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EFFECTS OF AIR CURTAIN TO THE HEAT AND MASS TRANSFER IN A TYPICAL URBAN TRANSPORT VEHICLE

H J Poh, C P Tso and S C M Yu

School of Mechanical and Production Engineering
Nanyang Technological University
Singapore

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Poh, H.J., Tso, C.P. and Yu, S.C.M.
School of Mechanical and Production Engineering,
Nanyang Technological University, Singapore.

Synopsis

A computational study had been carried out on hot and cold air interaction across the door of an urban transport vehicle. The studies show that within 20 s after the door is opened all the cool air beside the door of the vehicle would flow out when the ambience is 30^0C. The mixing flow across the door would cause maximum mass exchange of 0.55 kg/s during the transient phase. An additional cooling load of 0.4 kW is required to cool down the hot air after the door is closed. The constant flow rate and temperature air curtain is effective in preventing hot air from going into the bus. Various factors that affect air curtain effectiveness such as air curtain velocity, delay door opening time and the fan characteristic curve for the air curtain are investigated. It is found that for an ambient 30^0C, air curtain of 6 ms^{-1} with door delaying time 5 s would give the best sealing effect in order to maintain the controlled environment within 24^0C.

1.0 Introduction

The flow of cold air out from an air-conditioned bus when the door of the bus is opened is a major problem on energy loss to the air-conditioning system in the interurban air-conditioned bus. Furthermore, the air exchange through opening door will also bring in pollutants dirt from the outside and also increase temperature and humidity inside the bus. The installation of air curtain beside the door is an important tool to reduce the cooling load and also to maintain a comfortable level of temperature in the bus[1].

This present numerical study uses Body-Fitted Co-ordinates to set up the geometry and apply the computational fluid dynamics package, FLUENT[2] to solve difference equations that are derived from the conservation of the mass, momentum and energy of a fluid in motion[3,4]. In this 2-D simulation, the domain involving the area beside the door of the bus and outside environment is as shown Figure 1.

The objective of this study is to investigate the transient effect of hot and cold air interaction when the door of the bus is opened. After that, the effectiveness of an air curtain in preventing hot and cold air interaction is simulated. Various factors that can improve the performance of the air curtain is also investigated. Finally the mass exchange through the door and the additional heat load to the cooling coil of the bus are estimated.

2.0 Computer Simulation Procedures

2.1 Geometry Set-up and Grid Generation

The domain is mapped with a structured rectangular grid and the area of outside environment is much larger than the inside domain of the bus as shown in Figure 2. The front view of the bus is taken at the section beside the door. The dimension of the bus is 2.2 m high x 2.4 m width x 1m depth (considered as the width of the door).

Besides that, a staircase step of dimension 0.3 m x 0.3 m is also included in the area of the bus. The domain of numerical calculation will cover up to 10 m to the right, left and top side of the bus, which will represent outside hot environment.

The domain inside the bus is given finer grid than the outside environment, being mapped with square cells 0.05 m x 0.05 m. The density of grid is reduced gradually to the left, right and top side from the domain of interest up to the extreme end of outside environment as shown in Figure 3.

2.2 Physical System and Boundary Conditions

The k-ε turbulence model is applied in this model with gravitational force activated because buoyancy plays an important role in the simulation. For the boundary conditions, the two air-conditioned jets blowing 20^0C cool air at an angle of 45^0 into the area of the bus are specified at 1 ms^{-1} while the air curtain is specified with constant temperature 20^0C, blowing cool air vertically downwards at the hot-cold air interface at various velocities. As for the boundary conditions of extreme end of outside environment and wall of the bus, they are specified as adiabatic boundary wall. The outlet is located at the centre top of the bus, and can be considered as return air for the air-conditioning system.

3.0 Results and Discussions

3.1 Without air curtain

When the door is opened, hot air from outside would flow in at the top, and cold air inside the bus will flow out from the bottom, as shown in Figure 4. This is a transient effect and the air exchange through the door is increased until it reaches a maximum at 7s.

