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Vacuum insulation in cold chain equipment: A review

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Abstract

In 2017, 11.41 million refrigerators and 1.85 million freezers were sold in USA alone; each unit consuming approximately 500 kWh/year with an average life expectancy of 12 years. Traditionally, fridges and freezers have been insulated with polyurethane foam (thermal conductivity >0.020 W/m.K). There is a significant scope of reducing the heat gain by the cooled interior space from external environment by employing better insulation materials such as vacuum insulation panels (VIPs) than polyurethane foam. VIPs can achieve a thermal conductivity of <0.002 W/m.K. This paper presents an overview of heat transfer theory for VIPs and historical research into VIPs suitable for fridges, freezers and reefer trucks. A refrigerator with 56% of its external surface area covered with VIPs is reported to reduce the energy consumption by 21% compared to that consumed when using polyurethane foam. This means a potential energy saving of 1260 kWh_p over the lifetime of a refrigerator and 5 billion kWh_p if 25% of all fridges were VIP insulated. A proportionate reduction in the concomitant carbon emissions is predicted.

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Keywords: Vacuum insulation panels; Refrigeration; Cold chain; Review.

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1. Introduction

In 2017, 11.41 million refrigerators and 1.85 million freezers were sold in USA alone [1], as seen in figure 1. Each refrigerator unit consumes approximately 500 kWh_p/year leading to total consumption of 6 MWh_p of electrical energy over its life time. Cooling up food contributes just 6% of the total thermal load of the fridge [2]; the major contributor being heat gain by conduction through the side walls, see figure 2. The rate of heat gain (q) is governed by the Fourier's law (equation 1).

$$q = -kA\frac{\Delta T}{l} \tag{1}$$

where, q is the heat gain in cold compartment from outside, k is the thermal conductivity of the wall, A is the cross-sectional area of wall, ΔT is the temperature difference across the wall and l is the thickness of the wall. Temperature difference, which depends on the cooling demand and ambient conditions, has an average value of 55 °C for fridges and 75 °C for freezers [2]. The marginal benefit one gets by decreasing temperature difference is not justified for the effort it requires. For example, a drop of 2 °C in temperature difference results in just 1.8% drop in electrical energy input. Decreasing wall area will mean decreasing volume of the fridge, which is again undesirable. Increasing insulation thickness can either mean increasing the outer volume or decreasing the inner volume of fridge both of which are undesirable from customer's perspective. The best option to reduce the heat gain through side walls is to employ insulation materials with lower thermal conductivity.

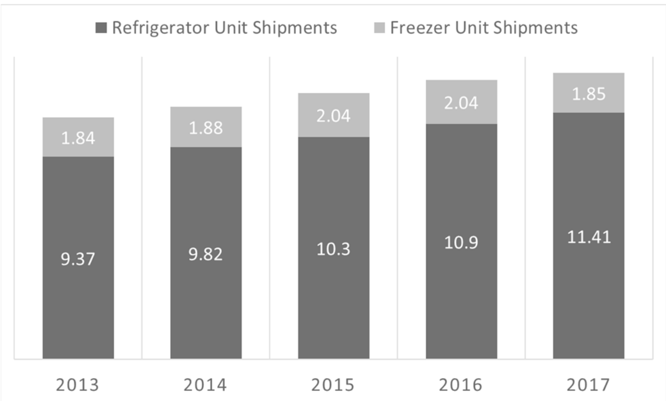


Figure 1. Refrigerator and Freezer sales data (in millions) for USA [1]

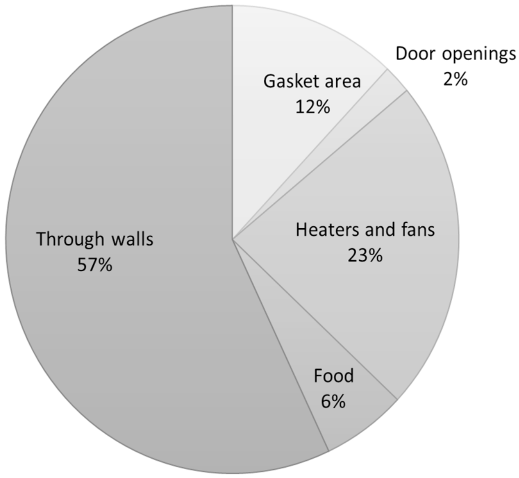


Figure 2. Major heat gain areas in refrigerator [2]

