5 % turbulence intensity (TI) was assumed for the jet.

The numerical model was formerly validated with reference to experimental results obtained by the authors in a laboratory scale facility (Gonçalves *et al* (2009[a,b])).

3 Results and Discussion

The sensible energy Q that leaves the inside climate space since the door opening up to a generic instant t is calculated by:

$$Q = \int_0^t \left(\int_V \rho \times c_p \times T \times dV \right) dt \tag{1}$$

where V, ρ and c_p represent the volume of the conditioned compartment, the density and the specific heat at constant pressure of the air, respectively.

The sealing efficiency of the air curtain is defined as the ratio between the reduction of the energy loss obtained with the air curtain operation $(Q_0 - Q)$ and the loss of energy Q_0 with the door open (and the ACD turned off):

$$\eta = 1 - \frac{Q}{Q_0} \tag{2}$$

3.1 Downward blowing air curtain

<u>Air curtain installed in the heated space</u> (typical winter configuration)

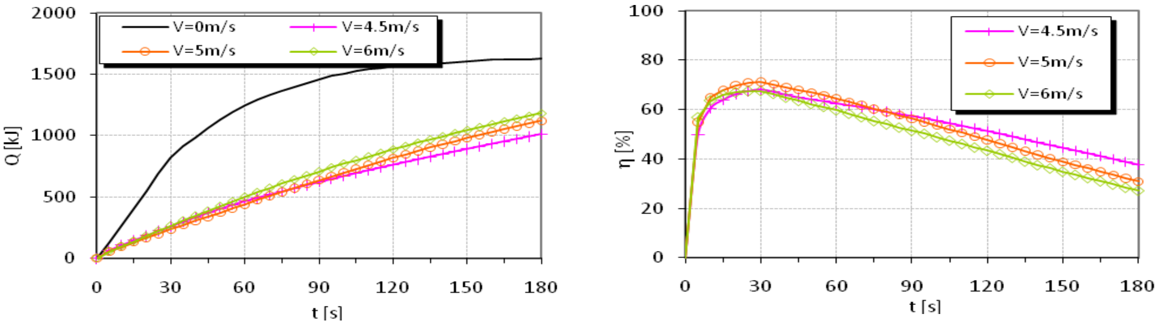
In its most common configuration, the ACD system is installed inside a store (or building), corresponding to a typical winter situation (ACD installed in the heated space).

The sealing ability of an air curtain depends on the balance between the initial momentum of the jet and the forces in the cross-direction that it is intended to neutralize. This sealing ability is represented by the deflection module D_m (Hayes and Stoecker (1969[a,b])). In the case of an air curtain equipment installed over a doorway with height H_p, the sealing effectiveness between two spaces featuring a temperature difference ΔT, depends on the correct selection of the nozzle thickness, b_0, velocity, V_0, and orientation angle, α_0, of the discharged jet.

The optimal value found for the discharge velocity of the vertical jet, V_0, corresponding to the optimal sealing effect, will be taken as a reference for further simulated configurations.

Figure 2(a) shows the time evolution of the thermal energy lost by the conditioned space, since the moment the door is opened ($t = 0$). It is observed that when the air curtain is switched off ($V_0 = 0$ m/s), , the energy flow rate through the doorway is approximately constant (≈28 kJ/s) in the early 30 s after opening the door, and then decreases gradually to ≈7.5 kJ/s until about 120s, reaching ≈ 1kJ/s at $t = 180$ s. In fact, at 120 seconds, the energy transfer takes place mainly by diffusion (see figure 3(a)), and the airflow through the doorway is quite low.

