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Energy Procedia 161 (2019) 207–215

Energy Procedia

www.elsevier.com/locate/procedia

2nd International Conference on Sustainable Energy and Resource Use in Food Chains, ICSEF 2018, 17-19 October 2019, Paphos, Cyprus

Numerical investigation into the influence of air curtain discharge angles in refrigerated trucks

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Abstract

Over the years, the use of air curtains has been considered as one of the most effective ways of preventing warm-air infiltration in cold storages and now in refrigerated trucks as well. It is estimated that energy savings of almost 40% can be achieved using an air curtain. Previous studies have suggested that the energy efficiency of air curtains could be further improved through several mechanical adjustments, including the adjustment of discharge angle. This study focuses on the influence of different discharge angles on air curtain mechanisms and energy performance for an air curtain with warm-air suction (ambient air intake). The results suggest that adjusting the angle in the positive direction (outwards) can help prevent the bending in the discharge jet- created as a result of dominating natural convection showing a discharge angle of 10° to be more effective in controlling the bend than 0°. However, the effectiveness of the discharge angle is highly dependent on the discharge velocity. When the discharge velocity is low (2 m/s), the released jet is too weak and hence the effect of the discharge angle is also small, resulting in similar recovery energy for both the 0° and 10° cases. However, when the discharge velocity is medium to high (above 4 m/s in this case), the bending effect is also significant and hence adjusting the discharge angle can prove to be more advantageous, providing an energy saving of up to 17.6%.

Selection and peer-review under responsibility of the 2nd International Conference on Sustainable Energy and Resource Use in Food Chains, ICSEF2018

Keywords: infiltration; refrigerated vehicle; aircurtain discharge velocity; discharge angle; air curtain;

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Selection and peer-review under responsibility of the 2nd International Conference on Sustainable Energy and Resource Use in Food Chains, ICSEF2018.
10.1016/j.egypro.2019.02.083

1. Introduction

Air curtains have been proposed as one of the most-effective protective mechanisms for controlling the rate of air interchange during door openings- reducing energy consumption by almost 40% and warm mass flowing in to the cold room by almost 38% (1,2). Foster et al. estimated the air curtain to have an effectiveness of almost 0.71 for the elimination of air infiltration in cold rooms (where an effectiveness of "1" represents total elimination) (3). The energy efficiency can be further improved through several mechanical adjustments (4). Majority of the studies indicate discharge velocity to be the most important factor in improving the efficiency and has been investigated widely. However, only few have focused on the influence of discharge angle.

An experimental study conducted by Jaramillo et al. assessed the energy consumption rate for different air curtain discharge angles (4). The assessment considered four different jet discharge angles: -15°, 0°, 15° and 30° (positive direction assigned to be towards the cold room) for an air curtain inlet facing towards the cold room (cold air suction). The results showed that angles of 30° and 15° had greater energy consumption than a straight vertical discharge. The energy consumption of a discharge angle of -15° was estimated to be slightly lower than that of 0°.

An experimental study conducted by Valkeapaa et al. showed that adjusting the discharge angle could also improve air-curtain tightness (control the air leakage) (5). Blowing angles above 20° (positive outwards) could help prevent further air leakage losses. Along with preventing air leakage, a large discharge angle can also lower the discharge velocity, minimising pressure losses and power consumption in the fan - thus improving the economy of the air curtain system. However, all these studies are conducted in larger cold rooms with stronger air curtains unlike the ones installed in refrigerated vehicles.

This numerical study focuses on the influence of air curtain discharge angle, at different discharge velocities, on energy performance. The air curtain for this study is modelled using the features and dimensions of a commercial product available in the market. The air curtain inlet receives warm air from outside (warm suction) and releases it through a bottom discharge vent. The study also verifies if any improvements in the deflection at lower jet discharge velocities can be achieved by adjusting the trajectory of the air curtain jet.

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. Modelling methodology

2.1. Physical domain

For the model, a cuboid was used to represent the truck's body with internal dimensions of 8.03 m × 2.50 m × 2.20 m (L × W × H). The truck was placed in another larger cuboid which represents the outer atmosphere with dimension of 25 m × 8 m × 8 m (L × W × H), as illustrated in Fig 1. Ten food pallets were placed inside the truck's body with dimension of 1.20 m × 0.80 m × 1.60 m (L × W × H) each.

A pentagonal solid, as illustrated in Fig 1 (b), was used to model the air curtain near the opening of the door with length of 2.30 m, the vertical inlet facing outwards with a height of 0.10 m, and with the discharge outlet located on the lower face with width of 0.05 m. The cooling unit is modelled using a parallelepiped solid with dimensions of 1.50 m × 0.75 m × 0.20 m (L×W×H). Two inlet fans are modelled in the inlet face with diameter of 0.40 m and outlet vent dimensions of 0.75 m × 0.20 m.

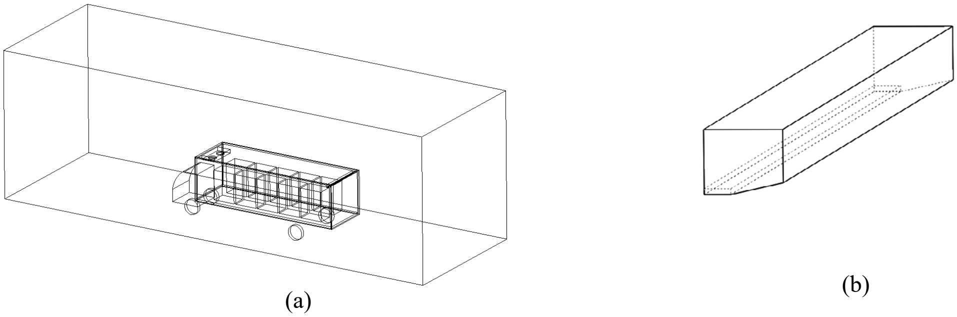


Fig 1. (a) Isometric view of the model, (b) the air curtain.

2.2. Numerical method

Two commercial codes were used for the numerical modelling, Ansys ICEM CFD 14.5 for the meshing of the domain; and Ansys Fluent 14.5 and 18.2 to simulate the meshed domain. The transient 3-D model is based on a numerical simulation of the jet airflow from the air curtain at different discharge angles. The angle of the jet discharge is controlled by adjusting the flow direction. The air curtain is modelled as having warm-air suction (air intake from ambient). The solution is estimated using the Reynolds-averaged equation for conservation of mass, momentum and energy and turbulence effects modelled using the standard k-epsilon model for standard wall functions. The gravitational effect has been set in the negative-y direction such that the airflow takes gravity into account. An average door opening time of 15 minutes was estimated from an internal investigation carried out in distribution trucks, and hence a total simulation time of 15 minutes was assigned for each case. This model uses an approach of pressure jump condition to control the jet flow velocity from the air curtain and cooling unit (which is switched off during door opening).

2.2.1 Mesh independence test

Before all the cases are simulated, it is essential to run a mesh independence test to ensure high accuracy of the results. Mesh independence is achieved when the same results are obtained for the case regardless of the number of elements used. A structured hexagonal mesh was adopted for the physical domain using Ansys ICEM with refined elements in the regions of higher gradient (especially the small gaps between food products). Mesh independence was achieved for the domain with a total of 6.1 million nodes.

2.3. Boundary, initial and test conditions

Two different discharge angles, 0° and 10°, have been investigated for this study. Discharge angle 0° represents straight vertical airflow. Fig 2 illustrates two discharge angles assessed for this study. An angle 10° is defined to be positive towards the opening, with its reverse side towards the bend.

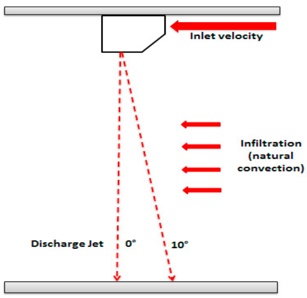


Fig 2. Infiltration test condition at different discharge angles.

Initially, the truck is modelled to be moving at a constant velocity with the cooling unit fully switched on and with a cooling capacity of 3800 W. The cooling unit is switched off when the truck comes to halt and the door is opened.

