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Study of sorption systems for application on low-emission fishing vessels

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ABSTRACT

Waste-heat driven refrigeration technology represents a promising alternative for food preservation on-board, that could help reducing pollutant emissions and, at the same time, limiting fuel consumption. Aim of the present work is the assessment of possible benefits arising from the use of thermally driven systems, with focus on two technologies: absorption and adsorption. A dynamic simulation of the whole waste heat recovery system and the sorption refrigerators has been performed. For the modelling of the thermally driven chillers, experimental data from two prototypes have been employed. The results show that, for a cooling load typical of the Italian fishing fleet, fuel savings up to 1600 kg/y can be achieved, corresponding to 3 ton/y of avoided CO_2 emissions. Moreover, for bigger vessels with 10 kW cooling load needed, up to 7 times higher fuel savings can be obtained.

1. Introduction

In 2012, international maritime fleet has been responsible for the emission of about 900 million tonnes of CO_2 [1] and, despite the efforts devoted to environmental care, a relevant decreasing trend cannot be identified. Moreover, suggested scenarios up to 2050 predict an increase in the total amount of GHG emitted, because of a higher transportation request [1]. Among these, about 10,000 tonnes are due to refrigerant losses: even though some ozone depleting refrigerants have been replaced, the most commonly used ones still present GWP higher than 1000 [1]. Moreover, 25% of total gaseous emissions are associated to the whole operation of HVAC and refrigeration systems on board [2], because of the additional fuel consumption due to the mechanical power required by the compressors. In such a context, the utilization of waste heat and a general better exploitation of energy sources on board are of primary importance. One of the main and still underexploited possible energy sources is heat recovery from the main engine: despite a lot of efforts [3,4] and methods suggested, the main topics for research is still the optimization of the Diesel engine. However, as discussed in Ref. [4], more than 30% of waste heat from exhaust or coolant water of the main mover of a ship is recoverable, at temperatures up to 180 °C.

Different methods have been proposed for the utilization of recovered heat, including space heating [5], application of ORC cycles [6], and desalination [4]. Space heating and cooling through sorption technologies has also been the central topic of various studies. Fernandez-Seara et al. [7] have developed a heat recovery system, consisting in a generator and an economizer, to provide thermal energy input to an absorption chiller. Results showed that energy recovered from the engine of a ship is suitable for the application considered, as temperature level and heat available exceed those required. Ouadha et al. [8] have carried out a thermodynamic analysis of an ammonia-water system, considering also the energy balance for a marine Diesel, demonstrating that this is able to provide sufficient waste heat to drive the absorption chiller. Cao et al. [9] developed a TRNSYS model to simulate an absorption chiller used for space cooling in a cargo ship in Miami conditions, finding out that the system is able to provide comfort conditions in the examined route. The same authors, in Ref. [10], have developed a TRNSYS model to compare the absorption system of a baseline VCC one, performing also a payload and economic analysis that have demonstrated the feasibility of such systems. Ezgi [11] performed a thermodynamic analysis on a LiBr/water system for both space heating and cooling on a naval surface ship driven by waste

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Nomenclature

A	heat exchange area, m^2
E	energy, kWh
P	power, kW
ΔCO_2	avoided CO_2 emission, kg
m	mass, kg
U	overall heat transfer coefficient, W/m^2K

Abbreviations

chw	chilled water, °C
cw	cooling water, °C
COP	coefficient of performance
EES	electricity energy savings, kWh
el	electric
EGE	exhaust gas economizer
FS	fuel savings, kg
GHG	greenhouse gas
GRT	gross registered tonnage
GWP	global warming potential
HVAC	heating, ventilation and air conditioning
HT	desorption temperature, °C
MT	medium temperature, °C
LHV	lower heating value, kWh/kg
LT	low temperature, °C
NTU	number of Transfer Units
ORC	organic Rankine cycle
PLR	part load ratio
th	thermal
VCC	vapour compression chiller

Greek symbols

α	leakage rate
β	scaling factor
ε	heat exchanger effectiveness
δ	scaled value
Δ	displacement, t
η	efficiency
η_{CO2}	national CO_2 emission factor, t/MWh

Subscripts

gen	generator
ref	reference
s	sorption

heat from the engine, showing that the seawater cooled system not only meets the actual heating and cooling loads of the examined ship, but also provides more.

Refrigeration represents a crucial sector as well, since it heavily demanding in terms of fuel consumption and determining high amount of GHG emissions [2,12]. Focus of the research for refrigeration on board has been the study on icemakers for the production of flake ice. Wang et al. [14] developed a carbon/methanol adsorption icemaker suitable to be driven by waste heat for the production of flake ice. Wang et al. [15] developed a heat-pipe adsorber with a compound sorbent for application in icemakers on board. Recently, Shi et al. [16] studied an absorption chiller suitable for refrigeration purposes and for driving circuits with lower temperatures than a traditional single effect absorption chiller. In Ref. [17], Lu and Wang compared two adsorption refrigerators and an absorption refrigerator for waste-heat driven applications, by experimental measurements, showing that ammonia/water absorption presents the best performance.

A summary of the studies available in literature regarding the application of sorption technology to the marine sector is shown in Table 1, where the application field and type of study is described.

As highlighted from such a literature survey, the studies in literature focus almost solely on air conditioning. On the contrary, preservation of food on-board has not been extensively considered. The few attempts to do so have been directed towards the development of ice-makers. Instead, the refrigeration of the cold rooms has not been considered up to now. The peculiarity of the present work is the study of sorption devices for food preservation below 0 °C by applying the performance data of two experimentally measured systems under the boundary conditions of marine refrigeration. Moreover, the study focuses on two different technologies: ammonia-water absorption and ethanol-activated carbon adsorption. On the one hand, ammonia-water absorption is a well-proven commercially available technology that has been applied in a variety of fields for refrigeration purposes, showing values of thermal COP above 0.5 with a driving temperature of approximately 180 °C. Thus, analysing the potential of this technology can provide the basis for comparison for alternative sorption technologies that are less mature. Moreover, even though the application of ammonia refrigeration is consolidated in other application areas, on-board refrigeration has not been fully analysed or exploited and, as shown in Table 1, the majority of studies on absorption technology on-board deal with LiBr/water chillers. On the other hand, ethanol-activated carbon adsorption is still under development, and despite lower thermal COPs it can be driven by lower temperatures (<90 °C). With respect to other working pairs, activated carbon-ethanol has a great potential for food preservation applications, since ethanol is non-toxic.

For such reasons, there is a need to study how these two technologies can fit in the application of interest for this work, in order to assess the benefits obtainable as well as the open issues still. To this aim, in the present work, TRNSYS environment has been chosen for the modelling of the two waste-heat driven refrigeration systems, including the definition of heat recovery system, auxiliary pumps, and control strategy, in order to assess their performance. The absorption and the adsorption chillers, which represent the core of the two systems under investigation, have been modelled using experimental data of two already existing prototypes and applying scaling rules in order to match the refrigeration capacity required by the application. Subsequently, an energy and environmental analysis has been performed, comparing the sorption systems to a traditional VCC one. Finally, a sensitivity analysis was realised, in order to generalise the obtained results to other scenarios.

2. The case study

Reference application for the developed analysis has been the Italian fishing fleet, with particular focus on the vessels stationed in Mazara del Vallo, which represents the biggest fishing port in Italy [18]. Among the fishing boats available, the case corresponding to the most diffused types of vessels has been considered [19], i.e. a vessel with GRT about 20 and engine power of 195 kW.

For the vessels under investigation, the traditional refrigeration system on board is mainly composed of four components [20]: