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# Three-dimensional investigation on the positioning of air curtain on its effectiveness in refrigerated vehicles used for food distribution

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**Abstract**

Two different positioning of an air curtain have been investigated for this study, inside the trailer and just outside the trailer's door. The distance of the position was based on the results assessed during several pre-trial runs. The study identified that the energy performance of an air curtain placed outside is better than the energy performance of an air curtain placed inside by almost 8%. However, the energy performance of an air curtain is highly dependent on the discharge velocity. The energy savings are based on the optimal discharge velocity range. However, at lowest and highest discharge velocity, 1 m/s and 5 m/s in this case, the energy performance of an air curtain positioned outside is almost similar and even less than the air curtain positioned inside, making the inside positioning of the device to be more effective. One of the disadvantages of placing an air curtain outside would be allowing space for air leakage to take place. The sealing efficiency, however, is much better for the air curtain positioned inside the chamber.



*Keywords:* infiltration; refrigerated vehicles; protective mechanism; air curtain; aircurtain position;

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## 1. Introduction

Door openings in temperature-controlled vehicles during multi-drop distribution can result in significant heat gain requiring more energy to recover the temperature gain. Heat load due to infiltration can be in the same order magnitude as the heat load due to conduction, and even higher at times depending on the regularity and duration of door openings (1). Numerical study by Foster et.al.(2) estimated air infiltration to be half of the total refrigeration load in cold stores. Numerical and experimental study conducted by Micheaux et.al.(1) on refrigerated vehicle with internal volume of 32.4 $m^3$ estimated the sensible heat flow rate to reach a peak of 250 kW in just first 10 s of opening the door for external temperature of 40°C and internal temperature of -20°C. The heat flow however stabilises to 50 kW after 20 s. Tso et.al.(3) experimentally estimated the total heat exchange rate through a 0.9 $m^2$ doorway of a refrigerated truck body to be 3.27 kW for door opening time of 2 minutes.

The PVC strip curtains and air curtains have previously been proposed as effective protective mechanisms in controlling the rate of warm-air infiltration. PVC strip curtains are generally considered to be unsafe, inefficient, unhygienic, and obstructive during loading and unloading process requiring regular maintenance (4). In contrast, air curtains are appropriate to configuration where solid barriers become unsuitable for practical, technical or safety reasons (5). Study by Foster et.al. (4) estimated the effectiveness of an air curtain to be 0.71, where effectiveness 1 represents total elimination of warm-air infiltration. In follow-up study by the author, the effectiveness of air curtain can be further improved to 0.77 through careful setting i.e. adjusting the jet velocity and angle (4). However, it has been reported that air curtain are often not installed at their optimum.

Although adjusting the angle and discharge velocity does improve the efficiency of air curtain, the location of air curtain is also an important factor that can influence its effectiveness. CFD modelling study conducted by Jaramillo et.al. (5) on a space with cold room (210 $m^3$) and warm room (27 $m^3$) with open door (2 $m^2$) in between showed that placing an air curtain (warm-suction) on warm side increased the efficiency of the air curtain performance rather than placing it exactly in the center or cold side. When the air curtain is located in the cold side, it prevents warm air from entering the top part, but the warm air still crosses the jet and causes an increase in temperature in the bottom part.

However, when the air curtain is placed in the warm side, though it still brings warm air to the bottom part of cold room, it still remains cooler in comparison to the temperature when air curtain is placed in cold side. The author also suggested placing the air curtain outside a better option for long door opening period.

Majority of the studies in relation to improvement in air curtain effectiveness were mainly conducted on cold rooms and larger warehouses. There still lacks adequate studies on use of air curtain in refrigerated vehicles. Due to the nature of distribution, door openings are unavoidable during distribution drops allowing significant amount of warm air to enter the space. Though an air curtain can provide an effective solution, the performance can be further improved through several adjustments. This aim of this study is to measure the energy efficiency of a commercial air curtain when placed at different locations, on the cold side (inside the refrigerated chamber) and on the warm side (outside the refrigerated chamber). The energy efficiency is measured in form of recovery energy i.e. the energy required to pulldown the temperature back to its set temperature.

