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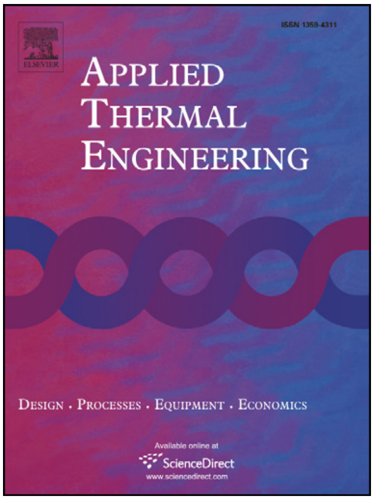

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FOOD TRANSPORT REFRIGERATION - APPROACHES TO REDUCE ENERGY CONSUMPTION AND ENVIRONMENTAL IMPACTS OF ROAD TRANSPORT

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Abstract

Food transport refrigeration is a critical link in the food chain not only in terms of maintaining the temperature integrity of the transported products but also its impact on energy consumption and CO_2 emissions. This paper provides a review of a) current approaches in road food transport refrigeration, b) estimates of their environmental impacts and, c) research on the development and application of alternative technologies to vapour compression refrigeration systems that have the potential to reduce the overall energy consumption and environmental impacts. The review and analysis indicate that greenhouse gas emissions from conventional diesel engine driven vapour compression refrigeration systems commonly employed in food transport refrigeration can be as high as 40% of the greenhouse gas emissions from the vehicle's engine. For articulated vehicles over 33 tonnes, which are responsible for over 80% of refrigerated food transportation in the UK, the reject heat available form the engine is sufficient to drive sorption refrigeration systems and satisfy most of the refrigeration requirements of the vehicle. Other promising technologies that can lead to a reduction in CO_2 emissions are air cycle refrigeration and hybrid systems in which conventional refrigeration technologies are integrated with thermal energy storage. For these systems, however, to effectively compete with diesel driven vapour compression systems, further research and development work is needed to improve their efficiency and reduce their weight.

Keywords: refrigerated transport, CO_2 emissions, alternative refrigeration technologies, energy conservation.

1. Introduction

The commercial food sector, including agriculture, food manufacture transport and retail is responsible for 22% of the UK's total greenhouse gas emissions. Food distribution and retail accounts for approximately one third of this, with food transport estimated to be responsible for 1.8 % of total emissions [1].

Road transport refrigeration equipment is required to operate reliably in much harsher environments than stationary refrigeration equipment. Due to the wide range of operating conditions and constraints imposed by available space and weight, transport refrigeration equipment have lower efficiencies than stationary systems. This, together with increasing use of refrigerated transport arising from the much wider range of transported goods, home delivery and greater quality expectations, are placing considerable pressures on the food industry to reduce the energy consumption of refrigerated transport. The reduction in energy consumption, however, cannot compromise the temperature control of the transported food products which is governed by legislation.

EU and UK legislation covers temperature control requirements during the storage and transport of perishable foods. These regulations have been revised in early 2006 and regulation EC No 852/2004 on the Hygiene of Foodstuffs requires manufacturers to have suitable temperature controlled handling and storage facilities that can maintain food at appropriate temperatures and enable these temperatures to be monitored controlled and recorded [2,3].

The transport of perishable food products, other than fruit and vegetables, and the equipment used for the carriage of these products is governed by an agreement drawn by The Inland Transport Committee of the United Nations Economic Committee for Europe in 1970-1971 [4]. The agreement is known as the ATP agreement and its aim is to facilitate international traffic by setting common internationally recognised standards for temperature controlled transport vehicles such as road vehicles, railway wagons and sea containers.

The ATP classifies insulated vehicles and bodies as either Normally Insulated Equipment (IN, isotherme normal: U coefficient equal or less than 0.7 W/m^2 K or Heavily Insulated Equipment (IR, isotherme renforcé: U coefficient equal or less than 0.4 W/m^2 K. The overall heat transfer coefficient can be calculated from:

$$U = \frac{Q}{S} \quad (\mathrm{W/m^2\,K})$$

where, Q, is the heat flow through the insulated walls per degree difference between the air temperature inside and outside the body (W/K) and, S , is the mean section of the body, which is the geometric mean of the inside surface area, I , and the outside surface area, O , of the body. The mean section can be calculated from:

$$S = \sqrt{O\,I}\ .$$

The ATP also classifies refrigeration and heating equipment in terms of temperature control at -20 °C, -10 °C, 0 °C and +12 °C. The most common ATP classification for equipment, FRC, certifies it for all temperature classes.

The refrigeration equipment installed on a refrigerated vehicle must also possess a valid ATP capacity report. The agreement states that new refrigeration equipment installed on a refrigerated vehicle must have a heat extraction capability at the class limit temperature of at least 1.35 times the heat transfer through the walls in a 30 °C ambient temperature and 1.75 times if the refrigeration unit was tested separately outside the vehicle to determine its effective cooling capacity at the prescribed temperature. The ATP certificate ensures that the insulated body and the refrigeration unit have been tested by a third party and that the two have been appropriately matched [5]. An ATP certified vehicle or body could carry a single certificate that covers both the insulated body and the refrigeration unit.

The ATP certificate is valid for six years but can be extended by another three years on condition that an “in service” examination is carried out [3]. There are concerns, however, that in-service testing procedures are not stringent enough and this may lead to higher energy consumption than necessary [6,7]. In the UK, the average number of ATP certificates issued in one year is approximately 1500. ATP certified bodies frequently operate in service for 9 to 12 years depending on the type of operational service impacting on the body [3].

This paper reviews technologies and approaches currently employed in food transport refrigeration and their environmental impacts. The impacts are expressed in terms of greenhouse gas emissions arising from the fuel consumption of the vehicle and refrigeration system engines and refrigerant leakage to the environment. The emissions are expressed in ‘kg CO_2 per pallet km’ which can easily be converted to kg CO_2 per kg or litre of product per km. The data presented will facilitate the determination of the carbon footprint arising from the transportation of both ambient and refrigerated food products and will contribute to the overall effort to quantify and reduce the carbon footprint of the food chain. The paper also reviews research into the development and application of alternative refrigeration technologies for transport applications that could lead to a reduction in energy consumption and environmental impacts.

2. Technologies currently in use in food transport refrigeration

2.1 Vehicles

The majority of refrigerated road transportation is conducted with semi-trailer insulated rigid boxes. In Europe the external length and width of a semi-trailer rigid box are fixed but the external height and internal dimensions can vary depending on the individual design type. These dimensions are as follows [3]:

External dimensions: 13.56 m length, 2.6 m width and 2.75 m height.
Internal dimensions: 13.35 m length, 2.46 m, width and 2.5 m height.

