Carbon Dioxide Cryogenic Transport refrigeration Systems

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Abstract

This case study considers the use of CO_2 based cryogenic refrigeration systems for food transport refrigeration applications and provides a comparison between these systems and conventional vapour compression systems driven by an auxiliary diesel engine. In the absence of field data the analysis was based on a spreadsheet model which was developed to analyse the thermal loads of refrigerated transport. The model takes into account the construction of the insulated container, the properties of the food cargo, the weather conditions and the operating schedule and determines the thermal loads from: i) the food product, ii) transmission and infiltration through the container walls, iii) precooling of the space, iv) infiltration due to door openings for loading and unloading. For a cryogenic system the amount of cryogen required is determined from the thermal load and the latent heat of the cryogenic liquid.

The analysis has shown that the use of liquid CO_2 for refrigerated transport applications is feasible in both large articulated vehicles and smaller rigid vehicles and such systems are already commercially available. The economics of these systems are to a large extent dependent on the relative cost of diesel fuel and the cost of liquid CO_2. The cost of liquid CO_2 is in turn depended on the bulk quantity purchased as well as the infrastructure cost. These costs reduce significantly as the number of vehicles supplied from the same storage facility increase.

The uncertainty in diesel and CO_2 prices makes investment in CO_2 systems difficult to justify purely on economic grounds. It is therefore likely that in the short-term investment decisions on CO_2 systems will be based primarily on environmental considerations.

1. Introduction

Food transport refrigeration is a critical link in the food chain not only in terms of maintaining the temperature integrity of perishable products but also its impact on energy consumption and CO_2 emissions. Refrigerated food distribution in the UK takes place through the following channels: Primary distribution from food factories to regional distribution centres (RDCs), either directly or via primary consolidation centres (PCCs), secondary distribution from RDCs to shops and tertiary distribution from wholesale depots to independent retailers. Primary distribution takes place almost always with articulated vehicles (32–44 ton). Articulated vehicles are also mainly used for secondary distribution to supermarkets and superstores. Tertiary distribution to small shops and catering outlets is mainly performed with rigid vehicles (up to 32 ton). Articulated vehicles over 32 ton, account for around 80% of the total ton-km goods movement in the UK [1].

The most common refrigeration system in use for refrigerated food transport applications is the vapour compression system. Mechanical refrigeration with the vapour compression cycle offers a wide range of options for compressor drive methods. The choice may be based on duty required, weight, noise requirements, maintenance requirements, installation cost, environmental considerations and fuel taxation. A number of alternative drive systems are available for mechanical transport refrigeration systems which include electrically driven systems driven directly from the vehicle engine or indirectly through an alternator unit and auxiliary diesel engines which are built into the refrigeration unit. Auxiliary diesel engine driven systems are used in the vast majority of medium to large vehicles. Other technologies include eutectic systems based on eutectic thermal energy storage, ‘total loss’ cryogenic systems and hybrid systems, which are combinations of vapour compression systems, and eutectic or cryogenic systems [2].

The main advantages of cryogenic systems are rapid pull-down of temperature and very low noise, which make them suitable for multi-drop deliveries in urban areas. Cryogenic systems using nitrogen or carbon dioxide also offer advantages of low energy consumption and environmental impacts compared to vapour compression systems. Disadvantages of theses systems are the relatively high cost of the cryogenic fluid and the infrastructure required for the filling stations.

Cryogenic systems have been in operation for a number of years but their market penetration has been very small, around 1%, mainly due to their high operating cost compared to conventional vapour compression systems [3]. In recent years, however, concerns over the environmental impacts of diesel driven vapour compression refrigeration systems due to the combustion of the diesel fuel and refrigerant leakage and developments in technology have increased interest in cryogenic systems using liquid CO_2 as a cryogenic fluid.

This case study provides a comparison between conventional and cryogenic systems using a spreadsheet based simulation programme developed specifically for the application.

2. Recent Developments in liquid CO_2 transport refrigeration systems

The most recent development in cryogenic transport refrigeration is the Thermo King's cryogenic systems, the ST-CR 300 for trucks the SB-III CR for trailers [4]. The ST-CR 300 has been in operation since 2002 in the USA and Northern Europe and is now also being trialled by a number of supermarket chains in the UK. A schematic diagram of the system is shown in Figure 1.