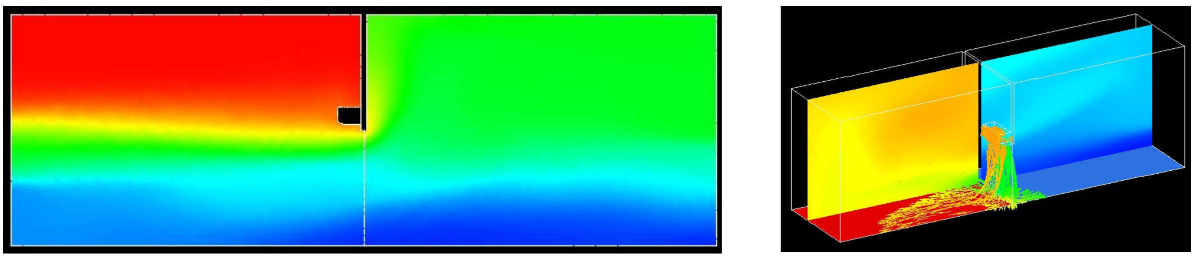
With the door open and the ACD turned on, the heat flow rate across the doorway is almost constant (≈6 kJ/s)



(a) (b)

Figure 2: Time evolution (a) of the energy lost by the inside heated space and (b) of the sealing efficiency, for different discharge jet velocities. Maximum efficiency. 71.3% (V_0=5 m/s), 67.5% (V_0=6 m/s) and 68.1% (V_0=4.5 m/s). [H_p=2 m, ΔT=25 ºC, b_0=10 cm, α_0=0º].

If the discharge jet velocity is enough to reach the floor, the airflow splits to both compartments (Figure 3(b)). In this case, the air intake at the return section of the ACD contributes to the destruction of the thermal stratification near the ceiling, returning the warm air to the occupied zone and rendering more uniform the temperature within the compartment. In much higher spaces, the usage of air ducts connected to the return frame is suggested, in order to capture the air near the ceiling. This represents a double benefit when using an air curtain.



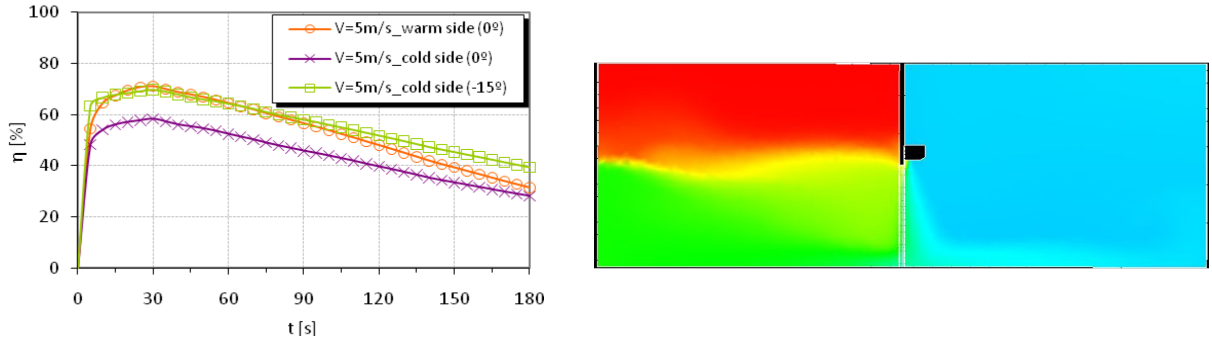
(a) (b)

Figure 3: Temperature fields at t=120s (a) in the vertical plane z = 2.9m with the air curtain turned off (V_0=0 m/s), and (b) in the plane z =1m with V_0=5 m/s, together with an iso-velocity surface. [H_p=2 m, ΔT=25 ºC, b_0=10 cm, α_0=0º].

<u>Air curtain installed in the cooled space</u> (typical summer configuration)

For a typical summer situation, the ACD system is installed in the cooled space, to minimize the intake of outside hot air. To simulate this configuration, the same initial temperature values (*Tin*=-5 ºC and T_{out}=20 ºC) where kept, but the temperature gradient has been inverted. Although this condition does not correspond to thermal comfort temperatures (i.e., inside temperature = -5 ºC), the objective was to compare with the previous situation.

Figure 4 shows the comparative results of the two configurations, corresponding to the installation of the air curtain in the warm and in the cold space. For the same jet discharge velocity, the maximum sealing efficiency obtained with the air curtain installed in the cold space is much lower (58.2% for V_0=5 m/s) than that verified with the air curtain installed in the warm space. However, even with the air curtain installed in the cold side, directing the jet towards the warm space produces a sealing effect (69.6% with α_0 = -15º) equivalent to that obtained with the air curtain installed in the warm space.



