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Assessment of Thermal performance of Transport Refrigeration Vehicles by Modifications in the Compartment Design and Storage Pattern

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ABSTRACT: *The demand for transport refrigeration system in Bangladesh is rising at a tremendous pace. However, there is a considerable lack of knowledge in the vehicle body design, cooling load management and appropriate product storage pattern inside the transport refrigerated vehicles. A numerical analysis is carried out to assess the performance of refrigerated vehicles with proposed design modifications which include horizontal and vertical partitioning or shelving of the refrigerated chamber. Computational fluid dynamic (CFD) modelling is used to study and compare the outcome of the proposed models to that of the conventional design and storage practices followed locally. It is found that the thermal performance improves more when vertical partitioning of the chamber is introduced. The percentage of stored products within an acceptable temperature increases up to 200% in certain case of chamber partitioning and modified storage pattern. Several scenarios with chamber design modification and storage pattern are studied, the results are reported here in detail.*

Keyword: Cold Chain; Transport Refrigeration; Refrigerated Chamber; CFD; Horizontal and Vertical Partitioning.

1. INTRODUCTION

The food cold chain begins after the processing of fruits, vegetables, meats and dairy products when the food is pre-cooled to bring its temperature below a certain value and then transported and stored at a distribution point. The chain termination takes place when the consumer places the food in a domestic refrigerator [1]. Transport system through land, water and air plays a big role in cold chain by delivering the products safely to the customer. Temperature sensitive products such as fresh fruits, meat, vegetables, medicine etc. are safely transported via refrigerated transport system. Active refrigeration system is present in the insulated body of the refrigerated road transport vehicles such as vans and trucks for regulation of temperature [2]. The purpose of a refrigerated transport system is to maintain a uniform temperature of the load which is essential to maintain the quality, safety and extend shelf life of the perishables. Temperature has been recognized to be the single most important factor which dictates the horticultural products' quality [3]. Temperature gradient inside cold chamber is heavily influenced by the air-supply method. Therefore, controlled temperature itself is not enough to avoid product deterioration as adequate air circulation within refrigerated truck chambers is also a dominant factor for maintaining the quality of perishables. Consequently, road transport refrigeration plays a significant role in the cold chain through optimum temperature regulation of the transported products and through affecting energy consumption and greenhouse gas emissions [4]. These refrigerated vehicles perform the job of providing products safely to the customers through supplying to the distribution points such as supermarkets. Supermarkets containing temperature sensitive products such as vegetables, frozen fish or meat etc. in refrigerated cabinets account for huge consumption of electricity and this demand of excessive energy contributes to global warming by the burning of fossil fuels and resulting in an undesirable increase of CO2 to the atmosphere [5]. Moreover, air-conditioning system has also been proven to have higher global warming potential (GWP) than other prime contributors of global warming [6]. At the same time, demand of refrigeration has also increased incredibly all over the world which makes it even more important to consider the efficiency of energy consumption. Refrigeration for appropriate temperature management of food products requires close to 8% of electrical energy consumption of the whole world [7]. Economic cost related to the cold chain is reliant on the optimization of the energy consumption which will dictate net improvement of the cost efficiency of the food industry [8]. So, lower energy consumption will undoubtedly enhance the potential growth of the industries of international food products. In the recent years, an increase in international food trade has emerged along with trade in other forms of goods and services. The increase of food products was observed in global trade of $450 billion in 1995 to $739 billion in 2006 (United Nations Conference on Trade and Development [UNCTAD] 2008) [9]. Food (excluding fish) exports and imports of the world in 2016 reached beyond triple the value of exports and imports of 1995 [10]. Hence, high quality product supply has become essential and it is one of the primary difficulties faced by the worldwide industries due to microbial degradation of the temperature sensitive and perishable products. Top strawberry exporting countries like Spain, Mexico, United States etc. are greatly dependent on the proper maintenance of the quality of the product. This only signifies the ever-growing importance of refrigerated transportation.

The use of refrigerated vehicle is increasing among the food companies as well as pharmaceutical companies worldwide and Bangladesh is no different. It was found in a recent study that a total number of 2518 refrigerated vehicles of various type, size and capacity have been imported to Bangladesh between the periods of 1987 to the first-half of 2018 according to the information in the BRTA database [11]. These vehicles are generally seen consisting of direct diesel engine-driven or battery powered refrigeration system but in the case of Bangladesh, the refrigerated transport sector is governed by the diesel engine-driven small and often retrofitted refrigerated trucks and moreover the dimensions of imported refrigerated truck's refrigeration chamber are directly copied by the local body manufacturers without much knowledge on design parameters and they tend to use intuition in order to refit 3-5ton capacity trucks with reverse engineered refrigeration chamber [2]. Cold-chain industry is growing swiftly and refrigerated vehicles are proving to gain popularity in recent years in Bangladesh with an increase of about 500% of registered refrigerated vehicles from the year 2007 to 2017 [11].

Fig. 1. Storage system of crates inside the refrigerated chamber of the transport vehicles commonly practiced in Bangladesh

Most developing countries are lacking behind the developed countries in terms of satisfactory refrigeration applied for food preservation due to a combination of reasons such as insufficient resources that are required for proper refrigeration, hefty cost of energy consumption alongside lack of awareness for food safety. Food starts to degrade in the absence of appropriate refrigeration even for a small amount of time and that is why constant maintenance of optimum temperature has become an unavoidable matter.

