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PERFORMANCE ENHANCEMENT OF MARINE INERT GAS GENERATOR WITH COMBUSTION

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ABSTRACT

The heat generated in the combustion inert gas generator (IGG) is usually discharged with the flue gas cooling water. This paper proposes a system for recovering part of the heat generated in the IGG and using it in an absorption chiller for advanced cooling of the inert gas. The thermodynamic analysis showed that for an IGG consuming 240 kg/h of marine gas oil, 132 kW can be recovered to drive a lithium bromide-water absorption chiller, which can cool the inert gas down to 15°C, a temperature at which the water vapor content of the inert gas is 12.79 g/m^3, much lower than if the inert gas is cooled only down to 50°C (82.5 g/m^3) as is done in most IGGs. By recovering waste heat, the quality of the inert gas is improved (humidity is reduced) without additional energy consumption.

Keywords: inert gas generator, humidity, absorption chiller, waste heat recovery

1. Introduction

Oil and chemical tankers of 8000 DWT and above carrying low-flash point (<60°C) cargoes, built after 1 January 2016, should be equipped, according to the International Convention for the safety of Life at Sea (SOLAS), with inert gas generator [1]. The inert gas generator (IGG) must produce, by burning a fuel with a sulphur content of less than 0.5% [2], the required quantity of inert gas, with an oxygen content below 5% (to create non-flammable conditions in the cargo tanks), a maximum temperature of 60°C and a low humidity content (to avoid degradation of the transported materials, corrosion of metal components inside the tanks or the piping system) [3].

An IGG consists mainly of a water-cooled combustion chamber, a flue gas scrubber with a cleaning and cooling function, a droplet separator and fans that send the inert gas to the tanks [4]. Some IGG manufacturers have combined the traditional IGG with a two-stage dehumidification system, by cooling with a mechanical vapor compression refrigeration plant and by adsorption [5]. Since seawater can cool the inert gas to a maximum of 10°C above its temperature (the temperature difference being necessary for heat exchange), a refrigeration plant (chiller) is used. The average temperature of seawater is about 17°C, varying from 30°C in the tropics to 0°C in the polar regions. Since cooling the inert gas to temperatures below 0°C does not completely remove the moisture, the inert gas must be passed through a dryer with a desiccant (adsorbent) material.

In commercial IGGs, the heat resulting from combustion is usually discharged together with the flue gas (inert gas) cooling water. This paper proposes a system for recovering part of the heat generated in the IGG and using it in an absorption chiller to further cool the inert gas. Cooling the inert gas using an adsorption refrigeration plant has the advantage of eliminating the electricity consumption required to drive the compressor of the mechanical vapor compression refrigeration plant. The only electricity consumption of the proposed system are the combustion chamber coolant circulation pump and the lithium bromide or ammonia aqueous solution circulation pump (the fuel feed pump, the seawater circulation pump for cooling and the inert gas blowers are not considered). This results in a reduction in electricity consumption and the production of an inert gas with a lower moisture content.

2. System description

Figure 1 shows the schematic of the system that recovers part of the heat produced in a combustion IGG and uses it in an absorption chiller to further cool the inert gas, to reduce the moisture content of the inert gas.

The IGG is divided into the combustion chamber (cooled) and the scrubber with the role of cleaning and cooling the flue gases (inert gas). The heat taken from the combustion chamber must correspond to the heat required by the chiller. In the scrubber, seawater is sprayed into the flue gas stream. Due to the large specific surface area of the water droplets, an intense heat and mass transfer between the droplets and the flue gas occurs. As a result, the flue gas is cooled while the water droplets are heated. Depending on the temperature of the two fluids and the moisture content of the flue gas, evaporation or condensation of the vapours takes place. For the temperature of (40-50)°C of the inert gas (temperature below the dew point), at the exit of the scrubber, it is saturated with water vapor.

The system contains a circuit with coolant of the IGG combustion chamber, which supplies heat to an absorption refrigeration plant, to operate a refrigeration cycle through a refrigerant-absorbent pair (water and lithium bromide or ammonia and water). The cold water generated by the chiller is used to cool the inert gas, in a finned tube heat exchanger.

The absorption chiller is very suitable to be used in applications with abundant residual heat (with a thermal level between 70°C and 170°C) and with cooling needs. An absorption refrigeration plant consists of the desorber (vapour generator) powered by a heat source, the absorber and condenser that require a cooling source and the evaporator in which the water required for the cooling process is cooled [6]. Absorption chillers are classified as single, double, or triple effect. Multi-effect cycles have higher coefficient of performance (COP) but they have more components and work with higher temperature waste heat [7].