1.1. History of refrigerator insulation

Towards the last decade of 1800s, many American households stored their perishable food in an insulated icebox that was usually made of wood and lined with tin or zinc. In 1927 General Electric started supplying affordable commercial refrigerators named Monitor Top with 88.9 mm thick insulation [3,4]. Later, refrigerators were insulated using fiberglass, which offered a thermal conductivity (k) of 0.033 W/mK [5]. Poor lateral strength, water permeability and high thermal conductivity of fiberglass led to the adoption of rigid polyurethane foam (k = 0.022-0.035 W/mK) [6]. The rigid polyurethane (PU) foam additionally imparts mechanical strength to the walls.

PU foam can be either open or closed cell. While closed-cell foams have stronger resistance against moisture and air leakage, the material is much denser (30-50 kg/m^3), expensive (£950/m^3 - £2000/m^3) and has lesser thermal conductivity (k=0.020-0.030 W/mK) [7,8]. Open cell foams are lighter (7-20 kg/m^3), cheaper (£600/m^3 – £1200/m^3) and have higher thermal conductivity (k=0.030-0.040 W/mK) because the pores are filled with air [9,10]. Gases with lower thermal conductivity, such as n-pentane, isopentane and nitrogen, can be added to these pores for reducing overall thermal conductivity. After a growing concern over ozone layer depletion potential of chlorofluorocarbons /

hydro chlorofluorocarbons, R11 and R123 were phased out and blowing agents such as pentane and methylformate came into use. Since 2003, all polyurethane foams have been HCFC-free in the EU [11]. The substitution of environmentally harmful blowing agents led to an increase in the conductivity; foams blown with HCFC-123, HCFC-141b and CO_2, showed an increase of conductivity by 5.5%, 11.7% and 45% respectively as compared against CFC-11 blown foam after one year of ageing [12,13].

Currently, vacuum insulation panels are being increasingly considered as the potential next generation insulation for refrigerators due to excellent thermal properties (k = 0.002-0.008 W/mK [14]). Figure 3 shows the sale figures for VIP insulated fridges in North American and European regions.

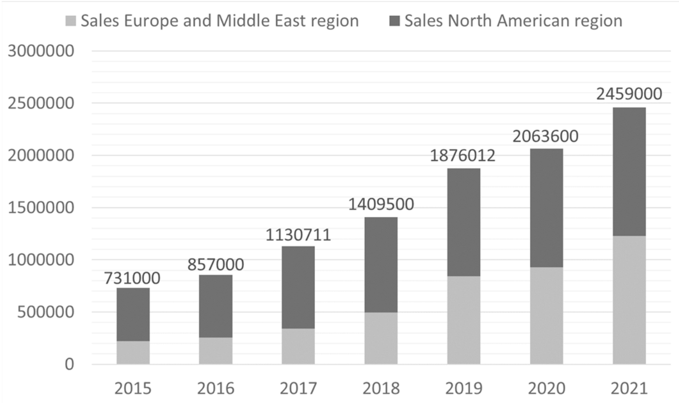


Figure 3. Historical and predicted sale volume of VIP insulated fridges in North America, Europe and Middle East

2. Vacuum Insulation Panels (VIPs)

It is well known that vacuum leads to supress convective heat transfer. Dewar flask, invented by Sir James Dewar, works on this principle. Forming a vacuum insulation panel, however, faces challenges such as large compressive forces caused by the difference between atmospheric pressure and the pressure in vacuumed space. For example, a compressive force of 4kN will act on the surface of an evacuated panel of area 200 mm x 200 mm held at a pressure of 10 mbars.

2.1. Basic structure and commonly used materials

In the conventional VIPs, a core material with high porosity and compressive strength is evacuated and sealed inside an envelope, see figure 4. The core material is desired to have low density and open cell structure. Several core materials employed in research studies and commercial products are mentioned in Table 1.