**Nomenclature**

| | |
|---|---|
| $Cp_{air}$ | Specific heat capacity of air [J/kg-K] |
| $Cp_{prod}$ | Specific heat capacity of food products [J/ kg·K] |
| $E_r$ | Recovery energy [MJ] |
| $M_{air}$ | Mass of air [kg] |
| $M_{prod}$ | Mass of food products [kg] |
| $T_{air}$ | Ambient temperature [K] |
| $T_{int}$ | Internal temperature [K] |
| $T_{ini}$ | Initial temperature of food products [K] |
| $T_{prod}$ | Final temperature of food products [K] |

## 2. Methodology

### *2.1. Model geometry*

The geometry used for the computation consists of several parts as illustrated in Fig 1. The dimensions of the truck body are 8.03 m × 2.50 m × 2.20 m (L × W × H) placed inside a cuboid, which represents the outer atmosphere, with dimension of 25 m × 8 m × 8 m (L × W × H). Ten food pallets are placed inside the refrigerated chamber with dimensions of 1.20 m × 0.80 m × 1.60 m (L × W × H) each. The truck walls have thickness of 0.075 m which represents the thickness of insulation.

The air curtain has dimension of 2.30 m × 0.15 m × 0.12 m (L×W×H). A narrow outlet vent with width of 0.05 m is constructed for discharge of air jet. The air curtain intakes air from outside and releases it through the vent at the bottom.

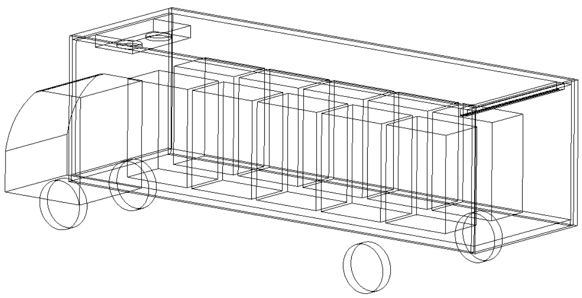


Figure 1: Geometry of truck body.

### 2.2. *Test conditions and assumptions*

Two different air curtain positions were assigned for the test, air curtain placed inside the chamber and air curtain placed outside the chamber as illustrated in Fig 2.

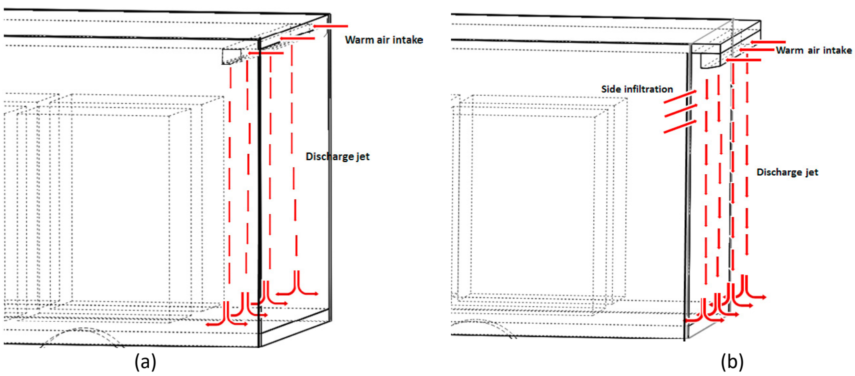



Figure 2: Location of air curtain (a) inside refrigerated chamber, (b) outside refrigerated chamber.

The truck's body uses polyurethane as insulation material. An insulation thickness of 0.075 m was set for the side walls and the ceiling and 0.1 m for the floor. The insulation material has thermal conductivity of 0.022 W/m·K, specific heat capacity of 1470 J/kg·K and density of 50 kg/m$^3$. The food products has density of 300 kg/m$^3$, specific heat capacity of 1000 J/kg·K and thermal conductivity of 0.2 W/m·K. The properties of air were set in accordance to the ideal gas law of compressible flow.

