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Study and evaluation of two innovative waste-heat driven refrigeration systems for fishing vessels applications

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Abstract

In the present paper, a simulation tool in TRNSYS environment is presented, aimed at assessing the feasibility of two sorption chillers, namely an adsorption activated carbon/ethanol chiller and an absorption ammonia/water chiller, for the air conditioning of a fish storage cell on board of fishing vessels. A case study, typical of Italian fishing fleet has been analysed and the results reported in terms of fuel savings and avoided emissions. With both technology, savings of more than 1000 kg of fuel per year have been calculated, avoiding the emission of more than 3 tons of CO₂. Energy analysis has proved that only a minimal fraction of exhaust gases is needed to run the systems and therefore great potentiality for further exploitation exists.

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1. Introduction

In 2012, international maritime fleet has been responsible for the emission of about 900 million tonnes of CO₂ [1]. Among these, about 10000 tonnes are due to refrigerant losses each year: even though some ozone depleting

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refrigerants have been replaced, the most common used ones still present GWP higher than 1000 [1]. However, such number should be increased to 25% of total gaseous emissions when taking into account the whole operation of HVAC and refrigeration systems on board [2]. In such a context, the utilization of waste heat and a general better exploitation of energy sources on board are of primary importance [3, 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, ranging from space heating [5], to application for ORC cycles [6] and desalination [4]. Space heating and cooling through sorption technologies has also been the central topic of various studies, that have demonstrated the thermodynamic and technical feasibility of such systems [7, 8, 9]. However, refrigeration represents a crucial sector as well, heavily demanding in terms of fuel consumption and determining high amount of GHG emissions [2]. Focus of the research for refrigeration on board has been, up to now, the study on ice-makers for the production of flake ice [10]. Nonetheless, no rigorous studies exists analysing the technical and energetic feasibility of sorption systems for application on board of fishing vessels for refrigeration and preservation of food. To cover this gap, in the present work, two different technologies are compared: absorption and adsorption. TRNSYS environment has been chosen for the modelling of the systems and energy and environmental benefits have been calculated and discussed.

Nomenclature

FS	fuel savings, [kg]	E	energy, [kWh]
GRT	gross register tonnage	α	leakage rate, [adm]
GWP	global warming potential, [adm]	η	efficiency, [adm]
LOA	length overall, [m]	COPt	thermal coefficient of performance
LHV	lower heating value, [kJ/kg]	COPe	electrical coefficient of performance
PLR	part load ratio, [adm]	TDC	thermally driven chiller
P	power, [kW]	cw	cooling water
chw	chiller water		

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 [11], choosing the most diffused types of vessels, which are characterised by GRT about 20 and engine power of 195 kW [11].

The sorption systems under analysis are tightly linked to the operation of the main engine and the available waste heat from such a component. For such a reason, a typical engine data profiles in terms of part load ratio for the engine, specific flow rate and temperature of exhaust gases (see Fig. 1) have been adapted from what reported in [7] for a representative cruise of 24 hours. The part load ratio (PLR) of the engine is here defined as the ratio between effective power output at a certain time and the rated power of the engine.

For the vessel under investigation, the traditional refrigeration system on board is mainly composed of four components: a 10/15 m² cell for rapid freezing of fish, employing a direct expansion system for quick refrigeration of fish at -20°C in less than 3 hours; a 40/50 m² cell for storage of frozen fish at temperatures of about -2°C; a 40/50 m² cell for storage of fresh fish at temperatures of +2/+4 °C and an ice maker for the production of flake ice.

All of the components for the refrigeration system employ a single screw-type compressor, driven by electricity produced by the main generator of the boat and R422a as refrigerant. For both the frozen fish and fresh fish cell, in the traditional system, a cooling coil with total surface of about 40 m² is generally employed. For the present analysis, only the replacement of traditional vapour compression system for the frozen fish storage cell has been considered. From the data gathered on the specific situation of Italian fleet, 2 different scenarios have been simulated, corresponding to three load profiles for the cell:

1. Introduction of 150 kg fish into the cell every 4 hours,
2. Constant introduction of 100 kg of fish into the cell every hour.

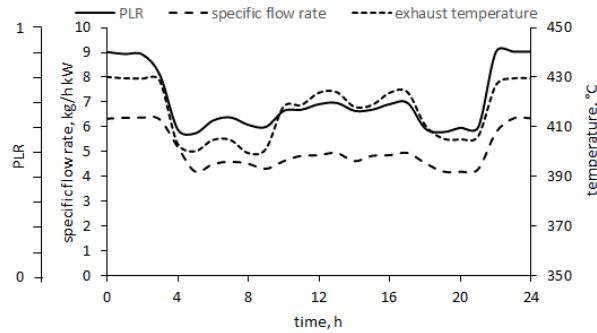


Fig. 1: Engine data profiles for the representative cruise.

