CFD MODELLING OF INDUSTRIAL AIR CURTAINS WITH HEATING UNIT

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Abstract. Industrial air curtains are used to prevent air from moving from one space to another space or to environment. The most common used type is downward-facing blower fan mounted over the entrance of a building, or an opening door between two spaces conditioned at different temperatures. In many factories and industrial buildings, heating or cooling applications are difficult due to the huge doors. These huge doors cause heat loses with convection phenomena of the inside air. In this study an air curtain having heater unit is analyzed numerically by CFD. The height of the air curtain from the bottom side is vary between 2.5 m, 3 m, 4m, 5m and 6 m mounted over the entrance door of the conditioned volume. For CFD studies proper mesh structure is created on the flow domain and Shear Stress Transport (SST) k-omega models were used in Unsteady Reynolds Averaged Navier-Stokes (URANS) computations. The blowing temperature of the air curtain has adjusted to 60 °C with the inside temperature was aimed to kept at +7°C while the outside temperature was -5°C. It is found that there is less flow occurred to the environment from conditioned volume at 2.5 3, 4 and 5 meter height cases. In these cases, the air curtain also contributes the heating of the conditioned room. But some ratio of the air flows through the atmosphere and the room cannot kept at the +7°C initial temperature at 6 m case. It is also found that the heating ratio at different blowing heights differs between 0,89-1,98 comparing the case without an air curtain.

Keywords: air curtain, heating, SST k-ω, CFD, heating ratio

1 Introduction

An air curtain is a fan-powered device that creates an invisible air barrier over the doorway to separate efficiently two different environments, without limiting the access of the people or vehicles. In industrial premises, such as industrial halls, workshops, warehouses and cold stores, doors are often open for longer periods of time or with frequent intervals to enable the loading and unloading of goods. The – often large – open doors cause a lot of heat loss and disturb the indoor climate. Air curtains that provide unrestricted access for transport purposes and prevent the different climates from intermixing, which leads to healthy working conditions and well-conditioned rooms. It should be mounted horizontally above the door to enable high-level warm air to be re-circulated to working level. Where over-door mounting is not possible, alternative units are available which may be mounted vertically at one or both sides of the door.

Mainly the air curtains use the ambient air without any conditioning. There are also different types of air curtains with cooling or heating units to contribute the conditioning process. During the past decade, air curtains have been used in different fields for various purposes such as in open refrigerated display cabinet in supermarkets and stores [1]. Foster et al. (2006) [2] compared the measured effectiveness of an air curtain device at different jet velocities against a three-dimensional CFD model. The air curtain device was not as wide as the entrance and had a geometry that encouraged 3-D flow. By carefully setting up the air curtain an effectiveness of 0.71 was achieved compared to the initial value of only 0.31 as set by the air curtain device installer. Lopes et al [3] presented a 3D numerical study comparing the sealing efficiency of doorways connecting two rooms, initially at different temperatures, obtained by air curtains with different configurations. The maximum aerodynamic sealing efficiency was observed for the configuration of down-blowing air curtain with air recirculation (η_{max} = 80.4%). On the other hand by horizontal air jet curtains, the maximum sealing efficiency obtained as 61.4% and 55.5%, depending on whether a return air section was considered or not. A numerical study is dedicated by Costa et al. [4] to calculate the influence of the different dynamic and geometrical parameters on the sealing efficiency of a downward blowing air curtain, which is installed between two contiguous rooms with distinct ambient temperatures. The two-dimensional CFD solution of the differential equations for the conservation of mass, momentum and energy was applied, using the k–ϵ turbulence model with two-layer wall functions. It is found that air curtains can provide energy savings up to 75–80%. Ji et al. [5] carried out a theoretical analysis and CFD simulations of smoke control by means of an air curtain in long channels and

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developed formulas providing the critical conditions to prevent smoke from intruding the protected side. Krajewski and Wegrzynski [6] studied the use of air curtains in fire safety as a barrier for heat and smoke by means of bench experiments and CFD. Again, they confirmed the potential use of air curtains as a tool for fire safety in buildings. Their work also shows the possibilities of CFD in designing air curtains. Experimentally and numerically investigation of the aerodynamic behavior and the effectiveness of an air curtain confining cavity and subjected to external lateral flow is studied by Moureh and Yataghene [7]. Experiments were carried out using LDV and PIV techniques. CFD was used with two turbulence models: the standard k–ϵ model and the RSM. Despite the chaotic of air flows, a reasonable agreement was obtained between the CFD model built with the RSM and experimental data. Parametric study of air curtain door aerodynamics performance based on experiments and numerical simulations is carried out by Qi et al. [8]. Optimum conditions, according to the characteristics of an air curtain jet under different pressure differences are investigated. D'Agaro et al. [9] performed 2D and 3D CFD simulations to investigate the effects of the cabinet length of the air curtain and longitudinal ambient air movement on air flow pattern and temperature distribution in a frozen food vertical display cabinet. The computed refrigerating power shows that even low room air velocity of 0.2 m/s, due to its interaction with the end-wall vortices, has a significant impact on cabinet performance up to 30%. Further numerical studies on aerodynamic sealing with air curtains can be referred [10–11], including those developed for industrial [12] or commercial applications [13].

Especially conditioning the buildings with large doors is not encountered in the literature in detail. In many industrial buildings the distance from top to bottom of the door change between 2.5-6 meters where big amount of heat losses occurred. In this study, different heights of the door cases are investigated by CFD method which has high precision and accuracy in the prediction of flow field structure and heat transfer [14-16].

2 Material and Methods

Continuity and momentum equations are used to analyze turbulent flows. In the case of turbulent flow, the time averages of these equations and compressible unsteady Reynolds Averaged Navier-Stokes equations are used for numerical simulations. The continuity and momentum equations for compressible flow are given in Equations 1 and 2, respectively.

$$\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0 \tag{1}$$

$$\frac{\partial\rho U_i}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_i u_j-\tau_{ij}\right)=\frac{\partial P}{\partial x_j}+S_{ij} \tag{2}$$

Where τ_{ij} is the viscous stress tensor:

$$\tau_{ij}=2\mu S_{ij}-\frac{2}{3}\mu\frac{\partial u_k}{\partial x_k}\delta_{ij} \tag{3}$$

$$S_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \tag{4}$$

$$\frac{\partial}{\partial x_i}\left(\rho u_i h-\lambda\frac{\partial T}{\partial x_i}\right)=u_i\frac{\partial p}{\partial x_i}+\tau_{ij}\frac{\partial u_i}{\partial x_i} \tag{5}$$

Here, u_i and u_j show the velocity components along the Cartesian coordinates x_i and x_j, respectively. P is the pressure, ρ is the density and ν is the kinematic viscosity of the fluid.

In addition to the continuity and momentum equations, the energy equation must be used for the solution of heat transfer (Equation 6):

$$\frac{\partial}{\partial t}(\rho E)+\frac{\partial}{\partial x_i}[u_i(\rho E+p)]=\frac{\partial}{\partial x_j}\left[\left(k+\frac{C_p\mu_t}{Pr_t}\right)\frac{\partial T}{\partial x_j}+u_i\left(\tau_{ij}\right)_{eff}\right]+S_h \tag{6}$$

In the energy equation, k is the thermal conductivity coefficient and E represents the total energy. In addition, $(\tau_{ij})_{eff}$ refers to the tensile tensor.

In the analysis, the equations of the turbulence model SST k-ω was used. The transport equations for the SST k-ω as follows:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_i}\left[\Gamma_k\frac{\partial k}{\partial x_j}\right]+G_k+ -Y_k+S_k \tag{7}$$

$$\frac{\partial}{\partial t}(\rho\omega)+\frac{\partial}{\partial x_i}(\rho\omega u_i)=\frac{\partial}{\partial x_i}\left[\Gamma_\omega\frac{\partial\omega}{\partial x_j}\right]+G_\omega+ D_\omega-Y_\omega+S_\omega \tag{8}$$

The terms of turbulence kinetic energy generation G_k is calculated same as in k- ε turbulence model. G_ω is the generation of ω. The terms of Γ_k and Γ_ω are the main difference from k- ε model which are indicated the effective diffusivity of k and ω. Y_k and Y_ω describe the dissipation of k and ω. Derivation of S terms is also defined the user-defined source terms.

The sensible energy, Q, that is gained by the refrigerated room, from the door opening time instant up to a generic instant t, is calculated by the following expression [18].

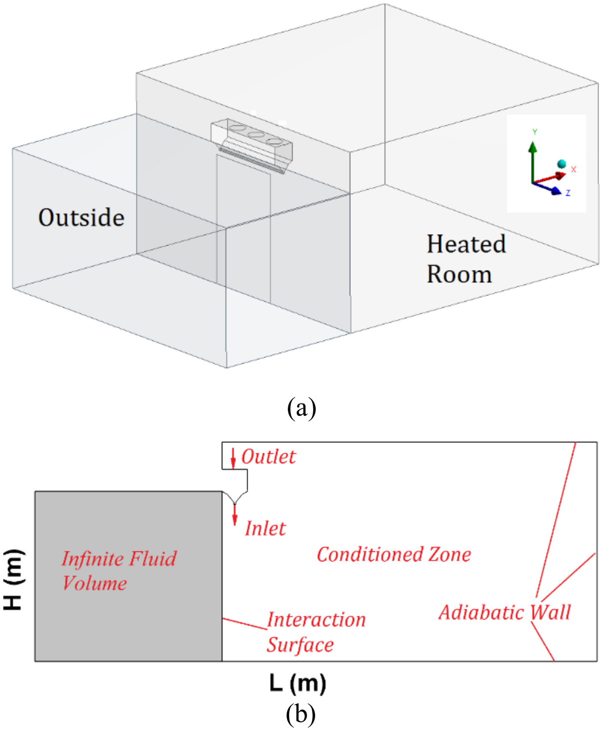
$$Q(t)=\int_v \rho(t)c_p\,[T(t)-T_{ini}]dv \tag{9}$$

where T_{ini} is the room initial temperature, v, ρ and c_p represent the volume of the refrigerated room, the density and specific heat of the air at the constant pressure, respectively.

The heating ratio provided by the air curtain $\eta(t)$ is defined as the ratio between the reduction of the energy obtained with the air curtain operating ($Q_0(t)$-$Q(t)$) and the gain of energy Q_0 with the door open without an air curtain. Because there will be a significant heat loss from inside to outside by convection if there is no air curtain.

$$\eta(t) = 1 - \frac{Q(t)}{Q_0(t)} \qquad (10)$$

The geometry of the physical domain consists of two adjacent volumes. One defined as atmosphere and the other is the conditioned room with dimensions, 6 m ×6 m projection area, connected by a door featuring 1.5 m width and changing height with 2.5, 3, 4, 5, and 6 meters (Fig. 1(a)), with an air curtain installed on the top. Conditioned zone represents the heated space to maintain sealed, and the other corresponds to the outdoor environment.



(a)

(b)

Fig. 1. (a)Geometry of the fluid domain (b) boundary conditions

Table 1. Initial conditions

Variable	Value
Ambient Temperature	-5 °C
Conditioned zone temperature	+7 °C
Blowing temperature of the AC	+60 °C
volume_Flow rate of the air curtain	4500 m^3/h
Heating capacity	18 kW
Blowing fan speed	25.4 m/s
Blowing air curtain heights	2.5-3-4-5-6 meters

The boundary conditions for the models given in Figure 1(b). The input boundary condition is defined as the air curtain blowing section where the output boundary condition is defined as the suction of the air curtain. The outside of the room defined as infinite fluid volume as atmosphere. In addition, an interface surface is defined in which the heat and mass transfer between the indoor and the external environment takes place. The initials conditions of the fluid domain is given in Table 1.

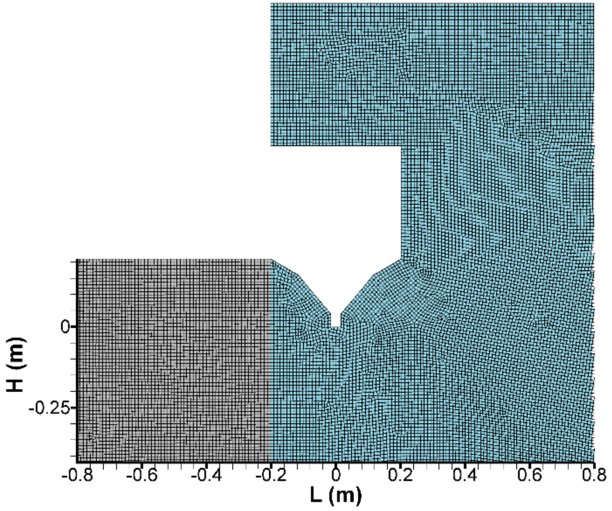


Fig.2. Mesh structure of the numerical study

A detailed view of the grid structure zoomed to the blowing region of the air curtain is given in Figure 2. The cut-cell structured grid was used. The grid independence study was carried out with the heating ratio change according to different grid elements for all cases and given in Table 2.

Table 2. Number of the mesh at different blowing heights

Height (m)	**Element number (x10^5)**
2.5	2.86
3	3.33
4	4.23
5	5.11
6	6.01

3 Results and Discussions

In all CFD analyses, the outside ambient temperature is defined as the atmospheric condition and it is assumed that the temperature does not change. For this reason, the temperature distribution and flow structure were evaluated only for the internal environment.

The unsteady CFD analyses of the air curtain with heating unit have done with SST k-ω turbulence model. The obtained results are given as streamline topology and temperature distribution of the heated zone in 5 different air curtain heights in Figure 2. The temperature in Kelvin unit in scale given between 268 and 314 K. The maximum temperature contour is limited to 314 K (+41^{0}C) to visualize the temperature distribution of the room in detail. As the atmosphere temperature has finite volume, the outside temperature assumed not to be changing and the results just focus the inside distribution. The analyses were carried out with a solution time of 50 seconds with a time step 5x10^{-3}.

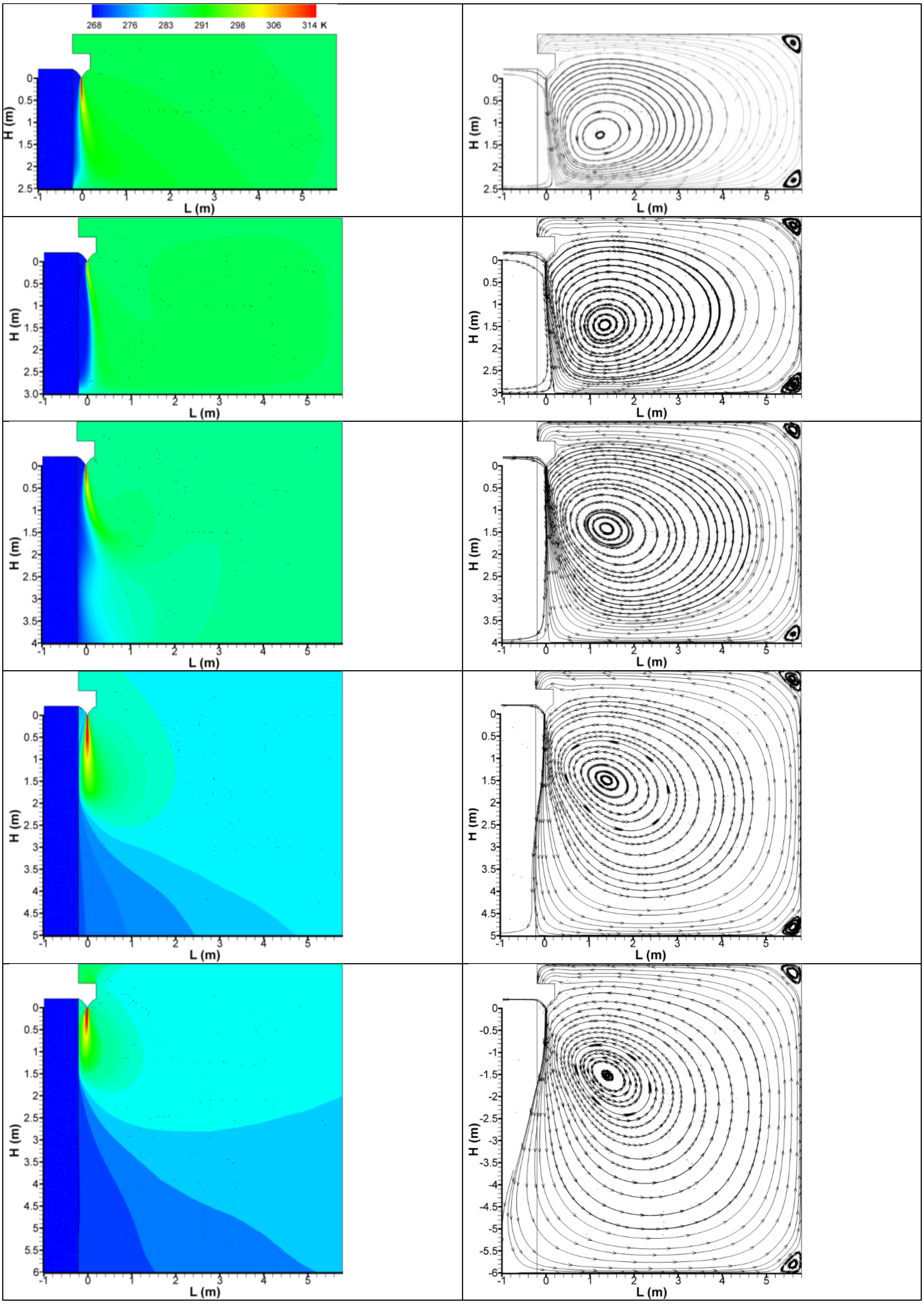


Fig. 3. CFD results of the temperature distribution (left column) and streamline topology (right column) of the air curtain with different heights as 2.5, 3, 4, 5 and 6 m.

The results in Figure 3 are given at the 50. s values where there isn't any significant change after this time period. When the temperature contour results are examined; it is seen that the heated air blown from the 2.5, 3, 4 and 5 m height cases, it contributes to the warming of the indoor environment for a period of 50 s and that the heat transfer between the external environment and the indoor environment is quite low. At the end of 50 s, it is seen that the air blown from the height of 2.5, 3, 4 and 5 m increases the indoor temperature to approximately +18.8^{0}C, 17^{0}C, 13.4^{0}C and 9.2^{0}C, respectively, and this temperature is an indication that the indoor temperature is maintained or even increased. When the air curtain was mounted at 6 m, it kept the indoor temperature to approximately +5.7^{0}C at the end of 50 s, indicating that the temperature at +7^{0}C decreased slightly.

Figure 3 (right column) shows the results of the streamline topology; a large air circulation zone is formed in the interior environment for all blowing heights. In addition, two small foci points were formed in the upper and lower corner of the room. In addition, it is concluded that air circulation in the room is formed in a homogenous manner. As the fan blowing height increases from 2.5 to 6 m, it is seen that the air flow direction from the room to the environment side increases. This is particularly evident in areas close to the base at heights of 4, 5 and 6 m. In the case where the height is 6 m, the blown air is directed mostly to the external environment and this indicates that the fan flow rate is insufficient.

Table 3 represents the heating ratios at different heights at 50. s. As the height increases, the heating ratios decreases as expected. In the air curtain which is evaluated at a height of 2.5 m, the temperature of the indoor environment is increased as well as providing thermal sealing. This situation is also same at the heights of 3, 4 and 5 m. In the case of 6 meter blowing height, the thermal heating ratio is below 1, but it provides the desired values according to the literature and industrial air curtains requirements. The result the heating ratio over 1 means the air curtain is capable to maintain the inside air temperature over +7 °C.

Table 3. The heating ratio variations of the air curtain for different heights

Height (m)	The heating ratio of the air curtain $\eta(t)$
2.5	1.98
3	1.83
4	1.53
5	1.18
6	0.89

4 Conclusions

According to the CFD results, it is found that the heating ratio of the air curtains with blowing heights 2.5, 3, 4 and 5 meters were capable of keep the inside temperature over +7 °C. In addition they also contribute the heating of the region.

At 6 m. blowing height of air curtain although the inside temperature has a decrease about 1.3 °C the air curtain still has enough heating efficiency over 80%.

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