NUMERICAL SIMULATION OF THE PERFORMANCE OF AIR CURTAINS FOR DOORWAY INFILTRATION CONTROL

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ABSTRACT

This paper is concerned with the numerical modelling and investigation of the performance of air curtains employed to reduce air flow and heat transfer across open doors and between conditioned and unconditioned spaces. It has been found that the model based on a commercial Computational Fluid Dynamics software package can successfully predict the critical velocities and efficiencies of air curtains and the influence of external parameters such as wind speed. A number of design parameters relating to the positioning of air curtains to reduce heat transfer across open doors of air conditioned rooms have also been considered.

Keywords: Air curtains, air conditioned spaces, Computational Fluid Dynamics

INTRODUCTION

Air curtains are widely used in commercial and industrial buildings to reduce infiltration loads. They have many advantages over other kinds of doorway infiltration protection devices, such as: not causing any obstruction to vehicles and people, transparent, easy to maintain and low investment. However, many problems exist in the installation of air curtains. One of these problems relates to the fact that the performance of air curtains is very site specific. It is affected by a large number of variables and generalisations are difficult to make. Downing [1] investigated the performance of air curtains installed in ten different cold stores and found their efficiency to vary quite widely, from -43% to +85%. This reveals that many of those air curtains were not properly installed. Contradictions also exist in the findings of many researchers who investigated the performance and design of air curtains. Longdill [2] suggested that air curtains had limited value when the temperature difference between the two spaces or between the conditioned space and the environment was less than 20°C. Lawton [3] on the other hand, found the performance of an air curtain installed on a 2.75 m high by 0.91 m wide high-traffic doorway to be very effective at a temperature difference of 12 °C.

The performance of air curtains is affected by many variables, the most important being: the number of the air jets, the thickness, width, velocity, initial turbulence of the air jet, the height of the door opening, the pressure and temperature difference across the opening, the wind velocity and angle towards the opening etc. To build a sophisticated model for such complicated flow and heat transfer case and solve it analytically is very difficult. For this reason, most of the research on air curtains so far has been carried out experimentally. Although the experimental studies have provided useful information, there are considerable difficulties in generalising the results and using them for the design of air curtains for specific applications.

Computational Fluid Dynamics on the other hand, provide a means by which multi-parameter flow and heat transfer problems can be investigated in detail. Once a CFD model is built and validated using experimental results, it can be used to optimise the design of air curtains for specific applications. Over the last few years, CFD has been successful used in HVAC applications including the study of flows in naturally ventilated and air conditioned rooms. Xiang[4] developed a model to study doorway infiltration in cold stores. The simulation results were successfully compared with experimental results obtained by Gosney on a scale-down model of a cold store[5]. This paper presents the results of a CFD model developed with the view to studying and optimising the performance of air curtains employed to reduce infiltration across open doorways of conditioned spaces.

PHYSICAL MODEL AND SOLUTION PROCEDURE

A simple physical model of an air curtain protected doorway consists of a single story room, a door with an air curtain and the attached environment. It is assumed that the temperature and humidity of the room is maintained constant by an air cooler or air conditioning unit. It is also assumed that the temperature and humidity of the external environment are constant. A schematic diagram of the physical model is shown on Figure 1.

When the door is opened, the flow inside the room, around the doorway and the attached environment will join together. The flow field has to be solved including the attached zone. Two problems arise when dealing with this sort of open-door flow and heat transfer problems. The first one is to decide on the size of the attached zone to be included in the calculation domain. If the attached zoom is too big this will lengthen the time required to reach a converged solution. If the zone is too small it may impair the accuracy of the solution and cause divergence. Wang[6] suggested that an attached zone should have the same height and width as the room to be modelled but the length S should be at least twice the height of the room. CFD calculations have shown that when $S \geq 2H$, the solution is independent of S. In the simulations carried out for this study, the length of the attached zone S was assumed to be twice the height of the room, $S=2H$.

The second problem associated with the modelling of air curtains is how to deal with the boundary conditions of the attached zone (there is no difficulty in dealing with the boundary conditions for the room). It is expected that there will be some warm air entering through the upper imaginary surfaces of the boundary of the attached zone and some cold air exiting from the lower imaginary surfaces of the boundary. Since the velocity distribution along the boundary is not known, velocity inlet and outlet conditions cannot be defined. However, because the air in the attached zone will not be strongly disturbed by the flows across the boundary except in the area very close to the doorway, it can be reasonably assumed that the pressure in the zone will not change greatly. If the boundaries are some distance away from the doorway, the pressure in the attached zone can be considered to be constant and equal to the pressure of the air outside the boundary. Furthermore, the temperature and mass fraction along the boundary are assumed to be the same as those of the air outside the boundary.

