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Minimizing energy consumption in refrigerated vehicles through alternative external wall

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ABSTRACT

Transporting fresh foods and raw agricultural produce have been widely acknowledged as a critical aspect of food chain. Raw fresh food must be conveyed at a low temperature conditions to preserve quality and prolong the shelf life of transported food. This paper takes an insight look at food transport system and proffers a sustainable ways of reducing energy consumption in diesel engine driven vapour compression system. Many studies have reported that 15% of world total energy is used in food preservation while some authors have predicted additional 2% annual increment of energy demand to sustain food chain. In the course of this study, the authors pragmatically identified sources of energy demand in food transport and maintained that the best approach to minimise energy consumption in refrigerated vehicles is to find a light weight and low thermal conductivity material as the external wall of refrigerated vehicles. This research is of high interest in view of continuous rise in earth temperature occasioned by emission of carbon monoxide from fossil fuel. The authors further showed that the usage of aluminium sheet as external wall of refrigerated vehicles reduces the longevity of insulation which increases heat infiltration into the cooling chamber thereby aggravating energy demand.

Contents

1. Introduction

Refrigerated road vehicles are of considerable quantities worldwide as evidenced in the latest data released by Browne et al. [5] that over 400,000 food transport system exist and many thousands of other forms of refrigerated transport systems are used to distribute chilled and frozen foods throughout the world. This report presented a dire and grave situation in view of energy demand to sustain these refrigerated vehicles. Bahadori and Vuthaluru [3] were among many researchers to discuss the environmental implication of maintaining this high numbers of food transport without developing a road map to contain the attendant implication of fossil fuel consumption. Sustaining the shelf life of fresh food must be done with best international practises and it is of interest to protect the climate from further descending into dungeon. Refrigerated vehicles have been a key driving force in preserving quality and its importance cannot be overemphasised.

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Nomenclature

K=U	Overall heat transfer coefficient (W/m^2K).
h_i	Convective heat transfer coefficient for inside surface of refrigerated chamber(W/m^2K).
h_o	Convective heat transfer coefficient for outside surface of refrigerated chamber(W/m^2K).
U_{ins}	Overall heat transfer coefficient of an insulated wall (W/m^2K).
Q	Heat flux (W).
PCM	Phase change material.
R_{ins}	Internal resistance of wall (m^2K/W).
R_{wall}	Internal resistance of wall (m^2K/W).
X	Insulation thickness (m).
T	Temperature (K)
T_e	External temperature (K)
T_i	Internal temperature (K).
S	Mean surface (the geometric mean of external and internal surface) (m^2).