The transient effect would cause the temperature inside the bus to increase exponentially until it reaches a maximum throughout the area beside the door of the bus at 20s. This is shown in Figure 5. As can be seen, the temperature at the high position is increasing faster than those at the low position, showing that hot air from the outside is coming into bus at the high position.

At that moment, the air-con jet near the door is not effective in cooling the bus area. Figure 6 shows that the area beside the door is filled with hot ambient air (30^0C), after the door is opened for 15s.The pressure difference across the door when it is opened is shown in Figure 7.

The air exchange follows the transient trend, and reduces the pressure difference to zero at the steady state, about 20 to 30s later. During the transient state, the pressure inside is higher than outside and this causes the airflow at the bottom greater than at the top. The situation lasting for about 20 s. Figure 8 shows the components of air exchange when door is opened.

When the door is opened, the air inside is getting hotter until it reaches the outside ambient temperature. This hot air is brought back to the bus evaporator through the return air duct. Assuming that the jet temperature is kept at 20^0C all the time, this will give an additional heat load to the cooling coil ($Q = m \times c_p \times \Delta T$). The mass flow rate m is equal to the mass flow rate from the jet, which is also equal to the mass flow rate through the outlet. The specific heat capacity C_p is constant at 1004 J/kg.K. and ΔT represents the temperature difference (T_{outlet} - 20^0C). Figure 9 shows the extra energy added to the cooling coil attributed to hot and cold air exchange.

After the door of the bus is opened for 60 s, it is closed back. At that moment, the inside area of the bus is at 30^0C. The temperature beside the door of the bus is investigated in order to find out how much time is needed to cool the bus area back to initial temperature. Figure 10 shows 240 s is required for the jet to cool down the bus back to initial temperature of 20^0C.

3.2 With air curtain

The performance of air curtain depends on many variables, including number of jets, thickness of air door, width of the doorway, height of the doorway, jet velocity, initial jet turbulence intensity and the pressure and temperature difference across the jet[5].

In this simulation, the jet velocity is taken into account in order to find out the optimum speed to seal the hot air from flowing into the bus. From the plot of the velocity vector in Figure 11, the flow of air curtain 2 ms^{-1} is not symmetrical at the hot-cold air interface. The pressure created by the difference in air density causes the curtain to break contact at the bottom part. In this case, the air curtain can only prevent the hot air flowing into the bus at the top. Some of the cool air which is flowing out from the bottom will be replaced by hot air and cause the temperature to increase. However, if the velocity of the air curtain were high, the rate of heat transfer through air curtain streamline would be increased. This can be shown in Figure 12, in which air curtain of 8 ms^{-1} will cause the average temperature to rise faster than 6ms^{-1}. Therefore, an optimum velocity of the air curtain, between 2 to 8 ms^{-1} need to be developed for the minimisation of air flow while still keeping the warm out.

Basically, 3 positions along the centre points (LOW[0.3m], MEDIUM[1m], and HIGH[1.8m]) are taken for temperature comparison for speeds 2 , 4 , 6 , and 8 ms^{-1}. Generally, the most suitable temperature for occupant comfort is 24^0C. Therefore, the air curtain can be considered as effective if it can keep the average temperature inside the bus less than 24^0C. Figures 13 shows the variation of the average temperature with different air curtain speed. From this figure, it is found that air curtain 6 ms^{-1} is capable of sealing the controlled environment within 24^0C for ambience 30^0C. Besides that, it can generally maintain a lower temperature as compared to 2,6 and 8 ms^{-1}. So, it can be concluded that an air curtain of 6 ms^{-1} is able to keep the warm air out. Again, the temperature contour in Figure 14 shows that 6 ms^{-1} can maintain temperature in bus cabin below 24^0C, even when the door had been opened for 60s.