Many factors are considered in the design of the envelope of a refrigerated transportation unit: extremes of exterior weather conditions, desired interior conditions, insulation properties, infiltration of air and moisture, tradeoffs between construction cost and operating cost and physical deterioration from shocks and vibrations.

A rigid semi-trailer box normally consists of expanded foam insulation sandwiched between two external skins. Each skin consists of a few millimetres of plywood covered with a glass reinforced polyester, steel or aluminium skin. The most popular insulation is expanded polyurethane (PU) foam with cyclopentane as the blowing agent. This construction achieves a thermal conductivity in the region of 0.022 W/m K. Another popular insulation material is extruded polystyrene. The thermal conductivity of extruded polystyrene is higher than PU foam but in floor and roof construction where there are fewer constraints for overall thickness, body builders can offset thermal losses by using thicker panels. In side walls, the insulation thickness is constrained by the maximum permissible insulated vehicle width of 2.60 m and europallet dimensions. A europallet is 1.0 m deep by 1.20 m wide and the need to accommodate 2 europallets side by side means that the insulation thickness can rarely be more than 45-50 mm.

The performance of insulation materials deteriorates with time due to the inherent foam characteristics. Recent data show a typical loss of insulation value of between 3% and 5% per year which can lead to considerable rise in the thermal conductivity after a few years [6,8]. If a 5% yearly ageing is assumed, a vehicle with an initial K-coefficient of 0.4 W/m^2 K will have a K-coefficient of 0.62 W/m^2 K after nine years of operation, resulting in a 50 % increase in energy consumption and CO_2 emissions. If one considers the large number of refrigerated vehicles and containers in use worldwide, the global impact of the reduction of insulation effectiveness is considerable.

2.2 Refrigeration units

The most common refrigeration system in use for refrigerated food transport applications today 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. The performance and power requirements of these systems are normally assessed at full load. In reality however, transport refrigeration systems operate over a wide range of loads. To match the varying load, the refrigeration system is either switched on and off or its capacity is modulated to maintain the set temperature with a consequent reduction in efficiency. Depending on the system design envelope, the expected Coefficient of Performance (COP) is generally in the range between 0.5 and 1.5.

The most common drive systems for refrigerated transport vapour compression systems are [3,9]:

Vehicle alternator unit: with this method which is commonly used in small delivery vans, the vehicle engine crankshaft drives an upgraded single alternator and a 70 Ah battery. The alternator charges the vehicle battery which feeds a small refrigeration system with 12 V dc supply. The system can also be driven with a 230V mains electric supply during standby.

Direct belt drive: with this system, which is used in the majority of van size vehicles, the compressor of the refrigeration unit is directly driven from the vehicle engine through a belt.

Auxiliary alternator unit: this system uses a dedicated large alternator driven by a belt from the main traction engine, generating power to drive an electric motor in the refrigeration unit. Fan motors for the heat exchangers and the control system are also fed from the alternator output. An alternative arrangement for an alternator system is to use a diesel generator system.

Auxiliary Diesel Unit: This system uses a diesel engine built into the refrigeration unit and is used in the vast majority of medium to large vehicles. Particle filters and catalysts in new engine technologies can reduce the exhaust emissions.

2.3 Air Delivery Systems

A typical arrangement of the refrigeration system and air distribution in a refrigerated semi-trailer is shown in Figure 1. In these vehicles, top air delivery is predominately used. Refrigeration unit fans cause temperature-controlled air to circulate around the inside of the vehicle, roof, walls, floor, and doors to remove heat which is conducted and infiltrated from the outside, returning to the cooling coil via the floor or space under pallets. For chilled cargoes horizontal channels are required between rows of cartons to allow good return airflow through the load. This is of particular importance when carrying fruit and vegetables, where heat of respiration may be a significant proportion of the heat load. To facilitate air return to the evaporator coil, some trailers are fitted with a false bulkhead wall with metal grill or holes in the lower part for return air passage.

The placement of air delivery and return on the same side of the refrigerated box for reasons of compactness and simplicity, makes the achievement of uniform temperature distribution in the cargo difficult. In recent years considerable effort has been devoted to the optimisation of air flow and temperature distribution in refrigerated cargoes using a variety of modelling techniques including computational fluid dynamics [10,11].

2.4 Multi-compartment vehicles

In multi-compartment vehicles the refrigerated space is subdivided into a number of compartments with individual temperature set-points to provide logistics flexibility for many business operations (Figure 2). It is common practice for supermarket chains to deliver produce inside multi-compartment semi trailers.

The different temperatures in each compartment are achieved by using distributed evaporator coils fed from a single condensing unit. In general practice, the coldest compartment is located at the front and the warmest is at the rear but any temperature configuration is possible. The design and control of refrigeration systems for multi-compartment vehicles is much more challenging than that for single compartment vehicles. Factors specific to the design of multi-compartment refrigeration systems are the heat transfer between the compartments, product loading patterns and door openings and method of temperature control [12].

2.5 Other road transport refrigeration technologies

2.5.1 Eutectic systems

Eutectic systems consist of hollow tubes, beams or plates filled with an eutectic solution (phase change material - PCM) to store energy and produce a cooling effect whenever necessary to maintain the correct temperature in the refrigerated container. An example of a eutectic system is shown in Figure 3. The Eutectic concept is different to conventional refrigeration systems in that a cold source (heat absorption) is provided by phase change material rather than direct expansion of refrigerant gas. The plates or beams that contain the eutectic are charged (frozen down) at night on mains power. Once the beams are frozen they operate silently and provide reliable, rapid cooling for a specific duration of time.

Systems for food transport applications can be based solely on eutectic thermal energy storage or can be a combination of eutectic and vapour compression system. Such systems, which may be suitable for short delivery rounds where the heat loss through frequently opening doors can be a major problem, can offer savings by: i) using a smaller refrigeration system and reducing losses arising from frequent on/off cycling of the unit.

There are fixed sizes of plates or beams available and selection involves calculations based on the prescribed delivery rounds, the journey length, number of door openings, time period etc. Some manufacturers have now developed static refrigeration units that are capable of charging eutectic systems when linked up via a connector. This removes the requirement for each refrigerated vehicle to have its own condensing unit and therefore decreases costs.

A variation of the eutectic plate is eutectic roll containers in which the food is stored in containers with wheels equipped with eutectic plates or PCM material within the walls of the insulated box. The refrigeration capacity of the PCM material in the roll container can be supplemented by a cryogenic ‘total loss’ system such as dry ice or a small vapour compression system driven by 12 V, 24 V d.c. or 230 V a.c. power. Roll containers are useful in applications where product has to be moved manually fairly quickly.