### 2.3. Numerical method

The model was created using CAD software Solidworks 2017 and imported in Ansys ICEM CFD 14.5 for meshing purpose. The simulations were run in Ansys Fluent 14.5. Structured hexagonal mesh was adopted for the truck with refined elements at regions of higher gradient. Tetragonal mesh was adopted for the atmosphere as the area does not require much refinement.

The cooling unit was initially run to pulldown the temperature of refrigerated chamber and food products to 0°C. The truck was assigned at stationary position during door openings i.e. set the inlet and outlet velocity of the atmosphere to zero. A door opening period of 15 minutes was assigned for each simulation case. The outdoor temperature was set to 20°C. The solution was estimated using the Reynolds-averaged equation of conservation of mass, momentum, and energy. The turbulence effect was modelled using k-epsilon model for standard wall function. The velocity of the air curtain inlet and outlet was controlled using pressure jump conditions. The gravitational effect was set to negative y-direction.

Mesh independence was achieved at mesh number 6.1 million for air curtain located inside and at 4.6 million for air curtain located outside.

## 3. Results and discussions

### 3.1. Recovery energy for different air curtain locations at different air curtain discharge velocity

Recovery energy is the energy required to pulldown the temperature of internal air and food products back to their initial set temperature and defined as;

$$E_r = \left(M_{air} Cp_{air} \left(T_{air} - T_{int}\right)\right) + \left(M_{prod} Cp_{prod} \left(T_{prod} - T_{ini}\right)\right)$$

Fig 3 illustrates the recovery energy for air curtain placed inside and air curtain placed outside at different discharge velocities.

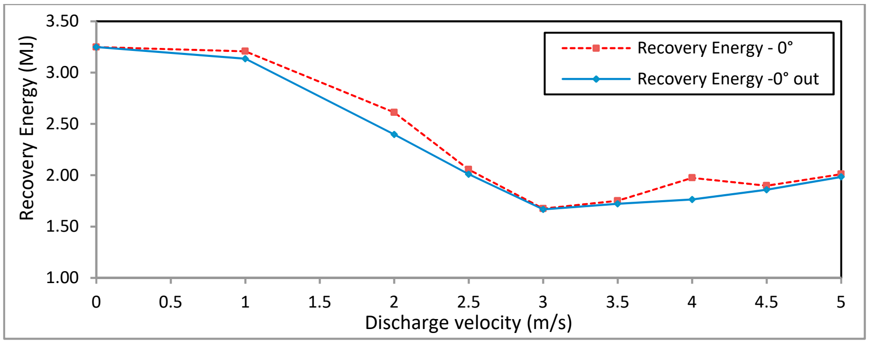


Figure 3: Recovery energy at different discharge velocities for different air curtain locations.

As can be seen in the graph, in terms of energy performance, the outside air curtain is better than the inside air curtain.

When the discharge velocity is as low as 2 m/s, the recovery energy of outside air curtain is better than inside air curtain by about 8.24%.

However, as the velocity increases to 3 m/s, the recovery energy of outside air curtain is almost similar to inside air curtain.

An abrupt rise in recovery energy can be seen at discharge velocity 4 m/s for inside air curtain. However, for outside air curtain, the rise is much steadier illustrating the outside location to prevent any abrupt rise in temperature. At higher velocity of 5 m/s, the outside air curtain is still better than the inside air curtain, but not to a significant level.

### *3.2. Influence of different air curtain locations at low air curtain velocity of 1 m/s and 2 m/s*

Fig 4 illustrates the velocity contours of inside and outside air curtain at discharge velocity 1 m/s and 2 m/s.