In countries like Bangladesh, due to the tedious and often lengthy traffic jams, the long journey becomes even longer. So, it is highly recommended to provide appropriate temperature regulation in the refrigerated chamber which might not be the case as lack of concern on quality degradation of products is very common among the operators.

Each air-supply method has its own advantage based on operating conditions as well as applications. Although potential configurations of air-distribution systems are numerous, only a handful of cases are actually seen in practice [4]. In a recent study, it was observed in a numerical study that storage pattern with specific clearance improved the temperature distribution in comparison to the stockpiling of crates which is generally practiced in Bangladesh [2].

In Bangladesh, during our field survey, it was observed that the crates are kept close to the evaporator side of the refrigerated chamber and there is an ample amount of unused space at the end of the refrigerated chamber (see Fig.1). The products are typically stored in plastic crates and occupy a small portion of the refrigerated compartment and a major portion of the vertical and horizontal space remain unused. As a result, a large space is required to cool unnecessarily, and thus making the system energy inefficient. It was found in the survey that there is significant lack of scientific knowledge on the efficient product storage methods, refrigeration system performance and energy efficiency among the stakeholders and people working in the transport refrigeration sector in Bangladesh.

Although methods such as internal shelving and racking, or the use of movable or sliding horizontal/vertical barriers and partitional walls are used occasionally in commercial applications, no systematic study could be located in the open literature on the effects of the such partitioning of the refrigerated container on the cooling

performance and energy efficiency. In the present study, different design modifications of the container of the refrigerated vehicles is carried out in the form of movable or sliding horizontal and vertical partition with different arrangements of the product storage. Computational Fluid Dynamics (CFD) simulations are performed for each of the designs and crate arrangements along with the compartment design and product storage pattern typically followed in Bangladesh. In all the modified designs, a better air circulation and more uniform temperature distribution were observed which would result in an improved cooling and storage of the goods.

2. METHODS

2.1 Design Considerations

In this study, two modified chamber designs with different crate or storage arrangements are analyzed and compared to the conventional chamber design and product storage practice in refrigerated vehicles in Bangladesh-

A. Refrigerated vehicle compartment design with adjustable horizontal shelving/partitioning

B. Refrigerated vehicle compartment design with adjustable vertical partitioning.

A total of seven number of different cases were examined in this study with different compartment designs. 40 and 60 number of crates containing food products were used for each design to observe the change in thermal performance (see Fig.2).

In the refrigerated compartment with horizontal shelving, two equal compartments are separated by the adjustable partition and the design consists of one evaporator in each compartment. The power rating of the refrigeration units is equal which is one-half the power rating of the typical refrigeration unit with a single compartment.

In the refrigerated compartment with vertical partitioning, the adjustable partition is placed close to the last row of crates in the refrigerated chamber. The power rating of this refrigeration unit is similar to the commonly used refrigeration unit in a single-compartment refrigerated vehicle.

2.2 Geometry

The cargo dimensions were based on the local refrigerated trucks used for food transportation. The refrigerated container was 4.23*1.68*1.68 m^3 in

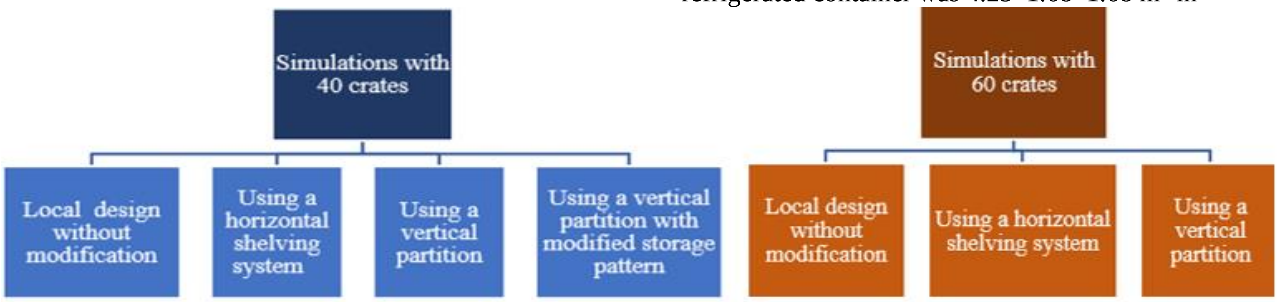


Fig. 2. Different design modification and storage pattern scenarios for which simulations were conducted in this study.

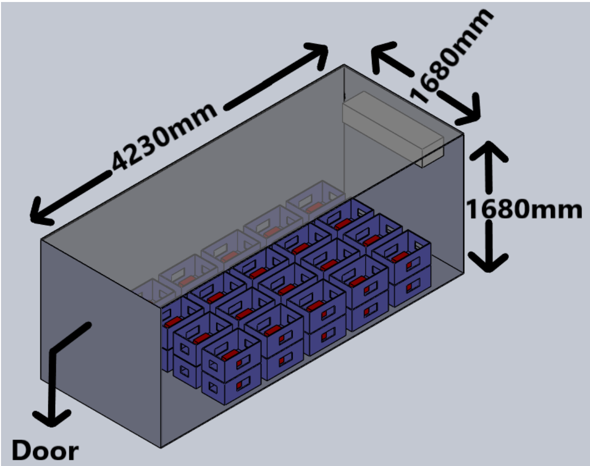


Fig. 3. Storage pattern with 60 crates (Case-1) and 40 crates (Case-2) inside the chamber for the typically practiced scenario.

