2022

Thermo-economic Design and Optimization of Cooling Systems Employed in Cruise Ship

Alfonso William Mauro

Giovanni Napoli

Francesco Pelella

Luca Viscito

Thermo-economic design and optimization of cooling systems employed in cruise ships

Alfonso William MAURO[1], Giovanni NAPOLI[1,2], Francesco PELELLA[1], Luca VISCITO[1]*

[1]Department of Industrial Engineering, Università degli studi di Napoli – Federico II, P.le Tecchio 80, 80125 Naples, Italy

[2]Dipartimento di Ingegneria Gestionale, dell'Informazione e della Produzione, Università degli Studi di Bergamo, Viale Marconi 5, Dalmine, BG 24044, Italy

* Corresponding Author: wmauro@unina.it

ABSTRACT

The recovery of the available waste heat from the operating engines of a modern cruise ship plays an important role in the reduction of the environmental impact of these huge means of transport. The cooling load required by the ship passengers can be handled with innovative air-conditioning systems that employ a vapor single-phase ejector and are fed by waste heat. On the contrary, these systems are usually more expensive than vapor compression cycles, representing the conventional technology.

In this paper, a thermo-economic-environmental analysis of a combined cooling system for a cruise ship operating in the Baltic Sea is proposed. Two different cooling plants are compared, namely a typical vapor compression cycle and a multi-ejector hybrid ejector cycle integrated with a cold storage tank aiming to buffer the load variations. The approach is numerical, and the simulations are carried-out with dedicated sub-models for each component. Volumetric machines (pumps, compressor) are modeled through phenomenological equations, calibrated and validated on real data, whereas the heat exchangers are simulated by using specific heat transfer prediction methods and typical geometries. The objective is to size the whole system and optimize the tank size and the control strategy, to minimize the investment cost and maximize the seasonal performance. Also, an economic comparison, concerning the total costs (investments costs plus operating costs) between the solution chosen and the reference one has been carried out considering the fuel cost as a parametric input. Finally, an environmental analysis is performed to assess the reduction in pollutant emissions with the proposed system.

1. INTRODUCTION

The environmental impact of the human activities is an ongoing issue, leading to an increase of the Earth surface temperature up to 4°C by 2100 without any intervention (New et al. 2011). For this reason, the COP 21 in 2015 recognized the need to contain the temperature increase below 2°C compared to the pre-industrial level. However, the maritime transport eludes this agreement because it has no nationality, although it contributes for the 2.89% of the global CO_2 emissions in 2018, according to the 4th GHG study of the International Maritime Organization (2021). The same organisation, in 2018, scheduled the reduction of greenhouse gases emission by 50% within 2050 (IMO 2018). Among the several kinds of maritime transport, one of the most impacting with respect to the air pollution are cruise ships, since their energy demand is connected not only to propulsion but also to the electric production and air conditioning demand, both for cooling and heating. Despite the improvement of the energy systems, such as the engines employed, a promising solution to reduce cruise ships environmental impact, is the recovery of exhaust gases exergy by means of waste heat recovery systems. A review regarding waste heat recovery on ships has been performed by Shu et al. (2013). This study pointed out that the main technologies allowing the recovery of heat from exhaust gases are gas turbines, and the use of absorption machines for refrigeration purposes, Rankine cycles, desalination and combined cycles. Among them, gas turbines, Rankine cycles and desalination systems are the most widespread, whereas no applications of absorption cycle were found for ships. This result is confirmed by Zhu et al. (2020), who also reviewed waste heat recovery systems from the marine engines. In particular, they highlighted that a Rankine cycle combined with a power turbine is more suitable for engines with powers higher than 25 MW. The ORC cycle, instead, is recommended for small size ships. CO_2 based power cycle are appropriate for high size ships, while the Kalina cycle is not diffused so far.

However, one of the main issues related to power application for waste heat is the low thermal efficiency. Alshammari et al. (2018) experimentally evaluated an ORC coupled with a diesel engine operating at steady conditions, measuring an efficiency close to 4.3%.

The literature analysis emphasizes that, to date, the use of waste heat for cooling or refrigeration purposes on board ships is still not widespread, despite some studies deal with it. Among the systems allowing cool production using waste heat, the most common are absorption systems. A Water-LiBr absorption system is proposed by Chaboki et al. (2021), that by means of steady-state energy, exergy and evinronmental analysis, pointed out that a 31% reduction in the total irreversibility can be achieved with the proposed system and a USD 45078 saving in the yearly penalty cost due to CO_2 emission can be reached. Similar findings were also reported by Salmi et al. (2017), that simulated absorption chillers using Water-LiBr and ammonia-water as working medium. An electric COP efficiency improvement, from 3.6 for the traditional chiller, to 9.4 for the absorption one, has been simulated by Cao et al. (2015). However, one of the main drawbacks of absorption chillers is the continuous need to waste heat, and eventually the necessity to provide the extra cooling load with conventional electric chillers. To overcome these issues, a new air conditioning technology is proposed in this study, namely a hybrid multi-ejector compressor assisted chiller using ammonia as working fluid. In particular, the presence of the multi-ejector system allows the use of waste heat to satisfy the cooling load and the booster compressor provides the additional load when the waste heat is not sufficient, avoiding the necessity of auxiliary electric chillers.