3. Thermodynamic model

The combustion reaction of liquid fuel in IGG is:

$$\underbrace{C + H + S + O + N + A + W}_{fuel} + \\ + \underbrace{(0.21O_2 + 0.79N_2)}_{air\ in\ excess} \rightarrow \\ \rightarrow \underbrace{CO_2 + H_2O + SO_2 + N_2 + O_{2exces} + A}_{flue\ gas} \quad (1)$$

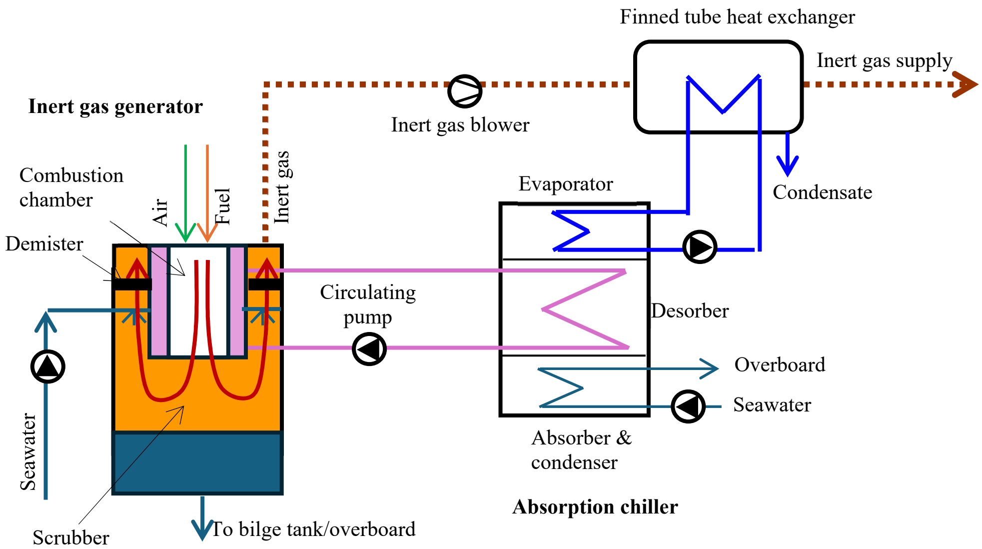

Figure 1. Schematic of the inert gas generator combined with absorption chiller.

Combustion chamber thermal balance is given by the following equation:

$$\eta_{CC} \cdot \dot{m}_f \cdot LHV = \dot{m}_{fg} \cdot h_{fg}(T_{ad}), \text{[kW]} \quad (2)$$

$$h_{fg}(T) = \underbrace{m_{CO_2}h_{CO_2}(T) + m_{N_2}h_{N_2}(T) + m_{O_2}h_{O_2}(T) + m_{SO_2}h_{SO_2}(T)}_{enthalpy\ of\ dry\ flue\ gas} \underbrace{+m_{H_2O}\left[h_{H_2O}(T) + h_l\right]}_{enthalpy\ of\ water\ vapour} \left[\frac{kJ}{kg\ comb}\right]$$

where: $\eta_{CC} = (83-95)\%$ is the combustor efficiency [7]; $\dot{m}_{fg}$ is the flue gas mass flow rate, in kg/s; $\dot{m}_f$ is the fuel mass flow rate, in kg/s; *LHV* is the lower heating value of fuel, in kJ/kg; $h_{CO_2}(T)$, $h_{N_2}(T)$, $h_{O_2}(T)$, $h_{SO_2}(T)$, $h_{H_2O}(T)$ are enthalpy of flue gas component corresponding to temperature *T*, in kJ/kg; h_l is the latent heat of water vapour (h_l = 2502kJ/kg) and T_{ad} is the adiabatic combustion temperature.

The heat flow rate transferred to the combustor coolant is:

$$\dot{Q}_{cl} = \dot{m}_{cl} \cdot c_{pl}(T_{le} - T_{lo}) = \dot{m}_{fg} \cdot \left[h_{fg}(T_{ad}) - h_{fg}(T_{fgo})\right], \text{[kW]} \quad (3)$$

where: $\dot{m}_{cl}$ is the cooling liquid mass flow rate, in kg/s; c_{pl} is the cooling liquid specific heat, in kJ/(kg·K); T_{le} and T_{lo} are the inlet and outlet temperature of cooling liquid, °C, and T_{fgo} is the flue gas exit temperature from the combustion chamber.

The water vapor content of the inert gas at the saturation temperature T_s is calculated as follows [8, 9]:

$$x_s = 0.622\frac{p_s}{p-p_s} \text{ [kg/kg]} \quad (4)$$

$$p_s = \frac{exp\left(77.345 + 0.0057 \cdot T_s - \frac{7235}{T_s}\right)}{{T_s}^{8.2}}$$

where *p* is the pressure of the inert gas (considered to be slightly lower than atmospheric pressure).

The variation of the absolute humidity of the inert gas with temperature is given in Fig. 2.

The energy performance of an absorption refrigeration system is given by the equation:

$$COP = \frac{\dot{Q}_c}{\dot{Q}_h - \dot{Q}_c} \quad (5)$$

where $\dot{Q}_c$ is the heat flow rate absorbed from the space to be cooled, in kW and $\dot{Q}_h$ is the heat flow rate consumed at the generator, in kW.