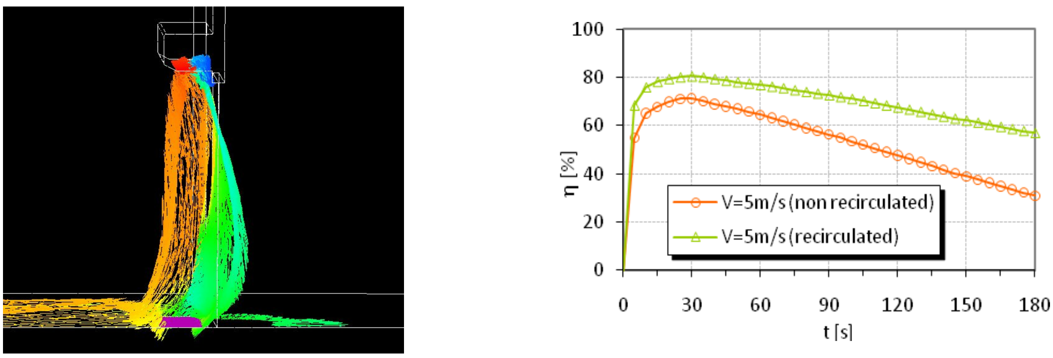
(a) *(b)*

Figure 4: (a) Comparison of sealing efficiency for the two configurations at the same jet discharge velocity, and (b) Temperature field in the plane z = 2.9m with air curtain installed in cold side (V_0=5 m/s, t=120s).

3.2 Re-circulated downward blowing air curtain

In the so-called "re-circulated downward blowing air curtains", there is a return grille at the floor level to collect the air from the jet and, after a filtration process, the air is conducted and re-injected through the discharge nozzle.

To simulate this configuration, an intake grille represented by a rectangular fence (2.1 m long and 0.3 m wide) was placed in the floor and centered on the vertical axis of the discharge nozzle (figure 5(a)). Following the considerations for the previous settings, the average temperature of the air, calculated each time on the intake fence, is assigned to the air injected through the discharge nozzle in the next instant.



(a) (b)

Figure 5: (a) Iso-velocity surface (1 m/s) with V_0=5 m/s and t=60s, and (b) comparison of the transient sealing efficiency for recirculated and non-recirculated air curtain.

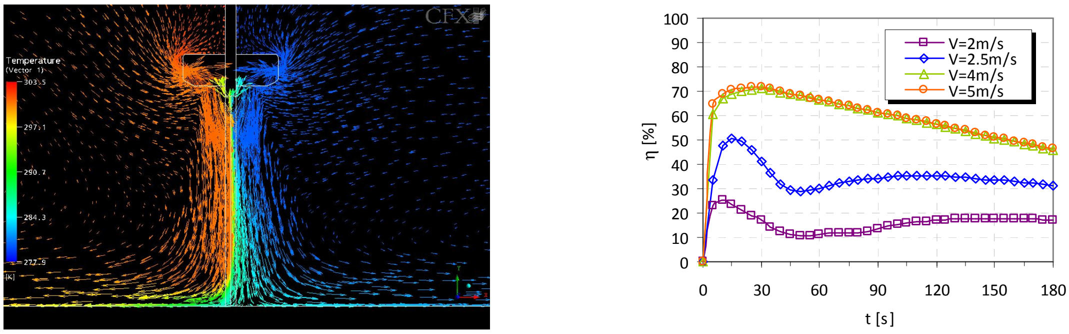
Regarding this configuration, results show an improvement of the maximum sealing effeciency (80.4%), compared with 71.3% for the configuration without air recirculation (v. figure 5(b)). These results agree with those reported by Hendrix *et al* (1989).

Despite the better sealing performance achieved with this configuration, it presents several disadvantages namely: (i) difficulty to set up the best dimensions of the return fence and its positioning at the floor relatively to the nozzle injection plane; (ii) the return fence and grille must be considered beforehand in the design of the building; (iii) higher investment costs of installation, operation and maintenance, (iv) regarding hygiene and health issues, supplying indoors the air collected long the ground may be a source of contamination and should be avoided (Longdill and Wyborn (1979)) .