Table 1. VIP cores employed in research

Powder cores		Foams		Fibres		Composites	
Fumed silica	[15-17]	PUR foam	[12,26]	Glass fibres	[28,29]	Aerogel based composites	[31,32]
Aerogel	[18-22]	Phenolic foam	[27]	Stratified fibres	[30]	Fumed silica based composites	[33-36]
Other silicas	[23-25]						

2.2. Heat transfer phenomena in VIPs

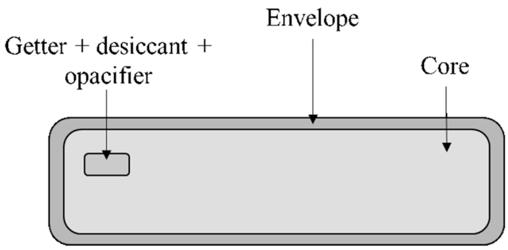


Figure 4. Schematic of a VIP

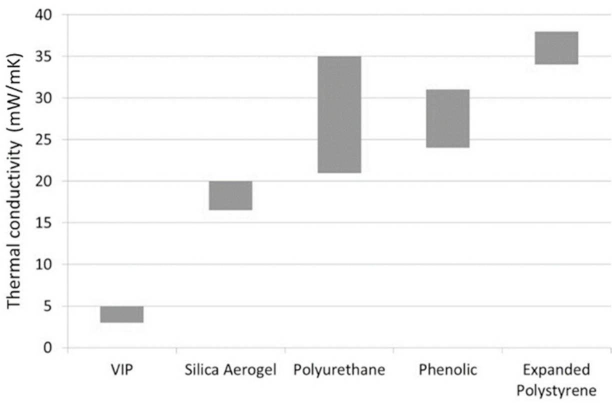


Figure 5. Ranges of typical thermal conductivities of conventional insulation materials and VIPs [51].

Although evacuation leads to suppression of convective heat transfer, but solid conduction, gaseous conduction and radiation still simultaneously exist in a VIP core. It is important to understand the factors on which these modes of heat transfer depend to characterise the thermal performance of VIPs. Effective thermal conductivity of an evacuated VIP core can be mathematically written as shown in equation (2).

$$k_{eff} = k_s + k_g + k_r + k_{coup} \tag{2}$$

where
k_s is the effective thermal conductivity of VIP core,
k_g is the gaseous conductivity,
k_r is the radiative conductivity,
k_{coup} is the coupling conductivity

2.2.1. Solid conductivity (k_s)

Solid conduction is a result of heat transfer through the matrix of core material. Its theoretical prediction is difficult due to a high degree of randomness in packing and defects. Fricke [37] presented an empirical correlation (equation 3) for solid conductivity.

$$k_s \propto \rho^{\alpha} \tag{3}$$

where ρ is the density of the material and α an index whose value is unity for foams and 1.5-2 for nanomaterials. This correlation provides a good starting point to get a relative value of solid conductivity and compare it across different materials, but it requires large amount of experimental data to calculate the absolute value of k_s and validate the value of α. It doesn't include the effect of factors like particle's properties including size, thermal conductivity, elastic modulus or Poisson's ratio or the orientation (in case of fibres). Kwon et al. [38] analytically calculated the solid conductivities of porous materials, such as powder, foam and fibre, using simplified elementary cell model, as summarised in Table 2.

Table 2. Analytical correlations for solid conduction [38]

Material	Expression	Solid conduction (k_s)
Powders	$k_p \left(\frac{96(1-\vartheta^2)P_{atm}}{E}\right)^{1/3} \geq k_s \geq k_p \left(\frac{3(1-\vartheta^2)P_{atm}}{E}\right)^{1/3}$	$0.0219\ W/mK \leq k_{s,silica\ powder} \leq 0.0634\ W/mK$
Foam	$k_s = \frac{4k_{st}t^2}{L^2}$	$k_{s,foam} = 0.005\ W/mK$
Fibre	$k_s = 16k_f \left[\left(\frac{\sqrt{2}\pi^4 E}{24P(1-\Pi^4)(1-\vartheta^2)}\right)^{1/3} + \frac{\pi^2}{4(1-\Pi)^3 sin^2\theta}\right]^{-1}$	$k_{s,fibre} = 0.0021\ W/mK$

In table 2, k_p is the thermal conductivity of a particle, P_{atm} the atmospheric pressure, E and ϑ the elastic modulus and the Poisson's ratio of a particle or a fibre strand, k_{st} the thermal conductivity of foam strut, t the thickness and the height of strut, L the length of a unit cell, k_f the thermal conductivity of a fibre strand, θ the orientation of fibre strands and Π the porosity.

