Proceedings of the 7th World Congress on Momentum, Heat and Mass Transfer (MHMT'22)
~~Lisbon, Portugal~~ Virtual Conference – April 07 – 09, 2022
Paper No. ENFHT 224
DOI: 10.11159/enfht22.224

Analysis of Thermal Performance of Different Materials and Configurations for Insulation Walls of Transport Refrigeration Vehicles

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Abstract – The transport refrigeration system is a vital part of the cold chain. Despite this, there is a substantial lack of knowledge and progress in the adoption of appropriate material, configurations, and thickness of the insulation wall for transport refrigeration vehicles. Local body manufacturers, particularly in Bangladesh, employ several non-scientific conventional approaches to optimize the abovementioned parameters of the insulation walls of reefer vehicles during the manufacturing process, resulting in a lower energy efficiency. In this study, the thermal performance of several insulation materials such as polystyrene, polyurethane, aerogel, and vacuum insulation panels (VIP) is analyzed numerically by using the 3D finite element method. Taking the weather condition and solar irradiation in Bangladesh into account, a transient thermal analysis is carried out to compare the traditionally employed configurations of insulating walls in Bangladesh with several proposed alternatives. With respect to the traditionally used polystyrene, polyurethane, aerogel and VIP exhibit around 33%, 54%, and 84% less heat flux at the peak hour through the wall from outside for the same insulating configuration and thickness, respectively. Multiple proposed configurations consisting of reflective metallic foil (RMF) and air-gap reduce the heat flux by 35% up to 60% compared to the conventional ones. Moreover, several sandwich panel configurations are introduced which demonstrate about 20% to 70% reduction in heat gain. In addition to the degradation of insulator performance due to ageing, the effect of body materials such as fiber-reinforced-polymer (FRP), fiberglass, stainless steel, and mild steel on the thermal performance of insulation walls is investigated in the context of the weather condition and usage pattern of refrigerated vehicles in Bangladesh.

***Keywords*:** Cold Chain, Transport refrigeration Vehicle, Insulation, Configurations, Transient Analysis, Ageing.

1. Introduction

The term "cold chain" refers to the continuous transportation and distribution of perishable goods, such as vegetables, fish, meat, and pharmaceuticals, while maintaining a favorable temperature to retain the desired quality for consumers. Transport Refrigeration (road, marine, air) is one of the vital elements of cold chain system. Refrigerated road vehicles are one of the biggest components of the transport refrigeration system [1]. Global road freight transit is expected to rise at a 2.5 percent annual rate by 2030 [2]. In 2016, food (excluding fish) exports and imports exceeded the value of exports and imports in 1995 by more than three times [3].

One of the major concerns for the refrigerated vehicles is to maintain a desired temperature for the perishables by preventing heat transfer from outside to the inner compartment. Minimizing the external environment's impact such as solar irradiation, temperature on the refrigerated compartment, is critical for improving the thermal performance of the reefer vehicle. The environmental implications associated with greenhouse gas emissions from the transport refrigeration vehicles were examined by Tassou et al. [4]. It is estimated that the refrigerated transport sector consumes around 15% of global fossil fuel energy and there has been an increasing interest in the recent decades to optimize these systems to mitigate their environmental impact [5].

It is obvious from the environmental, economic, thermal, and mechanical point of view that insulation system of the reefer vehicle is one of the most significant factors to gain higher efficiency and thermal performance in the cold chain system. Lawton et al. [6] reviewed the state-of-the-art insulation materials such as polyurethane, aerogel, and vacuum insulation panels (VIP) that have been utilized in refrigerated transport since the phase-out of CFC and HCFC refrigerants. To minimize the energy consumption, Adekomaya et al. [7] studied alternate external walls for transport refrigeration vehicles by utilizing insulating materials with low thermal conductivity and low weight. By using a 2D transient thermal model, Glouannec et al. [2] investigated the insulating wall of a refrigerated panel van experimentally and numerically.

Bahadori et al. [8], Soylemez et al. [9], and others have studied the optimum insulation thickness for the compartment of reefer vehicles.