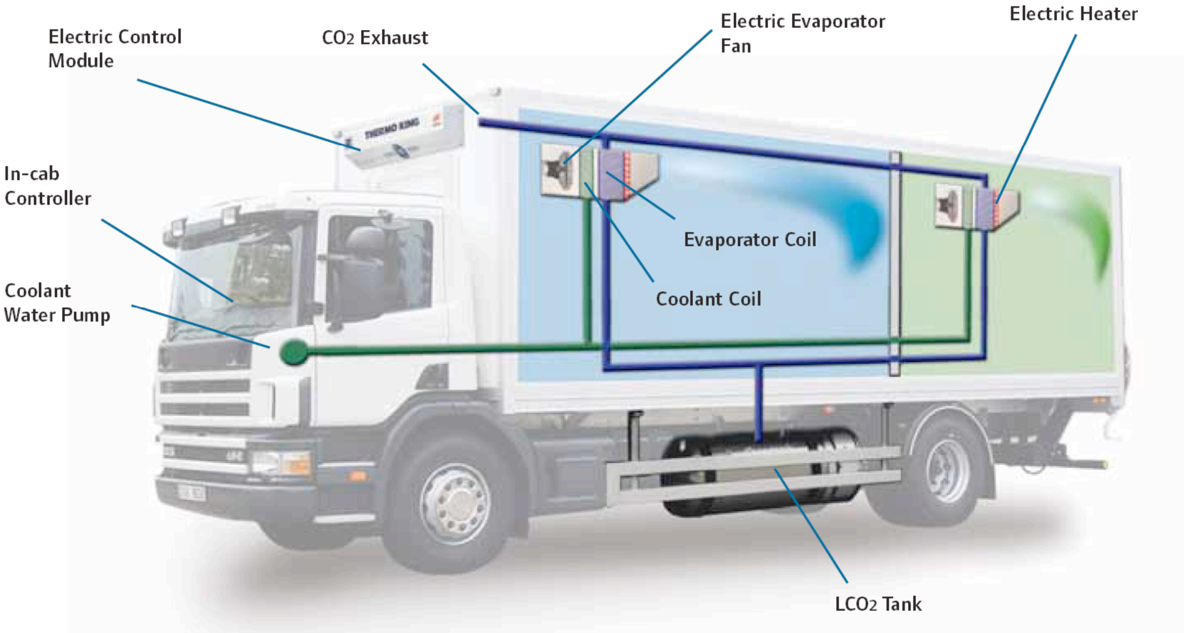


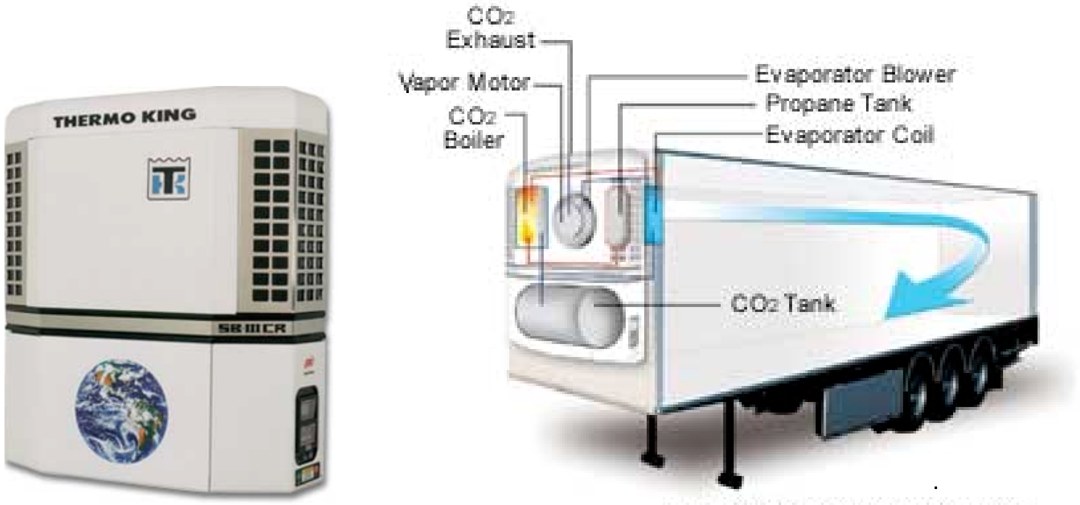
Figure 1. Thermoking liquid CO_2 ST-CR 300 transport refrigeration system (Courtesy Thermoking) [4]

The system consists of a vacuum insulated stainless steel refillable tank mounted on the underside of the truck. The liquid CO_2 from the tank flows through piping to sealed evaporator coils inside the cargo space where it is expanded, cooling the coil. An electric fan circulates air from the cargo space through the coil where it is cooled by the expanding CO_2 and is returned to the cargo space. The CO_2 vapour once it transfers all its thermal energy to the cargo air is exhausted to the atmosphere. Unlike early cryogenic systems, the CO_2 system is completely sealed and the CO_2 vapour does not mix with the cargo air.

Heating for temperature control and defrosting of the coil is provided by the vehicle engine coolant or by electric heaters in the case of stand-by operation.

The SB-CR III system is a recent development for trailers (Figure 2). It is a single piece of equipment mounted on the front (nose) of the trailer in a similar manner to a conventional system, and is used to both cool and heat the trailer. It consists of a CO_2 storage tank, a propane storage tank, a propane fired CO_2 boiler and a CO_2 vapour motor fan. The vapour motor fan is driven by high-pressure carbon dioxide gas and circulates air from the trailer through the evaporator coil. The boiler heats carbon dioxide, which is, used both for heating and evaporator coil defrost.

There are also hybrids to the truck and trailer units, which incorporate a second heat exchanger inside the evaporator section of the conventional vapour compression system. When the truck doors are closed after a delivery stop and the unit begins to recover from the temperature gain during the stop, conventional units run in high speed cool mode. During this period of high-speed operation, low temperature CO_2 is circulated through the second heat exchanger to accelerate the pull-down cycle. This results in fewer hours of high-speed operation, which leads to lower fuel consumption.



Full cryogenic system (trailer)

Figure 2. Thermoking liquid CO2 SB-CR III transport refrigeration system for trailers (Courtesy Thermoking) [4]

3. Method

In the absence of data from field trials the analysis is based on a spreadsheet model that has been developed to determine the energy requirements of a conventional unit and the amount of CO_2 required by a cryogenic system.