The flow around the doorway and inside the cold store is turbulent and therefore the k-ε turbulence model has been adopted in the study. Buoyancy is quite important in this problem and therefore the buoyancy terms have been included in the momentum equations. An irregular grid has been employed with smaller elements near the doorway, especially, near the bottom and top of the opening where velocity changes are high. The FLUENT[8] code was used to solve the equations.

SIMULATION RESULTS AND COMPARISON WITH EXPERIMENTAL DATA

To validate the CFD model, experimental results obtained by Van Male [9] at Delft University, Holland, were used. Male's experiments were conducted for the purpose of investigating a new vertical air curtain design for cold stores. Unlike normal air curtains Male's design introduced the air curtain into a tunnel as shown in Figure 2. The air curtain was enclosed over its full height with its edges on both sides flash with the tunnel side walls. Advantages claimed for this design include: zero air by-pass and reduced impact of the wind on the curtain performance.

In the absence of information regarding the air cooler in the cold store, it was assumed that the fan of the air cooler directed the air towards the doorway with a total circulation rate of 35 cycles per hour. The temperature of the supply air was adjusted to keep the average temperature in the room at -20°C.

Howel l[10] suggested that the initial turbulence intensity has a moderate effect on the rate of heat transfer across an air curtain. His experimental results showed that for an initial jet velocity Uo=3.5m/s and a curtain height to width ratio $H/b_0=23$, the sensible heat transfer across the curtain increased from 3500 Watts to 3800 Watts when the turbulent intensity changed from 3% to 10%. The results presented by Male [9] do not specify the initial turbulence and CFD results with different levels of turbulence showed the influence of the initial turbulence on the heat transfer across the air curtain not to be significant. In the simulation results presented in this paper an initial turbulence level of 10% was assumed.

Figure 3 presents velocity vectors for an air curtain of 15 mm initial jet width and an initial velocity of 6.4 m/s. It can be seen that the air curtain divides the simulation domain into three distinct areas: the inner room area, the doorway influent area, and the attached area. The air jet initially entrains air from both sides of the curtain at the top of the doorway and spills back air on both sides at the bottom of the door. It is interesting to note that the jet entrains only a small quantity of air from the chamber itself and the entrainment occurs at the beginning of the jet. The jet entrains much more air from the attached area with the entrainment occurring at least over 2/3 of the length of the jet. The air then spills back into the attached area towards the bottom of the jet and very near the floor. The velocity inside the room, except near the door area, remains fairly undisturbed by the open door due to the presence of the air curtain. Air from the room entrained by the air curtain is spilled back into the room towards the bottom of the curtain with very little mixing between the room air and the air from the attached area.

Figure 4 shows the velocity vectors for an air curtain with the same geometric characteristics as the one used in Figure 3 but with a lower initial velocity of 6.2 m/s. It can be seen that in this case the air curtain is not very effective close to the floor and air from the cold room escapes through the bottom of the curtain to the attached area. Further simulations showed that the critical velocity for the specific air curtain tested is 6.3 m/s. Velocities above 6.3 m/s would provide effective sealing but at the expense of higher fan power whereas velocities below 6.3 m/s would provide inadequate sealing at floor level.

Comparison Between Calculated and Performance Determined from Experiments

The efficiency of the air curtains is normally defined as [2, 9]:

$$\eta = 1 - V_{AC} / V_{ref} \tag{1}$$

Where V_{AC} is the volume flow rate of air through the air curtain and V_{ref} is a reference volume flow rate calculated from a relationship proposed by Gosney and Olama[8]. In experimental investigations the value of V_{AC} can be determined using tracer gas techniques or laser dopler anemometry (LDA). In simulations using CFD, the value of V_{AC} can not be obtained directly. For this reason, equation (1) has been rewritten in terms of the heat flow through the air curtain as follows:

$$\eta = 1 - V_{AC} / V_{ref} = 1 - (\rho_i V_{AC} \Delta h) / (\rho_i V_{ref} \Delta h) = 1 - Q_{AC} / Q_{ref} \qquad (2)$$

and,

$$Q_{AC} = Q_S + Q_L \qquad (3)$$

Where Δh is the enthalpy difference between the environment and the room. Q_S and Q_L are the sensible and latent heat transfer components through the air curtain.

$$Q_S = c_p m (T_R - T_S) \qquad (4)$$

$$Q_L = m (g_R - g_S) L \qquad (5)$$

Where m is the mass flow rate of the air cooler. T_R and T_S are the temperatures and g_R and g_S are the mass fractions of the return and supply air respectively. L is the latent heat of water vapour.

