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Numerical investigation of the protective mechanisms of air curtain in a refrigerated truck during door openings

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Abstract

Warm air infiltration during door openings of refrigerated delivery trucks can account for approximately 34% of the overall refrigeration load, with this share estimated to be higher for longer and/or more frequent door openings. An increase in refrigeration load can have a direct impact on the energy usage (higher thermal loads require greater energy consumption). Many sources in the literature suggest that the use of an air curtain to reduce the impact of warm air infiltration during door openings. However, the majority of these studies focus on air curtain use in large cold rooms and warehouses. The main purpose of this study is to investigate the protective mechanisms of an air curtain against natural infiltration in a refrigerated vehicle during door openings. This study analyses the airflow behaviour in the refrigerated truck body with and without the protection of an air curtain during door openings. Different air curtain velocities have been tested for this particular investigation to study the influence of discharge velocity on energy performance. The airflow analysis suggests that natural infiltration is mainly caused by cold air flowing out from the lower part of the opening as warm air infiltrates in from the upperpart to fill the space. It has been found that an air curtain at optimum velocity (3.1 m/s in this study) can help reduce the energy consumption by almost 48%.

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Keywords: infiltration mechanisms; infiltration; refrigerated vehicles; protective mechanism; air curtain;

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1. Introduction

Refrigerated vehicles used for the delivery of perishable food products are probably the most energy-consuming type of road freight transport, accounting for an estimated annual emission of 4.0 $MtCO_2e$ in the UK (1,2). The refrigeration units in the majority of rigid and articulated trucks are independently powered using an auxiliary diesel engine (3). The number of these transport refrigeration units (TRUs) is predicted to reach 97,000 by 2025, in comparison to 84,000 currently in use. This will require an additional 340 million litres of diesel and indicates the need for energy saving measures (4,5).

Modelling studies conducted by Tassou et.al. (6) and Rai and Tassou (3) have identified infiltration of warm air during door openings to be one of the dominant causes of refrigeration load in refrigerated delivery trucks and hence one of the main causes of increased energy consumption. The results indicated that infiltration load can account for almost 34% of the overall refrigeration load, with share estimated to be higher for longer door opening durations. Using the DIN8959 standard, investigation work by Micheaux et.al. (1) estimated infiltration heat load in refrigerated trucks to be of the same order of magnitude as the conduction heat gains, and even 30% higher at times. Tso et.al. (7) assessed the heat exchange across the door to be 3.27 kW for door opening time of 2 minutes in a refrigerated truck with volume of 7.2 m^3.

Many investigations and studies aimed at finding ways to minimise the rate of warm air infiltration in temperature-controlled environments have suggested the use of an air curtain as the most-effective mechanism for controlling infiltration (8-11). Experimental work conducted by Azzouz et.al. [8] estimated that an air curtain can reduce the mass of warm air entering the cold room by almost 38%. An experimental study conducted by Tso et.al.(7) estimated an energy saving of up to 40% through the use of air curtains in refrigerated trucks; this is similar to the 30% energy saving claims provided by manufacturers (12).

Along with experimental work, numerical simulation using CFD has also proven to be an effective way of studying the airflow behavior during door openings and the efficiency of air curtains in controlling infiltration. Using a CFD modelling approach, Foster et.al. (10) estimated an air curtain to have an effectiveness of 0.71 (1 represents total elimination of air infiltration). Liangzhou et.al.(11) used a numerical approach to study the flow characteristics of air curtains in buildings for different ambient temperatures, pressure differences across the air curtain, and different door usage frequencies. For a range of pressure differences, the air curtain was able to significantly reduce the infiltration through door entrances in buildings. However, the majority of studies of air curtain flow characteristics were mainly conducted on cold room and building doorways. Very little work has been done on the performance of air curtains in refrigerated trucks during door openings.

This work presents a transient 3-D numerical study on the airflow behaviour and temperature changes in a refrigerated truck body during different door opening periods to investigate the energy efficiency of an air curtain as a protective mechanism at different discharge velocities. Multiple CFD simulations have been conducted to study the changes in thermal flow pattern inside a refrigerated truck body with and without an air curtain.

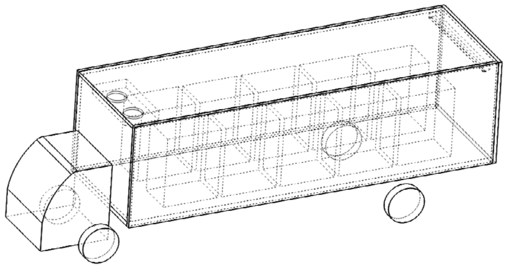
Nomenclature

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]

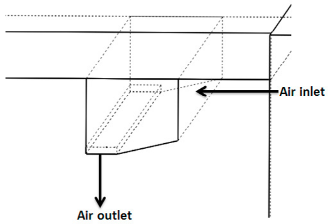
2. Numerical model and methodology

2.1. Domain geometry

The geometry of the physical domain is shown in Fig 1.



(a)



(b)

Fig. 1. (a) Geometry of the truck body and (b) geometry of the air curtain.

The physical domain consists of a cuboid that represents the truck's body with internal dimension of 8.03 m x 2.50 m x 2.20 m (L × W × H). The insulation thickness is 0.075 m for the sidewalls and ceiling, and 0.1 m for the floor. The dimensions of the door is 2.50 m x 2.20 m. The truck is fully loaded, with food products placed on pallets with dimensions of 1.20 m × 0.80 m × 1.60 m (L × W × H).

The air curtain is modelled using a pentagonal prism solid with length of 2.30 m. The vertical inlet is facing outwards with a height of 0.10 m and the discharge nozzle is on the lower face with width of 0.05 m. The air curtain takes in air from outside (ambient air) and discharges it from the nozzle at a given velocity.

The cooling unit is modelled using a parallelepiped solid, as illustrated in Fig 1 (b), with dimension of 1.50 m× 0.75 m× 0.20 m (L × W × H), with two air inlet fans of diameter 0.40 m and an outlet vent of 0.75 m× 0.20 m.

The physical domain is positioned inside another cuboid solid, which represents the outer atmosphere with dimensions of 25 m× 8 m× 8 m (L × W × H).

2.2. Numerical solution procedure

A fine hexagonal mesh was adopted for the model using commercial code ANSYS ICEM CFD 14.5. The meshed domain was implemented and simulated using ANSYS Fluent 14.5. The solution is estimated using Reynolds-averaged equations for the conservation of mass, momentum and energy. Turbulence effects were modelled using the standard k-Ɛ model for standard wall functions. Gravitational acceleration of 9.8 m/s^2 was assigned in the negative y-direction and varying density of air based on the ideal gas law was used for the simulation of natural convection. The transient terms were discretised using a first-order Euler scheme. A total simulation time of 15 minutes was assigned for each case to study the flow pattern for the maximum door opening period.

2.2.1 Boundary, initial and test conditions

For initial condition, the air inside and outside is static. The internal temperature of the refrigerated truck body and products are set to 0°C and the ambient temperature is set to 20°C (based on the climate of the UK). Table 1 summarises the thermal properties of different categories.

Table 1. Thermal properties for CFD simulation

	Density (kg/m^3)	Specific heat capacity (J/ kg·K)	Thermal conductivity (W/m·K)
Air	Ideal gas	1006	0.0242
Insulation (polyurethane)	50	1470	0.022
Food product	300	1000	0.200

The cooling unit is switched off when the door is opened; hence no cooling source is accounted for during door openings. The air curtain is initially switched off to simulate the heat and mass transfer without an air curtain. In other cases, the air curtain velocity varies from 1 m/s to 6 m/s.

This model employs a fan using a pressure jump across a virtual "fan surface" to control the discharge velocity from the air curtain. The pressure rise is considered to be constant for each case and is calculated using average conditions. Viscous resistance is assigned in adjacent directions to the air curtain nozzle to control the direction of flow.

2.2.2 Mesh independence

A structured hexagonal mesh was adopted for the spatial discretisation of the physical domain, ensuring refined elements in the region of higher gradient. Tests were conducted to verify the independence of the mesh, as illustrated in Fig 2. At a fine mesh of 4.6 million elements, mesh independence was achieved.