This is set as the initial condition for the simulation. Table 1 presents the simulation test parameters for this study.

Table 1. CFD simulation parameters

Categories	Parameters
Air curtain discharge velocity (m/s)	1, 2, 3, 4, 5
Outdoor temperature (°C)	20
Initial truck air temperature (°C)	0
Initial food product temperature (°C)	0

Table 2 illustrates the thermal properties of the truck's body. It has been assumed that the same insulation material is used for all sides of the vehicle.

Table 2. Thermal properties of the truck's body

	Conductivity (W/m·K)	Specific heat capacity (J/kg·K)	Density (kg/m^3)	Thickness (mm)
Ceiling	0.022	1470	50	75
Floor	0.022	1470	50	100
Front wall	0.022	1470	50	75
Lateral wall	0.022	1470	50	75

The air is considered to be a compressible fluid with properties based on an ideal gas for compressible flow. The food product has density of 300 kg/m^3, specific heat capacity of 1000 J/kg·K and thermal conductivity of 0.2 W/m·K.

3. Results and discussion

3.1. Influence of different air curtain discharge angles at different air curtain velocities in energy savings

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

$$E_r = \left(M_{air}Cp_{air}\left(T_{air} - T_{int}\right)\right) + \left(M_{prod}Cp_{prod}\left(T_{prod} - T_{ini}\right)\right) \tag{1}$$

Fig 3 illustrates the recovery energy required for different air curtain velocities at air curtain discharge angles of 0° and 10°.

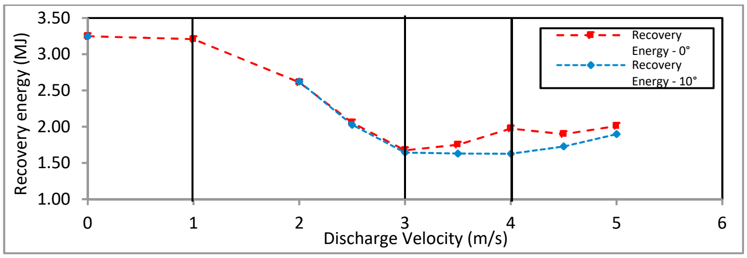


Fig 3. Recovery energy of internal air and food products at air curtain discharge angle 0° and 10°.

When the velocity is as low as 1 m/s, the recovery energy is almost the same as no air curtain, indicating air curtain to be very weak to prevent any natural infiltration. Angles 0° and 10° present similar performance at this velocity.

When the velocity increases from 1 m/s to 3 m/s, the recovery energy decreases swiftly indicating the air curtain to be more effective in preventing natural infiltration. At 3 m/s, a slight difference can be observed between the cases 0° and 10°.

When the velocity increases from 3 m/s to 4 m/s, the angle effect is more prominent in the case of 0°. It can be observed that the recovery energy increases more rapidly indicating more infiltration to have occurred. In contrast for the case of 10°, the recovery energy is almost the same. When the velocity increases from 4 m/s to 4.5 m/s, the recovery energy decreases in 0° case and increase in 10° case. When the velocity increases beyond 5 m/s, the recovery energy of both the cases, 0° and 10°, increase alongside.

3.2. Influence of air curtain discharge angle on temperature distribution and trajectory of the jet at different discharge velocities