For steady state conditions and adiabatic walls, the total transfer through the air curtain is equal to cooling load of the air cooler.

Figure 5 presents a comparison between experimental and simulation results displayed as air curtain efficiency against jet initial velocity for two curtain angles of 0^o and 15^o. The results indicate that the performance of the air curtain can be predicted successfully with CFD modelling. For an air curtain (jet) angle of $\alpha = 0°$ the experiments indicated a critical velocity of 6.0 m/s and maximum efficiency of 80%. For the same jet angle CFD modelling indicates a critical velocity of 6.3 m/s and a maximum efficiency of 79%. For a jet angle of α=15° the critical velocity was determined to be 5.6 m/s from experiments and 5.5 m/s from CFD modelling whereas the respective maximum efficiencies were determined to be 82% and 81%.

The small difference between the simulation and experimental results could be due to a number of factors such as the assumption of uniform initial jet velocity in the simulations and the use of higher initial turbulence intensities than perhaps was the case in the experiments.

Influence of Wind Velocity on the Performance of the Air Curtains

Air curtains are often exposed to wind. However, the effect of the wind on their performance has not been studied in detail and there are some contradictions in the published information. Longdill [2] suggested that wind could greatly deteriorate the performance of air curtains whereas Male [9] indicated that the effect of the wind may not be significant. To investigate the effect of wind on air curtain performance simulations were carried out at different air curtain jet velocities with no wind and a wind velocity of 4 m/s for a normal air curtain and a curtain positioned in a tunnel. The results are presented in Figure 6. For the case where the wind velocity was equal to zero there was not much difference between the two types of air curtain. In the presence of wind blowing at right angles towards the air curtain the deterioration in performance was greater for the normal curtain than the curtain positioned in a tunnel. The difference in efficiency between the two air curtains was in the region of 5% over a range of curtain jet velocities between 7 m/s and 10 m/s.

Application of air curtains to air conditioned Spaces

Once the developed CFD model was validated, it was used to investigate the effectiveness of air curtains in reducing infiltration into air conditioned spaces. For this purpose, an air conditioned room of dimensions $5000(L)\times 2500(H)\times 2500$ mm with a doorway protected by an air curtain was investigated. The door dimensions were taken as 1650mm height and 500mm width. The following conditions were used in the simulations:

In winter $T_r = 20^{0}C$ $\varphi_r = 60\%$ $T_e = 0^{0}C$ $\varphi_e = 90\%$

In summer $T_r = 20^{0}C$ $\varphi_r = 60\%$ $T_e = 35^{0}C$ $\varphi_e = 50\%$

The width b_0 of the air curtain was taken as 40mm giving a height to width ratio of approximately 41. The initial air curtain jet velocity was assumed to be 6 m/s.

There are two possibilities in the installation of air curtains to protect conditioned rooms. i) The air curtain can be installed inside the room or, ii) outside the room. If the air curtain is installed inside the room, the initial air will come from the room. The temperature and humidity of the curtain will be equal to those of the room air. If the curtain is installed outside the room, the initial temperature and humidity of the curtain air will be equal to those of the ambient air close to the curtain.

The simulations show that in winter, the air curtain efficiencies would be in the region of 50% with the air curtain installed inside the room giving a slightly better efficiency. Looking at Figures 7 and 8 that show the temperature distribution in the room for the two cases it can be seen that when the air curtain is installed inside the room and draws air from the room, the temperature distribution is much more uniform with only a 3 °C temperature difference between floor and ceiling height. This happens because the curtain draws warm air from close to the ceiling and pushes the air towards the floor creating good air circulation and mixing. When the curtain is installed outside the room severe stratification takes place in the room with a maximum temperature difference of 12°C between floor and ceiling height. When air curtains are to be used to protect heated spaces it will therefore be advisable to install them inside the room.