3. The analysed sorption systems

Aim of the present study is to assess the feasibility and the energy implication of the utilization of sorption systems for the production of continuous refrigeration effect. For the simulations, data of two real prototypal system, whose main features are reported in the following, will be employed and scaled to the capacity that best fits the requirements of the representative application, corresponding to 5 kW.

3.1. Adsorption refrigerator

The adsorption refrigerator employed for the simulations is described in [12]: it is a lab-scale prototype employing activate carbon and ethanol as working pair. Such a choice, contrarily to the more common use of methanol has been preferred to avoid possible corrosion issues due to methanol and to avoid toxicity problems, that do not arise in case of contact of working fluid with food. The system is characterised by a double-bed architecture for the production of continuous cooling effect. The employed adsorbent is a commercial activated carbon in grains, with grain size of 0.4-0.7 mm, packed into radiator-type aluminium heat exchangers. Condenser and evaporator are made, each of a finned-tube heat exchanger, with copper fins and stainless steel tubes. Volume and weight of the prototype are 142 dm³ and 120 kg, respectively. It is worth noticing that, despite the rated power of the prototype is 500 W, extremely lower than expected cooling load on board, since the aim of the present work is a feasibility study, its choice is still suitable, providing also that no other reports of activated carbon/ethanol prototypes for waste heat applications exist in literature. The prototype was tested at CNR-ITAE and the results employed to draw a map of performance, which represents TRNSYS input for the model of the adsorption chiller.

As driving source for the adsorption system, waste heat from coolant of engine has been chosen: it is a low-grade heat source, easier to manage than exhaust gases and compatible with operation of a carbon/ethanol system. Moreover, its temperature is independent of load ratio of the prime mover, thus guaranteeing a stable operation. A control logic has been implemented, turning the chiller on only when there is a load demand and the temperature of the exhaust water exceeds 70°C.

3.2. Absorption refrigerator

The thermally driven absorption chiller is a derivation of a gas-fired 15 kW unit manufactured by Robur. The working pair is ammonia-water and the thermodynamic cycle is of the GAX type, as described e.g. in [13]. The generator is converted from gas fired to heat driven by means of a spiral baffled jacketed heat exchanger, mounted around the bottom section of the generator. The performance of the modified unit are estimated based on laboratory test data [14]. In order to achieve a good UA-value, the flow rate of the driving fluid (diathermic oil) is set to 3500 l/h. The pressure drop across the generator heat exchanger is 1.0 bar, whereas pressure drop of 0.3 bar can be considered for both the cooling water and the chilled water heat exchangers, at their respective nominal flow rates. The auxiliary energy consumed by the chiller for solution pump and control is 200 W. Thermal COP and refrigeration capacity are shown in Fig.2.

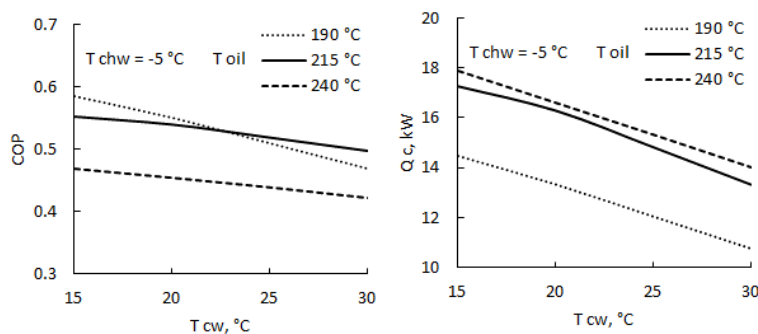


Fig. 2: Thermal COP and refrigeration capacity for the absorption chiller.

The absorption chiller is driven by the exhaust gases through the heat recovery system (HRS) shown in Fig. 3, which comprises a finned-tube heat exchanger (FHX), a flue gas bypass line and a diathermic oil loop. The flow rate across the heat exchanger is controlled by flap valves.