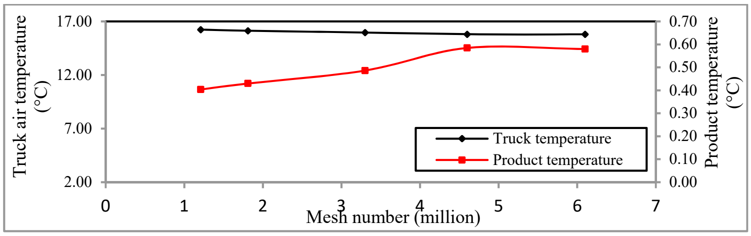


Fig. 2. Mesh independence test.

3. Results and discussions

3.1. Infiltration behavior without air curtain

3.1.1 Temperature history

Fig 3 shows the temperature changes in the food products and internal air of the truck for a door opening period of 15 minutes.

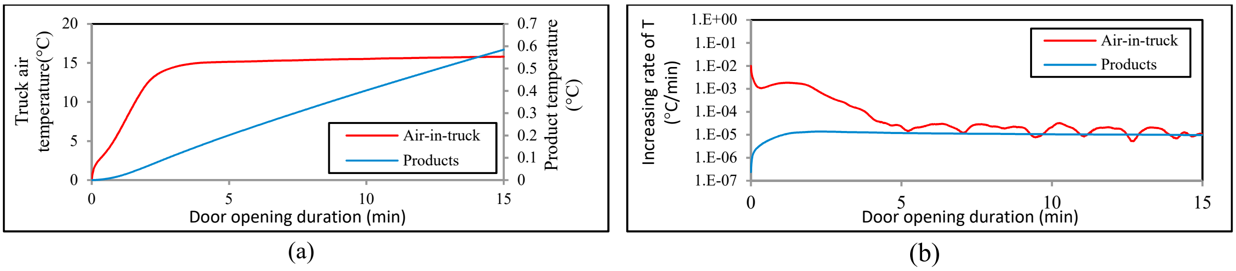


Fig 3. (a) Average temperature of food products and internal air, (b) temperature increase rate of food product and internal air.

It can be seen that the temperatures of both the product and internal air increase with time once the door is opened due to the infiltration of warm air through the opening. The air temperature increases from 0 °C to 15.8 °C in 15 minutes, while the product temperature increases from 0 °C to 0.58 °C. The temperature increase of the products is smaller than that of the internal air due to the far higher thermal mass of the products.

The temperature increase, however, does not occur at a constant rate. When the door is opened, the air temperature increases rapidly to 12.3 °C (77.8% of the final temperature increase at 15 minutes) in the first 2 minutes, before slowly increasing to 15.15 °C during the following 3 minutes, accounting for 95.9% of the final (15 minutes) temperature increase. In contrast, the product temperature only increases to 0.58 °C at an almost constant rate over the entire 15 minutes. However, before this steady rise, the temperature increase of the food products is much slower. After 5 minutes, both the air and product temperatures increase quite slowly, indicating that the heat transfer and air flow are quasi-steady.

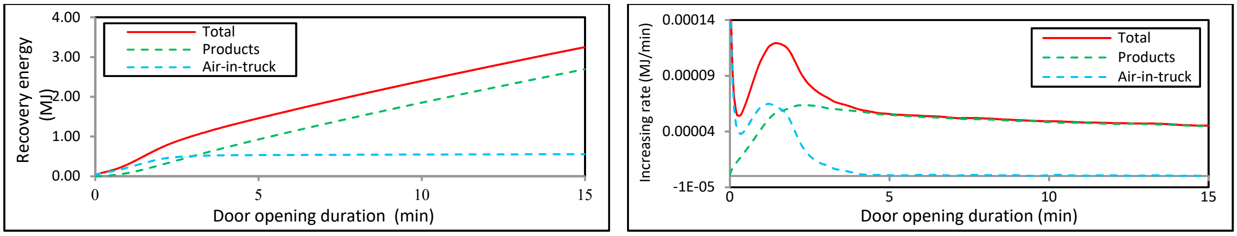
The features of the temperature increase rate can be observed more clearly in Fig 3 (b). In the initial 2 minutes, the temperature increase rate of internal air is estimated to be 2.0 x 10^{-3} °C/min on average, much higher than that of the product temperature, which is estimated to be 1.38 x 10^{-5} °C/min. In the next 3 minutes, the temperature increase rate of internal air undergoes a rapid decrease to approximately 1.5x10^{-5} °C/min, while the increase rate of product temperature declines to 1.19x10^{-5} °C/min. From 5 to 15 minutes, the temperature increase rates of the internal air and product decline to 1.07x10^{-5} °C/min and 0.97x10^{-5} °C/min, respectively.