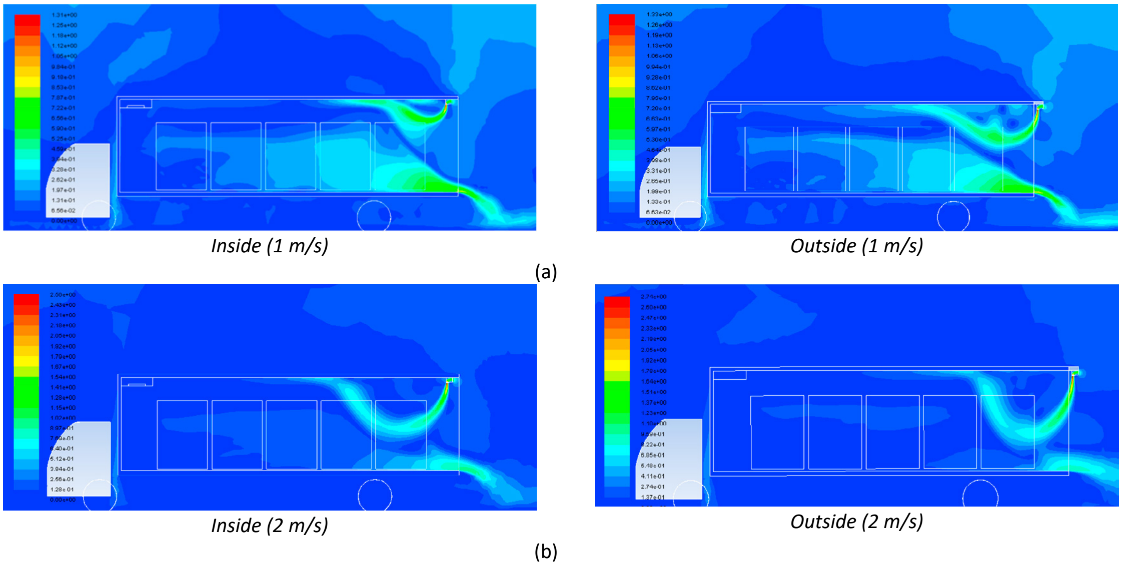



Figure 4: Velocity contours of air curtain placed inside and outside at discharge velocity (a) 1m/s and (b) 2 m/s.

As can be seen in Fig 4, when the air curtain is weak, the natural infiltration pushes the discharge jet into the truck causing the jet to bend. This bending prevents natural infiltration from the upper part allowing natural infiltration from the lower part only. The bending in flow pattern is shown in Fig 5.

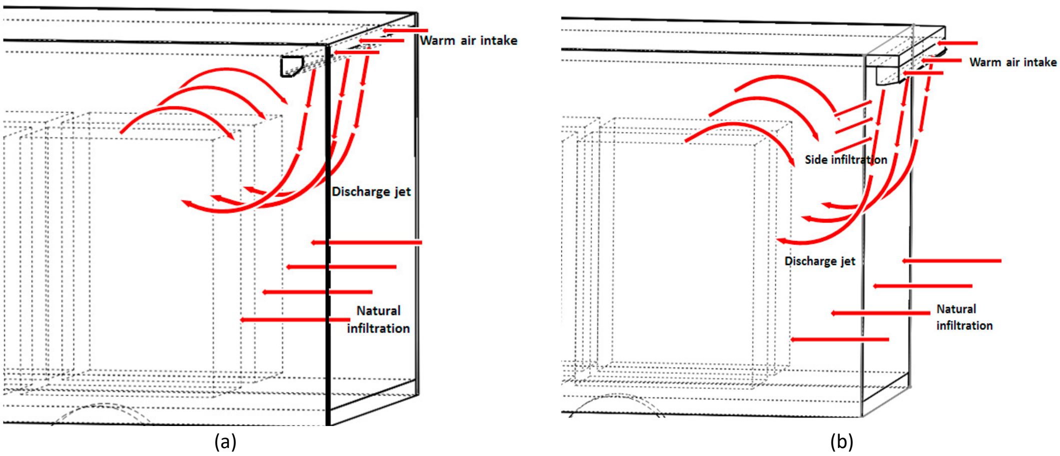



Figure 5: Side infiltration and main infiltration (a) inside air curtain and (b) outside air curtain.