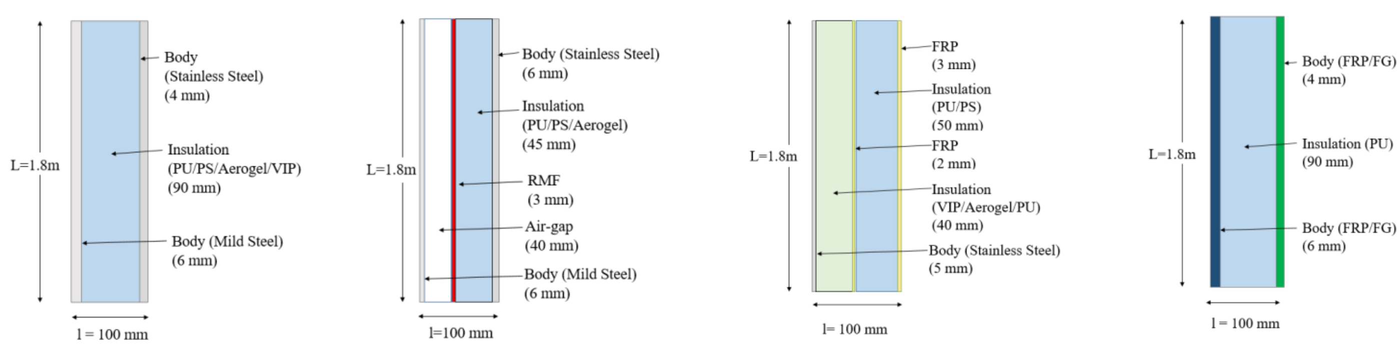
The use of reefer vehicles is increasing at a tremendous pace in Bangladesh in the recent years [10]. Diesel engine driven transport refrigeration vehicles with locally retrofitted body are used predominantly in Bangladesh. The homogeneity of the temperature and air flow inside the refrigerated compartment in the context of Bangladesh was investigated by Imtiaz et al. [11] using CFD simulations. Islam et al. [12] carried out a numerical analysis on the thermal performance of reefer vehicles with conventional product loading patterns used in Bangladesh and proposed several alternate storage patterns for improved performance. Polystyrene has been utilized as the major insulating material for a long time in Bangladesh by local manufacturers due to its low cost, while polyurethane has been introduced recently due to its superior thermal performance [10]. However, the local manufacturers use non-scientific, traditional methods for selecting the insulation materials, thickness of insulation wall and several other parameters without any consideration for energy efficiency. No study could be found in the open literature analyzing the thermal performance of the insulating wall configurations utilized in Bangladesh.

In this study, the thermal performance of locally used insulator configurations in Bangladesh is analyzed numerically and is compared to the same of several alternate configurations in search for an improvement in the insulation performance. Additionally, by using transient thermal analysis for sixteen hours of a day, variation in peak heat flux permeation through the refrigerated wall for different insulation materials is investigated. Moreover, several wall configurations, economical and easy to avail, are proposed as the alternatives for the traditionally used insulation walls in Bangladesh. Effect of body materials on the thermal performance of the insulation wall and the ageing effect of insulation materials considering the weather condition of Bangladesh are examined and reported.

2. Materials and Methods

2.1. Physical Modeling

To investigate the thermal performance of insulation wall of transport refrigeration vehicles, several configurations were analyzed. As per the data collected from local industry, a wall 4.25 meter long, 1.8 meter high, and 100 millimeter thick was used in this study [10]. To begin with the reference (local) configuration, the model shown in Fig.1(a) was analyzed primarily. In this configuration, mild steel (MS) was used outside of the wall as the body material, then insulation material inside, and finally stainless steel (SS) was placed as the inner body material. This study focuses mainly on four insulation materials, e.g., polystyrene (PS), polyurethane (PU), aerogel, and VIP. The thermal performance of polyurethane, aerogel, and VIP was compared to that of polystyrene which is widely used in Bangladesh locally. Additionally, performance of several proposed configurations containing Reflective Metallic Foil (RMF) and air-gap were analyzed. The effect of body material on thermal performance replacing SS and MS with FRP and Fiber glass (FG) was assessed. The thermo-physical properties of different materials used in the analysis of the present study are provided in



(a) (b) (c) (d)

Figure 1: Schematic of insulation wall (a) reference (local) configuration, (b) alternate configuration with RMF and air-gap, (c) alternate configuration of sandwich insulation panel, and (d) local configuration with varied body metal.