The spreadsheet model was based on the thermal load calculation procedures outlined in ASHRAE [5]. The main sources of heat and mass transfer across the refrigerated body are illustrated in Figure 3.

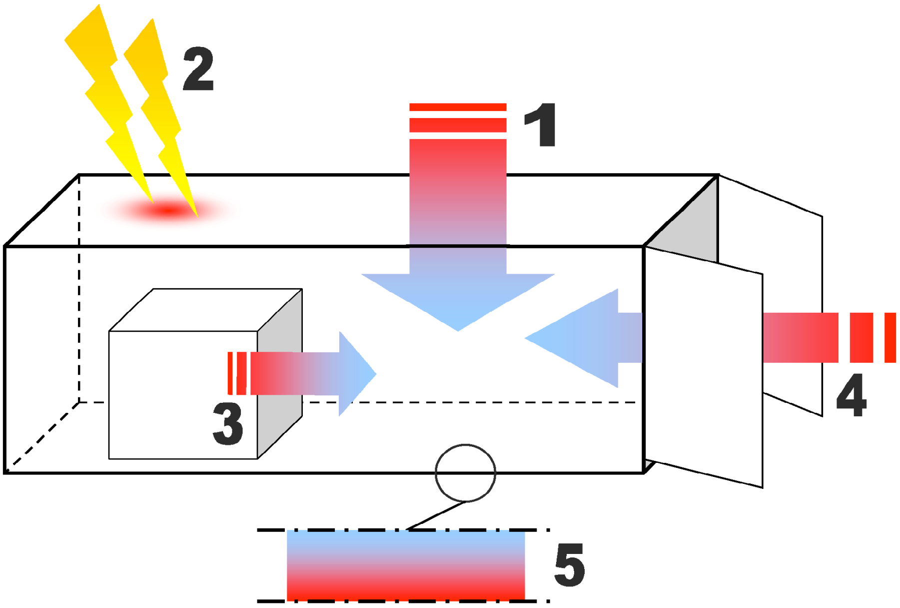


Figure 3. Main sources of heat in refrigerated transport

1. Transmission load, which is heat transferred into the refrigerated space through its surface.
2. Solar radiation load. In the analysis the solar radiation load was integrated with the transmission load using an external temperature adjustment as proposed by ASHRAE [6].
3. Product load, which is heat produced by the products brought and kept in the refrigerated space.
4. Infiltration air load, which is heat gain associated with air entering the refrigerated space (during door openings).
5. Precooling load, which is heat removed from the vehicle to bring its interior surfaces to the planned thermostat setting before product loading.

The spreadsheet model comprises three main section:

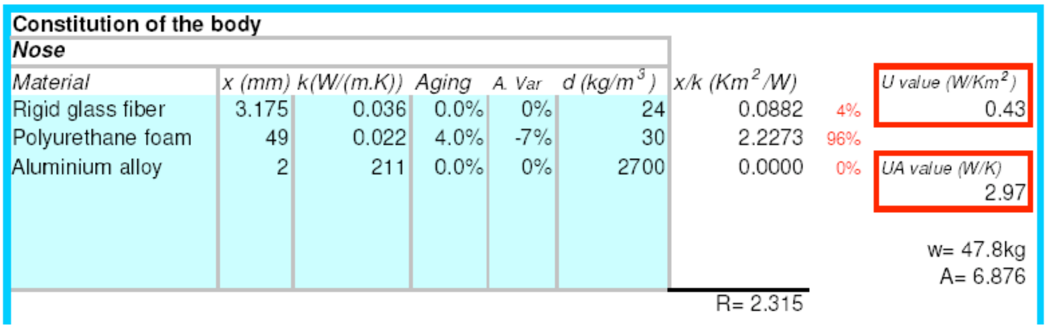
- Body of the refrigerated vehicle.

- Aging of the insulation and deterioration of heat transfer performance.
- Daily thermal load calculator.

3.1 Calculations of vehicle body thermal characteristics

In the first section, the user can define the technical specifications of the refrigerated vehicle to be studied. The following characteristics are entered (Figure 4):

- Internal dimensions of the insulated body (which is assumed to be plane-parallel).
- Constitution of the body: for each section of the trailer (nose, side walls, ceiling, floor and rear doors), it is necessary to input the constituting materials, their thickness, their thermal conductivity, their mass density and their aging behaviour (aging coefficient and yearly variation of this value).
- Air infiltration: infiltration through the vehicle body and closed doors is normally included in the UA value given by manufacturers. The model requires the input of the overall infiltration rate, the specific heat of air and the air density to calculate the heat transfer due to infiltration. A yearly increase of the overall infiltration rate can also be entered to take into account physical damage and door seal deterioration.



Constitution of the body

Nose

Material	*x (mm)*	*k(W/(m.K))*	*Aging*	*A. Var*	*d (kg/m^3)*	*x/k (Km^2/W)*	
Rigid glass fiber	3.175	0.036	0.0%	0%	24	0.0882	4%
Polyurethane foam	49	0.022	4.0%	-7%	30	2.2273	96%
Aluminium alloy	2	211	0.0%	0%	2700	0.0000	0%

R= 2.315

U value (W/Km^2) 0.43

UA value (W/K) 2.97

w= 47.8kg
A= 6.876

Figure 4. Thermal characteristics of vehicle body.