3.1.2 Recovery energy

Recovery energy can be defined as the energy required to pulldown the temperature of the internal air and products back to their initial set temperature. Recovery energy is an integral parameter to evaluate the amount of warm air infiltration.

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

The graphs illustrated in Fig 4 represent the recovery energy during the door opening period without any protective mechanism.



(a) (b)

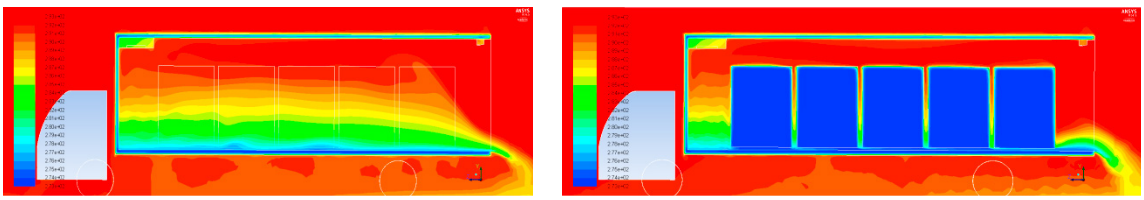
Fig 4. (a) Recovery energy of internal air and food products without air curtains, (b) recovery energy increase rate.

It can be seen that the recovery energies continue to increase with door opening duration, which illustrates that warm air infiltration occurs throughout the whole period of door opening. At the beginning, the recovery energy of air is higher than that of food products, showing that the warm air infiltration is initially mainly used to heat the truck air. After 2 minutes, the recovery energy of air increases very slowly, showing that the truck air absorbs less infiltrating heat. However, the recovery energy of products increases constantly and dominates the increase rate of internal air at 15 minutes. The truck air mainly acts as a heat-transfer medium between the warm air infiltration and the products. After 5 minutes of door opening, the total recovery energy increases at a steady rate, almost linearly, showing the warm air infiltration to be at almost steady state. At 15 minutes, the recovery energy is 3.25 MJ.

Fig 4(b) shows the increasing rate of recovery energy, representing the instantaneous amount of warm air infiltration. It can be seen that the infiltration fluctuates in the first 5 minutes and then decreases slowly, which will be discussed and explained in the next section.

3.1.3 Natural infiltration mechanisms

Fig 5 presents the temperature variations in the truck 15 minutes after door opening.



(a) (b)

Fig 5. Temperature distribution inside the refrigerated truck body when without an air curtain (a) mid-plane view, (b) product mid-plane view.

As can be seen in Fig 5, only the outer layer of the food products has been heated while the inner part still remains cold, resulting, in minimal increase in overall product temperature, as illustrated in Fig 3. The air temperature at the upper part is approximately the same as the ambient air, while the temperature at the bottom of the truck is much cooler due to the food products, which act as cooling sources providing cooling in the lower area.

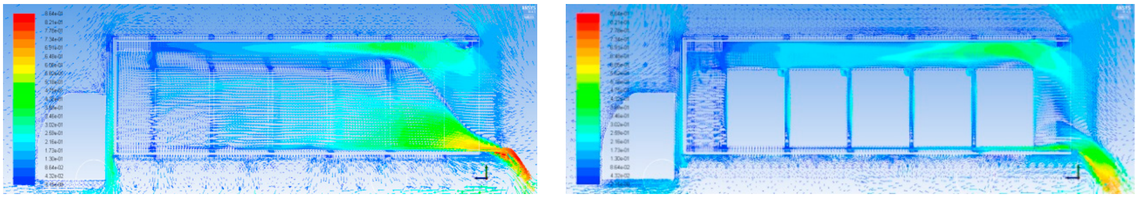

(a) (b)

Fig 6. Velocity changes inside the refrigerated truck body without an air curtain (a) mid-plane view, (b) product mid-plane view.

It can be seen that since the cold air is much heavier than the warm air, it stays at the bottom of the truck (due to gravity) and flows out of the truck from the lower part of the opening. In contrast, warm air is sucked in to the truck through the upper part of the opening until it dominates the space left by the cool air flowing out. This process is a typical natural convection and hence the warm air infiltration is “natural infiltration”.

The natural infiltration greatly relies on the temperature difference between the inside and outside. In this case, the instantaneous opening of the door also allows warm air to suddenly infiltrate the refrigerated space, resulting in a high infiltration rate in the beginning (Fig 3). As the natural convective airflow starts building up, the thermal mass of the products starts to work as the cooling sources keeping the internal air temperature lower than the ambient air and maintaining natural convection. As the product temperature increases, the air temperature also increases and the natural convection and natural infiltration become weaker and weaker, resulting in a lower increase rate of recovery energy, as illustrated in Fig 4.

3.2. Infiltration behavior with air curtain

3.2.1 Temperature and velocity changes with air curtain

Fig 7 illustrates the velocity vectors of the refrigerated truck with an air curtain at velocity 5.4 m/s.

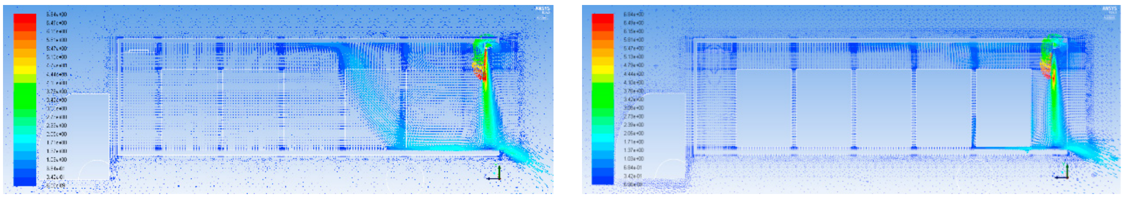
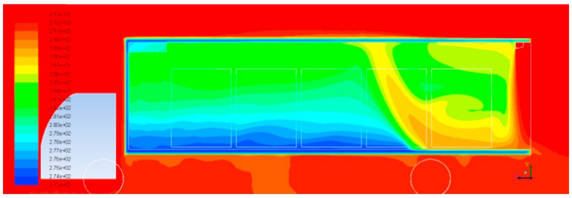

(a) (b)

Fig 7. Velocity changes inside the refrigerated truck body with an air curtain velocity of 5.4 m/s, (a) mid-plane view, (b) product mid-plane view.

The velocity is strongest at the outlet vent of the air curtain and gets weaker as it reaches the truck’s floor, almost like an impinging jet. The strong discharge velocity from the air curtain acts as a barrier, preventing warm air infiltration at the upper part of the opening. After impinging on the floor, it divides into two streams - one flows outside and the other flows inside, resulting in a clockwise airflow circulation inside the truck. The air curtain discharge velocity of 5.4 m/s is much higher than the highest natural convection velocity of 0.86 m/s in case without air curtain (Fig 3), indicating that the flow field will be highly dominated by the forced convection. Fig 8 presents the temperature contour of the refrigerated truck body after 15 minutes of door opening with an air curtain.



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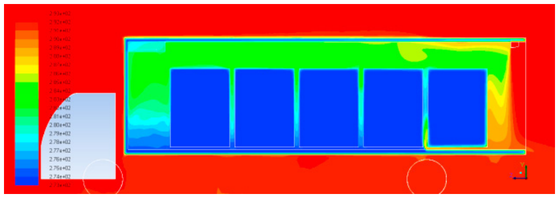


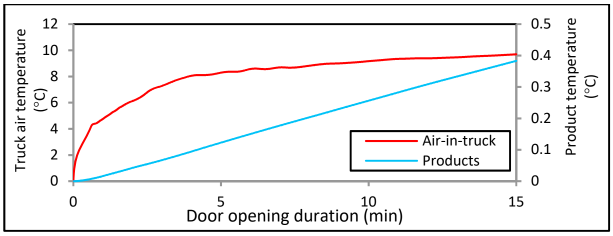
(b)

Fig 8. Temperature distribution inside the refrigerated truck body with an air curtain velocity of 5.4 m/s, (a) mid-plane view, (b) product mid-plane view.

In Fig 8, it can be seen that the temperature in the upper part is higher than that in the lower part of the truck's body. However, in the region near the open door, the temperature at the bottom is higher than the top, due to forced air circulation in the area caused by the discharge jet, indicating a strong warm air infiltration at the bottom opposing the natural infiltration. Since this infiltration is mainly caused by forced convection, it can be termed "forced infiltration".