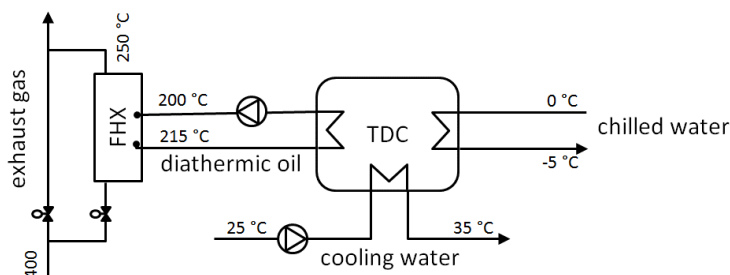


Fig. 3: Thermal coupling between exhaust gas and absorption chiller.

Chiller capacity is controlled by a thermostat that keeps chilled water at around -5°C. When refrigeration capacity is requested, a portion of the engine exhaust gas is diverted to the FHX and the diathermic oil pump is activated. The oil temperature increases and, when the threshold of 200 °C is reached, the solution pump of the chiller is started, along with the cooling water pump. A PID controller keeps the oil temperature below 220 °C by acting on the flap valves. When the refrigeration load turns off, the HRS is turned to bypass mode. In this way, the temperature of the oil loop decreases and when the lower threshold of 180 °C is reached, the oil pump is turned off. The solution pump and the cooling water pump are turned off after 5 minutes of inactivity of the oil pump.

4. Methodology

The purpose of the analysis is double: assessing the savings, in terms of electric energy and fuel consumption, deriving from the application of sorption systems, and defining the environmental benefits in terms of avoided CO₂ emissions.

Prior to the energy savings analysis, the availability of waste heat, from jacket water coolant for the adsorption system and from exhaust gases for absorption one, has been verified, calculating the fraction of waste heat needed for driving the sorption system:

$$WHF = \frac{E_{\text{driving sorption}}}{E_{\text{max, waste heat}}} \quad (1)$$

With waste heat energy calculated as the energy content of jacket water stream and exhaust gases. Electric energy savings with respect to the reference system can be calculated as:

$$ES = E_{\text{traditional}} - E_{\text{sorption}} \quad (2)$$

Where, for both cases, the energy consumption is obtained by adding the consumption of chiller and the auxiliaries (the pumps in all the circuits). Considering that electricity generation on board is obtained through a generator attached to the main engine, fuel savings can be calculated as:

$$FS = \frac{ES}{\eta_{\text{eng}} \eta_{\text{gen}} LHV_{\text{fuel}}} \quad (3)$$

Finally, avoided CO₂ emissions have been calculated taking into account both the direct emissions, due to the electricity consumption, and the indirect emissions due to leakage of refrigerants, as:

$$\Delta CO_2 = CO_{2,\text{traditional}} - CO_{2,\text{sorption}} = \frac{ES}{\eta_{CO_2}} + m_{R422a} \cdot GWP_{R422a} \cdot \alpha \quad (4)$$

5. Simulation model

For the simulation, TRNSYS environment has been chosen, with the main components (sorption chillers) modelled by means of performance map type 909. For all the circuits, variable speed pumps have been chosen, the speed controlled as a function of the actual load required over the rated one for the circuit. The heat exchangers for cooling water to the sorption chillers, exhaust gases and the jacket water heat recovery in case of adsorption chiller have been modelled defining the heat transfer coefficient for each one of them according to the values suggested in [15]. Finally, the control logic for the system, defining on/off of the chiller and part loads control, has been implemented as well. The fish storage cell has been modelled by means of type 56, where all the walls have been defined considering the transmittance value typical of the composite panels used for such applications. The heat transfer inside the cell is obtained by means of fan coil-type units, while the load expected has been considered as an additional internal gain.

In the case of the reference system, only the cooling and chilled water temperatures have been considered, identical to the ones for the sorption options, while a performance-map based chiller employing R422a as refrigerant, has been considered.

6. Results and discussion

At first, the size of the chiller's nominal capacity is selected. A capacity of 5 kW is found suitable to the match the representative loads. Subsequently, an energy and environmental analysis is carried out.

6.1. Adsorption refrigerator

In Fig. , results obtained for the simulations with adsorption chiller are reported. In particular, room temperature for the scenarios differing for thermal load is represented: the set-point for the temperature is -4 °C, with a set dead-band on the thermostat of ± 2 °C. It is clear that the set-point is maintained in both conditions, with the exceptions of short periods, corresponding to the introduction of fish into the cell. The effect of the regulation through on/off cycles is also clearly evident for load 1.