The model uses the above data to calculate:

- The inside area of the body (I), the outside area of the body (O) and the mean area of the body ($S = \sqrt{OI}$).
- The weight of all the materials that have been defined previously and the payload volume. This information is useful to compare different types and thicknesses of insulation (e.g. polyurethane vs. vacuum).

- The overall heat transfer coefficient (UA) of each section of the vehicle and of the vehicle itself as well as the K-coefficient (value usually provided by manufacturers) as defined by the ATP agreement.

Aging of thermal insulation

Insulation deteriorates with time, not only due to the obvious use factors but also due to the inherent foam characteristics. Data from Panozzo et al.[7] show a typical deterioration of insulation effectiveness of 3 to 4% per year in the first 5 years and an overall loss of around 30% in ten years (see Figure 5).

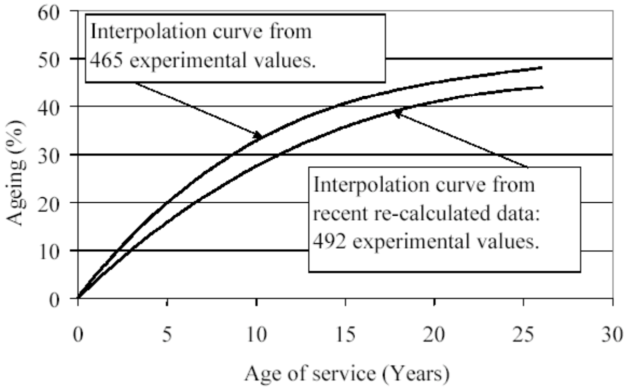


Figure 5. Ageing of vehicle body insulation.

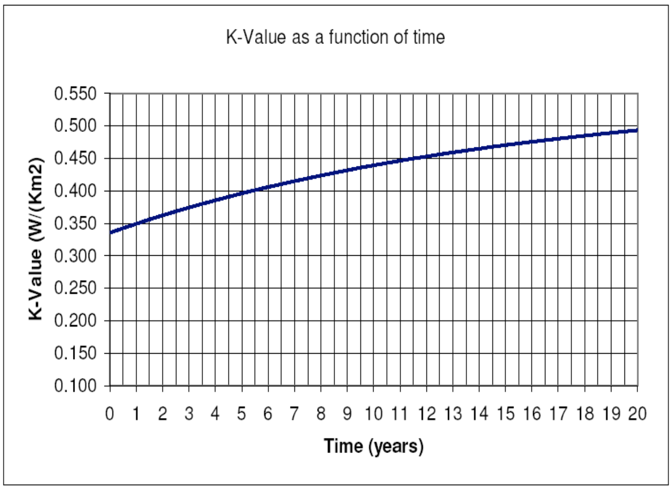


Figure 6. K-coefficient as a function of time.

Using the above information the model can calculate the K-coefficient as a function of time which is then used in the thermal load calculations. A typical variation of the K-value with time is shown in Figure 6.

3.2 Daily thermal load calculator

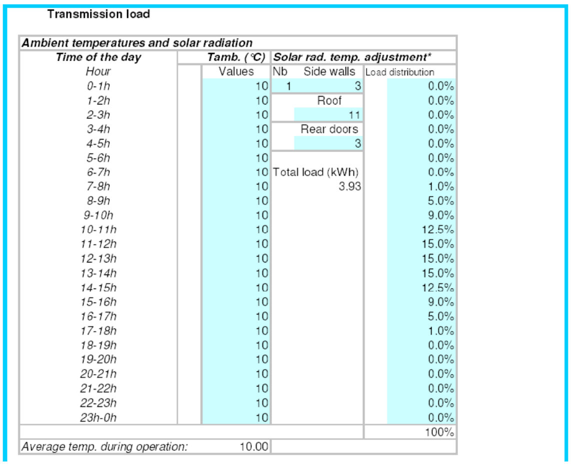
The daily thermal load calculator uses all the equations presented above and the information entered by the user in part 1 to calculate the variation of the thermal load of a refrigerated vehicle as a function of time during a day under specified working conditions.

Transmission load

This part takes into account the transmission load (conduction, convection and infiltration through the vehicle body and closed doors since it is part of the UA calculation and the temperature adjustment related to solar radiation. The user inserts:

- The ambient temperature for each hour of the day.
- The thermostat temperature setting for each hour of the day during which the refrigeration unit of the vehicle is in operation.
- The parameters concerning the solar radiation temperature adjustment and the distribution of this load during the day (it can be either distributed evenly between all the hours of the day or entered manually).

For example, different adjustments can be made for different parts of the body and as shown in Figure 7 the distribution of the solar radiation adjustment has been chosen to match approximately with that of solar irradiation on a sunny day.