Table 1 [13]. In total, this study can be divided into five scenarios as presented in Table 2.

Table 1: Thermo-physical properties of different materials [13]

Property	PS	PU	Aerogel	VIP	MS	SS	FRP	FG	RMF
Density, ρ(Kg/m^3)	35	50	150	200	7800	7750	1600	2000	35
Thermal Conductivity, λ(W/m.K)	0.035	0.022	0.015	0.005	52	15.1	0.6	2	0.035
Specific-Heat, Cp (J/Kg.K)	1500	1400	1000	800	425	480	1200	700	1000

Table 2: Different scenarios, considering the variation in insulation material, thickness, and configuration of the insulation wall, that were examined in the present study.

Serial No.	Case scenario	Parameters studied	Geometric configuration (outside to inside)	Thickness of different layers (outside to inside, mm)
A	Comparison of the performance of the insulators in the reference configuration for the same thickness	Incoming heat flux (HF) at the inner compartment and temperature at the inner wall	Refer to Fig.1 (a)	6, 90, and 4
B	Performance of three configurations (RMF_1, RMF_2, RMF_3) with the reflective metal foil (RMF) and air-gap	Incoming HF at the inner compartment and inner wall temperature	PS, PU, Aerogel employed as insulator for RMF_1, RMF_2, RMF_3 respectively. Refer to Fig.1(b).	6, 40, 3, 45, 6 (for each configuration)
C	Effectiveness of five sandwich insulation panels or configurations (SC_1, SC_2, SC_3, SC_4, and SC_5) SC = sandwich configuration.	Incoming HF at the inner compartment and inner wall temperature	SC_1: SS, VIP, FRP, PU, FRP; SC_2: SS, VIP, FRP, PS, FRP; SC_3: SS, Aerogel, FRP, PU, FRP; SC_4: SS, Aerogel, FRP, PS, FRP; SC_5: SS, PU, FRP, PS, FRP; Refer to Fig.1 (c)	5, 40, 2, 50, 3 (for every configuration)
D	Thermal performance of the wall replacing body metals with FRP and FG	Infiltrated HF at the inner compartment	(a) FRP, PU, FRP (b) FG, PU, FG; Refer to Fig.1 (d)	6, 90, and 4 (for both (a) and (b))
E	Ageing effect on insulator (PU) in the weather conditions in Bangladesh	Incoming HF at the inner compartment	MS, Insulator, SS	6, 90, and 4

2.2 Simulation Procedure

Commercial software Ansys Mechanical was used to conduct the numerical analysis of different insulation wall configurations of transport refrigeration vehicles. By utilizing 3D finite element method in Ansys, transient thermal analysis was used to investigate the time varying thermal performance. The time length considered for this analysis was from 5.00 AM to 9.00 PM, a total duration of 16 hours. To investigate the thermal performance of perishables during a critical seasonal period, solar heat flux irradiation and ambient temperature data were taken for the date 25 June in the context of Bangladesh particularly in Dhaka region [14, 15]. The temperature and incident solar irradiation data were provided for this analysis for 16 hours with an interval of 30 minutes. A convection coefficient of 12 W/m2K was applied to the wall's outside surface [16], whereas a convection coefficient of 3 W/m2K was applied to the wall's inner surface [2]. At the outer wall, an emissivity of 0.90 was applied [17]. But it was neglected for the inner wall due to the small temperature difference between the inner surface and its surrounding. For the configuration containing RMF and air-gap layers, an emissivity of 0.05 for RMF and 0.9 for other adjacent wall of air-gap were applied [18].

3. Results and Discussion

As per the scenarios stated in Table 2, this section is subdivided into five categories (A to E) for explaining the findings of the present study.