Some studies deal with the use of waste heat to satisfy both the electric power and the cooling demand. Bo et al. (2021) carried out a thermodynamic analysis evaluating a tri-generation system consisting of a Kalina cycle, an ejector booster refrigeration cycle and a humidication/dehumidification desalination unit for power, cooling, and freshwater production, reducing the fuel consumption and enhancing the energy outcomes of the ship. Zhang et al. (2021) proposed a simulation model for a novel combined system with transcritical CO_2 Rankine Cycle and ejector refrigeration cycle using waste heat on a cruise ship. They stated that the proposed system shows significantly thermodynamic advantages compared to the conventional one.

Butrymowicz et al. (2021) experimentally investigated a heat driven ejector refrigeration cycle driven by waste heat from a small maritime combustion engine having a nominal load of 100-250 kW. The system tested is able to produce 30 kW of cold by using 75 kW of heat recovered from gases. Moreover, by recovering the heat from water jacket cooling, it is possible to provide hot water and to satisfy the thermal load, covering almost all the mid-sized vessel needs for thermal energy. The same research group proposed an experimental study dealing with an ejector cooling cycle for air conditioning moved from waste heat and using the environmentally friendly fluid R1234ze as refrigerant. They demonstrated the feasibility to utilize waste heat from a piston engine driving the system, using a wide range of temperatures of the source at disposal, achieving a maximum thermal COP of 0.33.

The possibility to use a heat driven ejector cycle using waste heat as motive source has been also investigated by Lillo et al. (2020). They carried out a thermo-economic comparison between a waste heat driven ejector cooling system and other heat driven technologies (absorption and combined ORC/VCC systems). Among different working fluids, ammonia was found to be the most efficient solution. The comparison between the different technologies highlighted that the ejector system has lower COP and minor costs compared to single-effect absorption chiller, but higher performances and lower costs compared to combined ORC/VCC systems. Viscito et al. (2021) carried out a thermo-economic analysis of a 20 kW waste heat driven multi-ejector chiller, using ammonia as refrigerant, by analyzing the seasonal performances in three different climatic zones. Particularly, the results showed that an optimized system can achieve a seasonal performance ($SEER_{el}$) of 13.36 (in Milan), 8.1 (in Madrid) and 7.8 (in Athens), significantly higher if compared to traditional technologies. Regarding the economic convenience, it was seen to depend on the electricity price and on the climatic zone.

Only the work of Eveloy and Alkendi (2021) deals with the possibility to integrate a booster compressor in parallel with the multi-ejector system. In particular, they simulated a solar compression assisted multi-ejector system for a 36 kW air conditioning application. The results highlighted that the use of a multi-ejector pack contributes to widen the condenser temperature range of the system. Moreover, the proposed solution achieves a reduction of 24 MWh_e compared to split air conditioners, allowing a reduction of 15.7 tons of CO_2-equivalent emissions using R245fa.

As shown, there are very few studies dealing with the use of ejector cooling system for maritime application and even less dealing with the integration of the ejector in traditional vapor compression cycles realizing a hybrid cycle. Indeed, the booster compressor is fundamental to guarantee the satisfaction of the cooling demand even if the waste heat from the engine is not sufficient (i.e. for port stay of the ship). Moreover, to the best of our knowledge, there are no works performing a thermo-economic analysis of a hybrid cycle as air conditioning system for cruise ship applications. For these reasons, this paper proposes a thermo-economic analysis of a hybrid multi-ejector compressor-assisted chiller performing a dynamic simulation of the system through all the cooling season for a cruise ship operating in the Baltic Sea. Particularly, the system has been coupled with a tank for the chilled water, in order to buffer the load variation. The tank size and regulation logic have been optimized through dynamic modelling and the seasonal performance of the optimal configuration has been compared with the baseline vapor compression technology.

2. SYSTEM DESCRIPTION AND COMPONENTS MODELLING

2.1 Waste heat driven hybrid ejector vapor compression cycle

The schematic layout of the proposed system is shown in Figure 1a, while Figure 1b shows the thermodynamic cycle of the refrigerant in the hybrid cycle on the T-s diagram.