3.2.1 Influence of discharge angle at low discharge velocities of 1 m/s and 2 m/s

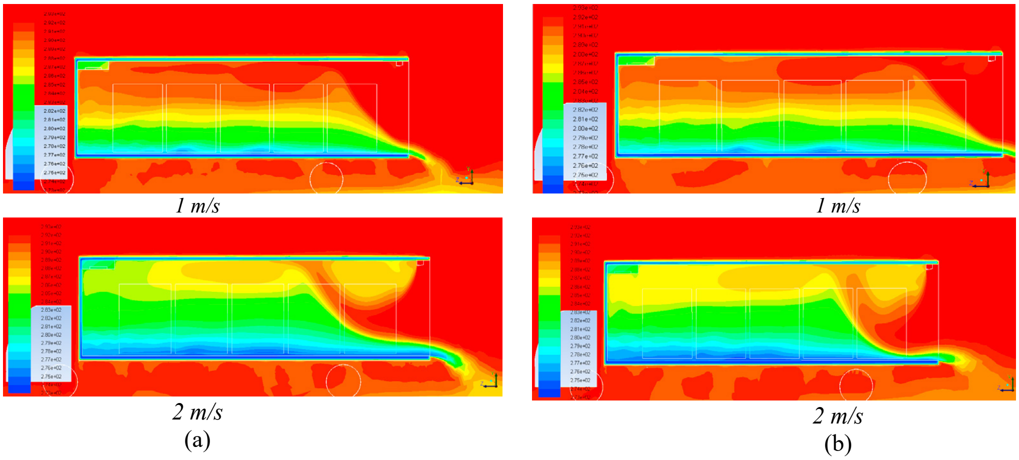
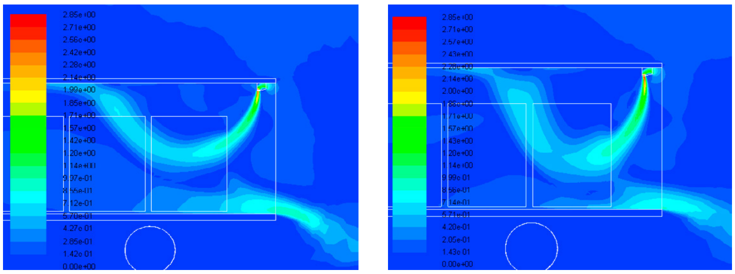


Fig 4. Temperature distribution inside the refrigerated truck with air curtain velocity of 1 m/s and 2 m/s at discharge angle of (a) 0° and (b) 10°.

Fig 4 presents the temperature contours at discharge velocity of 1 m/s and 2 m/s with discharge angles 0° and 10°. It can be seen that with the weak discharge velocity, the natural infiltration is barely affected. So the angle does not affect the recovery energy in these cases. When the velocity is as high as 2 m/s, the air curtain controls wider region and the natural infiltration is compressed, as presented in Fig 5, causing an abrupt drop in the recovery energy in Fig 3.

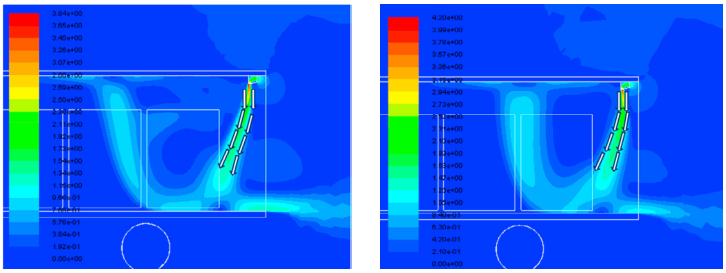


(a) (b)

Fig 5. Discharge jet from the air curtain outlet at velocity of 2 m/s and discharge angle of (a) 0° and (b) 10°.

3.2.2 Influence of discharge angle at low discharge velocities of 3 m/s

Fig 6 presents the velocity contours of 0° and 10° at 3m/s.



(a) (b)

Fig 6. Discharge jet from the air curtain outlet at velocity of 3m/s and discharge angle of (a) 0° and (b) 10°.

It can be seen that in both the cases the air curtain reaches the floor, preventing the natural infiltration thoroughly, causing quick decrease in recovery energy in Fig 3. In both the cases, the jet bends into the truck due to potential natural infiltration. However, in the 10° case the bending angle is smaller than that in the 0° case, causing larger share of the discharge jet to come in contact with the floor, also termed as 'attachment angle', than the food products at the end of the truck.