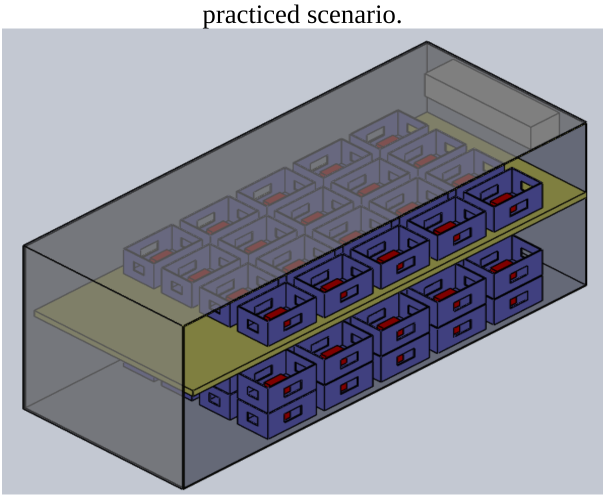


Fig. 4. Storage pattern with 60 crates inside the chamber with horizontal shelving and single evaporator (case-3).

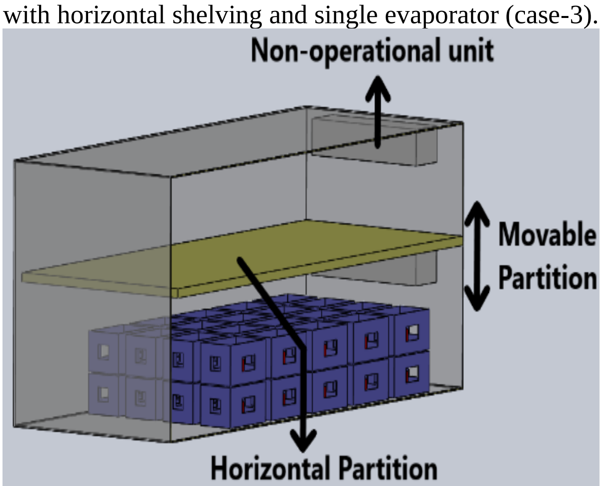


Fig. 5. Storage pattern with 40 crates inside the chamber with horizontal shelving and single evaporator (case-4).

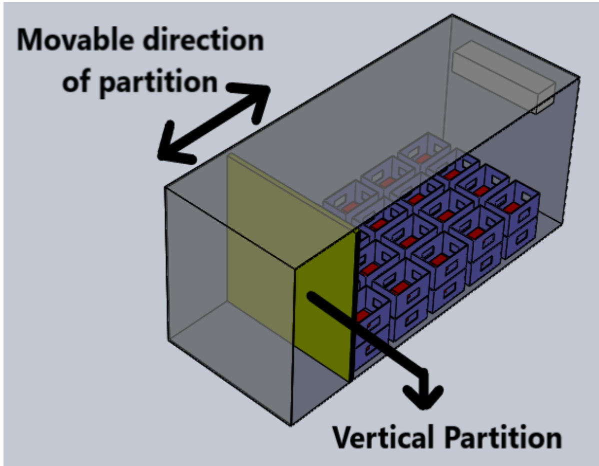


Fig. 6. Storage pattern with 60 crates (Case-5) and 40 crates (Case-6) inside the chamber with vertical partitioning.

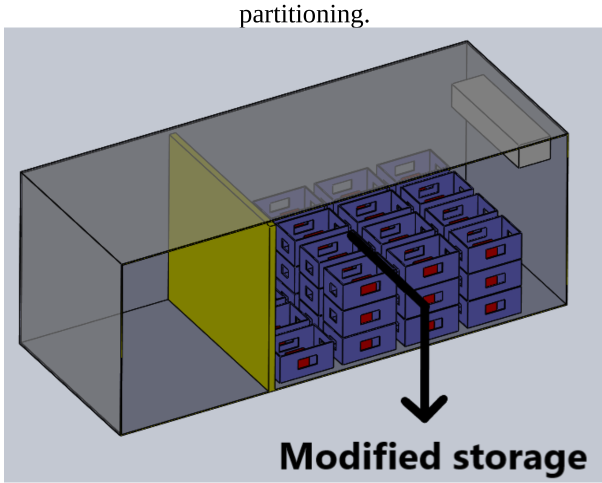


Fig. 7. Storage pattern with 40 crates stacked in 3 layers inside the chamber with vertical partitioning (case-7).