3.2.2 Energy performance with an air curtain

Fig 9 (a) presents the temperature change history for door opening duration of 15 minutes with an air curtain. It can be seen that the average air temperature increases to 9.7 °C and the average product temperature to 0.38 °C, which are much lower than that of case without air curtain. Fig 9 (b) shows the corresponding recovery energy performance. The total recovery energy is estimated to be 2.11 MJ, 65% of the case without air curtain.



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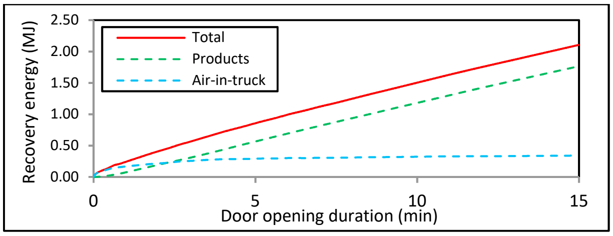
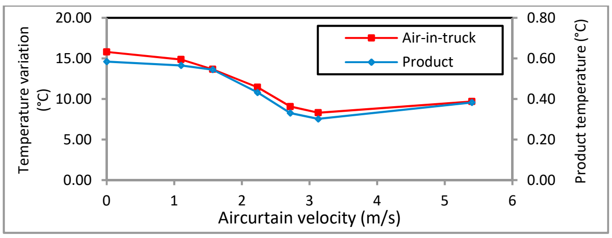


(b)

Fig 9. (a) Average temperature of products and internal air for a door opening period of 15 minutes, (b) recovery energy of internal air and food products with an air curtain.

3.3. Optimal air curtain velocity in respect to energy performance

Though strong flow from the air curtain does prevent natural infiltration at the upper part of the open door, it at the same time induces forced infiltration at the lower part of the open door. Considering the reverse air circulation during natural convection compared with forced convection, it would be ideal to cancel out the natural convection by controlling the strength of the forced convection achieving an optimum condition in respect to recovery energy.



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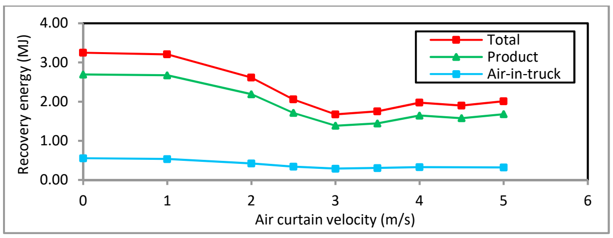

(b)

Fig 10. (a) Average temperature of products and internal air and (b) recovery energy of internal air and food products for different air curtain velocities.

Fig 10 shows the temperatures and recovery energies after 15 minutes with different discharge velocities. In terms of recovery energy, the optimum air curtain velocity is estimated to be around 3.1 m/s, reducing the required recovery energy by 48%. When the velocity is near the optimal velocity (3.1 m/s) the air curtain jet velocity is just sufficient to reach the truck's floor and forced infiltration is quite small. Despite the rather weak discharge jet, natural infiltration is still prevented thoroughly. It can therefore be determined that the air curtain velocity that can prevent natural convection from introducing additional forced infiltration into the cabinet is the optimum velocity with respect to recovery energy. For this particular study, the optimum velocity is estimated to be near 3.1 m/s. However, the velocity rate can change with different configurations such as dimensions of the truck, percentage of payload inside the truck, and temperature difference between inside and outside of the truck. This would, however, require further investigation.

4. Conclusion

The following conclusions can be drawn from the study:

- During door openings, warm air enters the refrigerated truck body from the upper part of the door due to the cold air flowing out from the lower part, resulting in natural infiltration of warm air.
- The recovery energy of the air in the truck increases faster for the first 2 minutes and is higher than that of the products. After that, the recovery energy of the air increase is much slower than that of the products. After 15 mins, the percentage of product recovery energy is over 80% of the total recovery energy.
- The air curtain creates a barrier (forced convection) against natural convection, thereby slowing the process of temperature rise in the refrigerated truck body. However, strong forced convection introduces forced infiltration of warm air at the lower part, which is in the opposite direction to natural infiltration.
- There is an optimal discharge velocity, which has the lowest recovery energy, saving 48% of the recovery energy when compared to the case without an air curtain.

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