Transmission load

Ambient temperatures and solar radiation

Time of the day	*Tamb. (°C)*	*Solar rad. temp. adjustment**		
Hour	Values	Nb	Side walls	Load distribution
0-1h	10	1	3	0.0%
1-2h	10		Roof	0.0%
2-3h	10		11	0.0%
3-4h	10		Rear doors	0.0%
4-5h	10		3	0.0%
5-6h	10			0.0%
6-7h	10	Total load (kWh)		0.0%
7-8h	10		3.93	1.0%
8-9h	10			5.0%
9-10h	10			9.0%
10-11h	10			12.5%
11-12h	10			15.0%
12-13h	10			15.0%
13-14h	10			15.0%
14-15h	10			12.5%
15-16h	10			9.0%
16-17h	10			5.0%
17-18h	10			1.0%
18-19h	10			0.0%
19-20h	10			0.0%
20-21h	10			0.0%
21-22h	10			0.0%
22-23h	10			0.0%
23h-0h	10			0.0%
				100%
Average temp. during operation:	10.00			

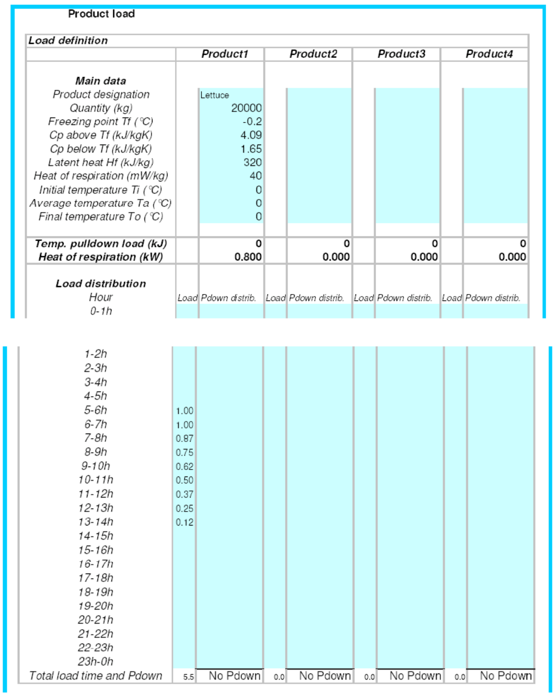
Figure 7. Environmenral conditions and load calculator.

Precooling load

This part requires input of the specific heat of the insulated body, the hours for which it is necessary to take into account the precooling load and the initial temperature inside the vehicle when the refrigeration unit is switched on. The precooling load is then calculated and displayed by the model on an hour-by-hour basis.

Product load

The model can handle four different products simultaneously. For each product, it is necessary to enter a designation, the quantity, the freezing point, the specific heat above freezing, the specific heat below freezing, the latent heat, the heat of respiration, the initial temperature of the cargo, the average temperature during carriage (temperature to consider when keying in the heat of respiration) and the final temperature of the cargo. Physical properties of many fruits and vegetables are provided by ASHRAE [5].



Product load

Load definition	Product1		Product2		Product3		Product4	
Main data								
Product designation		Lettuce						
Quantity (kg)		20000						
Freezing point Tf (°C)		-0.2						
Cp above Tf (kJ/kgK)		4.09						
Cp below Tf (kJ/kgK)		1.65						
Latent heat Hf (kJ/kg)		320						
Heat of respiration (mW/kg)		40						
Initial temperature Ti (°C)		0						
Average temperature Ta (°C)		0						
Final temperature To (°C)		0						
Temp. pulldown load (kJ)		0		0		0		0
Heat of respiration (kW)		0.800		0.000		0.000		0.000
Load distribution								
Hour	Load	Pdown distrib.	Load	Pdown distrib.	Load	Pdown distrib.	Load	Pdown distrib.
0-1h								
1-2h								
2-3h								
3-4h								
4-5h								
5-6h	1.00							
6-7h	1.00							
7-8h	0.87							
8-9h	0.75							
9-10h	0.62							
10-11h	0.50							
11-12h	0.37							
12-13h	0.25							
13-14h	0.12							
14-15h								
15-16h								
16-17h								
17-18h								
18-19h								
19-20h								
20-21h								
21-22h								
22-23h								
23h-0h								
Total load time and Pdown	5.5	No Pdown	0.0	No Pdown	0.0	No Pdown	0.0	No Pdown

Figure 1. Product load calculation cheet.

Two loads are differentiated for each product: the temperature pulldown load (if the product has not been properly precooled before being loaded) and the heat of respiration of the cargo. For the first one, the user can apply his own load distribution for each hour during which the cargo is carried (the default value is an evenly distribution). The heat of respiration of the cargo is assumed constant during the entire journey. It should be noted that it is possible to take into account the effects of possible deliveries (or additional loadings) on the actual payload mass carried by the vehicle by adjusting the load factor. For example, if only one quarter of the initial load (the quantity entered initially) remains after a delivery, a load factor of 0.25 in place of 1 should be applied.

Door openings

The thermal load related to the infiltration of warm air into the refrigerated space during door openings is calculated using the analytical model developed by Gosney and Olama. This requires entry of the width and height of the doorway, the time during which the doors are open for each hour of the day and the two values Q_s/A and R_s of the simplified equation developed by ASHRAE [5].