Normally the higher the discharge velocity, the further the air curtain discharges vertically and the smaller the natural infiltration. Due to the same discharge velocity, the course and verticality of each air curtain should also be the same or similar. However, in comparison to the inside air curtain, the outside air curtain's vertical discharge goes further resulting in smaller area left for the natural infiltration to occur, which is caused as a result of differences in the flow patterns of these two air curtains.

Fig 2 and Fig 5 show the 3-D structure of the outside air curtain. Because the air curtain is outside, there is gap between the air curtain outlet and the open door position, meaning that the open door area is not fully protected by the air curtain. There is a side gap which is out of the protection of the air curtain. For the outside air curtain case, the natural infiltration would not be fully stopped, but partly stopped only, which is different from the inside air curtain. At this time, some of the external air would pass through the gap between the air curtain and door opening, in form of ‘side infiltration’. The side infiltration reduces the strength of main infiltration in the lower part where the discharge velocity is weaker causing the bend to be less in comparison to inside air curtain.

However, as can be seen in Fig 6, the side infiltration does not enter the chamber and instead entrains and mixes with the discharge jet from the air curtain. This is because the air curtain introduces a circulation in the cabin which “sucks” the air out at the top and the side infiltration is “drawn” out. So, the side infiltration does not have any effect in internal air temperature.

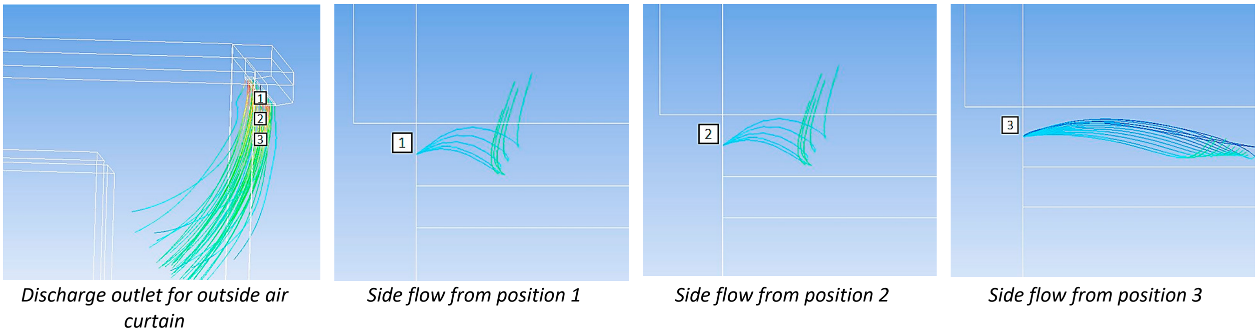



Figure 6: Flow pattern of side infiltration from different jet levels.

The greater the side infiltration the weaker would be the main infiltration and less would be the bending effect whereas the less the side infiltration the stronger would be the main infiltration and more would be the bending effect. The less bending effect would result in less opening for main infiltration, as can be seen in Fig 4, to enter the chamber and hence less recovery energy for outside air curtain. In contrast, for inside air curtain the side infiltration is almost equivalent to zero and hence the main infiltration is much stronger allowing greater bending effect and hence higher recovery energy.

Hence in regards to energy performance at lower velocity, the outside air curtain is better than inside air curtain.

## *3.3. Influence of different air curtain locations at discharge velocity 3 m/s*

Fig 7 presents the velocity contours of both the cases at discharge velocity 3 m/s.