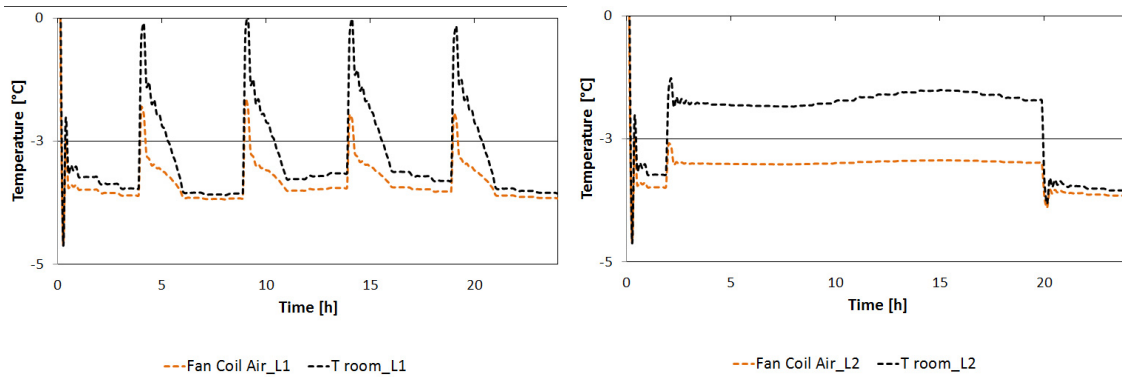


Fig. 4: room temperature for conditioning with adsorption chiller in the first (left) and second (right) scenario.

6.2. Absorption chiller

The room temperature profiles for the simulations with the absorption chiller are reported in Fig. 5. As shown, the system can control the room temperature between -6 and -4 °C. Moreover, the effect of on/off cycling is clearly visible. Due to the limited capability of the chiller to modulate capacity at low partial loads, cycling is the only possibility to control chilled water temperature for the given system configuration. The time constant of the chiller, necessary to simulate the dynamic response during cycling, was estimated equal to 10 minutes.

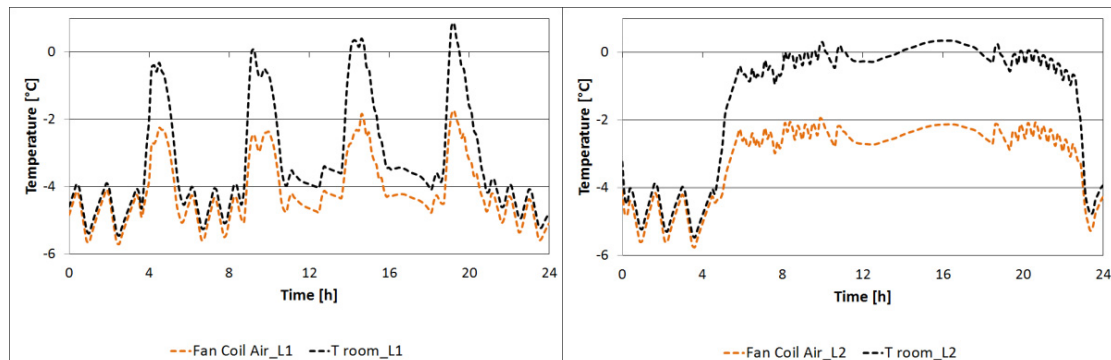


Fig. 5: room temperature for conditioning with absorption chiller in the first (left) and second (right) scenario.

6.3. Energy and environmental analysis

As previously described, the waste heat source used for the two systems is different: absorption chiller is driven by exhaust gases, adsorption chiller by the jacket water. In both cases, the waste heat fraction needed for the sorption system has been calculated and the results are reported in Table I, together with the electric and thermal COP for the chillers.

Table 1: fraction of waste heat utilised for the operation of sorption refrigerators.

	Adsorption chiller			Absorption chiller		
	COP _t	COP _e	WHF	COP _t	COP _e	WHF
Load 1	0.07	6.6	16%	0.55	10.38	4%
Load 2	0.07	11.76	35%	0.55	14.91	8%

In the case of the adsorption chiller, which is still at a prototypal stage, despite the extremely low COP, the system is still able to be operated by the prime mover, exploiting indeed only a fraction of less than 40% of available waste heat. However, such poor COP determines a higher electricity consumption for auxiliaries, thus leading to lower electric COP for the system, especially under load 1 conditions. The difference between the two cases can be explained considering the control logic imposed, with on/off cycles, that do not allow for any smoothing of the capacity needed, as would happen if continuous production of cold were to be implemented.