As can be seen from the velocity vector in figure 15, there will be a full circulation of air from the air curtain source to the return air after the door is opened for 10s. Before 10s, there is a transient state. There is two small air circulation air at both sides of the curtain streamline, and hot air from outside will be entrained into the bus at the bottom. However, after 10s, the mass exchange through the door will be approaching steady-state and the rate of mass exchange is zero. As compared to the case without air curtain in Figure 16, the significant result of air curtain is that to reduce the transient state time, besides reducing the average temperature at 3 positions by 7^0C, as shown in Figure 17.

The additional heat load to the cooling coil can be calculated by $Q = M \times c_p \times \Delta T$. Although the temperature difference ΔT of (T_{outlet} - 20^0C) is reduced by 3^0C, the total mass flow rate through the return air M is increased by 0.5 kg/s (from 0.06 kg/s to 0.56 kg/s). This is because the air curtain is drawing cool air from the return air. Therefore, the airflow through cooling coil is increased. The product of $m \times c_p \times \Delta T$ for the case with air curtain 6ms^{-1} shows that an additional energy of 1.3 kW is incurred when compared to the case without air curtain, as shown in Figure 18. Therefore, for ambient 30^0C there will be an extra energy wasted if we need to maintain the temperature inside the bus less than 24^0C by using air curtain with constant flow rate and temperature.

Delaying door opening time before the air curtain start operating will provide a chance for air curtain to fully develop its streamline and enhance the sealing effect. Figure 19 shows the velocity vector by delaying door opening for 5 s. From this figure, we can observe that the longer the delay time, the more established the velocity vector in order to form a full circulation from the air curtain source to the return air. This will form a strong blocking air stream in order to prevent the hot air penetrating into the bus. Moreover, the pressure inside the bus will be uniformly distributed and this will reduce the air exchange through the door when it is opened.

Figure 20 shows a comparison of average temperature of 3 positions of air curtain 6 ms^{-1} with and without door delaying time. Basically, it can reduce the temperature inside the bus by at least 1^0C within 20 s. After that, heat transfer through the air curtain will cause the temperature to increase gradually. Nevertheless, delaying door opening time after air curtain operate is still an important factor in order to prevent hot and cold air mixing.

4.0 Conclusions

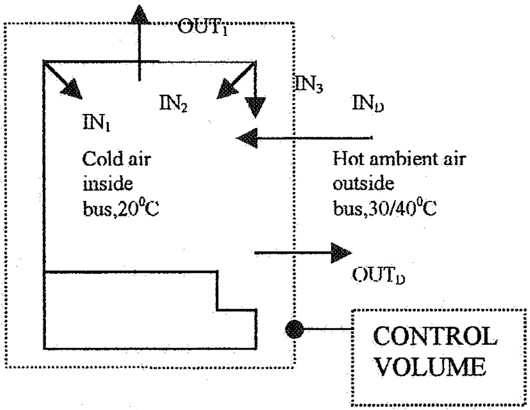
Simulation shows that without air curtain, the air exchange through opening door is tremendous and all the cool air will be replaced by hot air after 20 s. The process of air exchange is a transient state and it follows the quadratic trend from 0 to 20 s, with the maximum point occur at 10 s. By installing the "constant temperature (20^0C) air curtain", it is effective in preventing hot air going into the bus when the door is opened. However, using the 20^0C air curtain will increase the heat load to the cooling coil.

5.0 Acknowledgement

The authors gratefully acknowledge assistance given by Carrier Transicold Singapore Pte Ltd for the present studies.

6.0 References

1. CUFFE, K.W., "Air Conditioning and Heating System for Trucks," McGraw-Hill, New York, 1978.
2. FLUENT, User's Manual, Ver. 4.11, 4.2, Fluent Inc, 1993.
3. HUANG, C., "Three- Dimensional Analysis of Partially Open Butterfly Valve Flows," Journal of Fluids Engineering, ASME Transactions, Vol. 118, 1996, pp. 562-568.
4. PATANKAR, S.V., "Numerical Heat Transfer and Fluid Flow," McGraw-Hill, New York, 1980.
5. HAYES, F.C., and STOECKER, W.F., "Heat Transfer Characteristics of the Air Curtain," ASHRAE Transactions, No 2120, 1969, pp.153-165.