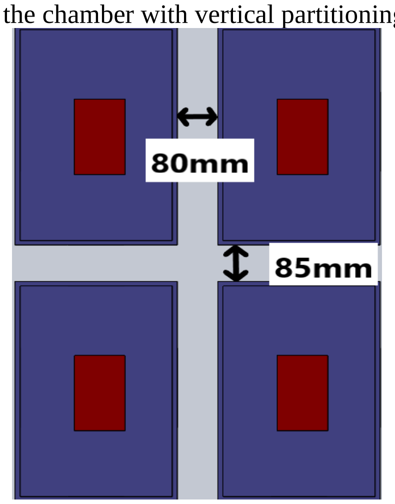


Fig. 8. Clearance between the stored crates in each row and column (Top view).

dimension. There were two types of evaporator used in this study. For the locally practiced design, a single 3-ton refrigeration unit was used which had a dimension of 1.4*0.38*0.3 m^3 (see Fig. 3). For the modified design with horizontal shelving at the middle, two 1.5-ton unit were used which were 1.1*0.3*0.2 m^3 each (see Fig. 4, 5). For the modified design with vertical wall or barrier at the end, a single 3-ton refrigeration unit was used which had same dimension as the locally practiced case (see Fig. 6, 7). The crates used for this study had an outer dimension of 0.51*0.32*0.26 m^3. The crates were 10 millimeters in thickness. There were 4 holes around the four surfaces of each crate. Along the length of the crate the holes were 0.184*0.094 m^2 in dimension and along the width the holes were 0.111*0.09 m^2. The product dimension used in all cases was 0.175*0.1*0.13 m^3. The crates were stacked with a gap of 0.085 meters between each row and a gap of 0.08 meters between each column (see Fig. 8). The gap from the innermost wall of the cargo and the first row of crates 0.39 meters to allow airflow under the evaporator. The thickness of the vertical and horizontal walls or barriers was 0.06 meters.

The different dimensions and other geometry values were taken based on the dimensions of the individual items that are typically used in the transport refrigeration sector in Bangladesh. Little clearance was applied in all of the simulations to represent the common attributes of the local practice of stockpiling as many products as possible at the expense of maintaining negligible clearance to maximize profit.

2.3 Simulations Methodology

In this study, ANSYS Fluent was used to perform the numerical analysis of different configurations. For turbulence modelling in the refrigerated cargo, shear stress transport, SST-k-omega model was used. The effect of radiation was ignored from outside as it was a forced convection application. The input air velocity was 8 m/s and 6.5 m/s for the 3-ton evaporator and 1.5-ton evaporator, respectively. The inlet temperature was 263K from the evaporator and the initial temperature of the cargo was 300K considering the average temperature in Bangladesh. The property of aluminum was used for the horizontal and vertical walls or barriers used for modification. In this study, temperature below 278K was considered to be acceptable to ensure product quality.

To observe the performance variation for each modification, simulations were conducted for the typical and modified chamber designs containing 40 crates and 60 crates of stored good in different arrangements. The conventional storage pattern of crates in Bangladesh cases (case-1, case-2) was observed to be 20 crates for each layer which results in 2 layers for 40 crates (Case-2) and 3 layers for 60 crates of stored goods (Case-1). For the case including horizontal shelving and 60 crates, 1 layer consisting of 20 crates were situated in the upper compartment and 2 layers with 20 crates each was in the bottom compartment with both evaporators operating (Case-3). In the case with 40 crates of stored goods, all the crates were placed in the lower compartment with only the lower evaporator operating (Case-4). The product storage pattern in the cases with vertical partitioning was similar to the local crating arrangement with the partition situated at a distance of 80 millimeter from the last row of the crates (Case-5, Case-6, Case-7). For the cases with vertical partitioning, another special case was analyzed where the 40 crates were stacked in 3 layers by placing 16 crates in the first layer, 12 crates in both second and third layer (Case-7). This arrangement allowed the vertical wall or barrier to be placed nearer to the evaporator.

3. RESULT AND DISCUSSION

3.1 Locally followed chamber design and product storage pattern with no modification (Case-1, Case-2)

There is a significant lack of knowledge of cooling performance, product storage requirement and energy efficiency in the existing practices of the refrigerated food transport system in Bangladesh. The goods are stored in the refrigerated chambers without any systematic pattern or concern for proper storage temperature or optimization of the system capacity. As there is a tendency to place the crates without much clearance and it can be seen that there is an ample amount of free space towards the outer section of the cargo, which results in more space for cooling for the evaporator and the overall temperature of the cargo increases. With 3 layers, each with 20 crates (see Fig. 9), the inner 3 rows of crates of the uppermost layer had received better cooling. The outer rows of each layer had an average temperature of 288K, which was above the acceptable limit considered in this study for food safety. The bottom two layers had a lower temperature compared to the upper layer. This was because only 80 millimeters spacing was allowed between crates which hampered airflow towards the lower placed products. With 2 layers of crates, the average temperature of the products was slightly improved as there was more space above the crates for better airflow (see Fig.10). The outer row of crates of the bottom layer had a higher and unacceptable temperature of around 287K. It was also observed that the innermost crates of bottom layer also had a higher and unacceptable temperature of 286K as the air velocity was quite low in this region. The inner 4 rows of upper layers had an acceptable temperature (in the range of 273K-275K).

3.2 Modified chamber design with horizontal shelving and 60 crates of products (Case-3)

In the modified design with horizontal shelving, the inner two rows of crates in the upper compartment close to the evaporator received better cooling effect with temperature ranging from 267K-273K (see Fig.11). In the lower compartment, the inner three rows of crates of upper layer had good temperatures ranging 272K-275K. This is due to reduced gap between the evaporator and the upper layer of crates. Consequently, there was an increase of about 5% in the number of products below the acceptable temperature compared to the case-1. However, higher temperature was observed in the bottom layer of lower compartment as well as upper compartment in products placed farthest from the evaporator. It was due to the fact that evaporator with a smaller capacity was used in this case (1.5-ton) which had an inlet air velocity of only 6.5 m/s. Thus, the air distribution on the outer side of the cargo was poor which resulted in a higher temperature, in the range of 287K-290K.