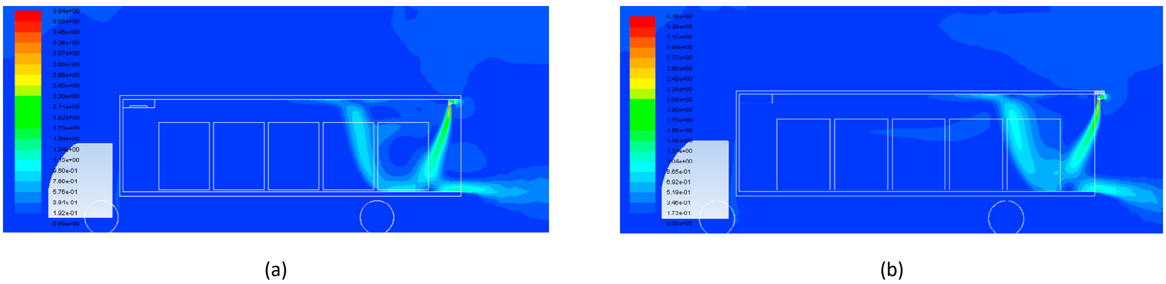



Figure 7: Velocity contours of air curtain placed (a) inside and (b) outside at discharge velocity 3 m/s.

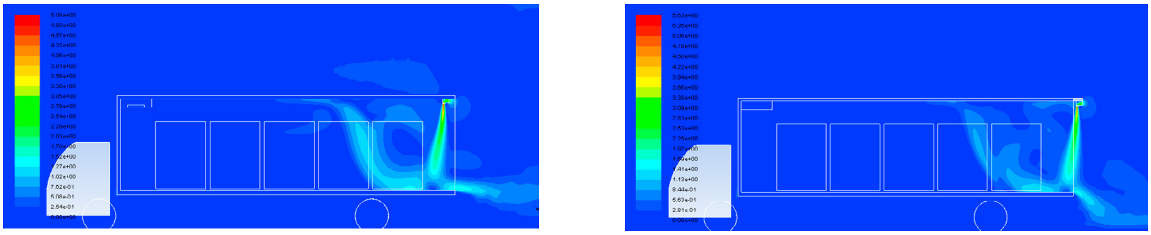
As can be seen in Fig 7, the discharge jet in both the cases reaches the floor and prevents the natural infiltration thoroughly.

Once the jet comes in contact with the floor, the jet divides in two parts, one part flows inside in form of forced infiltration and the other part flows outside. The forced infiltration entering the chamber is similar for both the cases, resulting in similar recovery energy as illustrated in Fig 3.

Though the jet is not completely vertical (inward bend created due to potential natural infiltration), it is still strong enough to prevent the effects of infiltration.

### *3.4. Influence of different air curtain locations at discharge velocity 4 m/s*

Fig 8 presents the velocity contours of both the cases at discharge velocity 4 m/s.

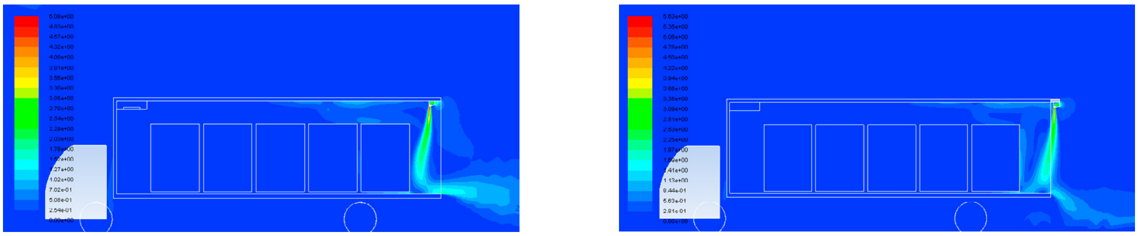


(a) (b)

Figure 8: Velocity contours of air curtain placed (a) inside and (b) outside at discharge velocity 4 m/s.

It can be seen that at discharge velocity 4m/s, the discharge jet is much more resilient and strong. Though a slight bend can still be observed, the bend is much less in comparison to the ones for lower velocities. It can be seen that in Fig 8 the contact area between the end products and discharge jet is much wider for air curtain placed inside (Fig 8 (a)) in comparison to contact area for air curtain placed outside (Fig 8 (b)). Larger contact area causes an abrupt rise in overall internal temperature and hence an abrupt rise in recovery energy (Fig 3). Since, the contact area of jet with end products is less for air curtain placed outside, this abrupt rise is prevented.