For powders, Kwon et al. [38] assume that a minimum thermal conductivity can be calculated when the particles are arranged in simple cubic fashion having porosity of 0.48, whereas, in reality the porosity of powders used in conventional VIPs ranges between from 0.8 (for perlites) to 0.95 (for fumed silica and aerogel). A higher porosity significantly lowers the solid conductivity value for these materials. Also, the effect of factors like particle size distribution and surface roughness of particles on the thermal conductivity has not been covered by the model. In the case of foam, one requires values of thermal conductivity of foam strut and porosity to calculate solid conductivity. Porosity can be measured by porosimetry test, but thermal conductivity of foam strut is difficult to measure or compute. The values obtained by Kwon et al. [38] for typical materials are reported in table 2.

2.2.2. Gaseous conductivity (k_g)

The gaseous conductivity at vacuum pressures maintained inside a VIP core is lower than the thermal conductivity of free gas. This is because, at low pressures, the mean free path length of gas molecules increases due to which they are unable to transfer energy to each other and instead collide with the solid matrix walls [39] of narrow pore spaces. This is known as Knudsen effect. The gaseous thermal conductivity in pores can be calculated by employing Kaganer's model [40], equation (4):

$$k_g = \frac{k_g^0}{1 + 2\beta K_n} \tag{4}$$

where k_g^0 is the gaseous conductivity of free gas, β is a coefficient depending on accommodation coefficient and the adiabatic coefficient of the gas, and K_n is known as Knudsen number and is defined as the ratio of molecular mean free path length to characteristic size, or the distance between heat exchanging surfaces i.e. pore size. The mean free path length, l_g, can be calculated by equation (5).

$$l_g = \frac{k_B T}{\sqrt{2}\pi d_g^2 p_g} \tag{5}$$

where k_B is the Boltzmann constant, T is the temperature of the gas, d_g is the diameter of gas molecule and p_g is the

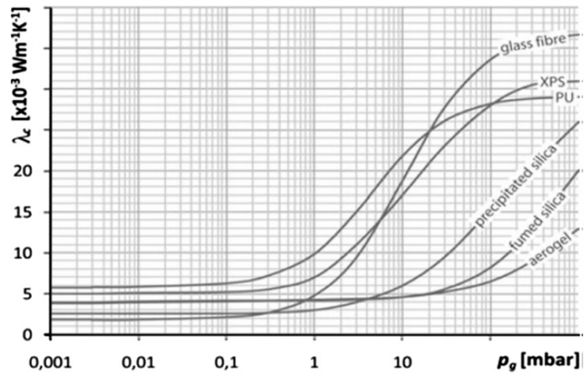


Figure 6. Variation of gaseous thermal conductivity with sealing pressure for core samples for various materials [41].

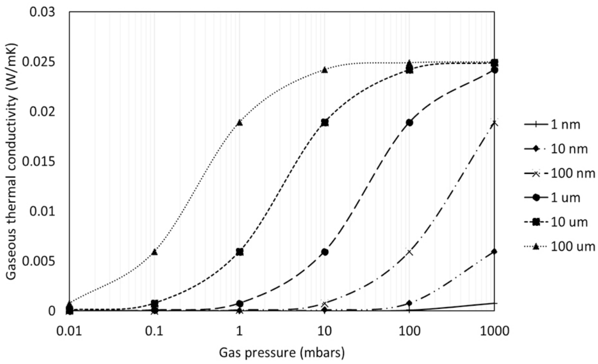


Figure 7. Variation of gaseous thermal conductivity with sealing pressure for core samples with varying characteristic pore size using equation (4).

gas pressure in porous media. Figure 6 shows the measured variation of effective thermal conductivity with sealing pressure for typical core materials [41]. Figure 7 shows the variation of gaseous thermal conductivity as a function of gas pressure for materials with varying characteristic pore size. Materials like aerogel and fumed silica, having mean pore size 2 nm – 10 nm, show remarkable overall thermal conductivity even at high sealing pressures because of their low gaseous thermal conductivity.