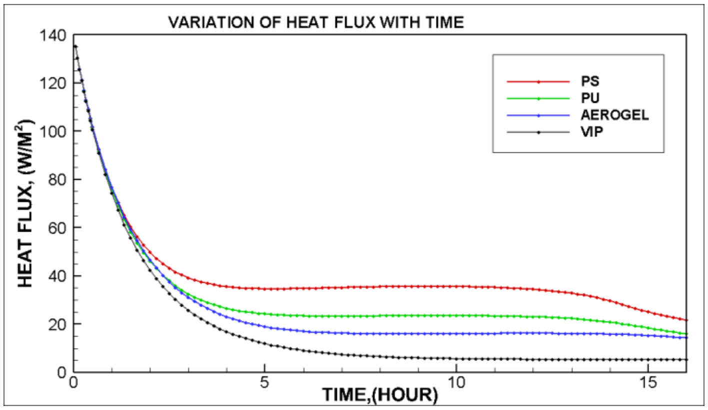
3.1 Comparison of the performance of the insulation materials for the same thickness (Scenario A)

The thermal performance of the four selected insulation materials, PS, PU, Aerogel and VIP, has been compared for the same condition and same thickness of insulation, which is shown in Fig. 2. It can be seen from Fig. 2 that although PS is the most widely used insulation material in Bangladesh (mostly due to its low price), it exhibits inferior insulation performance compared to the rest. By taking this thermal performance of PS as the reference (Ref_ps), it is evident from Table 3 that PU foam, Aerogel and VIP allow 32.6%, 54.3%, and 84% less heat flux than that of PS at peak time of solar irradiation (at about 15:00), respectively. It can also be seen from Fig. 2(a) that the incoming heat flux at the inner compartment is the highest for PS and lowest for VIP for whole sixteen hours of transient analysis.

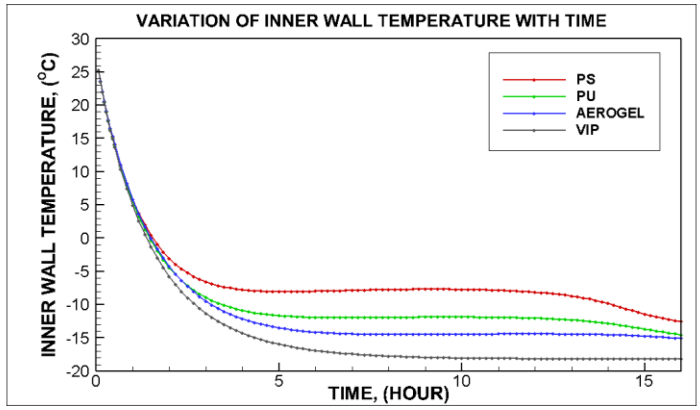
At the start of the analysis, due to the considerably high temperature difference (between the inner wall and inner compartment), large amount of incoming heat flux can be seen in the first few hours. It is also clear that the influence of the outside environment on the heat flux penetration is much lower for the aerogel and VIP insulation due to their very low thermal conductivity and high volumetric heat capacity (Fig. 2(a-b)). For the same reasons, the temperature gradient across the thickness of the insulation layer is maximum for VIP and lowest for PS (Fig.3).

3.2 Analysis of thermal performance for proposed configurations with RMF and air-gap (Scenario B)

In this case, thermal performance of 100 mm insulation panel containing air-gap and RMF of high reflectivity, accompanied by half of the insulation material used in the reference local configuration, is investigated. In the configurations containing RMF, the air-gap is an indispensable part to make RMF capable of acting as a radiant heat barrier. No heat will be reflected on the RMF layer of a sandwich insulation panel without an air-gap, rather heat transfer will be in a conductive mode through the RMF. Despite only utilizing one-half of the insulation material, it can be observed from Fig. 4(a) that the peak heat fluxes for cases RMF_1, RMF_2, and RMF_3 are significantly lower in comparison to the reference case with PS. The improvement in obtaining the desired inner wall temperature is shown in Fig. 4(b). It is found that the studied cases, denoted as RMF_1, RMF_2, and RMF_3, allow 14.6%, 40% and 56.3% less peak heat flux, respectively, with respect to the reference case scenario with PS. While comparing these proposed configurations with the locally emerging configuration of PU, it can be seen from Fig. 4(a) that RMF_2 and RMF_3 cases still allow less peak heat flux whereas the RMF_1 case allows more heat flux due to the inferior insulation performance of PS. Moreover, because of the utilization of lesser material and comparatively inexpensive RMF with air-gap, these recommended cases are cost effective and can also be easily implemented.