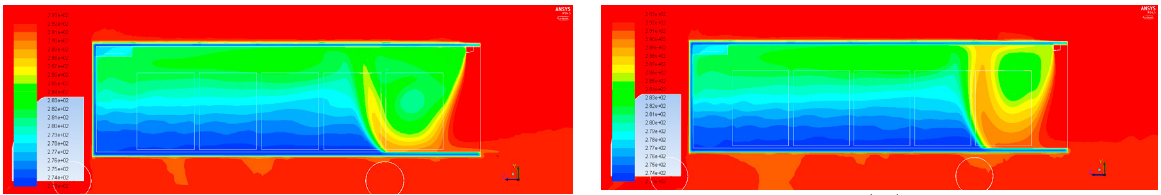
As a semi-impingement flow, the air curtain flow divides into two parts after impinging onto the floor. One portion flows into the chamber, causing forced infiltration, and the other portion flows outside.

$$Infiltration \propto \left(\frac{1}{attachment\ angle} \right) \tag{2}$$

Smaller attachment degree means more share of air curtain flow flowing into the chamber with higher forced infiltration.

$$Infiltration \propto \left(\frac{mass}{attachment\ angle} \right) \tag{3}$$

Even though the air curtain discharge velocity and flowrate are same for these cases, when at 10° discharge angle, the attachment angle is greater, resulting in smaller portion of inflow, i.e. smaller forced infiltration. However, the attachment angle difference is not as much due to the weak air curtain, so the recovery energy difference (Fig 3) is small as well as the temperature difference as presented in Fig 7.



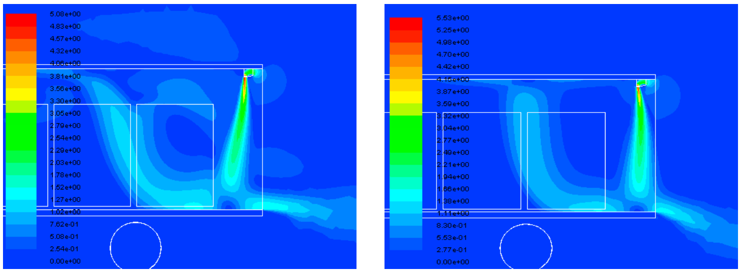
Mid-plane view
(a)

Mid-plane view
(b)

Fig 7. Temperature distribution inside the refrigerated truck for air curtain velocity 3m/s and discharge angles of (a) 0° and (b) 10°.

3.2.3 Influence of discharge angle at low discharge velocities of 4 m/s

Fig 8 illustrates the discharge velocity contours near the opening when the discharge velocity is increased to 4 m/s.

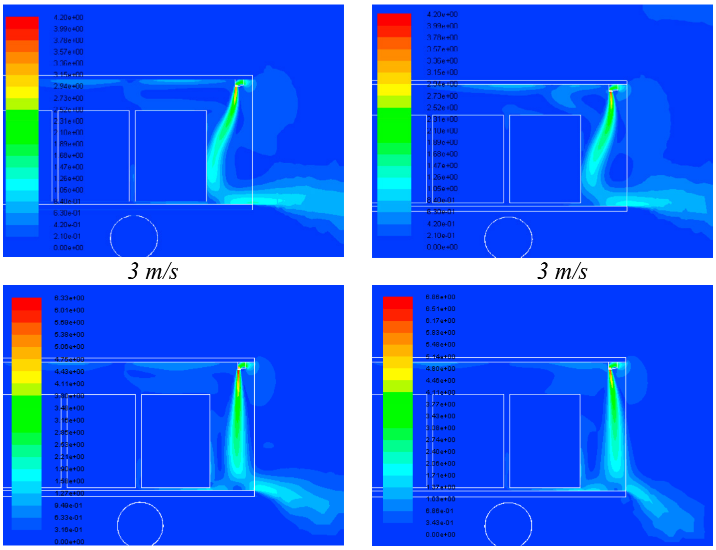


(a) (b)

Fig 8. Discharge jet from the air curtain outlet at velocity of 4 m/s and discharge angles of (a) 0° and (b) 10°.

It can be seen in Fig 8, the air curtain jet at velocity 4 m/s is stronger than that in 3 m/s and can overcome the bending effect better resulting in greater attachment angle with small share of air curtain jet flowing in the chamber. However, with higher discharge velocity, the total air curtain flowrate increases. When the jet is at 0°, this causes more share of jet to flow inside the chamber resulting in higher recovery energy from 3 m/s to 4 m/s (Fig 3). Having the jet at an angle, 10° in this case, presents similar jet flow behaviour resulting almost same recovery energy from 3 m/s to 4 m/s.