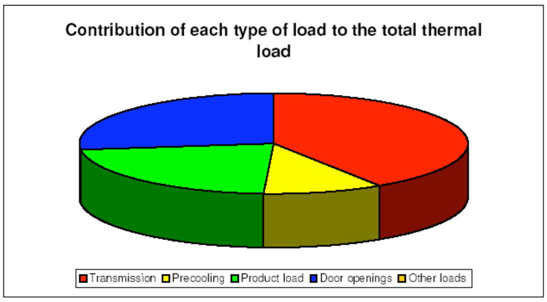
Other loads and safety factors

Main results

Hourly loads (kW)

	Transmission	*Precooling*	*Product load*	*Door openings*
0-1h	0.00	0.00	0.00	0.00
1-2h	0.00	0.00	0.00	0.00
2-3h	0.00	0.00	0.00	0.00
3-4h	0.00	0.00	0.00	0.00
4-5h	0.57	2.15	0.00	0.00
5-6h	0.57	0.00	0.88	0.66
6-7h	0.57	0.00	0.88	0.64
7-8h	0.61	0.00	0.77	0.64
8-9h	0.78	0.00	0.66	0.64
9-10h	0.96	0.00	0.55	0.64
10-11h	1.11	0.00	0.44	0.64
11-12h	1.22	0.00	0.33	0.64
12-13h	1.22	0.00	0.22	0.64
13-14h	1.22	0.00	0.11	0.64
14-15h	0.00	0.00	0.00	0.00
15-16h	0.00	0.00	0.00	0.00
16-17h	0.00	0.00	0.00	0.00
17-18h	0.00	0.00	0.00	0.00
18-19h	0.00	0.00	0.00	0.00
19-20h	0.00	0.00	0.00	0.00
20-21h	0.00	0.00	0.00	0.00
21-22h	0.00	0.00	0.00	0.00
22-23h	0.00	0.00	0.00	0.00
23h-0h	0.00	0.00	0.00	0.00
Total load (kWh)	8.80	2.15	4.82	5.79

	Other loads	*Total*
0-1h	0.00	**0.00**
1-2h	0.00	**0.00**
2-3h	0.00	**0.00**
3-4h	0.00	**0.00**
4-5h	0.00	**2.71**
5-6h	0.00	**2.11**
6-7h	0.00	**2.09**
7-8h	0.00	**2.02**
8-9h	0.00	**2.08**
9-10h	0.00	**2.14**
10-11h	0.00	**2.19**
11-12h	0.00	**2.18**
12-13h	0.00	**2.08**
13-14h	0.00	**1.96**
14-15h	0.00	**0.00**
15-16h	0.00	**0.00**
16-17h	0.00	**0.00**
17-18h	0.00	**0.00**
18-19h	0.00	**0.00**
19-20h	0.00	**0.00**
20-21h	0.00	**0.00**
21-22h	0.00	**0.00**
22-23h	0.00	**0.00**
23h-0h	0.00	**0.00**
Total load (kWh)	0.00	**21.56**



Total daily transmission load - aging effects (kWh)

Year	*Conduct.*	*Solar rad.*	*Total*	*Deviation*
0	12.37	3.93	**16.30**	
1	12.87	4.09	**16.96**	+ 4.1%
2	13.34	4.23	**17.58**	+ 7.8%
3	13.78	4.37	**18.15**	+ 11.4%
4	14.19	4.49	**18.69**	+ 14.6%
5	14.58	4.61	**19.19**	+ 17.7%
6	14.94	4.72	**19.65**	+ 20.6%
7	15.27	4.82	**20.09**	+ 23.3%
8	15.59	4.91	**20.50**	+ 25.8%
9	15.88	5.00	**20.88**	+ 28.1%
10	16.15	5.08	**21.23**	+ 30.3%
11	16.41	5.15	**21.57**	+ 32.3%
12	16.65	5.22	**21.88**	+ 34.2%
13	16.88	5.29	**22.17**	+ 36.0%
14	17.09	5.35	**22.44**	+ 37.7%
15	17.29	5.41	**22.70**	+ 39.2%
16	17.48	5.46	**22.94**	+ 40.7%
17	17.66	5.51	**23.16**	+ 42.1%
18	17.82	5.55	**23.37**	+ 43.4%
19	17.98	5.59	**23.57**	+ 44.6%
20	18.13	5.63	**23.76**	+ 45.8%

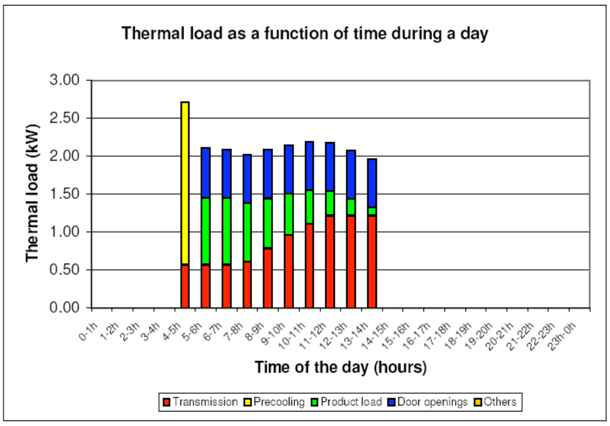


Figure 9. Typical report provided by the daily load calculator.

The user can include other possible thermal loads which have not been described above. These can be entered manually for each hour of the day. Finally, it is possible to enter a safety factor for each type of load (transmission, precooling, product load, door openings and other loads) to allow for possible discrepancies between the theoretical approach adopted and actual operation. Usually, the calculated loads are increased by 10% [6].

Model validation

Using all the parameters defined by the user and the equations described earlier, the spreadsheet model calculates the global thermal load for each hour of the day. The report that can be produced is shown in Figure 9. To validate the model, simulations were performed to calculate a number of parameters which were then compared with published information. Modelling of a refrigerated semi-trailer, the specifications of which were provided by a manufacturer gave exactly the same value of overall coefficient of heat transfer, $K = 0.34$ W/m^2 K, as the value obtained by the manufacturer. Bergeron [8], Hui et al.[9] and ASHRAE [6] provide data on the thermal load of refrigerated vehicles which were used to validate the results of the spreadsheet model. A comparison between the published results for different vehicles and loading conditions and the results obtained from the spreadsheet model is given in Table 1.