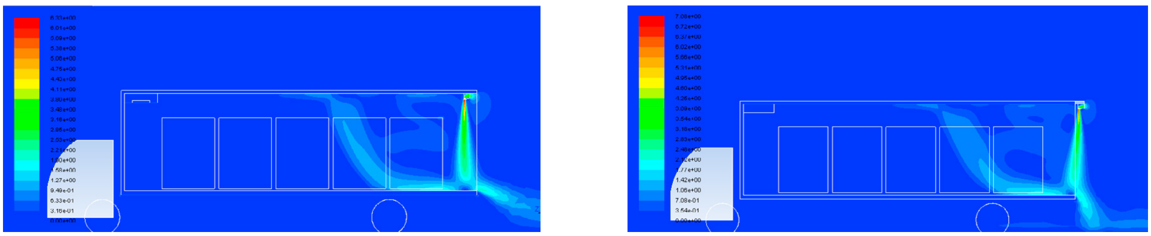
Fig 9 illustrates the contact area between the products and discharge jet.



(a) (b)

Figure 9: Velocity contours of air curtain placed (a) inside and (b) outside at discharge velocity 4 m/s from mid-product view.

### *3.5. Influence of different air curtain locations at discharge velocity 5 m/s*



(a) (b)

Figure 10: Velocity contours of air curtain placed (a) inside and (b) outside at discharge velocity 5 m/s from mid-plane view.

Fig 10 presents the velocity contours for both the cases at discharge velocity 5 m/s. At air curtain velocity 5 m/s, much stronger vertical jet can be observed for inside air curtain while a small bend in the lower part of the jet can be observed for outside air curtain. In both the cases the discharge jet prevents the natural infiltration thoroughly. The increase in internal temperature is mainly caused by the forced infiltration. If we observe the impingement point for inside air curtain, the jet flowing in and out is almost equally divided while for outside air curtain jet flowing inside is less than half due to the outer impingement point.

Ideally, the outside air curtain would not reach the floor but flow through just in front of the open door, causing low forced infiltration. However, due to Coanda effect, it bends at the door opening and reaches the floor, forming a “partly impingement”. Therefore, in outside air curtain, the jet flowing in inside is less than half. This causes the outside air curtain to be slightly better than the inside air curtain as presented in Fig 3.

## 4. Conclusion

The following conclusions can be drawn from the study.

- The energy performance of air curtain placed outside is better than of the air curtain placed inside, the performance however differs with different discharge velocity.
- The outside air curtain has “side leakage” or “side infiltration”, so the main infiltration is weaker than the inside air curtain, creating better protection at as low discharge velocity as 1 – 2 m/s, where the recovery energy of outside air curtain is lower than the inside one by about 6 – 8%.
- At 3 m/s of discharge velocity, the natural infiltration is fully stopped and the lowest recovery energy is observed at both cases. Due to the similar strength of these two air curtains, the forced infiltration is similar, resulting in similar recovery. But the outside air curtain is slightly lower than the inside one.
- At 4 m/s, the inside air curtain has an abrupt increase in recovery energy due to the side effects whereas the outside increases smoothly, resulting in much lower recovery energy.
- At 5m/s, the air curtain is strong enough and the flow is dominated by the forced convection as the discharge jet flows straight down like an impingement. About half of the air curtain flow enters the chamber in form of forced infiltration, causing the recovery energy to increase. Ideally, the outside air curtain would not reach the floor but flow through just in front of the open door, causing low forced infiltration. However, due to coanda effect, it bends at the door opening and reaches the floor. So a part of the air curtain flow rate works as forced infiltration. Therefore the outside air curtain has lower recovery energy but the difference is not as high as expected.

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