(a)



(b)

Figure 2: Comparison of the (a) incoming heat flux at the inner compartment, and (b) inner wall temperature for the different insulation materials (PS, PU, Aerogel, and VIP) for the reference configuration of the insulation wall.

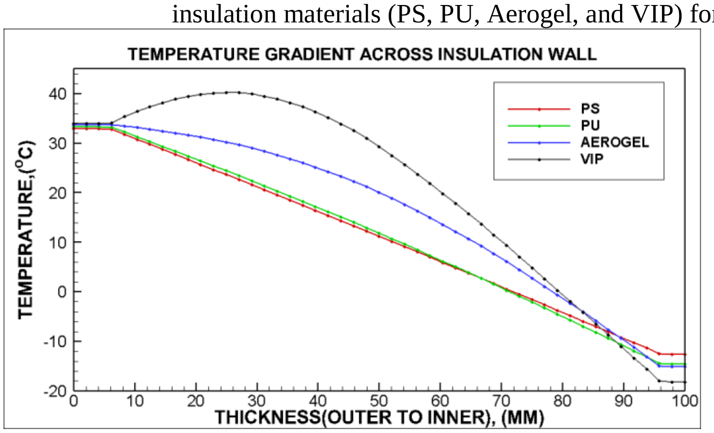


Figure 3: Temperature gradient along the thickness of the insulation wall

Table 3: Penetrated heat flux through the insulation at peak hour for the reference configuration

Insulation material	Heat Flux (W/m^2)	% Decrement of HF with respect to PS
PS	35.0	0.0
PU	23.6	32.6
Aerogel	16.0	54.3
VIP	5.7	84.0

3.3 Assessment of thermal performance for proposed configuration with sandwich panel (Scenario C)

Next, the thermal performance of several sandwich panel configurations consisting of different insulation materials is investigated (Fig 4(c), Fig 4(d)). It can be seen that the peak heat flux from the sandwich configurations SC_1, SC_2, SC_3, SC_4, and SC_5 is less than that of the reference local configuration employing PS (Fig. 4(c)). Besides, these cases also provide better insulation performance compared to the reference configuration containing PU material as insulation, which has begun to be used in the local market in the recent times. It is found that the proposed sandwich configurations SC_1, SC_2, SC_3, SC_4, and SC_5 permit 70.8%, 68.4%, 44.4%, 32.7%, 15.9% less heat flux at the time of peak solar radiation of the day than the reference local configuration of PS, respectively. The configuration where VIP is combined with PU to create a sandwich panel (SC_1) has shown superior performance than the other cases. Moreover, the improved insulation performance of the proposed cases (SC_1 to SC_5), by maintaining an inner wall temperature closer to desired temperature than that of reference case, is also evident from Fig 4(d).

3.4 Effect of body material on the insulation wall (Scenario D)

The amount of heat that can be transported through the wall is influenced by both the insulator and the body material. Fig. 5 shows the thermal responses of these body materials over a 16-hours period from 5.00 AM to 9.00 PM. For the first 5 hours, the wall comprised of SS and MS performed poorly in resisting heat transfer compared to the other body