3.3 Modified chamber design with horizontal shelving and 40 crates of products (Case-4)

From Fig.12, it can be observed that the upper compartment is empty allowing only the lower compartment evaporator for operation. As in this case

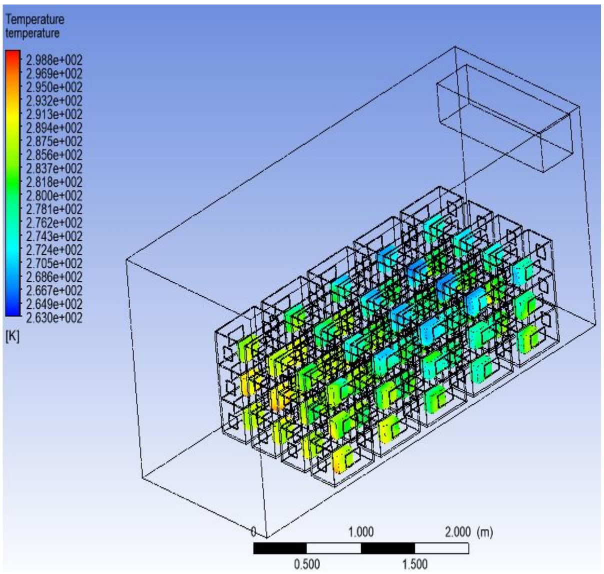


Fig. 9. Temperature distribution in the chamber and around the stored products for the typical compartment design and product storage in Bangladesh (Case-1).

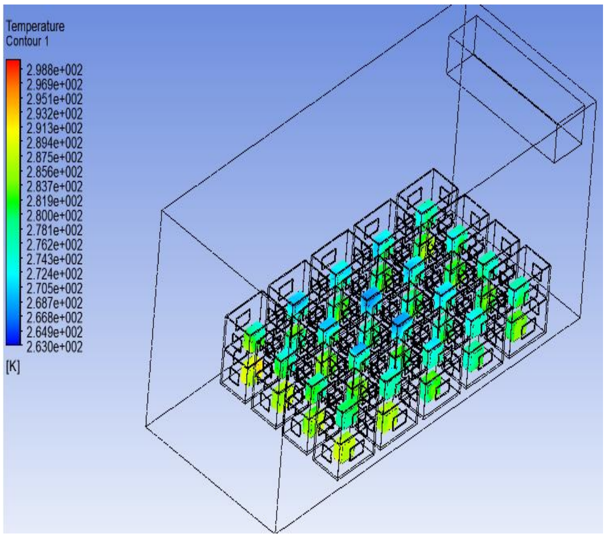


Fig. 10. Temperature distribution in the chamber and around the stored products for the typical compartment design and 40 crates of product storage (case-2).

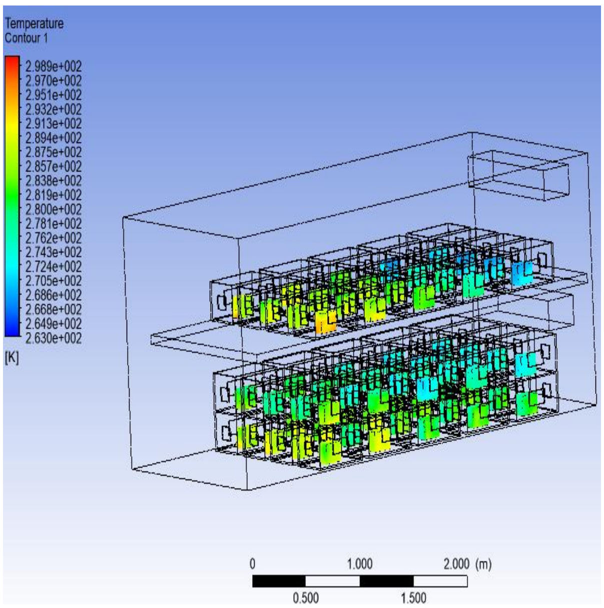


Fig. 11. Temperature distribution for the modified compartment design with horizontal shelving and 60 crates of stored goods (case-3). The temperature distribution is better than the conventional cases.

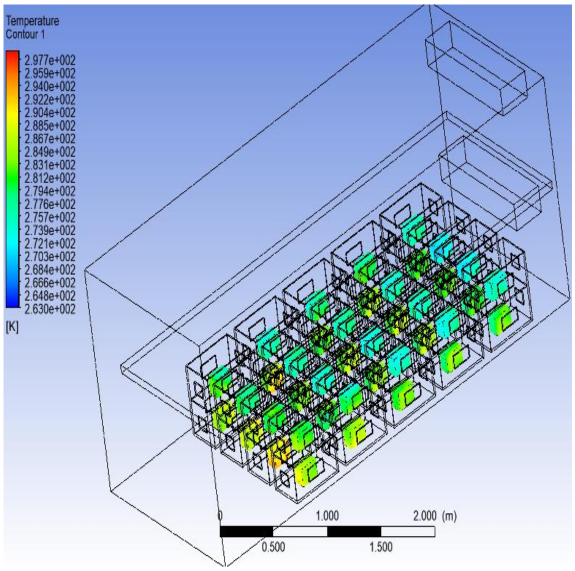


Fig. 12. Temperature distribution for the modified compartment design with horizontal shelving and 40 crates of stored goods (case-4). The upper chamber is empty, the products are in the bottom chamber, and only the bottom refrigeration unit is operational.

