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Environmental impacts of vapour compression and cryogenic transport refrigeration technologies for temperature controlled food distribution

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ABSTRACT

Cryogenic transport refrigeration systems using Liquid Carbon Dioxide or Liquid Nitrogen are proposed as good alternatives to current vapour compression transport refrigeration units powered by auxiliary diesel engines due to their potential for lower environmental impacts and rapid cooling capability. This paper analyses the greenhouse gas emissions of cryogenic and diesel driven vapour compression refrigeration systems for two different temperature controlled lorry sizes and a number of chilled and frozen food products. Both the production and operation emissions have been considered. The results showed that the production emissions of diesel and refrigerant in the vapour compression system can be up to 66% lower than the production emissions of cryogens. However, when taking total emissions into consideration, emissions from all three transport refrigeration technologies are fairly similar and within the margin of error of the assumptions made. The major disadvantage of cryogenic systems is their much higher mass intensity (20 to 60 kg/h), defined as the mass of liquid cryogen per mass of product transported per km, which is almost 10 times higher than that of diesel (2.0–4.0 l/h). This limits their food distribution range per cryogenic fluid tank and together with lack of refilling infrastructure present a barrier to the wider adoption of cryogenic systems for temperature controlled food distribution.

1. Introduction

The development of integrated food chains in developing countries is increasing the worldwide demand for temperature controlled food distribution. It is predicted that the number of refrigerated vehicles globally could increase from an estimated number of 3 million in 2013 to 15.5 million by 2015 [1]. The number of transport refrigeration units (TRUs) in the UK alone is predicted to reach 97,000 by 2025 compared to around 84,000 currently in use [2]. The vast majority of refrigerated vehicles employ vapour compression refrigeration systems driven through an auxiliary diesel engine and use refrigerants as the working fluid.

It is estimated that the commercial food transport, excluding food shopping, is responsible for annual emissions of 12 $MtCO_2e$ in the UK. Approximately a third of food transportation is temperature controlled with cooling invariably provided by vapour compression refrigeration systems driven through an auxiliary diesel engine [2,3]. These systems employ hydrofluorocarbon refrigerants with high Global Warming Potentials (GWP), such as R-404A and R134a (for chilled distribution only) with GWPs of 3922 and 1430 respectively [4]. Estimates of refrigerant leakage from vapour compression TRUs vary between 5% and 25% annual charge per year, with a recent study indicating a leakage rate in the UK of 8% per annum for refrigerant charge quantities between 3 and 8 kg [5]. Even though the direct environmental impacts from refrigerant leakage can be 65–86% lower than indirect emissions from energy consumption, they are still significant and need to be addressed [6].

Tassou et al. [7,8] estimated the average energy intensity and CO_2e emissions for temperature controlled distribution of different food products and different size lorries. The methodology employed is used in this study to compare the performance of vapour compression and cryogenic systems. Bagheri et al. [9] carried out field investigations into the real time performance of diesel driven vapour compression TR systems to identify opportunities for GHG emission reductions. The authors concluded that significant reductions of GHG emissions could be achieved by replacing the diesel engine-driven vapour compression systems with battery-powered systems [9]. Experimental work by Kayansayan et al. [10] investigated the thermal behaviour and COP of a diesel driven TR system in the laboratory. The authors concluded that the most important parameter influencing the performance of the refrigeration system is the air temperature difference outside to inside the refrigerated compartment.

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Nomenclature

C_p	specific heat capacity (kJ kg^{-1} K^{-1})
D	total distance (km)
D_{hr}	total distance travelled per hour (km/h)
EF_{diesel}	emission factor of diesel (kgCO$_2$e l^{-1})
EFP_{diesel}	production related emission factor of diesel (kgCO$_2$e l^{-1})
EFP_{LCO2}	production related emission factor of LCO$_2$ (kgCO$_2$e kg^{-1})
EFP_{LIN}	production related emission factor of LN$_2$ (kgCO$_2$e kg^{-1})
$EFP_{refrigerant}$	production related emission factor of refrigerant (kgCO$_2$e l^{-1})
F	total fuel consumption (l)
F_{fluid}	mass intensity of LCO$_2$/LN$_2$ [kg of fluid kg^{-1} km^{-1})
F_{fuel}	fuel intensity of diesel (l of diesel kg^{-1} km^{-1})
$GD_{operation}$	operation related GHG emission per kg of product per km (kgCO$_2$e kg^{-1} km^{-1})
$GD_{production}$	production related GHG emission of diesel per kg of product per km (kgCO$_2$e kg^{-1} km^{-1})
$GLCO2_{production}$	production related GHG emission of LCO$_2$ per kg of product per km (kgCO$_2$e kg^{-1} km^{-1})
$GLN2_{production}$	production related GHG emission of LN$_2$ per kg of product per km (kgCO$_2$e kg^{-1} km^{-1})
$GR_{production}$	production related GHG emission of refrigerant (kgCO$_2$e kg^{-1} km^{-1})
L_v	latent heat of vapourisation (kJ kg^{-1})
M_c	total mass of LCO$_2$/LN$_2$ consumed per hour (kg h^{-1})
M_{pallet}	total mass of food products on a pallet (kg)
m_c	mass of cryogenic liquid expanded (kg)
Q_c	energy required for transformation (kJ)
$Rate_{leakage}$	annual leakage rate (%)
Ref_{charge}	refrigerant charge (kg)
T_s	desired temperature of cargo space (K)
T_v	temperature of vapourisation (K)
V_{pallet}	average volume load (number of pallets)