Similar considerations can be referred to absorption unit: in this case, due to the higher efficiency of the system, electric COP up to 14 have been reported and the fraction of waste heat needed for the unit is lower than 10% of the total heat exploitable.

The considerations on the different behaviour of the reference, adsorption and absorption systems for all the examined cases are reported in Fig.6, where, for each load scenario, the contribution, in percentage, of each component to overall primary energy consumption is showed. Evidently, in the case of the reference system, 75% of total energy consumption is due to the chiller operation. The difference between adsorption and absorption chiller is due to the presence, in the absorption chiller, of the membrane pump, which causes an additional consumption, while in the adsorption chiller the electric consumption is due only to internal valves and control circuits. Moreover, the contribution of heat rejection is higher in the case of adsorption chiller, because of its lower thermal COP, while the higher consumption for the hot water pump is counterbalanced, in the absorption chiller, by the need of a pump for diathermic oil as high temperature fluid, that penalises the heat transfer.

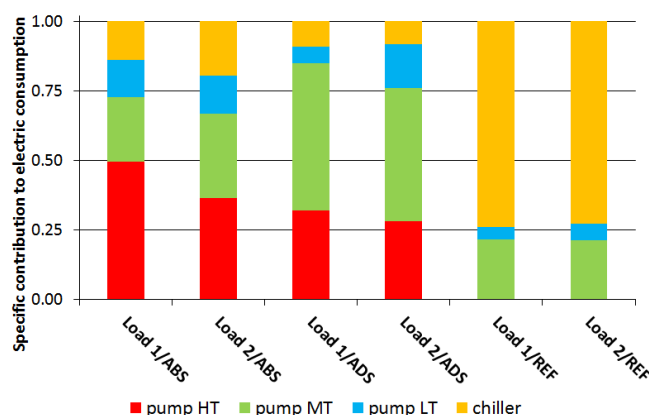


Fig. 6: contributions to primary energy consumptions in the different cases

Results of energy and environmental analysis are summarised in Table 2, where all the performance figures previously described have been included. All the results are based on yearly operation, considering 320 days of utilization of the system. For both systems, energy savings in replacing traditional system are over 4 MWh/y, with a fuel consumption reduction of more than 1 ton and the avoided emissions in atmosphere are of about 3 ton. It is worth noticing that, in the present analysis, only carbon dioxide emissions have been considered, but, for marine applications, also SOx and NOx emissions are of key importance, thus adding to the beneficial value of such sorption systems.

Table 2: fraction of waste heat utilised for the operation of sorption refrigerators.

	Adsorption chiller			Absorption chiller		
	ES (kWh/y)	FS (kg/y)	CO ₂ avoided(t/y)	ES (kWh/y)	FS (kg/y)	CO ₂ avoided(t/y)
Load 1	4135	1069	2.96	4687	1212	3.15
Load 2	4188	1083	2.98	4404	1139	3.05

7. Conclusions

In this paper, a lumped-parameters analysis has been performed, aimed at assessing the technical feasibility of two different sorption systems (absorption and adsorption) for the replacement of a vapour compression chiller in a fishing vessel. Among the main outcomes of the analysis, is the exploitation potential of waste heat recovery for refrigeration on board: for the examined scenarios, small size fishing vessels operating in the Mediterranean, only a minor fraction of waste heat recoverable is consumed and therefore potentiality exists for further development, e.g. by utilization of the chillers also in vessels of bigger size and for more than one cell. Calculated savings amount to up to 1 ton of fuel each year, but real ones could be higher, since efficiency of the vapour compression chillers, in installed system, is significantly lower than the theoretical one, due to the need of using a single compressor for three evaporating units at different temperature levels. In such a context, the replacement of the vapour compression chiller with sorption units for high and medium temperature fish storage (+4/-4 °C) and the exclusive use of vapour compression only for rapid freezing cell (evaporation temperature of -20 °C) could determine additional benefits that should be further analysed.

Another key issue that emerged from simulations is the control logic to be used for the sorption systems: on/off cycles have proved to be not the most effective strategy, and, especially in the case of absorption chiller, could lead to premature damage on the internal pumps of the chiller. The possibility of realising part-load operation and its control, through flow rate at the generator for absorption chiller, or through temperature control and mixing of inlet and outlet streams on the chilled water loop (for both sorption chillers) is an issue that needs to be further investigated.

Nonetheless, the results obtained, in terms of energy and fuel savings and avoided emissions, make sorption technology a promising alternative towards a greener marine field.

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