Table 1. Comparison of published and calculated loads for refrigerated vehicles

Source	Average thermal load published in the literature for specific refrigerated vehicles (kW)	Average thermal load calculated with the spreadsheet model (kW)	Difference (%)
Bergeron [8]	3.13	3.26	+4.15%
Hui et. al. [9] No precooling	22.29	22.43	+0.63%
Hui et. al. [9] With precooling	2.28	2.43	+6.58%
ASHRAE [6]	4.73	4.73	-

It can be seen from Table 1 that the spreadsheet model can predict fairly accurately the thermal load of a refrigerated vehicle under different environmental and loading conditions.

4. Use of the Model to Analyse the Use of Carbon Dioxide Cryogenic Refrigeration Systems in Food Transport Refrigeration

The model was used to determine the amount of carbon dioxide that would be required in cryogenic food transport refrigeration system and the cost and environmental impacts of the system were compared with those of a conventional diesel driven system. Two different foods and lorry sizes were considered as well as three different operating schedules for each. The characteristics of the foods are given in Table 2. The vehicles and loads for each food type are given in Table 3.

Table 2. Characteristics of cargo used

Type of cargo	Frozen food	Chilled food
Designation	Generic frozen	lettuce
Temperature condition (°C)	-18	0
Freezing point (°C)	0	0.2
Specific heat below freezing (kJ/kgK)	3	1.65
Specific heat above freezing (kJ/kgK)	4	4.09
Latent heat (kJ/kg)	275	320
Heat of respiration (W/kg)	0	0.040

Table 3. Vehicles and loads

Type of vehicle	Load	
	Chilled food	Frozen food
15 tonne (rigid lorry)	3 tonne	5 tonne
38 tonne (articulated lorry)	10 tonne	15 tonne

Many different schedules are possible for refrigerated food transport. In this case study three schedules were considered as follows:

Schedule 1 - Long hours and deliveries

The vehicle is intensively used for long distance delivery rounds and significant time between each delivery point. Precooling of the vehicle is included as well as infiltration loads during door openings are included in the calculations.

Schedule 2 - Delivery rounds

The vehicle is used for relatively short delivery rounds. Infiltration during door openings and precooling are taken into consideration in the calculations.

Schedule 3 - Short deliveries.

The vehicle is only used for short delivery rounds. Infiltration during loading and the daily precooling load are both included in the calculations since they account for an important part of the overall thermal load.

For each vehicle and load and operating schedule the quantity of liquid CO_2 required to satisfy the thermal load was calculated as follows:

Properties of carbon Dioxide

Carbon dioxide (CO_2) is the combination of oxygen and carbon. One of the main uses of liquid carbon dioxide is for the temperature regulation of food.

- Boiling point (1.013 bar) : -78.5 °C
- Latent heat of vaporization at 1.013 bar : 571.08 kJ/kg
- Specific heat capacity, constant pressure, Cp, at 1.013 bar and 25 °C): 0.03 kJ/(kg.K)
- Density of the liquid phase at 1.013 bar: 808.607 kg/m^3

When liquid CO_2 at high pressure is expanded it becomes gaseous. The energy required for this transformation is given by:

$$Q_c = m_c (L_v + C_p (T_s - T_v))$$

Where:

m_c : the mass of liquid CO_2 expanded

L_v : the latent heat of CO_2

C_p : heat capacity at constant pressure

T_s : space temperature

T_v : temperature of vaporization

5. Results and Discussion

Table 4 shows the mass required for the various food loads and operating schedules. It can be seen that for the operating schedules and loads considered mass of CO_2 between 45 kg and 330 kg will be required to satisfy the thermal load of the 15 tonne lorry. The 38 tonne lorry will require between 89 and 590 kg of liquid CO_2.

Table 4. CO2 mass required for different operating schedules.

Vehicle and Cargo	**Schedule 1** **17 hours operation**		**Schedule 2** **10 hours operation**		**Schedule 3** **5 hours operation**	
	Load kWh	Mass of CO2 Kg	Load kWh	Mass of CO2 Kg	Load kWh	Mass of CO2 Kg
15 tonne Chilled 3 tonne load	20.6	130.7	16.34	103.5	7.0	44.5
15 tonne Frozen 5 tonne load	51.0	322.9	46.6	294.9	8.5	53.9
38 tonne Chilled 10 tonne load	42.3	269.7	32.0	202.5	15.9	100.6
38 tonne Frozen 15 tonne load	92.8	587	79.9	505.5	14.13	89.40

Vehicle and Cargo	**Schedule 1**			**Schedule 2**			**Schedule 3**		
	Period of Operat (h)	Fuel cons. (l/h)	Total Fuel (l)	Period of Operat (h)	Fuel cons. (l/h)	Total Fuel (l)	Period of Operat (h)	Fuel cons. (l/h)	Total Fuel (l)
15 tonne Chilled 3 tonne load	17	1.5	25.5	10	1.5	15	5	1.5	7.5
15 tonne Frozen 5 tonne load	17	2	34	10	2	20	5	2	10
38 tonne Chilled 10 tonne load	17	2.5	42.5	10	2.5	25	5	2.5	12.5
38 tonne Frozen 15 tonne load	17	3.0	51	10	3.0	30	5	3.0	15

Table 5. Diesel fuel requirement by conventional food transport refrigeration system

Table 5 gives an estimate of the diesel fuel that will be required by a conventional diesel powered food transport refrigeration system for the different lorries, loads and schedules. Average values of fuel consumption were used from reference [2]. The data in Tables 4 and

5 were used to compare the conventional and cryogenic systems for the three schedules of operation. The results for the three schedules are given in Tables 6, 7 and 8 respectively.