2.5.2 Cryogenic Cooling Systems

As an alternative to mechanical refrigeration, total loss systems using cryogenic fluids such as liquid nitrogen or carbon dioxide may be used. The fluid is stored in tanks which are connected to a spray bar that runs the length of the vehicle. The cryogenic fluid on release into the vehicle vapourises very rapidly, reducing the temperature of the container uniformly.

Advantages of the total loss system are rapid pull-down of temperature and very low noise. For longer journeys, these systems are expensive to operate so cryo-mechanical systems can be used which combine the rapid pulldown of a total loss refrigerant with the more economical steady running of a mechanical system.

3. Energy Consumption and environmental impacts of refrigerated road transport

Food transport in the UK is responsible for 18444 kilotonnes of CO_2 emissions of which 45% (8300 kilotonnes) can be attributed to Heavy Goods Vehicle (HGVs) [13]. It is estimated that approximately a third of food transportation with HGVs is refrigerated but the above emissions are from the truck engine alone and do not include emissions from separate engine diesel driven refrigeration units and refrigerant leakage.

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 to 44 tonnes). 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 tonnes). Articulated vehicles over 32 tonnes, account for around 80% of the total tonne-km goods movement in the UK [14].

Table 1 shows typical figures for refrigeration duty and fuel consumption of self contained mechanical road refrigeration equipment. The data is based on ATP test conditions at +30°C ambient temperature. Multi-drop distribution will require a higher refrigeration capacity to counteract the infiltration load during door openings. Chilled distribution should normally require a lower refrigeration capacity than frozen food distribution due to the higher temperature difference between the refrigerated compartment and the ambient.

Not much data is available for energy consumption of transport refrigeration equipment during operation in the field. Field fuel consumption is dependent on many factors such as the type of operation and type of product transported, solar load, fuel density, control software setup e.g. continuous compressor modulation or on/off control and defrost cycle initiation and termination.. In many cases, the field energy consumption for chilled distribution can be higher than frozen food distribution due to the more stringent temperature control requirements, product respiration and the higher air flow rates required to maintain uniform temperature distribution [15].

The fuel consumption of various types of vehicles involved in freight transport in the UK is shown in Table 2. This fuel consumption excludes any energy that may be consumed by the refrigeration equipment. Two sets of data are presented. Data from the 2002 Key Performance Indicator (KPI) Survey of Transport Efficiency in the UK Food Supply Chain presented by McKinnon et. al. [14], and data from the government's Continuing Survey of Road Goods Transport [16]. It can be seen that the two sets of data are broadly in agreement. The 2002 KPI survey indicated that 85% of the articulated vehicles of gross weight greater than 38 tonnes had an average fuel consumption efficiency in the range 2.8-3.5 km/litre with the difference between the highest and lowest fuel consumption being 1.5 km/litre.

The survey also indicated that in 67% of the loaded journey legs the average load height was between 1.5 and 1.7 m, which corresponds to the average slot height in warehouse racking. The average volume and weight utilisation of the vehicles was found to be 53%.

A high fuel efficiency does not necessarily signify an efficient distribution operation because it can be offset by poor utilisation of the vehicle's capacity. A better measure of energy efficiency in food distribution is *energy intensity* which expresses fuel consumption on a pallet kilometre basis rather than vehicle kilometre basis. In the 2002 KPI survey the energy intensity of 46 fleets was found to very from 8 ml of fuel per pallet-km to 61 ml per pallet-km. The main reasons for the wide variation were considered to be the type and size of vehicle used and the nature of the distribution operation. The average energy intensity and standard deviation are given in Table 3.

It can be seen that tertiary distribution had the highest energy intensity and highest variability whereas primary distribution of ambient products had the lowest energy intensity and relatively low variability. A comparison of ambient and temperature controlled primary distribution indicates that the on-board refrigeration systems in the fleets considered in the survey were responsible, on average, for around 37% of the total energy consumption of temperature controlled primary distribution.

Table 4 shows the average fuel efficiency, payload weight and energy intensity of the different vehicles in the 2002 KPI survey. It can be seen that the energy intensity of rigid vehicles which are mainly used for mixed and tertiary distribution is much higher than that of heavy articulated vehicles which are predominantly used for primary and secondary distribution.

Table 5 provides data for 17 temperature controlled fleets [17]. The data did not distinguish between chilled, frozen or mixed temperature product transportation in multi-compartment vehicles or the distribution type. It can be seen however that irrespective of the type of vehicle type the average fuel consumption of the refrigeration systems in the sample varied between 15% and 25% of the engine fuel consumption. An analysis performed by Repice and Stumpf [18] on refrigeration unit fuel consumption for hypothetical urban and long distance distribution cycles showed that on average the urban cycle will result in a 16% higher fuel consumption than the long distance cycle.

Table 6 summarises the energy intensity of ambient and temperature controlled food distribution. To construct Table 6 a number of assumptions were made as follows:

i) The energy consumption of refrigeration equipment for temperature controlled food distribution is 16% higher for multi-drop compared to single trop distribution.

ii) the energy intensity of chilled food product distribution will be 20% higher than ambient distribution (Table 5).

iii) the energy intensity of frozen and mixed temperature food distribution will be 33% higher than that of chilled food distribution (Table 1).

The data in Table 6 shows that the energy intensity of temperature controlled distribution will depend on the class of vehicle used, the distribution type, long distance single drop or multi-drop, and the type of product transported, chilled or frozen. It can be seen that the energy intensity of multi-drop frozen or mixed temperature food distribution could be up to 30% higher than the energy intensity of ambient food distribution.

Table 7 shows the environmental impacts of food transportation using an emissions factor for diesel of 2.668 kg CO_2 per litre. It can be seen that, depending on the class of vehicle used and the type of distribution the CO_2 emissions can vary between 48 gCO_2/pallet-km for ambient single drop primary and secondary distribution with large articulated vehicles (above 38 tonnes), to 115 gCO_2/pallet-km for multi-drop temperature controlled tertiary and mixed distribution with medium rigid vehicles (7.5-18 tonnes). These emissions do not include direct emissions arising from refrigerant leakage.

Transport refrigeration units on small trucks and vans will have a refrigerant charge of around 2.0 kg, mid-size trucks 5 kg, and large articulated vehicles 7.5 kg [19]. These units predominantly use R404A and R410A as refrigerants. R134A is also used for chilled distribution only vehicles. It is reported that the refrigerant emissions from transport refrigeration systems are higher than those of stationary systems because they operate in a much more severe environment [15]. The operating environment involves vibration which will be dependent on road surface and a wide range of weather conditions and operating temperatures. Annual leakage figures reported are 10-37% of the refrigerant charge [19]. A study reported by Koehler et al. [20], which assumed a 10% leakage rate showed the direct emissions (refrigerant leakage) from the refrigeration system to be 21% of indirect emissions (engine fuel consumption) for R404A and 13% for R410A.

