Study on the inlet air velocity on the refrigerated container; comparison between flat floor and T-bar floor

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Abstract. The use of refrigerated containers plays an important role in perishable food transportation. The refrigerated container functions as a carrier that keeps the object's temperature fresh and even below freezing point. The distribution of air flow in the container is very important to ensure in maintaining the setting temperature. The aim of this paper is to study the inlet air velocity on the refrigerated container by simulation model. The analysis was carried out by comparing two geometric models of the container floor in the empty load condition, namely the flat floor and the T-bar floor. From the simulation results, the average inlet velocity of the refrigerated container with the T-Bar floor has a higher velocity than the flat floor. In this case, the airflow circulation on the refrigerated container of the T-bar floor and flat flow around 525 m$^3$ h$^{-1}$ and 314 m$^3$ h$^{-1}$, respectively. From this case study, it is found that the use of T-bar floors can increase airflow circulation approximately 26%.

Keywords: refrigerated container; airflow distribution; flat floor, T-bar floor

1. Introduction
Demand in refrigerated shipping containers continues to increase along with growth in the global demand for shipping containers. In the period 2017-2025 refrigerated containers are expected to be the fastest growing segment in the product type group, with an ambitious growth forecast of 10.2% [1]. Refrigerated containers commonly used for long distances transporting perishable food cargo from suppliers to consumers [2]. Temperature, airflow, and humidity must be managed to optimize the operation of refrigerated containers [3]. There are several factors influencing the efficiency of cooled container operation, including controlling the environmental conditions [4], structuring cargo pallet [5] and thermal insulation of containers [6], This also relies on variations in temperature and product respiration, as well as airflow [7].

Many studies have been performed to enhance refrigerated container efficiency and related to its energy consumption. Researchers have performed several studies on the use of natural coolant in order to improve the performance of refrigeration systems [8] and nano refrigerant [9]. Some researchers have also carried out work on managing environmental conditions, one of the experiments using a roof shade that effectively decreases heat penetration from the air [10], As well as the effects of stack containers, the energy usage of refrigerated containers was also affected [11]. Several researchers conducted work to enhance the thermal insulation of containers by attempt-
ing to use phase-change material [12], the results in controlling the cooling load on the cargo were very successful [13], apart from direct sunlight, heat penetration to thermal insulation was also induced [14].

Some researchers simulated the refrigerated container related to heat transfer and fluid flow during the term of airflow [15]. The use of computational fluid dynamics (CFD) to research operational and design parameters in the cold storage technology in recent decades has become popular [16]. Different studies were conducted on the effect of the angle to save energy in refrigerated containers [17] and environmental condition [18], the findings were good as compared with the experiment. The impact of floor design on airflow and cooling characteristics were explored in relation to the airflow circulated. The floor design airflow analysis can provide operators with strong information to optimize load pattern settings and other operating parameters. The purpose of this study was to analyse the airflow distribution between two floor design namely flat floor and T-bar floor inside the refrigerated container. The analysis was conducted using CFD simulation of the high-cube refrigerated containers with empty load conditions. The findings of this analysis contribute to the characteristic of airflow distribution between the flat-floor and the T-bar floors inside the cold containers.

2. Geometry model of refrigerated container

![Cross Section of the Refrigerated Container](image)

**Figure 1.** Cross-section of the refrigerated container with (a) the flat floor and (b) the T-bar floor

Refrigerated containers equipped integrated refrigeration system to carry perishable food products, generally, there are two sizes i.e. 20ft and 40ft. For the special 40ft high-cube refrigerated containers has dimension length 12.9 m, width 2.4 m, and height 2.8 m. Reefer containers maintain cargo for transit time, whether in chilled, frozen or regulated temperatures at the appropriate
temperature (between -30 °C to +30 °C). The wall of the refrigerated container is constructed with three-layer insulation material which consists of aluminium, polyurethane, and stainless steel. In the practical operation, there are two types of floor design widely used namely flat floor and T-bar floor. Figure 1 shows the geometrical difference between the flat floor and the T-bar floor. This study is performing a three-dimensional simulation to analyse the distribution of airflow within refrigerated high cube containers.