2.2.3. Radiative conductivity (k_r)

The amount of radiative heat transferred through a sample with large optical thickness and isotropic scattering is given by diffusion approximation provided in equation (6) [42].

$$q_r = \frac{-4}{3E_R}\frac{de_b}{dx} = -\frac{16\sigma n^2 T^3}{3E_R}\frac{dT}{dx} \tag{6}$$

where q_r is the one dimensional rate of heat transfer per unit area due to radiation, e_b the blackbody emissive power, E_R the Rosseland mean extinction coefficient, σ the Stefan Boltzman constant, n the refractive index of the material and $\frac{dT}{dx}$ the gradient of temperature in the direction of heat transfer.

The heat transferred by radiation mode can be expressed in terms of Fourier's law (equation 7).

$$q_r = -k_r \frac{dT}{dx} \tag{7}$$

Radiative conductivity (k_r) can be then derived from equations (6) and (7) as in equation (8):

$$k_r = -\frac{16\sigma n^2 T^3}{3E_R} \tag{8}$$

Specific extinction coefficient ($e_{\lambda,m}$) is an intrinsic property of a material and is a measure of scattering and absorption of electromagnetic waves caused by a material placed in the path of radiation. Fourier-transform infrared spectroscopy (FTIR) is used to calculate the radiative transmittance of materials by mixing them with potassium bromide [43,44]. Extinction coefficient ($E_{\lambda,m}$) is defined as product of density of the sample (ρ_s) and the specific extinction coefficient ($e_{\lambda,m}$). If scattering in the original beam is neglected, the relationship between transmittance and specific extinction coefficient is based on Beer's law shown in equation (9).

$$\tau_\lambda = \exp\left(-\int_0^L e_{\lambda,m}\rho_s dx\right) \tag{9}$$

where (τ_λ) is the wavelength dependent transmission, ρ_s is the density of the sample and L is the path length of radiation in the medium. If the material to be tested is homogenously mixed in the potassium bromide pellet, equation (9) can be written as equation (10).

$$e_{\lambda,m} = -\frac{\ln(\tau_\lambda)}{L\rho_s} \tag{10}$$

Wavelength dependent transmittance(τ_λ) can be derived from FTIR measured data as the ratio of incident intensity to transmitted intensity. Opacifiers such as carbon black and silicon carbide, which have high extinction coefficients, are added to the base core materials to lower the radiative conductivity. Figure 8 shows the variation of radiative conductivity with wavelength for samples with varying opacifier (silicon carbide) concentration [43]. The overall radiative conductivity decreases as the concentration of opacifier is increased. For engineering applications, Rosseland mean of extinction coefficient (E_R) is used to account for the overall effect of energy decay. It is calculated using equation (11).

$$\frac{1}{E_R} = \frac{\int_0^\infty \frac{1}{E_\lambda} * \frac{\partial e_{b\lambda}}{\partial T} d\lambda}{\int_0^\infty \frac{\partial e_{b\lambda}}{\partial T} d\lambda} \tag{11}$$

where $e_{b\lambda}$ is the spectral blackbody emissive power.

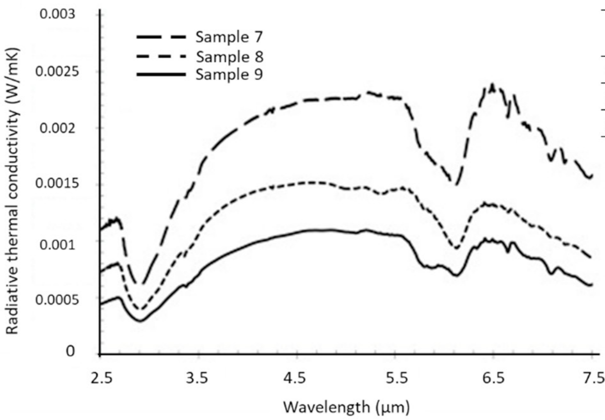
2.2.4. Coupling conductivity

Previous studies [45-47] have indicated that coupling conduction occurs because of thermal bridging effect caused by the presence of gas molecules in the inter-particle spaces. It results from interference of gaseous conductivity and solid conductivity. Heat flux along the powder solid skeleton is enhanced by the gas molecules in the gap between linked particles. For powder cores, equation (12) [61] was proposed to calculate k_{coup}.