IN$_1$: Air flow into the bus from air-con. Jet 20^{0}C blowing 45^0 into the bus.
IN$_2$:Air flow into the bus from air-con jet 20^{0}C blowing 45^0 into the bus.
IN$_3$: Air flow at the hot-cold air interface from air curtain, 20^{0}C into the bus.
OUT$_1$: Air flow out from the bus through the outlet, considered as return air.
IN$_D$: Air flow into the bus from ambient (30/40^{0}C) through opening door.
OUT$_D$: Air flow out from the bus through opened door

Figure 1: Air flow when the door is opened with air curtain

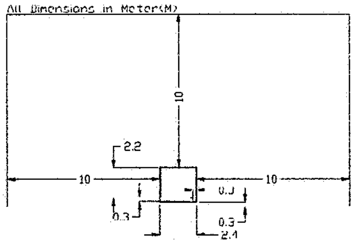


Figure 2: Dimension in 2d geometry set-up

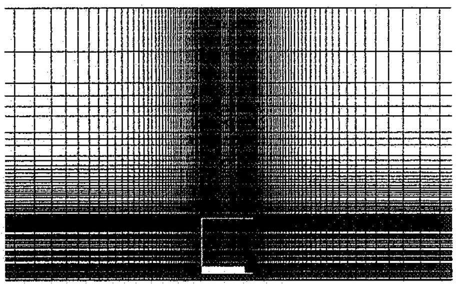


Figure 3 : Grid generation

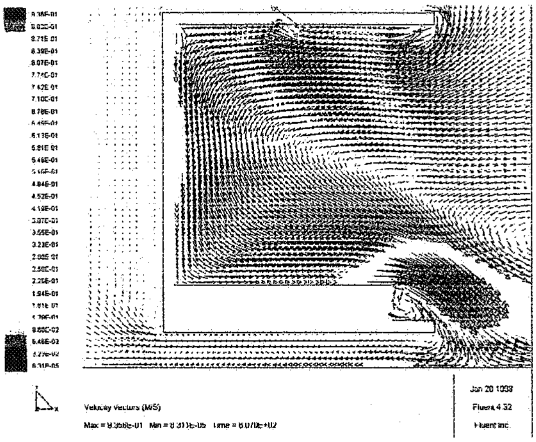


Figure 4: Air flow across the door after 7s opening, without air curtain

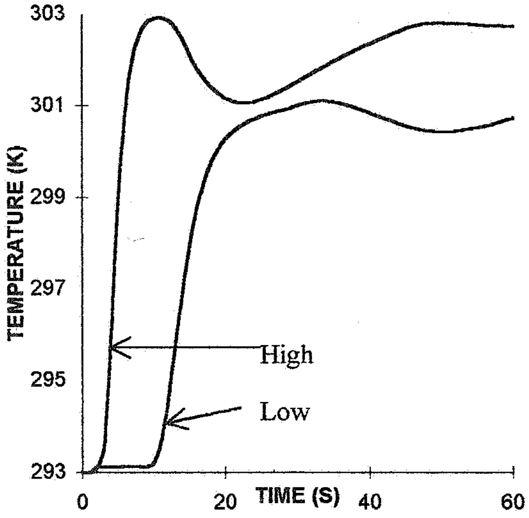


Figure 5:Temperature beside door of bus when door is opened without air curtain

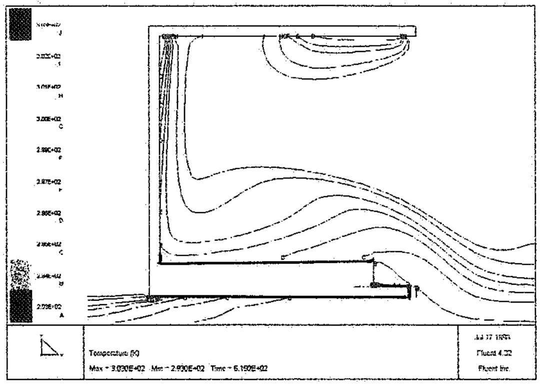


Figure 6: Temperature distribution for ambient 30^{0}C, without air curtain, door opening time 15s