Fig 9 shows the velocity contours when at air curtain 3 m/s and 4 m/s with 0° and 10° angle from mid-product plane.



3 m/s *3 m/s*

4 m/s *4 m/s*

(a) (b)

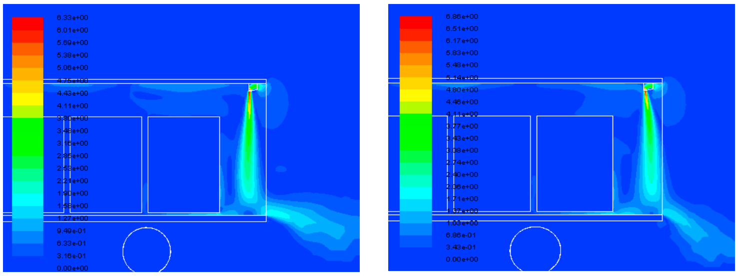
Fig 9. Discharge jet from the air curtain outlet at velocity of 3 m/s and 4 m/s and discharge angles of (a) 0° and (b) 10°.

It can be seen that when the air curtain velocity decreases, the width of the air curtain increases due to the dispersion of momentum. The central part of air curtain jet has the highest velocity, representing the main flow of the air curtain, termed as the core flow. The outer part of the jet velocity has lower velocity, termed as the boundary flow. In 3 m/s, although the core flow reaches the floor, the boundary flow does not and flows along the product outside the surface causing heat transfer. This is not explicit air infiltration flowing from outside, but implicit heat transfer which increases recovery energy too. This process can be termed as air curtain boundary effect. It can be analysed that this heat transfer is roughly proportional to the air curtain flowrate and inversely proportional to the heat transfer area.

$$Heat\ transfer \propto air\ curtain\ flowrate \times area \tag{4}$$

In 0° case, when the discharge velocity increases from 3 m/s to 4 m/s, the air curtain flowrate increases, causing higher heat transfer. However, due to the bending effect, the heat transfer area does not decrease as much, causing greater heat transfer as well as higher total recovery energy.

3.2.4 Influence of discharge angle at low discharge velocity 5 m/s



(a) (b)

Fig 10. Discharge jet from the air curtain outlet at velocity of 5 m/s and discharge angles of (a) 0° and (b) 10°.

At air curtain velocity 5 m/s, it is observed that the 0° case had a vertical jet, indicating very strong forced convection. For the 10° case, the air curtain flows outwards in the higher part and then bends to become near vertical, resulting impingement at a small angle. This indicates that the airflow rate of forced infiltration in the 10° is lower than that of the 0° case. As illustrated in the figures, the boundary flow effect is not as prominent as core flow effect at higher air curtain velocity. This is mainly due to the opposing effect between air curtain velocity and the boundary flow effect, i.e. higher the air curtain velocity lower would be the boundary flow effect.

4. Conclusion

The following conclusions can be drawn from the study.

- Along with obtaining a better verticality, having the discharge jet at certain angle decreases both the effects: the core flow effect and boundary flow effect.
- Discharge angle helps the air curtain to overcome the bending effect due to natural convection, resulting in a lower infiltrating airflow rate and lower recovery energy.
- When the discharge velocity is low (2 m/s and 3 m/s) and air curtain is weak, the effect of the discharge angle is small, which results in equal or similar recovery energy.
- When the discharge velocity is high (4 m/s) and the air curtain is medium-strong, the bending effect is high for the 0° case but is lower for the 10° case, providing recovery energy savings of 17.6%.
- When the discharge velocity is higher (5 m/s) and the air curtain is very strong, the bending effect cannot be seen in the 0° case but does have an impact for the 10° cases, resulting in an energy saving of 5.6%.

Acknowledgements

The work presented in this paper received funding from the Research Councils UK (RCUK) for the establishment of the RCUK Centre for Sustainable Energy Use in Food Chains (CSEF) through EPSRC grant No: EP/K011820/1. The authors acknowledge the financial support received from the Research Councils UK. The paper reports all the relevant data to support the understanding of the results. More detailed information and data, if required, can be obtained by contacting the corresponding author of the paper.

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