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Refrigerated transport: progress achieved and challenges to be met

Refrigerated transport, undoubtedly an essential link in the cold chain, aims at supplying the consumer with safe, high-quality perishable goods.
The goods concerned are perishable foodstuffs or non-food goods such as flowers, plants, pharmaceuticals or chemical products. There are three basic types of transport: sea transport (conventional ships, container ships), land transport (road, rail) and air transport. Intermodal transport combines more than one of these types of transport.
Frozen goods are transported at a temperature of –18ºC or lower, chilled goods at a temperature above the freezing point.
Driven primarily by the expansion of the chilled and quick-frozen foods market, with an annual sales level totalling 1200 billion USD[1] worldwide in 2000 according to IIR figures, refrigerated transport is a major economic player. About 550 000 refrigerated marine containers and about 1 200 000 refrigerated road vehicles are currently in use[2] and this clearly illustrates the importance of refrigerated transport worldwide.
This Informatory Note presents progress achieved in the refrigerated-transport sector, and discusses the challenges to be met, with a focus on hygiene, safety and energy consumption.

How refrigeration technology operates in refrigerated transport

For each transport mode there is specialized refrigerated equipment to provide temperature control. Intermodal systems exist for all modes except for air transport. It must be noted that transport refrigeration systems not only cool, but also heat if necessary in order to achieve the correct transport temperature, an important consideration for chilled goods in cold climates.[3]
As a general rule, transport refrigeration equipment is designed to maintain temperature, not to cool down goods, so goods should be loaded already pre-cooled to carriage temperature. Exceptions are shipments of bananas and citrus fruit, for which appropriate cooling regimes are established.
It is essential to establish rules governing hygiene, particularly with respect to cleaning of the body following transport.[4]
The majority of new transport refrigeration units use vapour-compression refrigeration with HFC refrigerants. Some equipment uses total-loss refrigerants (carbon dioxide or liquid nitrogen) for limited journey times.
Road transport units may operate either from the vehicle engine or from an independent diesel engine. Rail units may operate on electricity supplied from a generator wagon. Marine refrigeration is electrically driven from ships' supplies. Intermodal containers are also electrically driven, but can have portable diesel generator sets attached to them. Refrigerated equipment in air transport is relatively rare, and commonly uses "dry ice" (solid carbon dioxide), though some battery-operated systems are available.

What is achieved (controllability, energy use) in various sub-sectors

The technical requirements for transport refrigeration units are more severe than for many other applications of refrigeration. The equipment has to operate in a wide range of ambient temperatures and under extremely variable weather conditions (sun radiation, rain…); it also has to be able to carry any one of a wide range of cargoes with differing temperature requirements, and it must be robust and reliable in the often severe transport environment.
For frozen goods, low temperature is needed, but generally a close range of temperature is not a critical requirement. Frozen foods at –18ºC may not suffer if they go down to a lower temperature, so a simple on/off control system may be used, which provides cooling whenever the temperature rises to the set point. However, especially for long journeys, frozen foods must not be exposed to large temperature variations, which can lead to moisture migration and loss of quality. Chilled foods, on the other hand, require close temperature control between two limits — too low a temperature will damage them; too high a temperature will reduce shelf life. For example, chilled meat may need to be maintained throughout a long journey within a temperature range of between 0ºC and –1.5ºC, which modern equipment can achieve.[5]
Close temperature control systems for chilled goods require continuous, modulated refrigeration combined with high rates of air circulation. This involves a greater power and energy requirement than for frozen foods with on/off control.

Longer journey times need better control. Temperature control available in ship and intermodal container transport provides the best conditions; road transport can be comparable but less severe specifications are acceptable for shorter journeys or for frozen foods. Relatively poor temperature control can be acceptable for rapid air transport.

Estimated diesel power requirements (as equivalent fuel use) for road units are from 11 kW for a typical van unit to 23 kW for a trailer unit, giving an overall figure of around 0.05 kWh per tonne km.[6] This high power requirement is necessary to obtain a fast temperature pull down and fast recovery in distribution with many door openings. This corresponds to equipment with cooling capacity about 4 times the body heat loss cooled at –20°C and 10 times the body heat loss cooled at 0°C at 30°C ambient. Running hours may be between 1800 and 4000 hours per year.

Intermodal container units may require electrical power of around 2 kW for frozen goods and 5 kW for chilled, but this is very dependent on unit design and operating conditions. It is notable that the close temperature control requirements and more rapid air circulation needed for chilled goods result in higher power requirements than for frozen goods, despite the lower temperature differences to be maintained.