$$k_{coup} = \frac{D + d_p}{d_p}\frac{2k_p k_g}{k_g - k_p}\left[1 - \frac{D + d_p}{d_p}\frac{2k_p k_g}{k_g - k_p}\ln\left(1 + \frac{k_g - k_p}{k_p}\frac{d_p}{D + d_p}\right)\right] \tag{12}$$

where D is the mean pore size of aerogel, d_p the aerogel particle diameter, k_p the particle's thermal conductivity and

k_g the thermal conductivity of gas inside pore. Though useful, the validity has been verified only to aerogel.
To date, to the best knowledge of the authors, no publication has reported coupling conductivity calculation for fibre or foam cores, where it is expected to play a significant role. Further research is required to develop analytical correlations for full range of core materials. Other models which have attempted to predict effective thermal conductivity of aerogel have been well captured in Tang's review [48].



	Fumed silica	Expanded perlite	Silicon carbide	Polyester fibre
Sample 7	57	30	5	8
Sample 8	52	30	10	8
Sample 9	47	30	15	8

Figure 8. Variation of radiative conductivity with wavelength for samples with varying concentration of opacifier. Sample information is as provided [43].

3. VIPs in cold chain equipment

Studies [6,49-51] have reported the performance of refrigerators when installed with vacuum insulation panels against conventional PU foam, not only in terms of reduced thermal conductivity but also the reduced ozone layer depletion potential.

Thiessen et al. [49] performed reverse heat leak tests on 16 refrigerators, originally insulated with cycloisopentane-expanded PU, with a wall thickness of 70 and 50 mm respectively for fresh food compartment and freezer compartment. Fibre glass core VIPs, 8 mm thick, were fixed onto the inner surfaces of metallic wall, in series with PU insulation. The data collected was used to develop correlations for energy consumption (EC) and thermal load (Q_t) with varying area coverage in fresh food (A_c) and freezer compartments (A_r), and presented in equations (13) and (14)

$$Q_t = 67.9 - 1.771A_c - 2.966A_r \tag{13}$$
$$EC = 51.5 - 2.291A_c - 3.496A_r \tag{14}$$

The constant term represent the average Q_t and EC in the absence of VIPs. The coefficients of A_c and A_r show the sensitivity of adding a VIP on Q_t and EC. The negative sign represent that Q_t and EC reduce as the VIP coverage area is increased. It was also noted that the installation of 8 mm thick panels on 56 % of the refrigerator surface area caused a reduction of 21 % in the energy consumption.

Tao et al. [50] compared the performance of a baseline refrigerator with and without VIPs and vacuum glazing (VG). The baseline refrigerator consisted of triple glass layer with air inside in the display case (figure 9). The VIPs comprised of open celled PU foam core (800mm x 600mm x 2mm), with thermal conductivity of 0.008 W/mK at a core pressure of 0.05 mbars were applied onto the rear and side exterior surfaces of the display case refrigerator. VG consisted of double layer glass sheet with gap evacuated to 1.3×10^{-4} mbars supported by stainless steel pillars. The results from their reverse heat flux experiments are summarised in table 3.

Hammond et. al. [51] did thermal modelling for a range of fridges and freezers with and without VIPs assembled inside the insulating walls. The major barriers for widespread of VIP insulation in cold chain equipment according to them were cost of VIPs, application and fabrication cost and vulnerability of the barrier film. They calculated the potential energy savings and payback period for cold chain equipment with VIPs (600mm x 500mm x 20mm) with thermal conductivity of 0.004 W/mK costing £38/m^2 compared with PU foam (thermal conductivity 0.025 W/mK). Heat gain for different cases were calculated by thermal modelling and converted to electricity input required by coefficient of system performance (1.5 for fridge and 0.9 for freezer) and ultimately to payback period which came out to be 9.7 years for fridges and 4.5 years for freezers.

Table 3. Power consumption of display case refrigerator for different cases [50].

	Heat power (W)	Fan power (W)	Heat loss rate (W)	Percent decrease in heat loss rate (%)
Baseline	157.5	40.7	198.2	0
VG	138.7	40.7	179.4	9.5
VG + unevacuated space with glass pane	120.0	40.7	160.7	18.9
VIP	135.4	40.7	176.1	11.1
VG + unevacuated space with glass pane + VIP	100.2	40.7	140.9	28.9

Table 4 shows carbon footprint calculations for a typical refrigerator with a COP of 2 and single wall area of 0.89 m^2 and a temperature difference of 55°C across 30 mm thick walls. Considering an emission factor of 0.283 kgCO_2e/kWh [52], the energy usage of the refrigerator translates to CO_2e emissions of 388.2 kg. If this refrigerator were VIP insulated, carbon footprint would radically reduce by 1.9 times.