Figures 9 and 10 show the temperature distributions in the space when the curtain is used to protect an air conditioned space. In this case it can be seen that when the curtain is installed outside the room and draws air from the ambient, the temperature distribution inside the room is fairly uniform. When the curtain is arranged to draw air from inside the room, it destroys the coanda effect, creating a zone of low air velocity in the room. For air conditioning applications it is therefore advisable o install the curtain outside the room.

In cases where a space will be heated in the winter and cooled in the summer the best solution might be for the curtain to be installed inside a tunnel and air passage ways arranged in such a way that the curtain draws air from the room in winter and from outside in the summer.

CONCLUSIONS

This paper presents results of investigations into the performance of air curtains when used to protect refrigerated and air conditioned rooms. The results which have been obtained from simulations using a validated CFD model indicate that:

1. For each air curtain design a critical jet velocity exists at which the curtain provides maximum protection and attains maximum efficiency.
2. The initial angle of the air jet influences the performance of the curtain and a jet arranged at a small angle pointing towards the attached zone causes a reduction in the critical velocity when the curtain is used to protect refrigerated and air conditioned spaces. This aspect of air curtain performance requires further investigation.
3. In the presence of wind, air curtains installed in tunnels have higher efficiencies than normal air curtains. When the wind velocity is equal to zero there is no difference in the performance of the two types of air curtain.
4. For best performance when an air curtain is to be used to protect a heated space it should be installed inside the room and draw air from the room. If the curtain is to be used to protect a refrigerated or air conditioned space it should be installed outside the room and draw air from the ambient. When the air curtain is to be used for both summer and winter protection arrangements should be made so that the curtain can draw air from the appropriate areas in each case.

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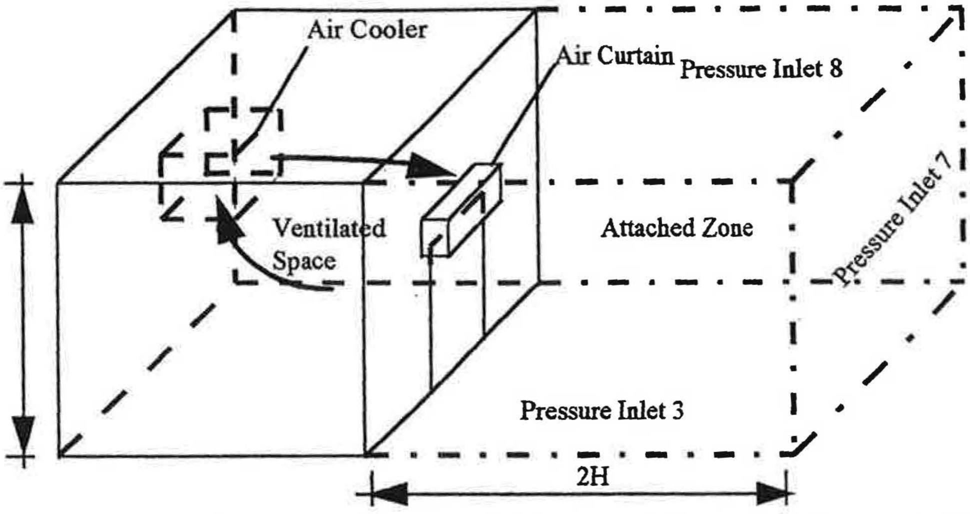