Table 6. Comparison between conventional and cryogenic system for schedule 1

Schedule 1						
Vehicle and Cargo	Conventional diesel engine system			CO_2 cryogenic system		
	Total Fuel (l)	Fuel cost £1.0/l (£)	CO_2 emissions (kg)	Mass CO_2 (kg)	CO_2 cost £0.1/kg (£)	CO_2 emissions assuming recovered CO_2 (kg)
15 tonne Chilled 3 tonne load	25.5	25.5	66.3	130.7	19.1	0
15 tonne Frozen 5 tonne load	34	34	88.4	322.9	32.3	0
38 tonne Chilled 10 tonne load	42.5	42.5	109.7	269.7	26.9	0
38 tonne Frozen 15 tonne load	51	51	132.6	587	58.7	0

Table 7. Comparison between conventional and cryogenic system for schedule 2

Schedule 2						
Vehicle and Cargo	Conventional diesel engine system			CO_2 cryogenic system		
	Total Fuel (l)	Fuel cost £1.0/l (£)	CO_2 emissions (kg)	Mass CO_2 (kg)	CO_2 cost £0.1/kg (£)	CO_2 emissions assuming recovered CO_2 (kg)
15 tonne Chilled 3 tonne load	15	15	39	103.5	10.35	0
15 tonne Frozen 5 tonne load	20	20	52	294.9	29.5	0
38 tonne Chilled 10 tonne load	25	25	65	202.5	20.3	0
38 tonne Frozen 15 tonne load	30	30	78	505.5	50.5	0

Table 8. Comparison between conventional and cryogenic system for schedule 3

Schedule 3						
Vehicle and Cargo	Conventional diesel engine system			CO_2 cryogenic system		
	Total Fuel (l)	Fuel cost £1.0/l (£)	CO_2 emissions (kg)	Mass CO_2 (kg)	CO_2 cost £0.1/kg (£)	CO_2 emissions assuming recovered CO_2 (kg)
15 tonne Chilled 3 tonne load	7.5	7.5	19.5	44.5	4.5	0
15 tonne Frozen 5 tonne load	10	10	20.6	53.9	5.4	0
38 tonne Chilled 10 tonne load	12.5	12.5	31.7	100.6	10.0	0
38 tonne Frozen 15 tonne load	15	15	39	89.4	9.0	0

Using data from Thermoking it was reasonable to assume that the weights of the conventional system and the cryogenic system with a full tank of CO_2 would be approximately the same, thus having little additional impact on the fuel consumption of the vehicle engine. The analysis also assumes that the capital cost of the two systems will be approximately the same even though a reasonable assumption could be that with increased sales the capital cost of CO_2 systems would be below that of conventional systems due to the smaller number of components employed in these systems.

The economics of the two systems will be dependent to a large extent on the relative cost of diesel fuel and the cost of liquid CO_2. The cost of liquid CO_2 will in turn depend on the bulk quantity purchased as well as the infrastructure cost. These costs reduce significantly as the number of vehicles supplied from the same storage facility increase. The analysis in this case study has assumed a cost of £1.0 per litre of diesel and £0.1 per kg of liquid CO_2.

It can be seen from the results in Tables 6 to 8 that with the assumptions made there is no clear-cut economic advantage between the two systems. The CO_2 system though offers significant advantages in terms of Greenhouse Gas Emissions as these will be zero if the CO_2 is recovered from the exhaust gases of combustion processes. Other advantages include very low noise and vibration compared to conventional systems, and much lower maintenance costs.

6. Conclusions

- Analysis made using a specially developed spreadsheet model for refrigerated food transport has shown that it is feasible to use cryogenic liquid carbon dioxide for food transport refrigeration for both rigid vehicles and articulated lorries.
- Such systems are now commercially available by at least one manufacturer and are either being used or are trialed by a number of supermarket chains and food haulage companies.
- Cryogenic systems offer a number of advantages over conventional diesel driven vapour compression refrigeration technologies. These include:
    - Effectively silent operation
    - Very few moving parts leading to increased reliability and much lower maintenance costs
    - Rapid load pulldown and vey good temperature control leading to faster temperature recovery and better product quality and life
    - Reduced waste from spoilage and no lubricating oil disposal
    - Potentially zero GHG emissions if CO_2 is recovered from industrial processes (exhaust gases of combustion processes)
- Operating costs of the two systems will largely depend on the relative cost of diesel fuel and liquid CO_2. The cost of CO_2 and the infrastructure required will reduce as the number of vehicles using cryogenic systems increases.
- The uncertainty in diesel and CO_2 prices makes investment in CO_2 systems difficult on economic grounds alone. It is therefore likely that in the short term investment decisions on CO_2 systems will be based primarily on environmental considerations.

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