Concerns about the environmental impacts of TRUs, have increased the urgency to seek alternatives to vapour compression refrigeration systems for food transport applications [2,7,11]. Among the alternatives, cryogenic TR systems using liquid carbon dioxide (LCO$_2$) or liquid nitrogen (LN$_2$) as cryogenic fluids have emerged as prominent options which can reduce the dependency on both diesel and refrigerants to provide cooling [12,14].

Only a limited number of investigations published in the open literature considered the environmental impacts of cryogenic TRUs and their comparison with the impacts of conventional vapour compression refrigeration TRUs. A report by UNEP on low GWP alternatives for commercial and transport refrigeration systems provided a small number of case studies on vapour compression and LCO$_2$ and LN$_2$ cryogenic food TR systems [13]. Bengherbi [15] and Tassou et al. [12] provided analyses of the potential economic and environmental benefits of using cryogenic TR systems in Europe. Pedolsky and LaBau [14] outlined the development of cryogenic refrigeration systems and detailed the economic and environmental benefits of these systems over the conventional vapour compression refrigeration TRUs.

A recent report published by the Californian Air Protection Agency assessed the Well-to-Wheel (WTW) GHG emissions of different TR alternatives, including cryogenic TR systems using data for the state of California [11]. The report includes estimates of the environmental impacts of LN$_2$ and makes an assumption that the environmental impacts of LCO$_2$ will be similar. The results showed the Well to Tank (WTT) emissions of cryogenic systems to be approximately double those of diesel due to the higher energy required to produce the cryogenic liquid compared to diesel. However, the overall Well-to-Wheel emissions for the cryogenic systems were estimated to be 50–60% lower than those of the diesel driven conventional TRUs due to the assumption of zero emissions from the use phase of the cryogenic fluids.

Apart from Ref. [11], previous comparative studies between vapour compression and cryogenic TRUs were based on the GHG emissions during the operation phase of the TRUs only and did not consider the emissions of the production phase of the fluids in the systems. To fill this gap, this paper investigates and compares the environmental impacts of diesel driven vapour compression refrigeration systems and LCO$_2$ and LN$_2$ cryogenic systems for temperature controlled distribution of a number of food products and delivery operations. The aim is to extend the research beyond previous studies and account for all the environmental impacts including those from the manufacture and use phase of the working fluids of both vapour compression and cryogenic systems.

2. Overview of vapour compression TRUs and cryogenic TR systems

The compressor drive method of vapour compression transport refrigeration system can vary depending on various factors such as, duty requirements, weight, noise, maintenance, environmental and fuel taxation [16]. The two most commonly used compressor drive methods, 90% of market, are auxiliary diesel engines with direct drive to run the compressor and fans, and auxiliary diesel engines which drive a generator that electrically powers the compressor and fans [17]. The fuel consumption of these engines can vary between 1 and 5 litres per hour depending on the size of the unit [7]. Besides auxiliary engines, there are TRU systems that are driven directly from the vehicle's main engine power using either an alternator unit or direct belt drive to run the compressor. However, the market share of these systems in long distance transport is still very limited [17]. Fig. 1 illustrates a simple schematic diagram of a vapour compression transport refrigeration unit run with a diesel engine.

The working principles of cryogenic transport refrigeration systems run using LCO$_2$ and LN$_2$ are very similar. A large vacuum-insulated tank, mounted underneath the chassis with storage capacity within the range of 420 and 700 kg, is used to store liquid cryogen at controlled pressure [18,19]. The storage pressure is a function of the thermophysical properties of the cryogen. LCO$_2$ is stored at 8.6 bar while LN$_2$ is stored at 3 bar [20,21]. The fluids in storage tanks at filling stations are at much higher pressure and lower temperature, LN$_2$ at 18 bar and −196 °C and LCO$_2$ at around 22 bar and −57 °C [20,22]. There are three variations of the system, direct type, indirect type and hybrid.

With direct systems, as illustrated in Fig. 2, the cryogenic fluid from the tank is directly injected into the cargo space using sprayers and is released to the atmosphere during door openings. The boiling temperature of LCO$_2$ at stored pressure is −44.074 °C and that of LN$_2$ is −185.24 °C. When the liquid fluid comes into contact with the higher temperature air inside the trailer, the fluid starts rapidly expanding to gaseous state. A cool down temperature