3.3 Twin curtains

When equipped with air curtains, food retail display cabinets include, typically, two or more air jets at different temperatures: an internal jet at the same temperature as the interior cold environment; a central jet at the temperature of the returned air; and an outside jet at the same temperature as the outside ambient air (Gaspar *et al* (2003)).

In order to simulate a configuration with twin air curtains applied in thermal comfort situations, two similar ACD systems working at the same conditions, placed one at each side over the door, were considered (cf. figure 6(a)). Both discharge nozzle feature a thickness b_0 = 10 mm.



(a) *(b)*

Figure 6: (a) Velocity vectors colored with temperature values for t = 120 s and V_0 = 5 m/s. (b) Sealing efficiency evolution of the twin air curtains.

In this configuration, provided that both jets have enough initial momentum, they reach the floor and are deflected towards the corresponding compartment. This behavior can be confirmed by figure 6(a), where one may notice that the separation point between the jets is located in the door plane.

Moreover, since the velocity is similar in both jets, the energy transfer through the door is expected to be mainly due to exchanges at the jets interface. Accordingly, it is expected that this configuration can present a better efficiency than a single air curtain.

The maximum sealing efficiency was computed as 71.8% and as 71.1% for jet velocities V_0=5 m/s and V_0=4 m/s, respectively.

These results are somewhat surprising when compared with the configuration of just one curtain. We could expect to achieve the same effect with two curtains at about half velocity (≈2.5 m/s). In fact, the initial jet discharge velocity of V_0=2.5 m/s is not enough for the twin jets to reach the floor and seal the doorway.

Additionally, a nozzle thickness of b_0=5 cm for each jet was considered. In this case the maximum sealing efficiency was 70.9% for an initial jet velocity of V_0=5 m/s.

Even considering this last configuration, we conclude that, in terms of the sealing effect, there is no advantage in using twin air curtains. This conclusion is further strengthened if one takes into account that, using two curtains, the acquisition and maintenance equipment costs are duplicated.

4 Conclusions

In the context of a parametric study, different configurations were simulated for an air curtain sealing. Table 1 compiles the main results in terms of maximum sealing efficiency, for α_0=0º as initial orientation of the jet and an initial temperature difference between spaces ΔT=25 ºC. Comparison of the performance of different installation options for the ACD was done taking as reference the most common configuration: non re-circulated downward blowing air curtain, installed in the warm side.

Table 1: *Comparison of the results for the different configurations studied. [ΔT=25 ºC, H_p=2m and α_0=0º].*

Type	ACD Location	b_0 [cm]	$V_{0,opt}$ [m/s]	η_{max}[%]
Vertical non re-circulated	Warm side	10	5	71.3
Vertical non re-circulated	Cold side	10	5	58.7
Vertical re-circulated	Warm side	10	5	80.4
Vertical (twin curtains)	Both sides	5 + 5	5	70.9

Thus, one can conclude that the installation of the air curtain in the cold side leads to a maximum efficiency (η_{max}=58.7%) which is significantly low. However, if the jet is oriented about 15º towards the warmer space, the sealing efficiency reaches a value of 69.6% (close to the reference configuration, vertical air curtain installed in warm side). This is consistent with the general recommendation of Hayes and Stoecker (1969[a,b]), stating that the jet curtain should be always oriented to the warmer side.

The maximum aerodynamic sealing effect was observed for the configuration of down-blowing air curtain with air recirculation (η_{max}=80.4%). However, the return fence and grille have to be predicted during the design of the building and, due to its complexity, this configuration implies higher costs of installation and maintenance.

Concerning the configuration with two equal air curtain equipments installed over the doorway, one in each side and working at the same conditions (twin curtains), a maximum sealing effect of 70.9% was achieved (V_0=5 m/s, in each injection nozzles, with b_0=5 cm). Since this is an overall performance close to the reference configuration with a single air curtain (b_0=10 cm), it does not justify the additional costs associated with such configuration.

In summary, it can be concluded that, in the interval of parameters analyzed, the most appropriate configuration for an air curtain device is the downward blowing air curtain without immediately recirculation of air jet.

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