It has been reported that on average HGV vehicles travel 100,000 km per year [1]. Data in Table 5 for different types of vehicle show a range of distances traveled per day between 300 km and 500 km. If one assumes an average distance of 400 km per day and that the vehicle runs for 260 days in a year this gives a total distance of 104,000 km per year which corroborates the figure of 100,000 km per year. Table 8 shows the CO_2 emissions from refrigerant leakage for different vehicles for R404A. R404A was chosen as it has the highest GWP (Global Warming Potential) of 3860 compared to 2060 for R410A and 1300 for R134A [19] and thus will lead to the highest CO_2 emissions.

From the data in Tables 5 and 8 it can be determined that if a 10% annual refrigerant leakage is assumed, for a large articulated vehicle and single drop chilled food distribution, CO_2 emissions from refrigerant leakage will be 17% of the emissions from the engine of the refrigeration system. This compares reasonably well with the 21% emissions reported by Koehler et al. for R404A [20]. For a medium rigid vehicle, and single drop chilled food distribution, emissions from refrigerant leakage will be approximately 18% of the emissions from the refrigeration system engine. For multi-drop frozen and mixed temperature food distribution, emissions from 10% refrigerant leakage will be approximately 11% of the emissions from the refrigeration system for large articulated vehicles and 12% for medium rigid vehicles.

From tables 7 and 8 it can be seen that vapour compression refrigeration systems employed in temperature controlled food transportation are responsible for significant CO2 emissions. For refrigerant R404A and 10% annual refrigerant leakage the emissions from the refrigeration system can be up to 40% of the emissions from the vehicle engine. These emissions can be reduced through the development and use of alternative refrigeration technologies.

4. Possible alternative technologies for transport refrigeration

Diesel engines used to drive transport refrigeration equipment, typically have a thermal efficiency of 40%. Assuming a heating value for diesel of 43.2 MJ/kg and a density of 820 kg/m^3, the amount of energy rejected in the form of hot exhaust gases and thermal energy dissipated by the radiator for each litre of fuel that is used is 21.25 MJ/litre or, 5.9 kWh/litre. Recovering a small portion of this “free” wasted energy to operate a thermally driven refrigeration system, would be more than enough to cover the refrigeration requirements of a semi-trailer.

In thermally driven refrigeration technologies, absorption and/or adsorption, the conventional mechanical compressor of the common vapour compression cycle is replaced by a ‘thermal compressor’ and a sorbent. The sorbent can be either solid in the case of adsorption systems or liquid for absorption systems. When the sorbent is heated, it desorbs the refrigerant vapour at the condenser pressure. The vapour is then liquefied in the condenser, flows through an expansion valve and enters the evaporator. When the sorbent is cooled, it reabsorbs vapour and thus maintains low pressure in the evaporator. The liquefied refrigerant in the evaporator absorbs heat from the refrigerated space and vaporises, producing the cooling effect.

4.1 Absorption systems for food transport refrigeration

Koehler et al. [21] designed, built and tested a prototype of a single-stage ammonia/water absorption system for truck refrigeration powered by the exhaust gases of the tractor. A schematic diagram of this prototype is shown in Figure 4. The prototype was tested for trailer temperatures between -20°C and 0°C and ambient temperatures in the range 20°C to 30°C. The results showed that for exhaust gas temperatures entering the generator of 440°C to 490°C and exhaust flow rate of 360 kg/h, cooling capacities in the range 6-10 kW and COPs between 0.23 and 0.3 could be obtained. The investigators also indicated that there was potential for significant improvement in the COP of the single-stage ammonia/water absorption system through further optimisation of the cycle.

The authors also analysed, through simulation, the likely performance of the system for a range of road conditions. In the analysis the temperature of the gases leaving the generator was assumed to be constant at 200 °C for a range of driving cycles. Several truck engines with power from 250 hp to 420 hp were also analysed to calculate the exhaust mass flow rate.

The simulation results indicated that such a system will have sufficient capacity to satisfy 80% of the refrigeration needs of the truck when driving on level roads. To address this deficiency as well as the cooling requirements of the truck in city driving conditions when the heat available from the engine exhaust gases will be even lower, an auxiliary cooling system will be required. Such a system could be a eutectic storage system which can be charged at night using a mains powered vapour compression refrigeration system.

Similar results were obtained by Horuz [22], who used the exhaust gases of a 6-litre turbo diesel engine to drive a 10 kW commercial aqua-ammonia vapour absorption refrigeration system. The refrigeration unit was powered successfully up to its rated capacity but a significant reduction in capacity (down to 1 kW) was observed when the engine was run at low speeds. The effect on the performance of the engine of introducing the generator in the exhaust system was found to be quite low, with a maximum decrease in efficiency of 2 %.

4.2 Adsorption systems for food transport refrigeration

Christy and Toossi [23] designed, modelled, built and tested a trailer refrigeration and bus air-conditioning ambient-air cooled adsorption system. The design employed four activated carbon sorbent beds and ammonia (R717) as a refrigerant. The sorption system was then theoretically characterized (size, weight, heat input, operational modes and layout configurations) for the purpose of being capable of maintaining temperatures in the range -18°C to 4.5°C for transport refrigeration. The heat available from diesel engines in the power range 225 hp and 525 hp was determined to be between 40 kW and 60 kW from the engine cooling circuit and between 40 kW and 140 kW from the exhaust gases.

The cooling requirements of large refrigerated semi-trailers were considered to be equal to the cooling capacities of the units usually installed on these vehicles, that is, around 15 kW. It should be noted that those units are usually 200 to 300 % oversized. Practical COP values used for system design were in the range 0.6 to 1 and specific cooling power rates (measure of the evaporator cooling load per mass of sorbent material) were considered to be around 614 W per kilogram of carbon for ammonia (R717) refrigerant and 198 W per kilogram of carbon for R134a refrigerant. Based on these assumptions, a feasibility analysis was carried out for R717 and R134a refrigerants and cooling capacities of 9 kW, 19 kW and 35 kW (bus air-conditioning).

Another interesting aspect of the study was the investigation of the layout of such a system on a conventional articulated vehicle. It was identified that the best arrangement would be for the adsorption refrigeration system to be installed on the tractor with the cooling transferred to the trailer using a secondary fluid. It was also found that when a 300 kg fuel tank for a conventional diesel engine driven vapour compression refrigeration system was considered an adsorption system could be potentially lighter than the conventional system.

4.3 Thermoelectric cooling and power generation.

4.3.1 Thermoelectric cooling

Thermoelectric devices are solid state devices that can convert electrical energy into a temperature gradient. This effect was discovered by Peltier in 1834 but the application of the thermoelectric principle remained fairly limited until the development of semiconductor materials. Thermoelectric devices were first used for refrigeration and air-conditioning purposes in the 1950s.