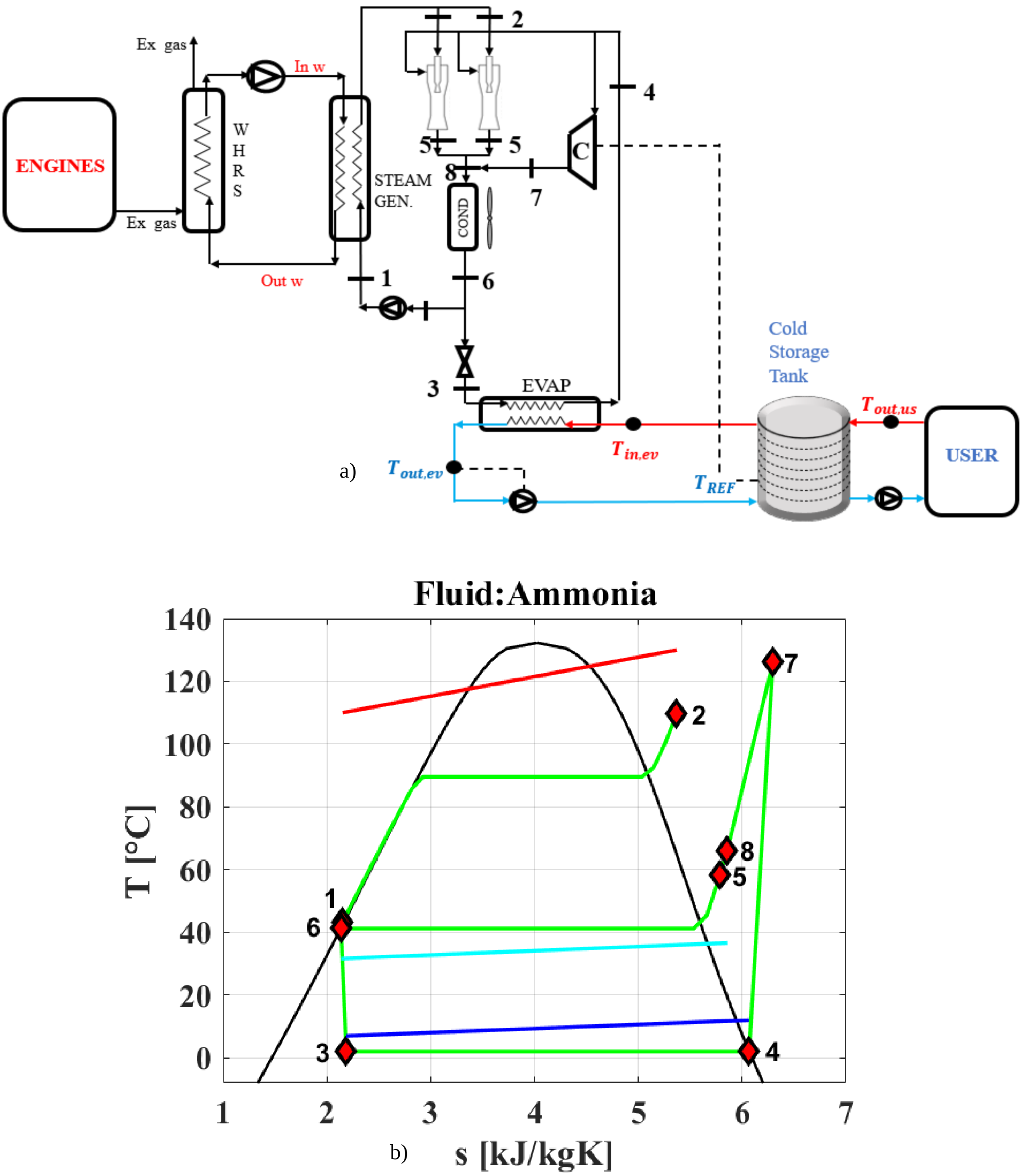

Figure 1: a) Schematic of the waste heat driven hybrid ejector cycle. b) Refrigerant transformation on the temperature-entropy diagram, in green, and the secondary fluids (in red the water in the vapor generator, in cyan the air in the condenser and in blue the chilled water)

In particular, the whole system is driven by means of residual heat of the exhaust gases from the several engines of the ship, that allow the production of hot water in the waste heat recovery system (WHRS). Subsequently, in the steam generator, the hot water warms the high-pressure refrigerant up to superheated conditions (from point 1 to point 2). The vapor generated constitutes the ejector's motive flow, since it expands into the motive nozzle, reaching a pressure lower than the one in the evaporator, and consequently entrains the low-pressure vapor from the evaporator. Then, the two flows are mixed up into the ejector mixing chamber and gain pressure into the diffuser, reaching the condenser pressure (point 5). Before entering the condenser, the vapor from the ejector is mixed (point 8) with the vapor eventually coming from the booster compressor (point 7), that allows the satisfaction of the cooling load in case the ejector is not able to elaborate all the mass flow rate from the evaporator (such as during the port stay of the ship when the main engines are not functioning). After the condenser (point 6), the total mass flow rate is split in two parts, the first going to the pump, that allows the refrigerant reaching high pressure and being the motive flow, whereas the second expands across the expansion device up to point 3 before cooling the chilled water in the evaporator, from where it leaves at saturated vapor conditions (point 4). Finally, in order to be independent from the waste heat availability and guarantee a longer functioning of the system without the need to activate the booster compressor, a cold storage tank is included in the system to decouple the cooling demand from the exhaust gas availability during propulsion.