Figure 1. Physical Model of Air Curtain Protected Ventilated Space

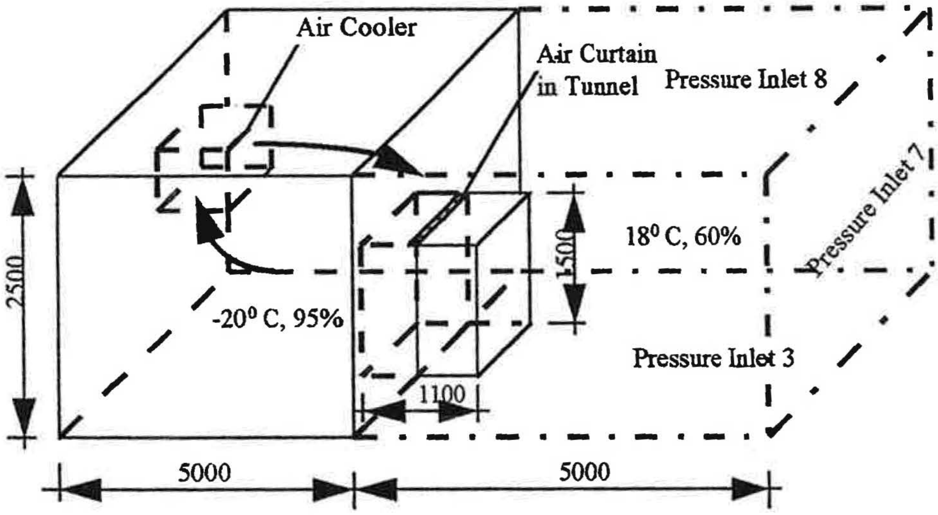

Figure 2. Experiment Set-up for Air Curtain Protected in Tunnel

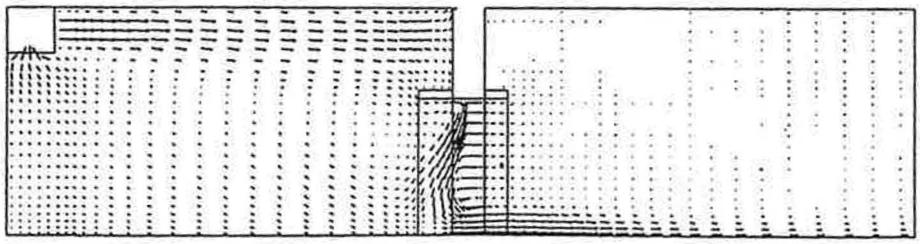

Figure 3. Velocity distribution in the cold store protected by an air curtain of initial velocity of 6.4m/s

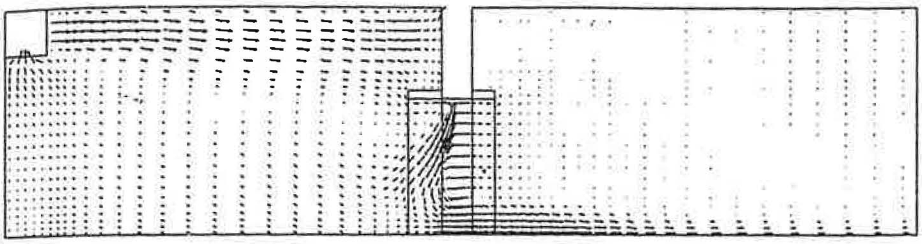

Figure 4. Velocity distribution in the cold store protected by an air curtain of initial velocity of 6.2m/s