Theoretical descriptions of the Peltier effect are given in many papers dealing with this field of research [24,25] and by manufacturers of thermoelectric devices such as Melcor [24]. In summary, the thermoelectric cooling effect is produced when a direct current is passed through at least one pair of n and p-type semiconductor materials, usually bismuth telluride Bi_2Te_3. As shown in Figure 5, when a direct current flows through the device, electrons pass from a low energy level in the p-type material to a higher energy level in the n-type material and as a result absorb heat from the environment. The heat is liberated at the other end of the device when the electrons return to a low energy level in the p-type material [26].

Cooling machines based on the thermoelectric principle offer several advantages over vapour compression refrigeration: they are inherently reliable, noise-free, maintenance-free and vibration-free since they do not contain mechanical moving parts, and have been found to have long life of more than 100000 hours. They are also environmentally friendly since they do not use HCFCs, HFCs or any other refrigerant, they are small in size, light in weight, and can allow for very precise temperature control. They are also fully reversible in operation, so that they can be used for either heating or cooling [26]. The main disadvantage of thermoelectric devices that has prevented them from being used in large scale refrigeration applications such as for food transportation and storage is their relatively low COP compared to conventional mechanically-driven vapour compression refrigeration systems.

Thermoelectric coolers are currently commercially available in a variety of module sizes and capacities for single modules up to 200 W. Prices are of the order of £0.3 per W, depending on specification [24]. The maximum ΔT that can be reached between the two sides of a Peltier cooler is 70°C but cascade mountings (multistage arrangement) enable a ΔT as high as 130°C and temperatures of -100°C to be achieved [25]. The COP of a thermoelectric cooler is defined by analogy with that of a mechanically driven vapour compression cycle. It is the ratio of the rate of the heat removed from the environment by the cold side of the device to the electrical power input that is required to do so. It can be expressed as:

$$COP = \frac{Q_c}{W_G}$$

where Q_c is the net heat absorbed at the cold end and W_G is the electrical power applied.

Low capacity thermoelectric units are now commercially available for cooling of electrical and electronic equipment and for use in small capacity refrigerators. The

COP of these units is currently below 0.5 but Bierschank and Johnson [27] showed that the theoretical COP of these devices can be significantly higher than 1.0 for ΔT less than 30 °C. Over the last six years, Hi-Z Technology, Inc (USA) has been developing quantum well technology over the past six years, with very promising results. A 11μm, Si/SiGe on 25μm Kapton cooling module sized 4.9 cm x 4.9 cm x 0.25 cm has been built and tested, showing a cooling capacity of 102 W and a COP of 2.85 at a ΔT of 30°C [24].

In their current state of development thermoelectric cooling machines cannot as yet compete with vapour compression systems for transport refrigeration because of the relatively high ΔTs and corresponding low COPs (0.5 for chilled food transport applications compared to 1.5 for vapour compression systems). This situation, however, may change with the development and commercialisation of the quantum well thermoelectric cooler technology.

4.3.2 Thermoelectric power generation

When a temperature differential is established between the two sides of a semiconductor material, a voltage is generated. This voltage is directly proportional to the temperature differential and the constant of proportionality is referred to as the Seebeck coefficient. A thermoelectric device can therefore also convert thermal energy into electric energy: this is the inverse of the Peltier effect, called the Seebeck effect, which was discovered in 1821. Like thermoelectric coolers, thermoelectric generators have no moving parts, are silent in operation and reliable. Their efficiency is typically low, around 5%. These devices can be used both for low power generation, for example using the heat of the human body to power electronic devices such as a watch, and for relatively high power generation using solar concentrators or converting waste heat into useful electricity [28,29]. Research is also being carried out on the use of the heat in the exhaust gases of cars and trucks to power on-board air conditioning and refrigeration equipment [30-32]. The maximum electric power generated from car exhaust systems so far has been around 200 W but this power was found to decrease significantly at idling engine speed.

A 1.0 kW generator designed for installation on a 300 hp truck was built and tested by Hi-Z Technology, Inc (Canada) using 72 modules of 14W each. This capacity is too low for semi-trailer transport refrigeration applications, but the development of the quantum well technology with potential energy conversion efficiencies in excess of 25% from the current 5% is expected to increase the attractiveness and range of applications of the technology. The goal of the company is to produce a basic low cost 10-20 watt module that can be used to build up any size generator such as a 5 to 10 kW waste heat recovery generator that can be used to drive refrigeration systems for trucks [33].

4.4 Air Cycle Refrigeration

For a number of years now, transport refrigeration has been identified as a potential application area for air cycle systems on the grounds of weight, robustness, leakage, reliability and maintenance [34,35,36]. Air cycle systems are also less sensitive to part-load operation.

Spence et al [37] reported on the design, construction and testing of an air cycle demonstrator plant for refrigerated road transport. The project objectives were to accommodate the air cycle system within the physical envelope of an existing R404A vapour compression refrigeration trailer unit and to achieve an equivalent refrigeration capacity, specified as 12 kW at 0°C trailer temperature and 7.2 kW at -20°C trailer temperature, both at 30°C ambient. The demonstrator unit was constructed utilizing commercially available or existing parts, including the diesel engine prime mover and air circulation fans of the existing vapour compression system.. Standard exhaust turbocharger components were selected for the two compressor stages and the turbine, the latter requiring modification to suit the significantly different conditions of the air cycle. The choice of heat exchangers was also compromised by cost considerations as well as packaging constraints imposed by the restricted layout inside the envelope of the existing unit. A schematic of the air cycle demonstrator plant is shown in Figure 6.

The performance of the unit was measured on a calorimeter test facility at two operating conditions, 0°C and -20°C, to allow comparison with the rated refrigeration capacities of the vapour compression unit. The demonstrator achieved a full-load capacity of 7.8 kW at -20°C (8% higher than the existing unit), but at 0°C the cooling capacity was 9.5 kW (21% lower than the existing unit). The fuel consumption of the air cycle plant was found to be approximately 200 % higher than for the vapour compression unit at both conditions. At a part load test condition of 3.4 kW refrigeration capacity (44% of the full load capacity), at -20°C, the air cycle plant fuel consumption reduced by approximately the same percentage, indicating that the overall plant COP remained almost constant for this load change. At the same part load condition, the vapour compression unit would require 73 % of its full load fuel consumption. From this it follows that the air cycle plant used only 80 % more fuel than the vapour compression unit at the part load condition, compared to approximately 200% more at full load.