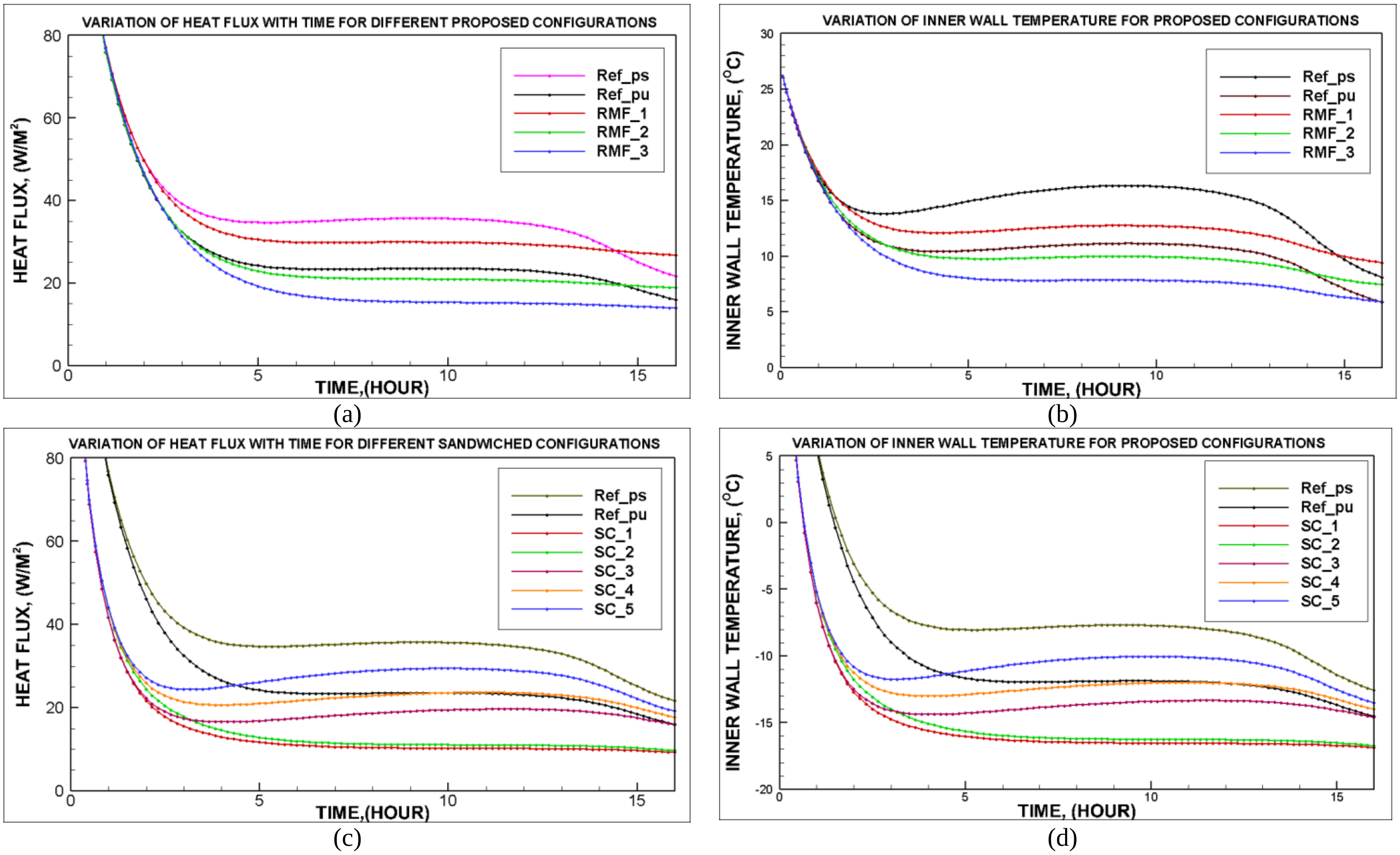


Figure 4: The variation of incoming heat flux at the inner compartment for different a) RMF configurations, and c) Proposed sandwich (SC) configurations compared with that of the reference configuration. The variation of the inner wall temperature for the configurations of RMF and SC shown in b) and d), respectively.

materials. After this time, there is no discernible difference in the penetrated heat flux through the different body materials. One of the main reasons for this type of outcome is that SS and MS have better thermal conductivity than FRP and FG. FRP, on the other hand, is 4.84 times lighter than SS and 4.87 times lighter than MS. Again, FG weighs 3.88 times less than SS and 4 times less than MS. Hence, the use of FRP and FG instead of using locally popular SS and MS as body materials could reduce the weight of the reefer system and minimize the fuel consumption.

3.5 Effect of ageing on the insulation performance (Scenario E)

The performance of insulators degrades over time due to the interaction with the environment. In Fig. 6, the incoming heat flux through the wall into the interior compartment over a time span of 20 years is shown considering both normal (dry) and humid weather condition of Bangladesh. From Fig. 6, it is found that the annual increments of peak incoming heat flux for the first two years for humid condition are 7.7% and 6.3%, respectively, which is higher than the annual heat flux increments for the other years. This is because the thermal conductivity of insulator (PU) rises significantly, about 8% annually due to the migration of water vapor in the insulator in humid conditions, and this migration is prominent for the first two years [19, 20]. On the other hand, the replacement of blowing agent by air continues over the entire lifespan of the insulation material, which is responsible for an increment of thermal conductivity by about 5% annually for both humid and normal (dry) weather conditions [21]. According to the local manufacturers of Bangladesh, an insulation wall for transport refrigeration vehicles is allowed to be used for more than 15 years [10]. Locally, water is employed as the

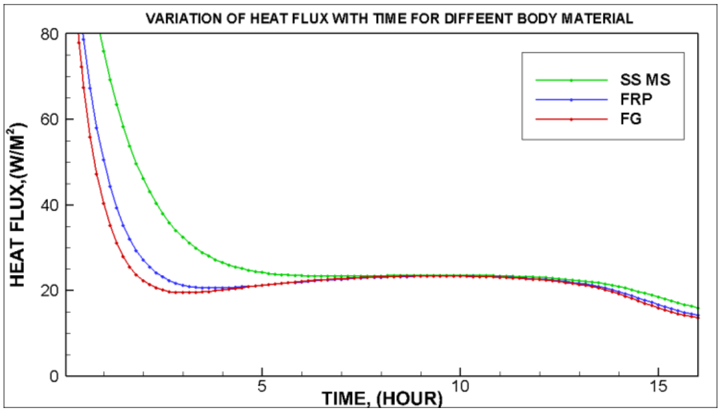


Figure 5: Comparison of the performance of different body materials in the insulation panel

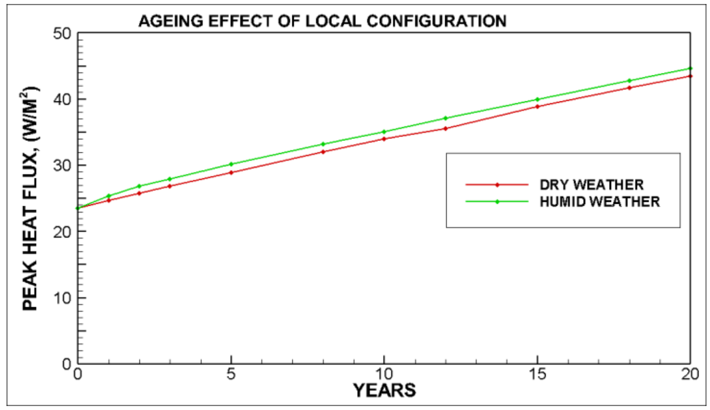


Figure 6: Ageing effect on insulation considering both humid and normal (dry) weather conditions

blowing agent for PS, PU foams, which results in greater deterioration of the insulating wall than when HFC or HCFC agent is used due to the rapid diffusion of blowing agent. Therefore, ageing effect has a substantial impact on the thermal performance of the reefer vehicles in Bangladesh.

4. Conclusion

This study presents a numerical analysis to compare the performance of different insulation materials for adopting the appropriate insulation material and configuration in the context of the weather condition and usage pattern in Bangladesh. It is found that PS, the insulation material most widely used locally, provides the poorest insulation performance with high heat infiltration. However, it is promising that some manufacturers have started using PU foam which provides better performance (allows about 33% less peak heat flux compared to PS). After a systematic analysis, several insulating wall configurations are recommended for use in Bangladesh as these configurations are found to provide superior thermal efficiency by allowing less heat flux into the refrigerated compartment (allowing up to 70% less heat flux) and are suitable from the economic point of view as well. Since locally used aluminum and steel have shorter lifetime and poor thermal efficiency, FRP, FG, or other composite fiber can be utilized as body material along with the insulation wall to achieve better energy efficiency. It is also found that the weather condition in Bangladesh can have significant ageing effect on the insulation material which subsequently has a substantial impact on the thermal performance of reefer vehicles.

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