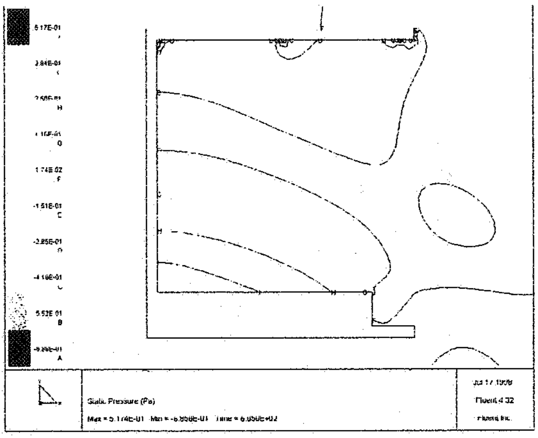


Figure 7: Pressure distribution for ambient 30⁰C, without air curtain, door opening time 5s

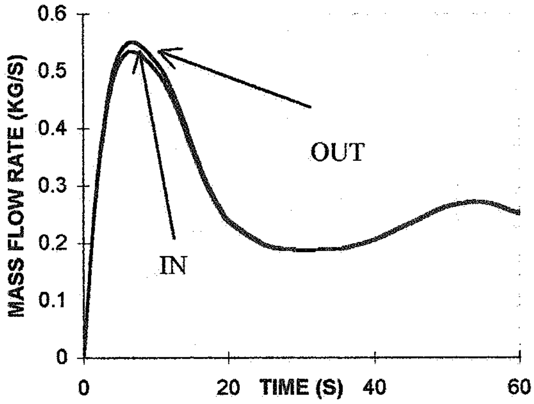


Figure 8: Variation of mass exchange through door for ambient 30^{0}C, without air curtain

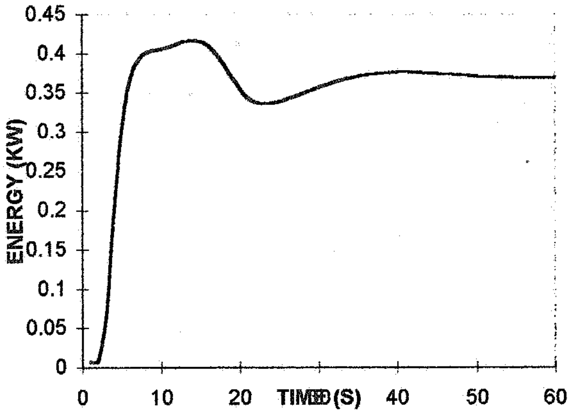


Figure 9: Additional heat load to cooling coil without air curtain

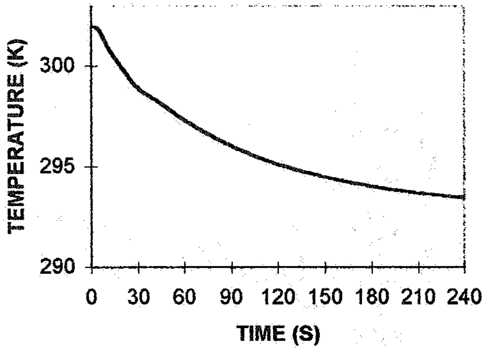


Figure 10: Temperature beside door of bus when door is closed back, without air curtain