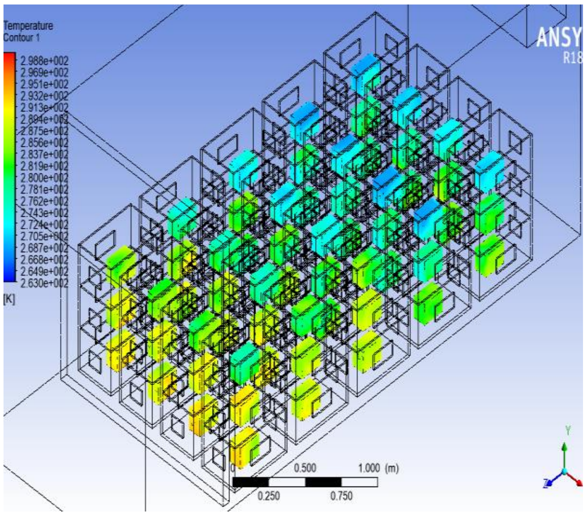


Fig. 13. Improved temperature distribution for the modified compartment design with vertical partitioning and 60 crates of stored goods (case-5).

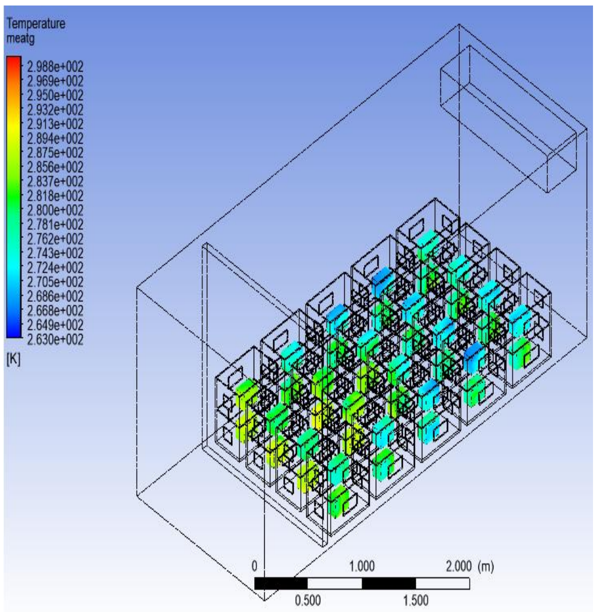


Fig. 14. Temperature distribution for vertical partitioning and 40 crates of stored goods (case-6).

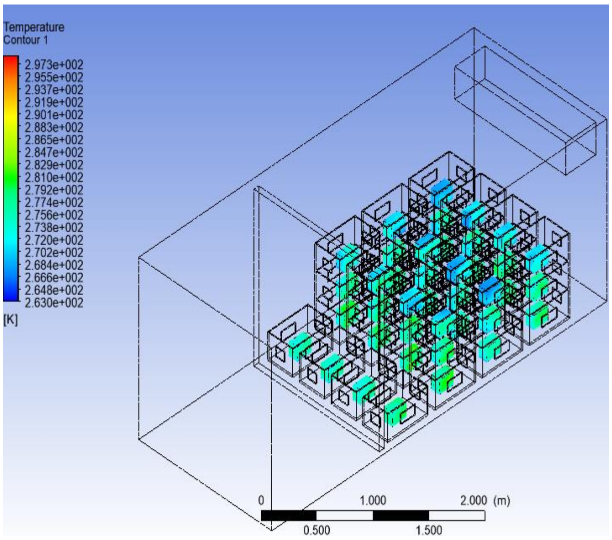


Fig. 15. Temperature distribution for vertical partitioning and special storage pattern with 40 crates of stored goods stacked in 3-layers (case-7). The temperature distribution was observed to be the best for this case with 100% of the stored goods within acceptable temperature limit

only one (out of two) refrigeration unit of 1.5-ton capacity was operational, the overall thermal performance was quite poor. In addition, another contributing factor was as the upper evaporator was not operational and the upper compartment was at 300K. So, there was heat transfer via convection between the compartments, resulting in a higher temperature of the lower compartment as well. Although the upper 4 rows of crates received better cooling effect and the upper layer crates were almost same in average temperature distribution with the previous case of horizontal shelving (case-3), the lower layer crates showed poor temperature distribution. However, the positive aspect of this case was that only one-half of the power was consumed compared to all the other cases observed in this study. There was a decrease of about 12.5% in the number of products below acceptable temperature limit compared to that in case-2.

3.4 Modified chamber design with vertical partitioning and 60 crates of products (Case-5)

In this case, a vertical partition was placed with 60 crates equally distributed in 3 layers (see Fig. 13). From the air circulation inside the refrigerated chamber, it can be seen that the air flow was confined within the region between the vertical wall or barrier and evaporator due to the placement of the partition and it improved overall cooling performance. The uppermost layer of crates received better cooling effect with temperatures averaging 273K-274K. But the temperature of the rest of the layers was higher, averaging 283K. This high temperature was due to the small clearance of only 80 mm between the crates. There was an increase of about 7% in the number of products below the acceptable temperature compared to the case-1.