2.2 System modelling

A dedicated model has been developed for each component constituting the hybrid cycle. According to Zhu et al. (2020), a standard marine two-stroke Diesel engine has a mechanical efficiency of 49.3% and the 25.5% of the thermal power is wasted through the exhaust gas. Thus, assuming that the gases enter the WHRS at 350 °C and that can be cooled until 130°C to avoid sulfuric acid formation, the recoverable heat provided to the hot water is given by:

$$\dot{Q}_{ex} = \dot{m}_f \cdot H_{Diesel} \cdot 0.255 \cdot \frac{\Delta T}{\Delta T_{av}} \tag{1}$$

Where $\dot{m}_f$ and H_{Diesel} are, respectively, the mass flow rate and the low calorific value of the fuel, $\Delta T/\Delta T_{av}$ is the ratio between the actual temperature difference of the gases in the WHRS, and the maximum temperature difference at disposal, considering a hypothetical outlet at ambient temperature.

As regards the hybrid cycle, the single-phase ejector is modelled according to the approach of Chen et al. (2014). For the steam generator, the evaporator and the condenser, a one-dimensional approach has been adopted, integrating the heat transfer differential equation in each elementary area of the heat exchanger. Concerning the refrigerant pump global efficiency, a function of the differential pressure has been chosen, as reported on the work of Declay (2015). Further information can be found in Viscito et al. (2021) as our previous work. The efficiency of the booster screw compressor is evaluated as a function of the compression ratio, calibrated on manufacturer data, whereas for the hot water and the two cold water pumps an efficiency of 0.7 is assigned. Regarding the cold-water tank, it is assumed to be a completely stratified thanks to a height-over-diameter ratio equal to 5. It is modelled as a one-dimensional item with water entering from the top and the bottom fully mixed, with several nodes of equal volume. Further information can be found in Tammaro et al. (2016).

Regarding the total cost of the system, it is assumed to be the sum of the cost of each component, given in Table 1.

Table 1: Cost functions for the components constituting the system

Component	**Cost [$]**
Pumps. Declay (2015).	$963 \cdot \left(\frac{W_{pump}}{300}\right)^{0.5}$
Evaporator. Wildi-Tremblay et Gosselin (2007).	$3.5 \cdot 10^4 \cdot \left(\frac{A_{ev}}{80}\right)^{0.68}$
Condenser. Botticella et al. (2018)	$26.75 \cdot A_{co}$
Compressor. Botticella et al. (2018)	$56.31 \cdot \dot{V}_{comp}$
Cold storage tank. Ferreira et al. (2020)	$3902.8 \cdot 0.32 \cdot \left(\frac{\mathrm{Vol}}{0.32}\right)^{0.3} \cdot 0.985$
Waste heat recovery heat exchanger. Sakalis (2022).	$69.55 \cdot \dot{Q}_{ex} + 120000$

2.3 Algorithm for system sizing

The solution algorithm for the system sizing has been implemented in MATLAB (MATLAB, The MathWorks, Inc.) environment. All the thermodynamic and transport properties are calculated by means of the software Refprop 9.1 (Lemmon et al. 2009) developed by NIST. The steps followed are the subsequent ones:

1) The evaporator saturation temperature is evaluated with the input data at disposal.
2) The generator saturation pressure is assumed and thus the temperature in point 2 is evaluated.
3) The condenser temperature is guessed. Points 5 (saturated liquid) and 3 (expansion device outlet) are evaluated.
4) The evaporator mass flow rate is calculated with the Eq. (2):

$$\dot{m}_{ev} = \frac{\dot{Q}_{ev}}{h_4 - h_3} \tag{2}$$

5) From the evaporator, condenser and generator pressure, using the ejector model the Area ratio and the entrainment ratio are evaluated.
6) If the secondary flow rate is lower than the mass flow rate at the evaporator, the difference is elaborated by the compressor. The condenser mass flow rate is evaluated by summing the ejector and the compressor mass flow rates.

7) The air temperature at the pinch point is calculated. If the value differs by the assigned one, the steps from 3 to 6 are reiterated until convergence.
8) The steam generator is solved and the temperature difference at the pinch point is determined. Steps from 2 to 7 are repeated until convergence.
9) The system COP is evaluated as reported in Eq. (3):

$$COP = \frac{Q_{ev}}{W_{p,ref} + W_{comp} + W_{fan} + W_{p,cold,1} + W_{p,cold,2} + W_{p,hot}} \tag{3}$$

where Q_{ev} is the cooling load, $W_{p,ref}$, W_{comp}, W_{fan}, $W_{p,cold}$, $W_{p,cold,2}$, $W_{p,hot}$ are, respectively, the work required by the refrigerant pump, the compressor, the condenser, the chilled water pump before the tank, the chilled water pump at the user and the hot water pump.

2.4 Algorithm for dynamic simulations

In this case the components dimensions are fixed (from the previous step). As reported in Viscito et al. (2021), the use of a multi-ejector pack provides a better regulation and guarantees the proper functioning of the system when the heat at disposal decreases. For this reason, the total cross section of the ejector sized in the previous phase has been divided on five ejectors following the next proportion in the nozzle area: 6.25%-6.25%-12.5%-25%-50%. The compressor has been sized in order to guarantee the satisfaction of the whole cooling load in case of insufficient waste heat.
The steps for the dynamic simulation are the following ones:
1) The multi-ejector configuration, the working fluid, the hot water temperatures, the refrigerant superheating in the generator, the chilled water temperature produced in the evaporator and the components size are given as input.
2) The tank control logic, which is object of optimization as will be shown in the next section, is here described:

- $T_{control}$<5°C: the chiller is switched off in order to avoid the water freezing.
- 5°C<$T_{control}$<$T_{set\ point}$+ΔT_{tol}: the chiller is working only in ejector mode.
- $T_{control}$>$T_{set\ point}$+ΔT_{tol}: the compressor is turned on, working at its nominal power in parallel with the ejectors. The system is giving a cooling load higher than that required by the user and thus the storage temperature decreases. The compressor is switched off when the temperature becomes lower than $T_{set\ point}$, in order to avoid continuously ON/OFF operations.

3) Evaporation temperature is guessed and thus the temperature profiles are calculated by means of the logarithmic mean temperature difference. The evaporator temperature is adjusted until the matching is reached.
4) The vapor generator and the condenser saturation temperatures are assumed.
5) From the waste heat at disposal and by solving the ejector model, the entrainment ratio, together with the primary and the secondary mass flow rate, is evaluated.
6) If the compressor is turned on, the corresponding mass flow rate is calculated.
7) The condenser is solved and the heat transfer surface is evaluated. The condenser temperature is adjusted and steps 3,4,5 and 6 are repeated, until the convergence is reached.
8) With the correct condenser temperature, the steam generator and the ejector are solved again. The generator temperature is modified, repeating steps from 3 to 7, until the convergence on the steam generator is reached.
9) The tank is integrated in order to evaluate its temperature in the subsequent time step, fixed to 60 seconds.
Finally, the seasonal performances are evaluated by means of the electrical SEER, according to European regulation (EU) 2016/2281, being the ratio between the annual cooling demand and the annual energy consumption for cooling, as defined in Eq. (4):

$$SEER_{el} = \frac{\sum Q_{ev}}{\sum(E_{el,p,ref} + E_{el,fan} + E_{comp} + E_{el,p,cold,1} + E_{el,p,cold,2} + E_{el,hot})} \tag{4}$$

3. RESULTS

.

3.1 Dynamic simulations

The cooling, heating and electric demands, and the propulsion and load, are given in Figure 2 for a typical summer day, as reported by Ancona et al. (2018). The system is assumed to work in cooling mode from the 1st of June till the end of August. Regarding the ambient temperature, it is assumed the weighted average between Stockholm and Mariehamn, since the cruise ships analyzed operates continuously in the whole year in the Baltic Sea between these two cities.
Initially, all components have been sized (plate heat exchanger as vapor generator, fin and tube condenser, flooded evaporator, screw compressor, refrigerant pump, multi-ejector system, two water loop circulating pumps and tank). Particularly, different solutions have been analyzed by varying: tank volume, set point value, set point position, deadband and water temperature at the evaporator outlet. All the reference parameters are reported in Table 2.

Table 2: Data and variables optimized in the sizing process

Quantity	**Value**	**Quantity**	**Value**
Cooling load [kW]	1350	Exhaust gas temperature (inlet/outlet) [°C]	350/130
User temperature [°C]	26	Air temperature difference at the condenser [K]	5
Water temperature at the vapor generator (inlet/outlet) [°C]	130/110	Pinch points for the heat exchangers [°C]	3
Superheating at the vapor generator outlet [°C]	10	Water temperature at the evaporator (inlet/outlet) [°C]	12/7
Working fluid	Ammonia	Condenser Fin step [mm] Fin thickness [mm] Tube diameter [mm] Rank number [#] Form ratio [-] Refrigerant mass flux [kg·m-2·s-1]	 5 0.2 6-9-12-15 1÷7 2-3 100-500
Climatic zone	Stockholm-Mannheim	η nozzle	0.95
Waste heat available [kW]	2700	η mixing	0.85
ΔT superheating in the vapor generator [°C]	10	η diffuser	0.95
Tank volume [m^3]	[1000 2000 3000]	Water temperature at the evaporator outlet [°C]	[3 4]
Set point temperature [°C]	[6 7]	Deadband	[0.5 1 2]
Set point position [%]	[25 50 75]		

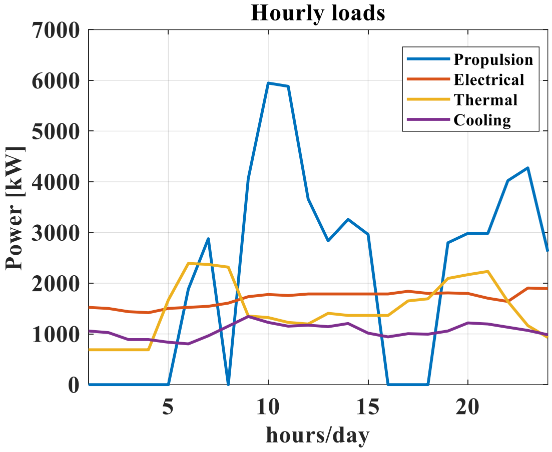

Figure 2: Hourly load curves for typical days during summer.

The only difference in cost among all the solutions investigated is due to the tank size, equal to 1000, 2000 and 3000 m^3, costing respectively 882, 885 and 887 k$. Thus, the sole tank has not a great influence on the system total costs. Also, the SEER differences are not huge among these configurations, ranging from 7.9 to 8.44. Particularly, in each range, the configuration with the best SEER have been chosen, named as solution A, B and C and resumed in Table 3. Particularly, solutions A has a SEER of 8.34, passing to 8.44 for solution B and to 8.33 for configuration C, denoting a very low influence of the tank dimension on the performance. On the other side, it can be noticed that a higher set point temperature and water temperature at the evaporator outlet improves the performance. Indeed, the increase of the set point temperature determines a lower compressor operating time, while a higher water temperature at the evaporator outlet causes higher evaporator temperature and thus a more efficient thermodynamic cycle.

Table 3: Tank optimization results

Point	**A**	**B**	**C**
Tank Volume [m^3]	3000	2000	1000
Price [k$]	887	885	882
Water temperature at evaporator outlet [°C]	4	4	4
Control position [%]	25	50	50
Set point temperature [°C]	7	7	7
Deadband [°C]	2	2	0.5

3.2 Economic and environmental comparison

Figure 3 shows the total costs (investments plus running) and the convenience lifetime for the configuration B and a traditional electric chiller, considering four different fuel prices. The running costs for each configuration are evaluated with Eq.(5):

$$RC_{lifetime} = \frac{Q_{user}}{SEER_{el}} \cdot \frac{1}{H_{Diesel}} \cdot \frac{1}{\eta_{eng} \cdot \eta_{el}} \cdot c_{fuel} \cdot \theta_{lifetime} \tag{5}$$

Q_{user} is the total energy demand during the whole cooling season for the analyzed configuration, H_{Diesel} is the fuel low calorific power, η_{eng} and η_{el} are, respectively, the combustion and electrical engine efficiency, c_{fuel} is the fuel cost and $\theta_{lifetime}$ is the lifetime, assumed to be 20 years. The specific fuel cost is treated as parametric variable assuming values of 1.0 $/kg, 1.5 $/kg, 2.0 $/kg, 3.0 $/kg.

As a result of the dynamic simulations, the electric SEER of the reference system and the proposed one are, respectively, 4.6 and 8.44. Particularly, it can be noticed that the scenario with a fuel cost of 1.0 $/kg has a convenience lifetime of about 11 years, passing to about 4 years when the fuel cost is 3.0 $/kg.

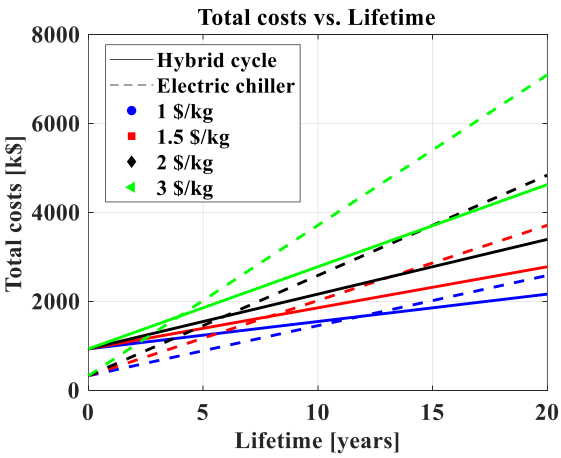

Figure 3: Comparison between total costs as function of lifetime and fuel unity price for the hybrid cycle and the electric chiller.