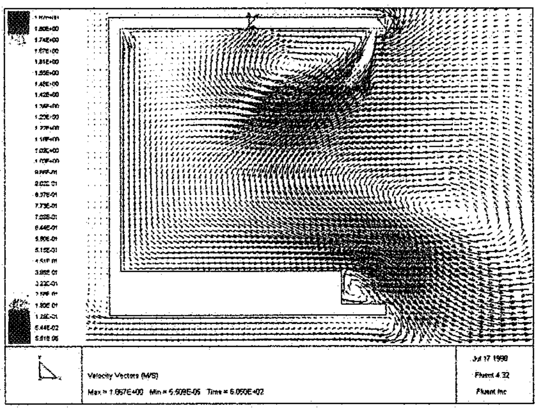


Figure 11: Velocity vector of air curtain 2 ms^{-1}, ambient 30^{0}C, 5s after door is opened

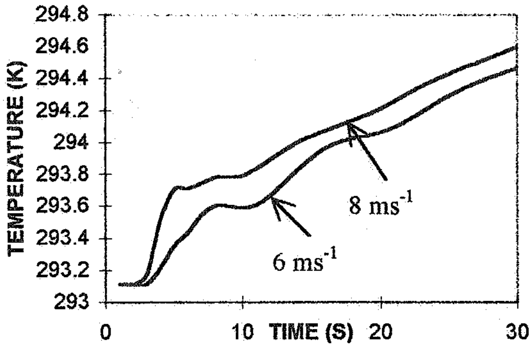


Figure 12: Average temperature beside door of bus with air curtain 6 & 8 ms^{-1}for the first 30s

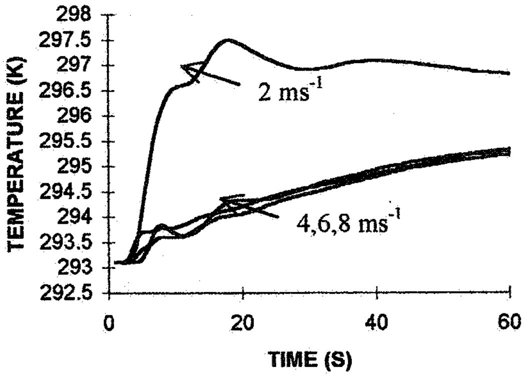


Figure 13: Average temperature for different air curtain velocity, ambient 30^{0}C

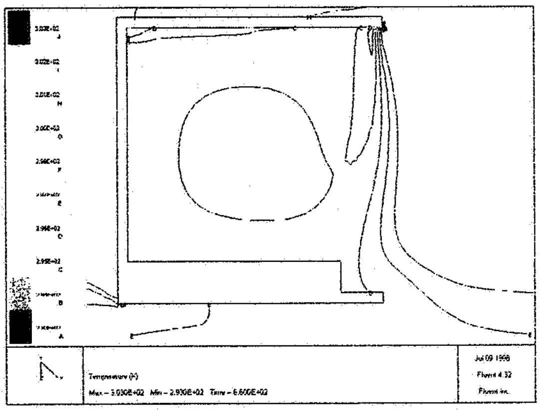


Figure 14: Temperature contour of air curtain 6 ms^{-1} for ambient 30^{0}C, 60s after door is opened

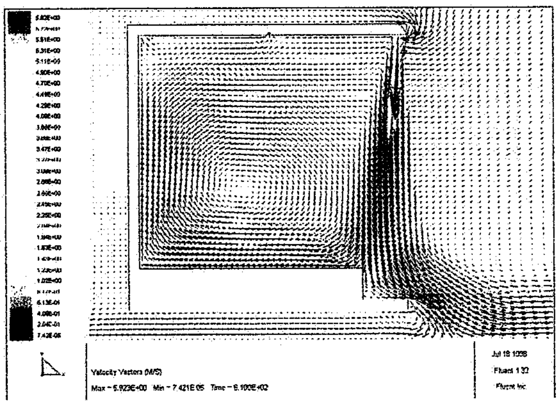


Figure 15: Velocity vector of air curtain 6 ms^{-1}, ambient 30^{0}C, 10 s after door is opened

