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# Thermodynamic, environmental and economic analysis of absorption air conditioning unit for emissions reduction onboard passenger ships

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ABSTRACT

In this paper, the waste heat of exhaust gases and jacket cooling water in marine diesel engines are analyzed to operate the absorption refrigeration unit (ARU). Thermo-economic and environmental analysis of the absorption refrigeration cycle operated with the two heat sources that use lithium bromide as an absorbent is carried out. The analysis is performed using Engineering Equation Solver (EES) software package where the thermodynamic properties of the steam and the LiBr-water mixtures are provided. The used EES code is verified by published experimental data. As a case study, high speed passenger vessel operating in the Red Sea area has been investigated. The results show that a considerable specific economic benefit could be achieved from ARU jacket cooling water operated over that gained from main engine exhaust gases. Environmentally, applying ARU machine during cruise will reduce the annual fuel consumption for the diesel generators by 156 ton with a reduction percentage of 23%. This will reduce the exhaust gas emissions by 6.3% from the applied main engine emissions. In addition, this will result in reducing $NO_x$, $SO_x$, and $CO_2$ emissions with cost-effectiveness of 4.99 $/kg, 13.18 $/kg, and 0.08 $/kg, respectively.

## 1. Introduction

The mid-range forecasted scenarios presented in the third International Maritime Organization (IMO) greenhouse gas study in 2014 show that the average annual sulfur oxides ($SO_x$) and nitrogen oxides ($NO_x$) emissions from ships between the years from 2007 to 2012 are 11.3 and 20.9 million tons, respectively. These emissions represent 13% and 15% of global $SO_x$ and $NO_x$ emissions of all man-created sources, respectively (IMO, 2014). In the same context, the contribution of carbon dioxide ($CO_2$) emissions from ships accounts to about 8.0% of the global $CO_2$ emissions from various transportations means as shown in Fig. 1. It is estimated that by 2050, $CO_2$ emissions from international shipping could grow by 50% to 250%, depending on future economic growth and energy developments (Peters et al., 2013, Boden et al., 2013). Moreover, recent studies of ship emissions state that shipping-related particulate matters (PM) emissions are responsible for approximately 60,000 cardiopulmonary and lung cancer deaths annually, with most of those deaths occurring along the coasts (Berechman and Tseng, 2012; Salvatore, 2015).

In addition to the above mentioned emissions, refrigerants which used onboard vessels for air conditioning and cargo cooling

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**Nomenclature**

| | |
|---|---|
| AMR | annual initial money recovery, \$/year |
| be | specific fuel consumption, kg/kWh |
| C | cost, \$ |
| $C_p$ | specific heat at constant pressure, kJ/kg K |
| $C_w$ | water specific heat, kJ/kg K |
| ER | emission reduction quantity, kg |
| F | circulation ratio |
| $F_e$ | engine emission factor, kg/kWh |
| h | enthalpy, kJ/kg |
| $\dot{m}$ | mass flow rate, kg/s |
| n | number of expected remaining ship working years |
| $N_{tu}$ | number of transfer unit |
| P | pressure, kPa |
| PI | yearly change in fuel price, \$ |
| $\dot{Q}$ | power, kW |
| $R_c$ | heat capacity rate ratio |
| T | temperature, K |
| Ts | sailing time, hr |
| v | specific volume, $m^3$/kg |

*Subscripts*

| | |
|---|---|
| a | absorber |
| c | condenser |
| m&o | maintenance and operating |
| e | evaporator |
| El | electric |
| exh | exhaust gases |
| f | fuel |
| fs | fuel saving |
| g | generator |
| H | high |
| HE | heat exchanger |
| ins | installation |
| Jcw | engine jacket cooling water |
| L | low |
| p | pump |
| r | refrigerant |
| ss | strong solution |
| ti | total initial |
| ws | weak solution |

*Abbreviations*

| | |
|---|---|
| ARU | absorption refrigeration unit |
| $CO_2$ | carbon dioxide |
| CRU | compression refrigeration unit |
| HC | hydrocarbon emissions |
| IMO | international maritime organization |
| $NO_x$ | nitrogen oxides emissions |
| PM | particulate matter |
| $SO_x$ | sulfur oxides emissions |
| LiBr | lithium bromide |

*Greek symbols*

| | |
|---|---|
| ε | effectiveness |

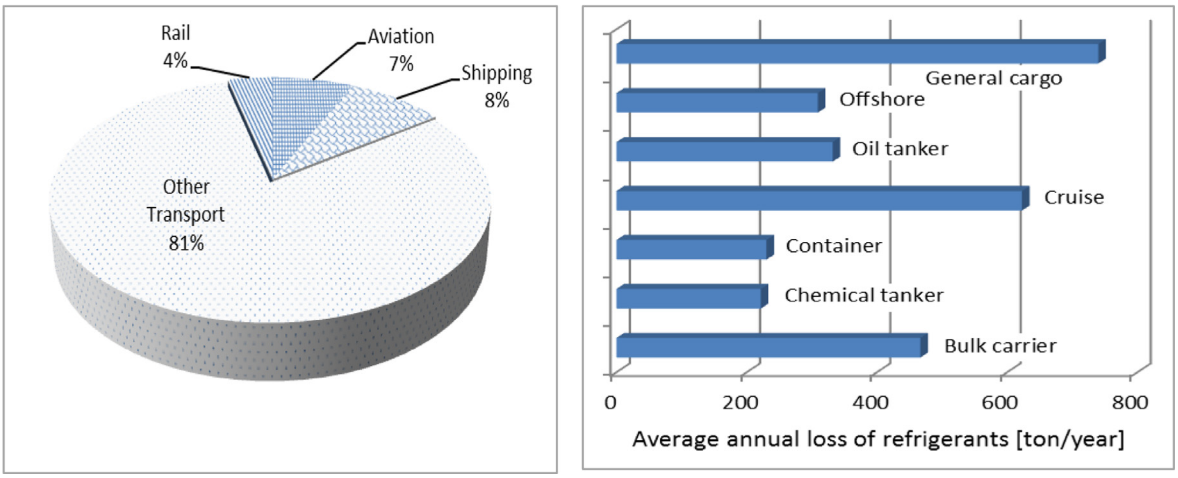


**Fig. 1.** $CO_2$ and refrigerant emissions from ships.

purposes consider another source of ship emissions. These refrigerants are either ozone-depleting substances like chlorofluorocarbons (CFCs) or their replacements like hydro fluorocarbons (HFCs) 1,1,1,2-tetrafluoroethane (R134a) and a mixture of pentafluoroethane, trifluoroethane and tetrafluoroethane (R404a). All these refrigerants have significant global warming potential (EC, 2017). The average annual loss of refrigerants from the global fleet, based on the latest statistics, indicates that air conditioning equipment is responsible for about 69.8% of the total loss of refrigerants; however 30.2% of this loss is cooling equipment based. Fig. 1 shows the contribution of each ship type based on the loss in refrigerants due to air conditioning. It noticed that general cargo and cruise ships contribute by considerable amounts of loss of refrigerants rather than the other various ship types (IMO, 2014).

Finally, the options applied onboard ships which reduce both the exhaust gas emissions and fuel consumption will have a good