3. Simulation model of refrigerated container

The model for the simulation is based on solution of partial differential equations which control flux of fluid flow fields based on the preservation equations of mass and momentum shown in equation 1 and equation 2.

\[
\nabla \cdot \mathbf{v} = 0
\]

\[
\rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla P + \mu \nabla^2 \mathbf{v} + \mathbf{f}_B
\]

Where \( \mathbf{v} \) is velocity vector (ms\(^{-1}\)), \( \rho \) is density of air (kg m\(^{-3}\)), \( P \) is pressure (Nm\(^{-2}\)), \( \mu \) is coefficient of viscosity (N s m\(^{-2}\)), \( t \) is time function (s) and \( \mathbf{f}_B \) is buoyant force. The \( k-\omega \) shear stress transport turbulence model is used in this analysis since it was shown to perform better than other models of turbulence. At the cooling air temperature of -0.5 Celsius, the air density is supposed to be constant. Description of the simulation model’s parameter setting are given in Table 1.

| Simulation Parameter | Setting Condition |
|----------------------|-------------------|
| Geometry of simulation model | Length 11.58 m  |
| | Width 2.27 m |
| | Height 2.54 m |
| Time step | Transient |
| Turbulence model | \( k-\omega \) |
| Number of mesh | 783395 element |
| Inlet area | 0.145 m\(^2\) |
| Inlet temperature | -0.5 °Celsius |
| Inlet velocity | 4 m s\(^{-1}\) |

The basic assumption that the simulation model starts from cold air, with some speed variations, enters the cargo area through evaporator inlets. Inlet cold air flows into the storage room of the refrigerated container, then air flows through an outlet on the ceiling. The variation in the inlet velocity was determined as a low-speed fan at 4 m s\(^{-1}\) (equal to 32 circulation hour\(^{-1}\)) according to field practices [19]. This model uses the no-slip rule for viscous fluid as a boundary condition assuming the fluid will have zero velocity relative to the boundary at solid limits. It is presumed that the physical properties of the air are constant, and the velocity of the outlet air flow does not vary around the outlet unit range. The total number of elements generated from mesh is 783395. Simulation model boundary condition and mesh generation are shown in Figure 2.
4. Result and discussion
Airflow distribution inside the refrigerated container with the flat floor and the T-bar floor shown in Figure 3 and Figure 4, respectively. On the flat-floor container, cold air enters the container horizontally perpendicular to the inlet surface as a jet at 4 m s\(^{-1}\). Otherwise, on the T-bar floor container, the airflow of cold air started to decrease at 6 meters from the refrigerator to 50 percent from the initial velocity, some turbulence occurs on this area. To determine the effectiveness of air distribution, it is necessary to look at the air velocity in the middle of the cargo room, in this case data is taken at a height of 1 meter from the floor. Figure 5 show airflow distribution at 1-meter height from the floor from the refrigerator unit until the door side. This figure clearly shows that the air distribution on the T-bar floor has higher than on the flat floor. The average velocity of this area is around 1 m s\(^{-1}\) on the T-bar floor and 0.6 on the flat floor. This velocity is equal to the 525 m\(^3\) h\(^{-1}\) and 315 m\(^3\) h\(^{-1}\), respectively. From the results of this simulation, a finding is that the airflow distribution on the T-bar floor is better than on a flat floor. The use of T-bar floors in refrigerated containers can increase air distribution by up to 27%, this result is consistent with other research that show the T-bar floor has an increase in vertical air circulation [20].
5. Conclusion
An analysis of the airflow distribution inside refrigerated high cube containers was carried out using CFD simulations. The design of two floors of refrigerated containers, i.e. the flat floor and the T-bar floor, has been investigated. From the simulation result shows that there is higher airflow distribution on the T-bar floor than on the flat floor. The average velocity for T-bar floor and flat floor is 525 m$^3$h$^{-1}$ and 315 m$^3$h$^{-1}$, respectively. The finding of this result is that T-bar floors can improve airflow distribution up to 27% in refrigerated containers. The findings of this study can be used as guidance for further research considering the cargo cooling speed and the refrigeration units' energy consumption.

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