Based on the test results of the demonstrator unit, the investigators developed a thermodynamic model which was used to assess the potential performance of an optimised air cycle unit employing state of the art technology, including specifically designed turbomachinery components, higher performance heat exchangers and air bearings. The predicted overall COP of the optimised unit (allowing for all cooling and circulating fan power) was found to be 0.53 at -20°C and 7.8 kW refrigeration capacity, which was only 7% lower than the corresponding COP for the vapour compression unit [38]. Moreover, based on the demonstrator test results, it was anticipated that under part-load conditions, which represent a large proportion of refrigerated transport long haul operations, the optimised air cycle would maintain its full-load COP and require lower driving power than the vapour compression unit.

5. Future trends and technology outlook for road transport refrigeration

The wider use of the internet is gaining rapid acceptance in the food retail sector and currently there is every indication that internet sales of food will continue to grow at a significant rate. In the process adopted by the major retailers in the UK, internet orders are sent to the nearest distribution centre which is normally a conventional store with an internet sales facility. A team of ‘pickers’ prepares the orders which are distributed to the customers using a fleet of light refrigerated vans. The delivery is scheduled to optimise travel, taking into account the customer location and the specified delivery time. With the increase in internet sales the thermal performance of light refrigerated vehicles and the efficiency of their refrigeration systems will become more important. Estrada-Flores and Eddy [39] considered thermal performance indicators of light refrigerated vehicles. The investigations were carried out in environmentally controlled test facilities and considered amongst other parameters the effects of door openings. The temperature variability of the products in the vehicle was found to be a function of the time required for the refrigeration unit to recover temperature control after door opening and the difference between the maximum and minimum temperature reached during the door opening.

The recent rapid increases in the price of diesel has also increased interest in cryogenic 'total loss' systems, particularly for urban distribution. Apart from low noise and rapid load pull-down, cryogenic systems may also have lower environmental impacts than conventional HFC (hydrofluorocarbon) based vapour compression refrigeration systems. This aspect needs to be investigated further.

The authors believe that the transport refrigeration systems of the future will be hybrid systems. The types of system in the hybrid arrangement will depend, to a large extend, on the size of the vehicle and type of distribution. Reduction in the cost of vacuum insulation will encourage its wider application and this will lead to a reduction in the refrigeration load. The lower load will enhance the potential for the application of thermally driven systems and solar refrigeration technologies, particularly in warm countries. Thermal energy storage with phase change materials (PCMs) will also increase in importance particularly if the PCMs are charged using renewable energy.

6. Conclusions

- Food transport refrigeration systems are predominantly based on the vapour compression refrigeration cycle. These systems, in order to meet the requirements of the ATP agreement and satisfy the refrigeration demands over a wide range of operating conditions are oversized by up to 1.75 times the calculated load.

- The COP of transport refrigeration systems is quite low, ranging for around 0.5 at –20 °C space temperature to 1.5~1.75 at + 3°C space temperature and 30 °C ambient temperature.
- Articulate vehicles over 33 tonnes are responsible for over 80% of refrigerated food transportation in the UK. Refrigeration systems in these vehicles are invariably driven by auxiliary diesel engines.
- The environmental impacts of diesel engine driven food transport refrigeration systems can be significant and up to 40% of the impacts of the vehicle engine. The capacity, size and environmental impacts of these systems can be reduced through the use of thermal energy storage (eutectics). For small journeys the vapour compression system can be eliminated completely.
- Sufficient reject heat is available from the engine of articulated vehicles to drive sorption refrigeration systems at normal out of town driving conditions but insufficient heat will be available in town driving. This shortcoming can be overcome through the use of an auxiliary heat source or eutectic energy storage. Other issues to be addressed are the size and mounting of the sorption refrigeration system.
- The air cycle technology is quite promising for food transport applications. Main disadvantages at present is the low COP compared to that of the vapour compression system, particularly for chilled food distribution applications, and the unavailability of off the shelf systems.
- Direct power generation from the heat in the exhaust of the engine to power refrigeration systems may be a promising technology for the future. Other technologies that need further investigation and consideration are Stirling cycle powered systems, magnetic refrigeration and solar energy driven systems and hybrid system arrangements.

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List of Tables:

Table 1. Refrigeration duties and fuel consumption of self contained mechanical transport food refrigeration units

Body Inside Length/Inside Volume/Type	Minimum refrigeration capacity long distance transport (W)		Required refrigeration capacity, multi drop distribution (W)		Fuel consumption (litre/hr)	
	-20 °C k=0.4 W/m^2 K	0 °C k=0.7 W/m^2 K	-20 °C k=0.4 W/m^2 K	0 °C k=0.7 W/m^2 K	-20 °C k=0.4 W/m^2 K	0 °C k=0.7 W/m^2 K
6.2 m/ 33.42 m^3/ Rigid Lorry	3765	3876	5630	4554	2.0	1.5
10.4 m/ 61.15 m^3/ Rigid Lorry	6155	6353	9897	7920	3.0	2.5
13.4 m/78.79 m^3/ Semi Trailer	7730	7986	13500	10078	4.0	3.0

Table 2. Average fuel efficiency

Vehicle Class	KPI 2002 Survey (km/litre)	CSRGT (2001) (km/litre)
Small rigid less than 7.5 tonnes	4.0	4.1
Medium rigid (7.5-18) tonnes	3.6	3.7 (7.5-14.0 t) 3.3 (14-17 t)
Large rigid greater than 18 tonnes	3.1	2.9 (17-25 t) 2.7 (> 25 t)
City semi-trailer	3.2	-
32 tonne articulated vehicle	3.2	3.2 (< 33 t)
38 to 44 tonne articulated vehicle	2.9	2.9 (> 32 t)

Table 3. Average Energy Intensity of Different Distribution Operations

Distribution type	Average energy intensity	Standard deviation
	(ml fuel/pallet-km)	(ml fuel/pallet-km)
All fleets	25.4	7.4
Primary distribution (temperature controlled)	19.3	4.9
Primary distribution (ambient)	12.2	6.5
Secondary distribution	19.2	4.9
Tertiary distribution	37.3	12.3
Mixed distribution	30.1	4.4

Table 4. Average energy efficiency and energy intensity by vehicle type

Vehicle class	Average fuel efficiency (motive only)		Average volume Load	Average payload	Average energy intensity by volume	Energy intensity by weight
	km/litre	mpg	Pallets	Tonnes	ml/pallet-km	ml/tonne-km
Medium rigid	3.87	10.94	5.78	2.25	33.0	83.8
Large rigid	2.91	8.21	8.69	7.41	31.8	37.1
City artic	3.14	8.87	11.24	6.57	21.4	36.4
32 tonne artic	3.35	9.48	14.38	10.37	19.1	26.4
38 tonne artic	2.79	7.88	17.11	11.83	18.0	26.0