3.5 Modified chamber design with vertical partitioning and 40 crates of products (Case-6)

Similar to the previous case but by placing 40 crates equally distributed in 2 layers with 20 crates each, an overall improvement was observed in the product temperature (see Fig.14). The upper layer of crates received better cooling especially the first three rows of crates placed nearer to the evaporator having temperature around 272K-274K. Due to the vertical partition, the flow of air was confined within the smaller space compared to the first four cases and it circulated around the products. There was more space for flow of air to travel to reach the farthest point in the refrigerated chamber as there was only 2 layers of crates. This configuration had improved average temperature distribution in comparison to Case-2. Although the maximum temperature of 286K was observed with a product placed at the bottom layer close to the vertical wall or barrier, there was an increase in number of products below acceptable temperature by about 3% in comparison to the conventional case. (Case-2)

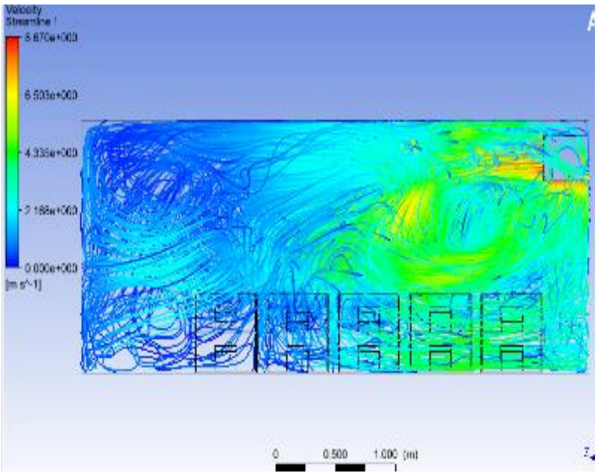
3.6 Modified design with vertical partitioning and storage pattern with 3 layers of products (Case-7)

In this case a special storage pattern of crates was implemented. Rather than placing 40 crates in 2 layers, an extra third layer was created by placing 16,12,12 crates in bottom, middle and upper layer, respectively (see Fig.15). As there were 4 rows of crates compared to the 5 rows in the previous designs, it allowed the vertical partition to be placed nearer to the evaporator by 510 millimeters resulting in a smaller space to cool. A definite improvement was observed as there was about 6.5K average temperature drop over the conventional design case (Case-2). Maximum temperature of 276K was observed in this configuration which was the lowest among all the cases studied. An important factor for this improvement was the fact that all the crates were placed closer to the evaporator and there were some spaces near the vertical partition for the air to circulate properly. The products in this configuration satisfied the acceptable temperature range.

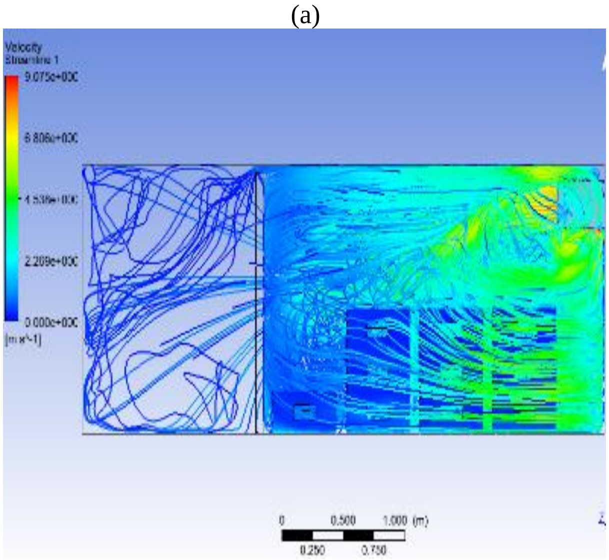
Case 2 and case 7 consists of two and three layers of crates respectively despite having the same number of total crates (40 crates). Hence, case 2 had more vertical distance between the evaporator and the upper level of crates which resulted in reduced air velocity and lower cooling efficiency. Despite having better cooling effect to the upper level crates near the evaporator in both cases, air circulation was confined within the inner region for the vertical partition which improved overall temperature of all the products of case 7. There were more crates far away from the evaporator in case 2 with open space near door side for which air circulated to the farthest distance of the cargo and this reduced the overall cooling effect of products especially the last row of crates. From the streamlines of both the cases, it can be observed that the air circulation was more uniform for case-7 due to the position of the vertical partition (see Fig. 16).

It can be seen from Table. I that among all the cases with 60 crates of stored goods, vertical partitioning of the compartment chamber (Case-3) has the highest amount of stored goods within the acceptable temperature limit.

For the cases with 40 crates, despite having more products in 273K or below region, horizontal shelving with a single operational refrigeration unit in one chamber (Case-4) resulted in poorer temperature distribution compared to the other cases. Modified design having vertical partitioning with 2 layers of crates (Case-6) has exhibited good thermal performance with more products within the acceptable limit. However, the modified chamber design case with vertical partitioning and special storage arrangement (case-7) showed the



(a)



(b)

Fig. 16. Streamlines for the storage of same number (40) of crates for - a) locally practice chamber design and storage pattern, and (b) modified chamber design with vertical partition and 3 layers of crate storage.

Table I. Number of products within different temperature range for each case.