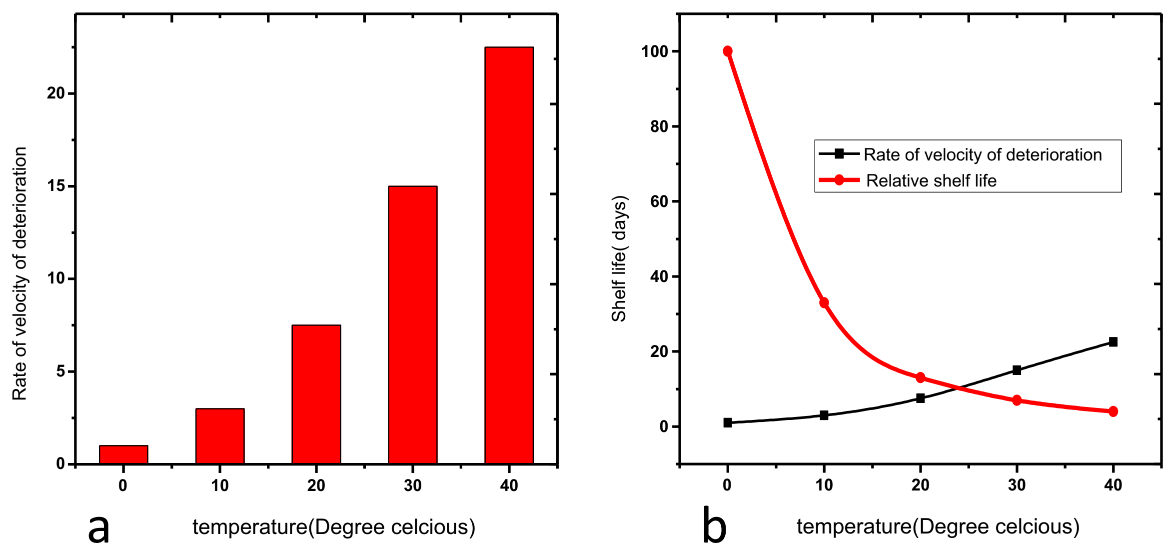

Fig. 1. (a) Impact of sudden rise in ambient temperature on rate of deterioration of perishable raw food (b) Prediction of shelf life after sudden rise in ambient temperature. Adapted from Salveit [25].

Fig. 1(a) showed that as the external temperature increases the rate of deterioration of perishable fresh food also increases while Fig. 1(b) further corroborated the fact that sudden rises in ambient temperature also affect the shelf life of fresh food. The temperature value at point of interception of the rate of deterioration and shelf life denotes the safe temperature value before minimum quality of fresh food is compromised. A lot of literatures have predicted that by 2030, global road freight transport will have grown by 2.5% a year [17,23,33,7] thereby resulting into high fossil fuel demand to maintain high thermal load. Therefore, in order to avoid the increased environmental impact of refrigerated vehicles, it would be of great interest to reduce their energy consumption, especially by improving and reinforcing insulation [13]. Insulated panel of refrigerated vehicles appeared to be only a medium to reduce heat infiltration into the cooling chamber [9,11]. Insulated panel are three layer plane structure where insulation typically polystyrene sandwiched between two thin layer of aluminium sheet [22]. Literature assessments have shown that many authors [28,31,32] have clearly reported various researches in insulating materials with low thermal conductivity, there seem no record on the impact of external wall on the insulation in one hand and on energy consumption in other hand.

Metallic external wall of the refrigerated vehicle is the conduit through which heat is transmitted into the cooling system of refrigeration system and every efforts must be directed to minimise the inflow of heat by improving insulation panel. Heat transmission through the external wall of most refrigerated vehicles continue to increase the thermal load of vapour compression system thereby resulting in energy demand in operational maintenance. These heat infiltrations remain a daunting challenges for most refrigerated vehicles [28]. Many researchers have proposed a more sustainable means of energy conservation in a refrigerated vehicles as the existing methods have not produced optimum results. Recent publications is also a testimony to the fact that the performance of insulation materials appear not to have produced a desirable results due to foaming properties of some insulations [1,24,34]. According to Tassou et al. [29], degradation of insulation properties through heat infiltration from external wall may lead to considerable rise in the thermal conductivity of such insulation. Söylemez and Ünsal [28] shows existing insulating materials and their respective thermal conductivity as illustrated in Table 1. Although, it is seen from the table that all the insulation value are low, this value may rise with continuous high ambient temperature.

Frequent door openings is also another widely-acknowledged medium of heat infiltration into the refrigerated chamber, resulting in the high thermal load [10,15]. The door opening must not be allowed to remain frequent as heat transmission could be aggravated which will increase the thermal load.

2. Thermal performance of refrigerated vehicles

The thermal load of insulated panel of refrigerated vehicles is measured by the value of its overall heat transfer coefficient (U-value) [14]. This value predicts the rate of heat infiltration through the external wall of a typical insulated panel and as the ambient temperature increases this U value tends to increase for metallic insulated panel. The implication of higher U value for metallic insulated panel is that the initial lower thermal conductivity value of sandwiched insulation rises thereby increases the heat transmission into the chamber. Many authors have reported some heat transfer model to predict thermal performance of refrigerated vehicles which gives an inflow of radiative heat transfer into the cooling chamber. Similar model were proposed by Wang et al. [32] which compared favourably with the relation developed by James [16]. These methods were primarily for estimating thermal conductivity value of insulated bodies at variable external temperatures. These afore-mentioned authors also reinstated that overall heat transfer coefficient (U) could be estimated once k value is known which may further predict the heat irradiation from the ambient temperature into the cooling chamber. According to Gvozdenac [14], overall heat transfer coefficient is defined by Eq. (1) and this requires constant external and internal temperature as well as constant stationary state which involves steady heat flow. This author further opined that any slight increase in overall heat transfer coefficient (U) may indicate that the thermal energy required in the refrigerated chamber may be high.