Finally, an environmental analysis has been performed to assess the reduction in pollutant emissions passing from the baseline solution to the proposed system. Table 4 summarizes the emission factors for the main pollutants, as reported by the Third IMO GHG study (2014) for a marine diesel engine. This analysis is carried out by considering average values of the emission factors.

Table 4: Emission factors for a Diesel marine engine.

Pollutant	**Emission factor [kg/kg fuel]**
CO	0.00277
CO_2	3.20600
NO_x	0.08725
SO_x	0.00264
PM_s	0.00102
NMVOC	0.00308

Figure 4 reports the pollutants released in atmosphere during the chiller operation in summer, both for the reference and the proposed configurations. Particularly, Figure 5a shows the CO_2 and NO_x emissions, while Figure 5b shows the CO,

SO_x, PM_s and VOC emissions. It can be noticed that, since the proposed system has a higher SEER, and thus a lower energy consumption, the emissions are almost reduced by 50% for each pollutant considered.

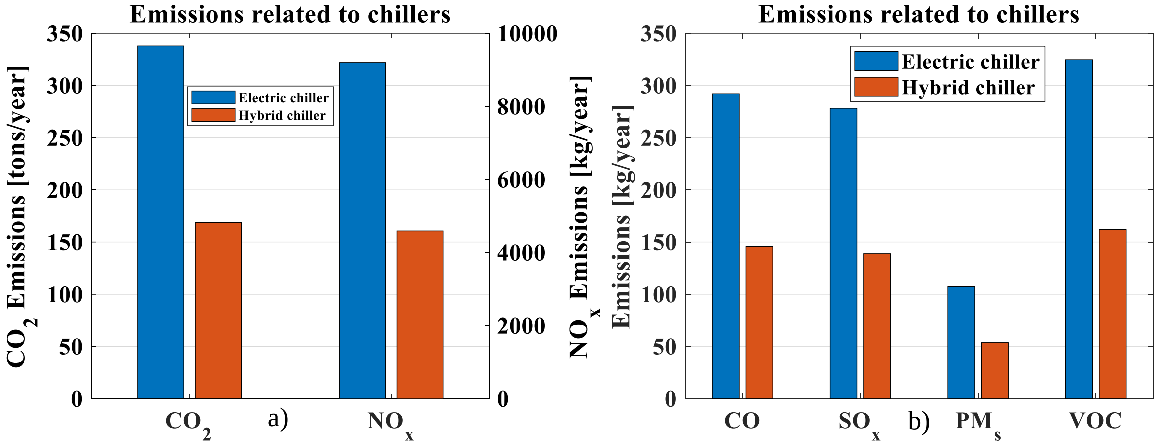

Figure 4: a) CO_2 and NO_x annual emissions for the electric chiller and the proposed system. b) CO, SO_x,PM_s, VOC annual emissions for the electric chiller and the proposed system.

4. CONCLUSIONS

In the present work, an innovative hybrid multi-ejector compressor assisted chiller driven by waste heat for maritime applications has been investigated. The system, integrated with a cold-water storage tank, has been sized for a cruise ship in the Baltic Sea and the tank is optimized in terms of dimension and control strategy. Finally, the solution with the highest seasonal efficiency has been compared with a conventional chiller in terms of emissions and total cost for a 20 year lifetime and considering four different scenarios of fuel cost (1.0 $/kg, 1.5 $/kg, 2.0 $/kg, 3.0 $/kg).
The main outcomes are the following:

- The tank dimension has a negligible effect on the SEER of the proposed system. Similarly, the set-up costs are scarcely affected by its volume. On the other side, higher tank set point temperatures and water evaporator outlet temperatures lead to higher SEER.
- The seasonal performance of all the configurations analysed is higher than that of the conventional electric chiller.
- The economic comparison between the proposed system and the reference one shows that the convenience lifetime is highly dependent on the fuel cost. For a Diesel cost of 1.0 $/kg, the hybrid cycle becomes convenient after about 11 years, while with 3.0 $/kg the convenience lifetime decreases to approximately 4 years.
- The proposed system allows for almost a 50% reduction in pollutant emissions to operate chillers during the summer season.

It is worth noting that the results obtained in the economic analysis are referred to the specific cost functions employed. Since the cost of the system strongly depends on the geographic area and on the market conditions, different results may be achieved using different cost functions.

REFERENCES

Alshammari F., Pesyridis A., Karvountzis-Kontakiotis A., Franchetti B., Pesmazoglou Y. (2018). Experimental study of a small scale organic Rankine cycle waste heat recovery system for a heavy duty diesel engine with focus on the radial inflow turbine expander performance. *Applied Energy, 215*. 543-555.