Total Number of Crates	Cases	Number of Crates of Stored Goods within different Temperature Range: 273K or below	274K-277K	278K-281K	282K or above
60 Crates	Case 1	14	9	13	24
	Case 3	16	10	10	24
	Case 5	11	16	8	25
40 Crates	Case 2	8	13	7	12
	Case 4	10	6	8	16
	Case 6	10	12	9	9
	Case 7	21	19	0	0

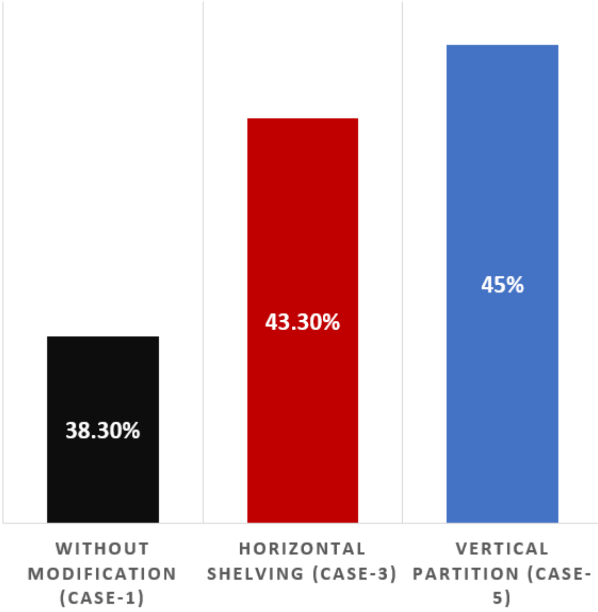


Fig. 17. Comparison of percentage of the amount of product within acceptable temperature (278K) for 60 crates of stored product in the refrigerated container.

most improved thermal performance with 100% of the stored goods within acceptable temperature.

The comparison of the percentage of stored goods that is within the acceptable temperature range for the different design and storage cases considered in this study is shown in Fig. 17 and Fig. 18. From Fig. 17, showing the bar chart comparing different cases with 60 crates of stored products, it can be seen that both the design modification results in better cooling performance and more products are within the acceptable temperature due to better temperature distribution for the modified cases. Vertical partitioning of the chamber results in the most improved thermal performance with 45% of products satisfying the temperature requirements compared to the 38% for the typical design case.

For the cases having 40 crates of products it can be seen that horizontal partitioning with empty upper layer and with one operational evaporator unit results in poorer thermal performance (see Fig. 18). However, in this case,

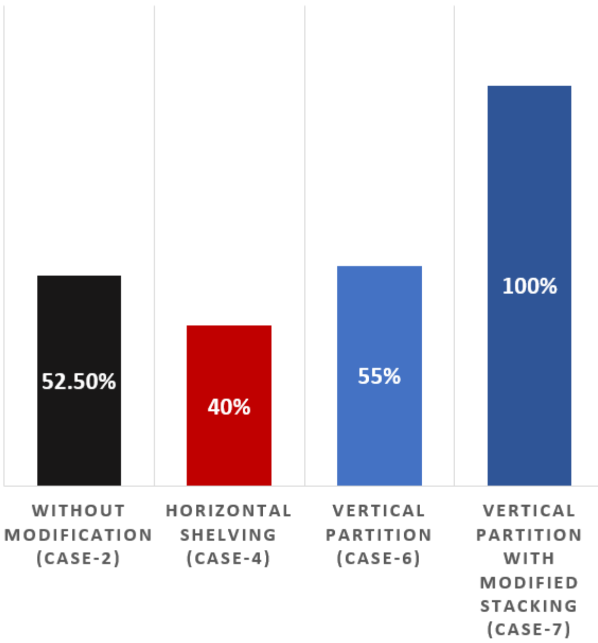


Fig. 18. Comparison of percentage of amount of product within acceptable temperature (278K) for 40 crates of stored products in the refrigerated container.

the energy consumption is one-half of the other cases. It can also be seen that design modification with vertical partitioning with similar product storage pattern as the conventional one improves the performance only slightly. However, for the vertical partitioning with special arrangement of the stored goods in 3 layers (case-7), it was found that the cooling performance improved significantly and all the stored good were found to be within the acceptable limit. In this case, the amount of stored good within acceptable limit was found to be almost 200% higher than the same for the conventional design case.

4. CONCLUSION

In this study, a detailed numerical study was conducted to assess the effect of design modifications in the form of horizontal and vertical partitioning of the compartment of refrigerated vehicles on the temperature distribution and air circulation within the refrigerated chamber. The results showed improvement in the cooling performance of the modified designs over the conventional chamber design and storage methods commonly practiced in Bangladesh. The thermal performance improved only slightly while using an adjustable horizontal barrier or shelving compared to the conventional design. The thermal performance improved more when vertical partitioning of the chamber was introduced. The percentage of products stored in the chamber within the acceptable temperature increased significantly (almost 200% in the case of vertical partition and modified storage pattern) when the chamber was vertically partitioned. Although thermal performance was poor in one of the cases with horizontal partitioning, the energy consumption was 50% compared to the other cases discussed in this study.

The design modifications discussed in this study are quite simple which would allow the local manufacturers to easily implement them in existing refrigerated trucks and the new trucks which are converted into refrigerated trucks. Further studies are being carried out to explore other options to improve the overall energy efficiency and thermal performance of the refrigerated vehicles.

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