$$K = \frac{Q}{S(T_e - T_i)} \tag{1}$$

According to the study presented by Söylemez and Ünsal [28], the overall heat transfer coefficient is defined as the inverse of the total resistance to the heat flow and the authors derived the relation as shown in Eq. (2). This equation has been affirmed by other authors [6,8] to predict the maximum instantaneous cooling load required for a refrigerated chamber.

$$U = \frac{1}{R_{wall}} \tag{2}$$

The resistance of an uninsulated wall, R_{wall}, could also be referred as the summation of the surface resistance of heat convective transfer over all layers of the reinforcing wall as defined by the underlying equation.

$$R_{wall} = \frac{1}{h_i} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + ... + \frac{x_n}{k_n} + \frac{1}{h_o} \tag{3}$$

Söylemez and Ünsal [28] later defined the overall heat transfer coefficient of an insulated wall, U_{ins}, of a refrigerated chamber and included the resistance of the insulated panel. These authors thereafter defined overall heat transfer as shown in Eq. (4).

$$U_{ins} = \frac{1}{R_{wall} + R_{ins}} \tag{4}$$

These Eqs. (1)–(4) may be useful to predict the energy demand of a typical refrigerated vehicle. The estimated value of U_{ins} also predicts the longevity of the insulation whether its performance has been altered by heat infiltration through the ambient temperature.

3. Insulated panel of refrigerated vehicles

Axaopoulos et al. [2] have reported the optimum insulation thickness for a typical insulated panel and re-affirmed that the thickness of an insulation with different composition and orientation, may not after all reduce heat infiltration from ambient temperature into the cooling chamber. In a related work, Galos et al. [12] created a scenario for thermally insulated wall by developing optimum insulation thickness at different orientation in which the thickness was in the range of 7.1 cm–10.1 cm. This study also demonstrated that heavily insulated panel may not necessarily prolong longevity of insulation but may further added to the payload of the existing vehicles. In many scientific literatures, the impact of payload on energy consumption have not been established but recent technological innovation in field of manufacturing is an indication that lightweight materials could further save more energy compared with materials with weight advantage. Critical assessment of existing insulated panels may also show the metallic external wall could also promote quick ageing of the insulation. Sarier and Onder [26] also experimented a case study where a reasonable number of polyurethane (PU) rigid foams were heavily sandwiched in a metallic panel as new insulation materials. The authors eventually concluded that much difference seemed not to have been achieved to mitigate heat infiltration.

Table 2 clearly shows a typical refrigerated vehicle and the corresponding energy consumption. It can be seen that sustainable energy conservation system must be put in place to mitigate the overall side-effects of burning fossil fuel. The environmental implication is better imagined than experienced. Also reported in the

Table 1
Thermal conductivity(k) data for different type of insulation materials [27,28].

Type of Insulation	K_{ins} (W/m°C
Cellulose	0.043
Perlite	0.054
Fiberglass-Urethane	0.021
Extruded Polystrene	0.029
Urethane (roof deck)	0.021
Fiberglass(rigid)	0.033
Urethane(rigid)	0.024
Fiberglass(batt)	0.045

Table 3
Disadvantages of PCMs at the evaporator.

Shortcomings	Comment
Excessive rise in condensation temperature	Slow performance on cooling chamber Possible heat transfer from condenser to cooling chamber.
Tendency for compressor to overstretch its working limit.	Resulting in more energy demand. Frequent maintenance on the compressor.

Table 2
Refrigerated vehicle class and its corresponding fuel energy consumption [29].