Options for consideration and development

Although the degree of temperature control (and thus the degree of security for food safety and quality) in refrigerated transport equipment is excellent, the effects of equipment, packaging and stowage mean that this is achieved at the expense of energy use. For chilled cargoes in particular, there are technical options to reduce this energy use.

Methods of modulating refrigeration power to part-load operational needs include:

- hot gas bypass
- suction throttling
- compressor unloading
- compressor speed control

Both hot gas bypass and suction throttling are thermodynamically inefficient and carry an energy use penalty. Compressor unloading is practised in multi-cylinder reciprocating compressors, but is limited in its capacity reduction. The scroll compressor demonstrates a wider and continuous control range by unloading: disengaging scrolls on a short time cycle appears to be a very effective way of saving energy.[7,8] Compressor speed control, either in stages or continuously through an inverter supply, is also effective but is limited in its unloading capacity and needs an additional control method to reach low levels.

As stated above, close temperature control also requires high air circulation rates. Fan power adds significantly to heat load and power consumption — all the energy supplied to fans has to be removed by the refrigeration system. The need for high air circulation rates reduces as the temperature difference between cargo and ambient reduces, so fan speed control by temperature difference can save energy. This saving is very significant, for the Fan Laws show that a doubling of fan speed results in an eight-fold power increase. Fan power savings are also possible for some frozen cargoes, as continuous fan operation is not always necessary when the compressor is off.

A certain amount of energy is used in defrosting evaporator coils. Depending on the sensing and control system, this can be more than is strictly necessary, and optimal control systems will only defrost when and as much as is needed. In order to achieve energy savings and better temperature control, and for certain chilled perishable applications, the coils can be defrosted naturally by just stopping the cooling effect, keeping airflow, and recovering the latent heat from the ice on the coil.

Energy is also used in cooling the fresh air necessarily introduced into respiring fresh produce cargoes. Improved systems which modulate this flow to that actually required are available, and these save energy.

For frozen foods, the use of lower than necessary temperatures results in extra energy use, not only to hold the greater temperature difference but also because of the lower efficiency of the compression cycle. Frozen foods should not be transported at temperatures lower than that required at destination, as this would result in additional energy use with no appreciable quality or safety benefit.

The options identified above need careful consideration, and should be co-optimized for minimum energy use whilst maintaining the required degree of product temperature control and equipment reliability. Diesel powered systems may offer further opportunities by improving engine efficiency.

Good thermal insulation is a necessary part of efficient use of refrigeration, and changes in insulation foams, necessary for other environmental reasons, may increase power consumption. Insulation suffers degradation of thermal properties with time, which must be allowed for in energy budgets. New technologies such as vacuum insulation should be evaluated. Other complementary techniques include protection from solar radiation and use of plastic door curtains which are essential in distribution. These factors can be especially important in hot climates.

Other transport options such as the use of insulated mini-containers of unit load size should be considered for continuous thermal protection of smaller lots of goods.

Scope for improvement, and how it should be achieved

From the data that has been published, it seems that energy savings of about 50% are possible for chilled goods transport. For frozen goods transport, the savings may be less, but are nevertheless worth investigation.
The following table summarizes key recent achievements and fields to be focused on in the near future and beyond in order to address the issues already described.

Table: Past and future development of refrigerated transport equipment

Field	Achievements	For Consideration	Scope
Energy and environment	RP: Continuous energy-efficient controls by unloading reciprocating and scroll compressors AC: Speed control of evaporator/air cooler and condenser fan(s)	In: High efficiency insulation constructions (micropores/ vacuum) RP&AC: Specification of part-load data RP: Improving efficiency of the diesel engine (Turbo)	Lo: Efficient modularity vehicle-unit loads RP&AC: Responsible choice of equipment and adjustments
Quality of equipment	TC: Close air temperature control ± 0.1 K at control sensor 1 K return-delivery	TC: Influence of air guidance devices, cargo units and stowage on air and /temperature distribution	TC: Definition of quality criteria for conditioning equipment TC: Definition of relations between air and cargo temperatures

Legend:
AC: Air circulation
In: Insulation
Lo Logistics
RP: Refrigeration power
TC: Temperature control

The IIR would like to highlight the following recommendations:

- providing consumers with safe, wholesome foods is a key priority;
- compliance with strict rules governing hygiene is essential;
- the development of high-energy-performance refrigerated-transport systems is a new requirement to be met;
- the awareness of end-users should be raised regarding the long-term environmental and economic benefits of energy-efficient equipment.

Energy savings of about 50% can be achieved in the field of refrigerated transport of chilled products.
Research focused on achieving greater energy efficiency must also take into account the need to provide consumers with safe, wholesome foodstuffs.

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This Informatory Note was prepared by Robert Heap, President of IIR Section D, and reviewed by 14 experts worldwide.