Ancona M.A., Baldi F., Bianchi M., Branchini L., Melino F., Peretto A., Rosati J. (2018) Efficiency improvement on a cruise ship: Load allocation optimization. *Energy conversion and Management*, *164*. 42-58.

Bo Z.,Mihardjo L. WW., Dahari M., Abo-Khalil A. G., Al-Qawasmi A., Mohamed A.M., Parikhani T.. (2021) Thermodynamic and exergoeconomic analyses and optimization of an auxiliary tri-generation system for a ship utilizing exhaust gases from its engine. *Journal of Cleaner Production*, *287*. 125012.

Butrymowicz D., Gagan J., Łukaszuk M., Smierciew K., Pawluczuk A., Zielinski T., Kedzierski M. (2021). Experimental validation of new approach for waste heat recovery from combustion engine for cooling and heating demands from combustion engine for maritime applications. *Journal of Cleaner Production, 290*. 125206).

Cao T., Lee H., Hwang Y., Radermacher R., Chun H. (2015). Performance investigation of engine waste heat powered absorption cycle cooling system for shipboard applications. *Applied Thermal Engineering, 90*. 820-830.

Chaboki Y. A,, Khoshgard A., Salehi G., Fazelpour F. (2021). Energy, exergy, and environmental analysis of meeting cooling demand of a ship with waste heat recovery, *Energy efficiency*, *14*,16.

Chen J., Havtun H., Palm B. (2014) Investigation of ejectors in refrigeration system: Optimum performance evaluation and ejector area ratios perspectives. *Applied Therma Engineering,64*. 182 191.

Declaye S. (2015). *Improving the performance of μ-ORC systems, Phd thesis.* Université de Liège, Liège, Belgium 2015.

Ferreira A.C., Silva A., Teixeira J.C., Teixeira S. (2020). Multi-Objective Optimization of Solar Thermal Systems Applied to Portuguese Dwellings. *Energies, 13*, 6739.

Fourth GHG Study 2020. IMO

Low carbon shipping and air pollution control. 2018. IMO

Kędzierski M., Smierciew K., Butrymowicz D., Gagan J. (2018). Application Of Waste Low Heat As A Motive Source For Ejection Air-Conditiong Systems For Motor Yachts. *In proccedings of International Refrigeration and Air conditioning Conference. Paper 2041.*

Lemmon E W, McLinden M.O., Huber M.L. (2009).REFPROP NIST Standard Reference Database 23, Version 9.0.

Lillo, G., Mastrullo, R., Mauro, A. W., Trinchieri, R., & Viscito, L. (2020). Thermo-economic analysis of a hybrid ejector refrigerating system based on a low grade heat source. *Energies*, *13*(3), 562.

New M., Liverman D.,Schroder H., Anderson K. (2011) Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications. *Phil. Trans. R. Soc. A.369,* 6–19.

MATLAB release. Natick, Massachussets, United States, The MathWorks, Inc.

Sakalis. G.N. (2022). Design and partial load operation optimization of integrated ship energy system based on supercritical CO2 waste heat recovery cycle. *Sustainable Energy Technologies and Assessments, 51.* 101965.

Shu G., Liang Y., Wei H., Tian H., Zhao J., Liu L. (2013). A review of waste heat recovery on two-stroke IC engine aboard ships. *Renewable and Sustainable Energy Reviews, 19.* 385-401.

Smith TWP., Jalkanen JP., Anderson BA., Corbett JJ., Faber J., Hanayama, S., et al. (2014). Third IMO GHG study. London, UK.

Tammaro M., Mauro A.W., Montagud C., Corberan J.M., Mastrullo R. (2016). Hot sanitary water production with CO2 heat pumps: Effect of control strategy on system performance and stratification inside the storage tank. *Applied Thermal Engineering, 101.* 730-740.

TRNSYS 17 (2010). A Transient System simulation program. Solar Energy Laboratory; University of Wisconsin-Madison.

Viscito, L.; Lillo, G.; Napoli, G.; Mauro (2021) A.W. Waste Heat Driven Multi-Ejector Cooling Systems: Optimization of Design at Partial Load; Seasonal Performance and Cost Evaluation. *Energies. 14*, 5663.

Zhang Q., Luo Z., Zhao Y., Pavel S. (2021). Thermodynamic analysis and multi-objective optimization of a transcritical CO2 waste heat recovery system for cruise ship application. *Energy conversion and Management, 227.* 113612.

Zhu S., Zhang K., Deng K. (2020). A review of waste heat recovery from the marine engine with highly efficient bottoming power cycles. *Renewable and Sustainable Energy Reviews, 120.* 109611.