Vehicle class	Distance travelled and fuel consumption (motive)		Fuel efficiency (motive)	Fuel consumption of refrigeration engine	Overall vehicle fuel efficiency (motive plus refrigeration)	Percent refrigeration energy to motive energy
	Km/day	l/day	Km/l	l/day	Km/l	%
Medium rigid	409	111.3	3.7	21.0	3.09	18.9
Large rigid	286	90.71	3.15	17.7	2.63	19.5
City articulated	335	112.33	2.98	26.1	2.42	23.2
32 t articulated	419	140.8	2.97	34.1	2.40	24.2
38 t articulated	486	159.62	3.04	24.9	2.52	15.6

Table 4
Criteria for PCM as energy storage materials.

Thermal properties	Physical properties	Chemical properties	Economic considerations
1. Phase change temperature fit to application	1. Low density variation	1. stability	1. Cheap and abundant
2. High change of enthalpy, melting point is near the temperature of use	2. High density	2. No phase separation	
3. High thermal conductivities in liquid and solid phases	3. Small or no sub cooling	3. Compatibility with container materials	
		4. Non-toxic, non-flammable, non-polluting.	

table is that a 38 t articulated vehicle requires almost 25 l per day for refrigeration engine. This is a difficult and highly demanding task in terms of resources and in the long term may not improve the value chain Table 3.

4. Existing technologies in mitigating heat transfer system

Mitigating heat transfer in refrigerated vehicles have been studied in many literatures and some of the existing approaches have not improved the cold chain. According to Tinti et al. [30], various insulation materials have been widely used as sandwiched insulation panel but the challenge of foaming properties of most insulation continue to weigh on its performance. In the light of the above, application of phase change material (PCM) for cold storage application appeared to have gained momentum in the last decade until some researchers [19–21,30,35,36] x-rayed some of the inherent shortcoming in PCMs. These authors, at different publications corroborated one another by emphasising the key disadvantages as reported in Table 4. The introduction of PCMs for energy conservation system in refrigerated vehicles continue to receive criticism as against its merit due to the fact that this concept is suitable for short distance delivery of perishable raw food. This shortcoming has made PCMs not popular as many perishable raw food are being conveyed over a long period of distance.

Some authors [4,18] have side-lined the application of phase change material in refrigerated vehicles. Some of their arguments were collated and presented in Table 3. This further heightened controversies around the application of PCMs.

5. Conclusion

This research study was aimed at generating ideas and innovation toward energy preservation and sustainability. As noticed in many literatures, refrigerated vehicles have been widely discussed and the concept of energy demand in this medium of transportation is still not solved. In the course of this research, it is clearly seen that there is still no better method to diesel engine driven food transport system and it is therefore important to explore better and reliable energy reduction technique. Insulated panel of a refrigerated vehicle remains the channel through which heat infiltration into the cooling chamber is checkmated. As defined by Gvozdenac [14], insulated panel is a three layered structure where insulation is sandwiched in-between two thin layer of metallic sheet. From all indications, the performance of insulated panel depends primarily on the thermal conductivity value (K) of sandwiched insulation. Many studies have raised concerns on the longevity of insulation in view of its sudden rise in its thermal conductivity value. Using metallic sheet as the cover wall for insulation could aggravate thermal conductivity value of insulation. This is as a result of high thermal conductivity of all metallic sheet and the ambient temperature continues to degrade the insulation through the metallic sheet. Based on the above, the authors believe that lightweight polymer material could be adapted as external wall which is one of the issue around energy drain. Another possible area of exploration could be fiber reinforced polymer composite which is generally reported to be lighter in weight and have better dimensional and tensile properties. More detailed work still need to be embarked upon on polymer material and its reinforcement properties. One possible advantage of these materials is its thermal conductivity value. Thermal conductivity of polymer related composite is generally low and it is much more difficult to dissipate heat in fiber reinforced composite when compared with aluminium sheet which is currently being used as external wall. With this new idea thermal load will reduce which will ultimately reduce global warming.

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