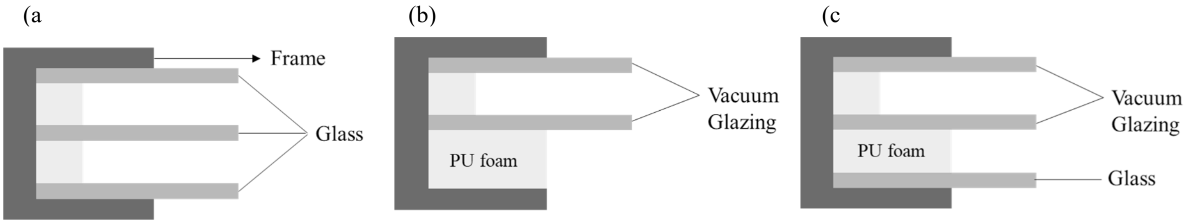


Figure 9. Display case of the refrigerators used in Tao et al.'s experiments [50]. (a) Baseline, (b) VG, (c) VG + unevacuated space

Table 4. Thermal and carbon footprint performance of a typical refrigerator

	Polyurethane foam [53]	Phenolic foam [54]	Fumed silica core VIP
Thermal conductivity (W/mK)	0.035	0.032	0.008
Rate of heat gain from side walls (W)	178.5	166.3	31.4
Total heat gain rate (W)	313.1	300.9	166.0
CO_2 produced per year (kg)	388.2	373.1	205.8

A similar analysis for any cold storage system can be done. The underlying assumption is that heat gain from side walls comprises of 57% of the total heat gain in the refrigerator insulated with PU foam [2]. Heat gain rate from other sources is kept constant as the insulation is changed and hence total heat gain rate is calculated.

Refrigeration systems consume a tremendous amount of energy leading to large quantities of GHG. Furthermore, about 20% of the total global refrigerant emissions come from mobile air conditioning and refrigeration systems [55]. Usually, polyurethane foam is used for insulating the walls of reefer truck which provides a U-value of 0.38 [56]. If the walls were VIP insulated, the thickness required to provide same U-value would be 21 mm (Table 5). The thinner insulation directly contributes to the increased container storage volume decreasing the carbon footprint of the food.

Typical reefer truck consumes 20 gallons of fuel per day travelling 200 kms, which translates to an emission of 5.1 tonnes of CO_2 per month [57]. Use of VIPs in place of PU foam will increase the internal volume by about 3%. For illustration, consider 1030 tonnes of food is to be transported in reefer trucks, each weighing 5 tonnes with a capacity of 10 tonnes. Clearly, 103 journeys will be required to complete the task, but if these trucks are VIP insulated, they can carry 10.3 tonne food each requiring 100 journeys.

Table 5. Calculations for a reefer truck wall insulation.

	Polyurethane foam [53]	Phenolic foam [54]	Fumed Silica based VIP
Thermal conductivity (W/mK)	0.035	0.032	0.008
Density (kg/m^3)	80	60	200
Thickness for U-value = 0.38 W/m^{2}K (mm)	92.1	84.2	21.1
Weight per unit area (kg/m^2)	7.4	5.1	4.2

4. Conclusion

Vacuum insulation panels are proposed to be an excellent alternative for present PU foam insulation. The adoption of VIPs in cold chain market is increasing but its full potential has not been reached yet. The major reasons for slow uptake of VIPs include high cost and lack of knowledge about the complex technological phenomena (materials, heat transfer, permeation of gas and vapours through envelope) that are yet to be fully deciphered and employed for developing reliably performing VIPs over full length of useful life. This knowledge gap leads to usage of materials and manufacturing processes that potentially increase VIP cost, extend payback period and reduce user confidence. These issues can be addressed by further research into understanding and characterising relevant heat, fluid and vapour exchange phenomena, ageing effect and thermal bridging due to envelopes.

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