Table 5. Motive and refrigeration fuel consumption

Vehicle class	Distance traveled 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	Litres/day	km/litre	Litres/day	km/litre	%
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 artic	335	112.33	2.98	26.1	2.42	23.2
32 tonne artic	419	140.8	2.97	34.1	2.40	24.2
38 tonne artic	486	159.62	3.04	24.9	2.52	15.6

Table 6. Energy intensity of ambient and temperature controlled distribution

Vehicle class	Average fuel efficiency (motive only)	Average energy intensity (ambient)	Average energy intensity (chilled single drop)	Average energy intensity (chilled multi-drop)	Average energy intensity (frozen and multi-temperature single drop)	Average energy intensity (frozen and multi-temperature multi-drop)
	km/litre	ml/pallet-km	ml/pallet-km	ml/pallet-km	ml/pallet-km	ml/pallet-km
Medium rigid	3.6	33.0	39.6	40.7	41.8	43.2
Large rigid	3.1	31.8	38.2	39.2	40.3	41.7
City artic	3.2	21.4	25.7	26.4	27.2	28.0
32 tonne artic	3.2	19.1	22.9	23.5	24.2	25.1
38 tonne artic	2.9	18.0	21.6	22.2	22.8	23.6

Table 7. CO_2 emissions of ambient and temperature controlled distribution excluding refrigerant leakage (gCO_2/pallet-km)

Vehicle class	Ambient	Chilled (single drop)	Chilled (multi-drop)	Frozen and multi-temperature (single drop)	Frozen and multi-temperature (multi-drop)
Medium rigid	88	106	109	112	115
Large rigid	85	102	105	108	111
City artic	56	69	70	73	75
32 tonne artic	51	61	63	65	67
38 tonne artic	48	58	59	61	63

Table 8. CO_2 emissions from refrigerant leakage (gCO_2/pallet-km)

Vehicle class	Refrigerant charge (kg)	Average Volume load (Pallets)	Annual leakage rate for R404A (percent of system charge)					
			5%	10%	15%	20%	25%	30%
Medium rigid	5.0	5.78	1.7	3.3	5.0	6.7	8.3	10
Large rigid	6.0	8.69	1.3	2.7	4.0	5.3	6.7	8.0
City artic	6.5	11.24	1.1	2.2	3.3	4.5	5.6	6.7
32 tonne artic	7.0	14.38	0.9	1.9	2.8	3.8	4.7	5.6
38 tonne artic	7.5	17.11	0.8	1.7	2.5	3.4	4.2	5.1

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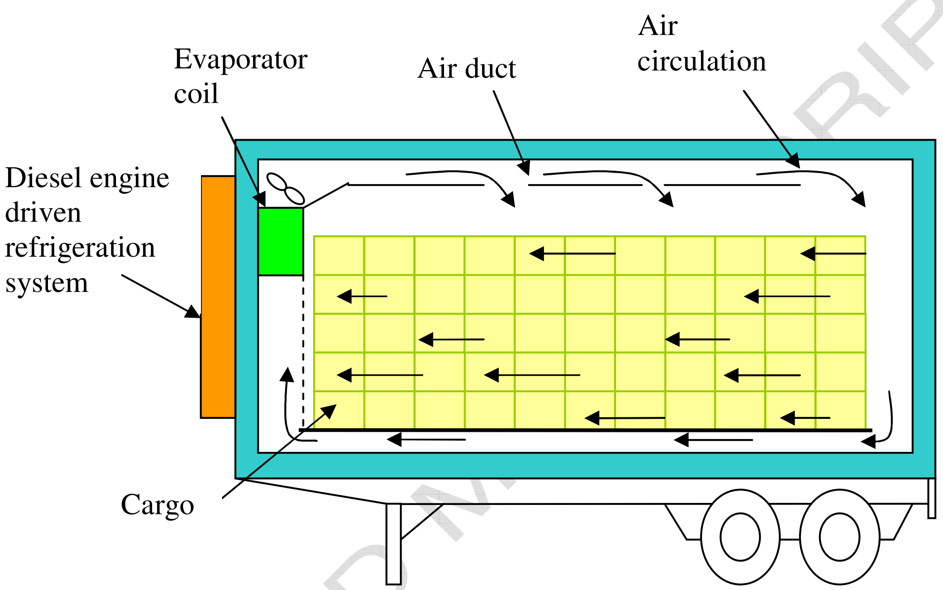

Figure 1. Refrigeration system and air circulation in a semi-trailer

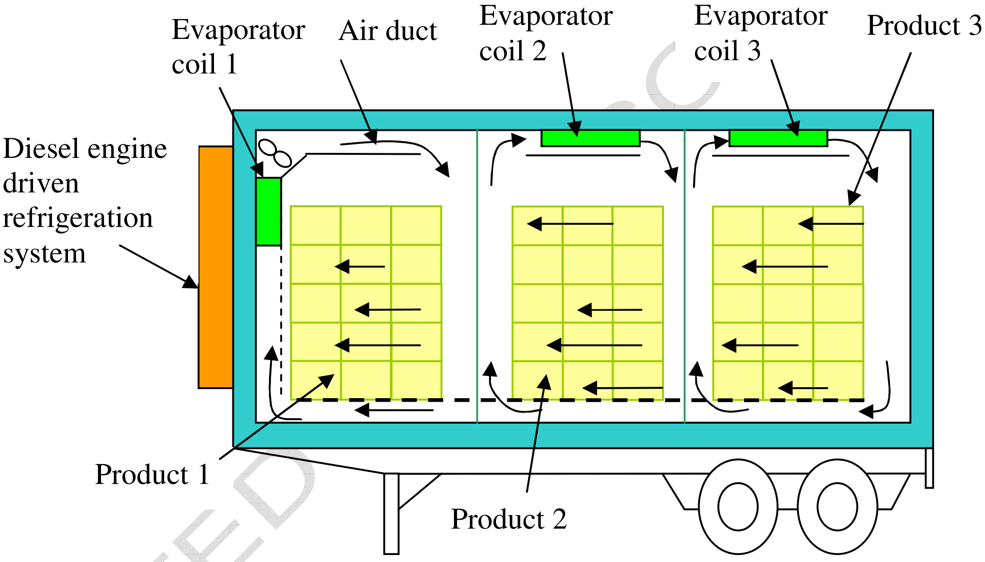

Figure 2. Multi-compartment semi-trailer

Figure 3. Example of Eutectic Beams (source:Frigoblock, www.frigoblock.de)