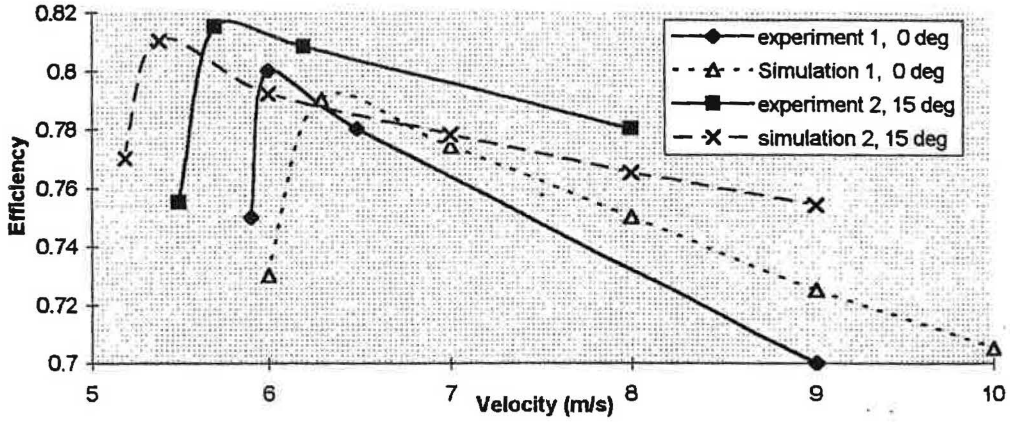

Figure 5. Air curtain performance vs. velocity and angle

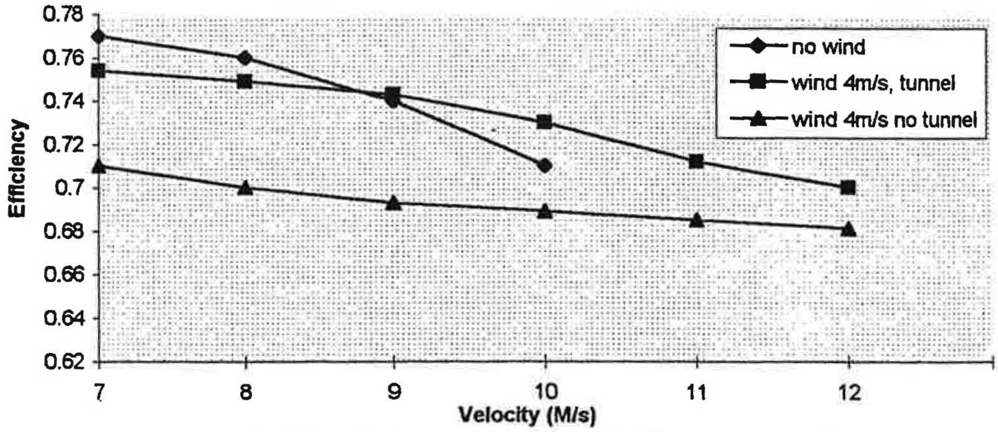

Figure 6. Air curtain performance at different situations

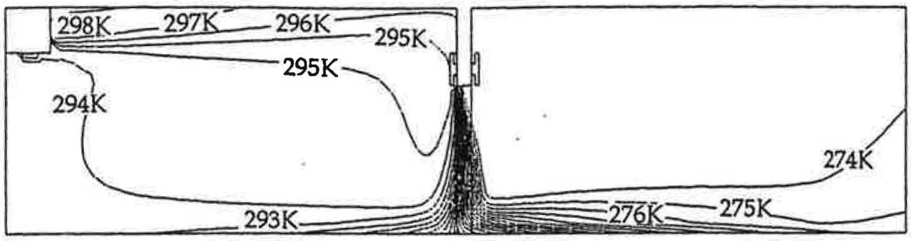

Figure 7. Temperature distribution of the heating room when the air curtain is installed inside the door

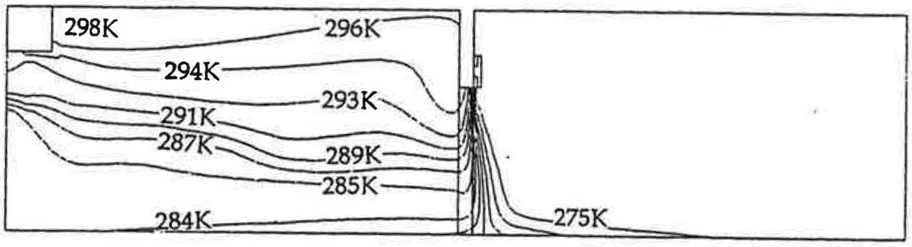

Figure 8. Temperature distribution of the heating room when the air curtain is installed outside the door

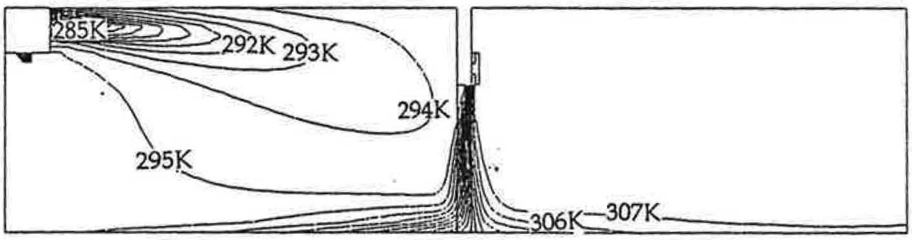

Figure 9. Temperature distribution of the air conditioning room when the air curtain is installed outside the door

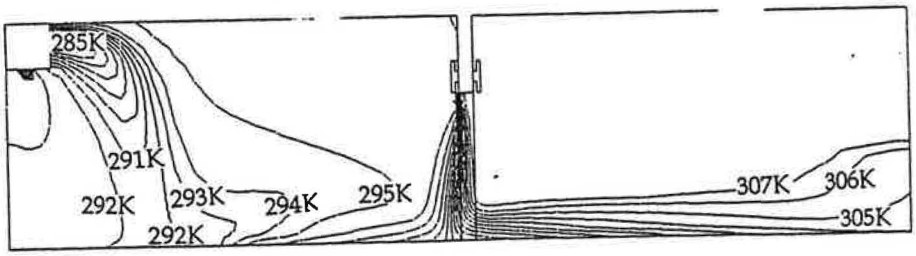

Figure 10. Temperature distribution of the air conditioning room when the air curtain is installed inside the door