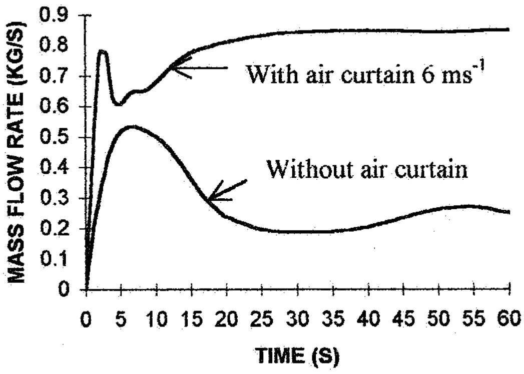


Figure 16: Mass exchange with and without air curtain

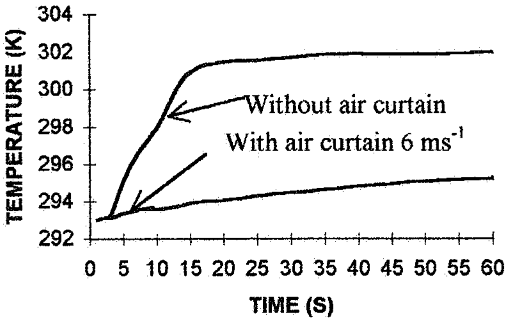


Figure 17: Temperature variation with and without air curtain

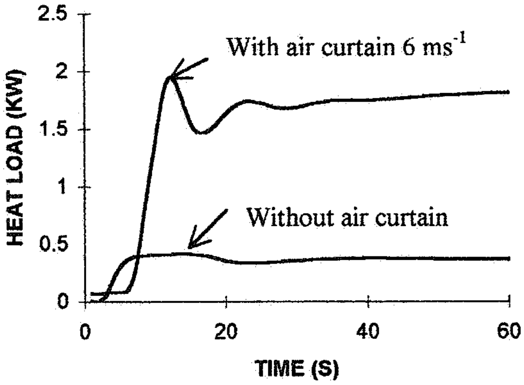


Figure 18: Additional energy for cooling coil with and without air curtain

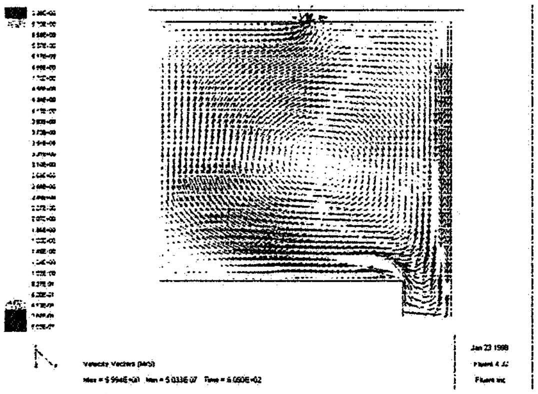


Figure 19: Velocity vector of air curtain by delaying door opening time for 5s

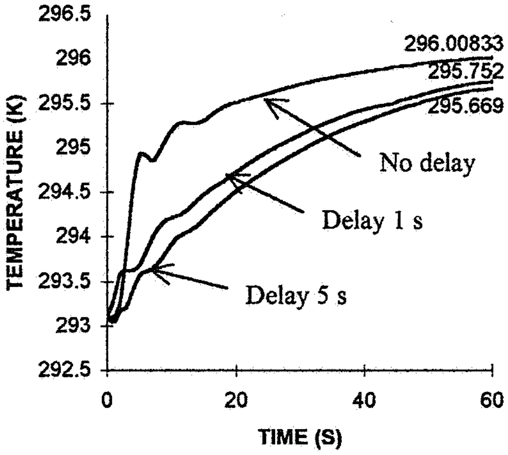


Figure 20: Average temperature of 3 positions of air curtain 6 ms^{-1}, with and without door delaying time