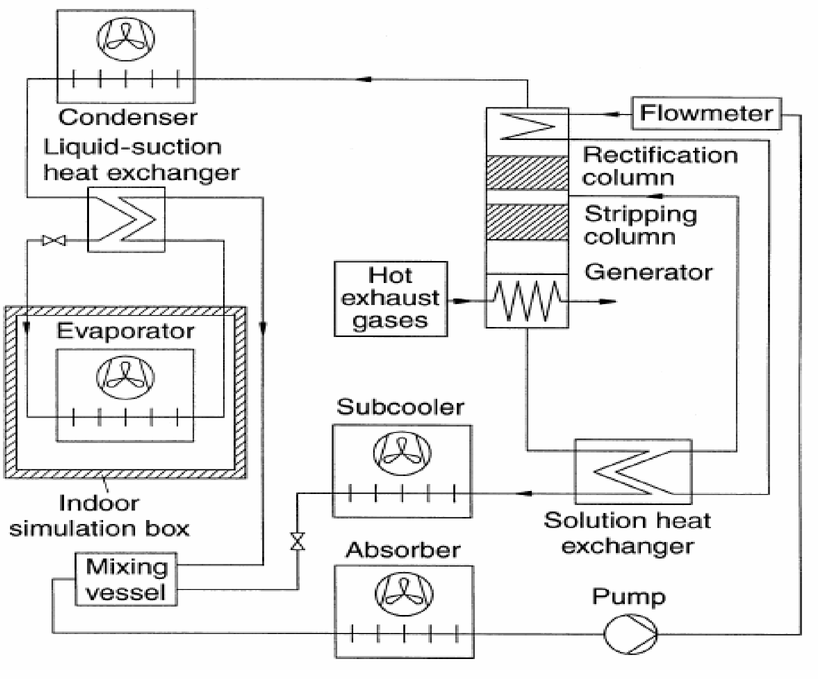

Figure 4. Schematic of absorption refrigeration system prototype for transport refrigeration [21]

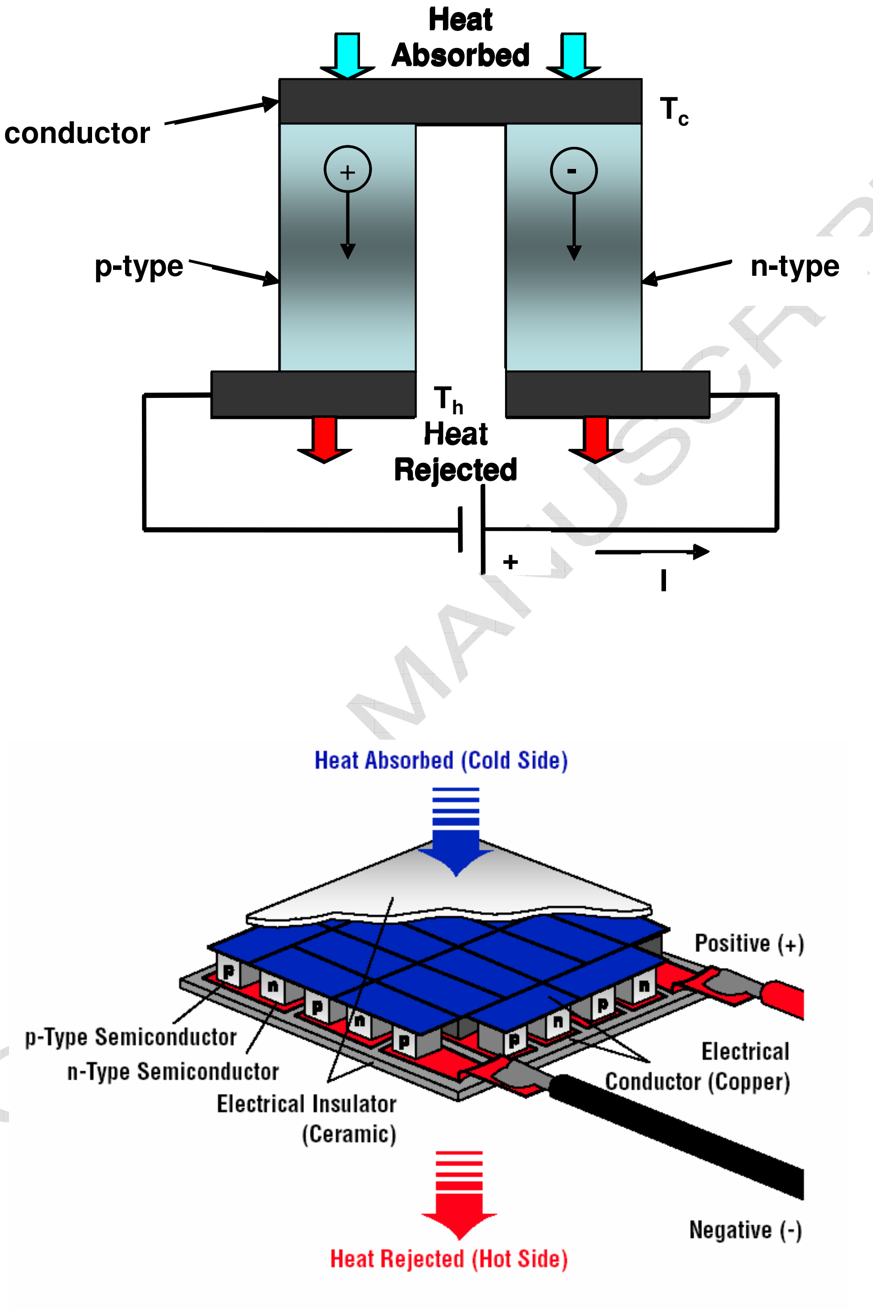

Figure 5. Schematic of a thermoelectric module [24]

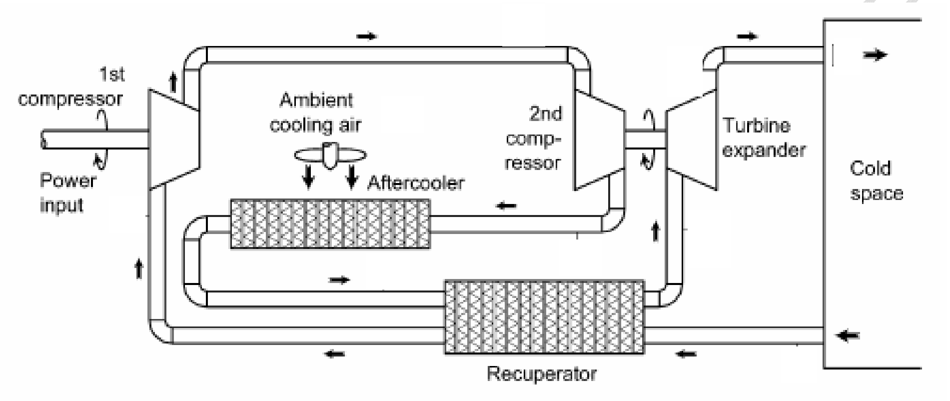

Figure 6. Air cycle demonstrator plant for refrigerated transport [37]