The fluids entering the inert gas cooler (finned tube heat exchanger) are:

- dry flue gases with flow rate $\dot{m}_{fgd}$ and temperature T_1;
- water vapor with flow rate $\dot{m}_{w1} = x_1 \cdot \dot{m}_{fgd}$ and temperature T_1;
- cooling water with flow rate $\dot{m}_{cw}$ and temperature T_{cw1}.

The fluids leaving the cooler are:

- dry flue gases with flow rate $\dot{m}_{fgd}$ and temperature T_2;
- water vapor with flow rate $\dot{m}_{w2} = x_2 \cdot \dot{m}_{fgd}$ and temperature T_2;
- cooling water with flow rate $\dot{m}_{cw}$ and temperature T_{cw2};
- condensate with flow rate $\dot{m}_c = (x_1 - x_2) \cdot \dot{m}_{fgd}$ and temperature T_2.

The heat balance equation of the heat exchanger – inert gas cooler is:

$$\dot{m}_{fgd}\left[h_{fgd}(T_1) + x_1\left(h_{w,g}(T_1) + h_l\right)\right] + \dot{m}_{cw} \cdot c_{pcw} \cdot T_{cw1} = \dot{m}_{fgd}\left[h_{fgd}(T_2) + (x_1 - x_2)\left(h_{w,g}(T_2) + h_l\right)\right] + \dot{m}_{cw} \cdot c_{pcw} \cdot T_{cw1} + (x_1 - x_2) \cdot \dot{m}_{fgd} \cdot c_{pcw} \cdot T_2 \quad (6)$$

4. Case study

An IGG fuelled with marine gas oil is considered, with a flow rate of 240 kg/h. The inert gas leaves the scrubber at a temperature of 50°C (T_1) and is then cooled, using an absorption refrigeration plant with lithium bromide solution, to a temperature of 15°C (T_2) (Fig. 2). For these temperatures of the inert gas, the moisture content is 50.91 g/m^3 and 12.79 g/m^3, respectively (Fig. 3). To further dry the inert gas, it must pass through a dryer with adsorbent material.

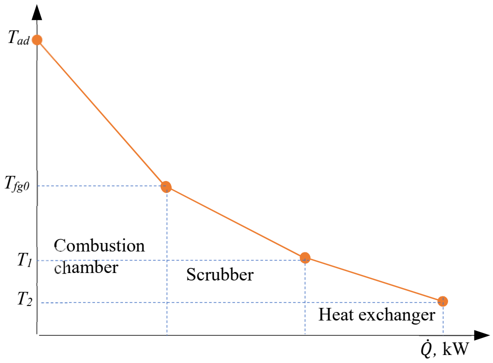

Figure 2. Inert gas temperature variation inside the IGG components.

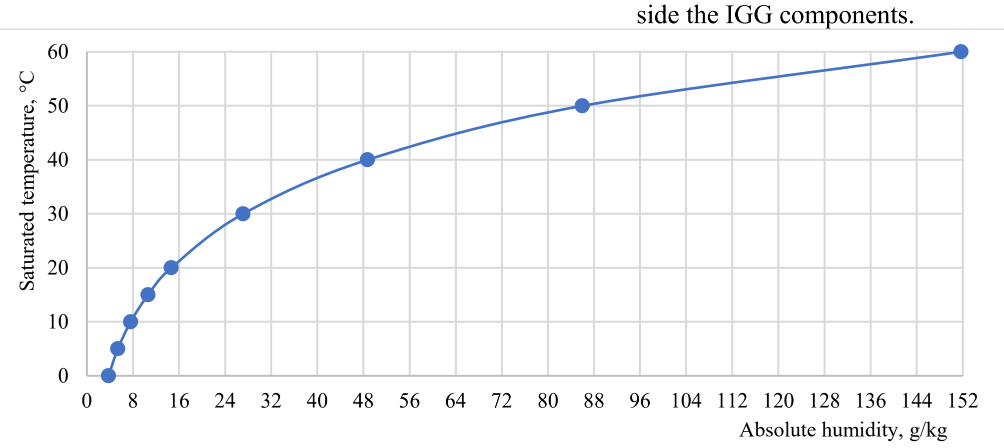

Figure 3. Absolute humidity of inert gas as function of saturated temperature.

The mass and volume composition of the inert gas generated by combustion with 15% excess air is given in Tab. 1.

Table 1. Inert gas composition.

Gas	Volume, m^3_N/kg fuel	Mass, kg/kg fuel
Carbon dioxide	1.61	3.16
Water vapour	1.55	0.25
Nitrogen	9.86	12.65
Sulphur dioxide	0.00035	0.002
Oxygen	0.34	0.49
Dry gas	11.81712	16.302
Total	13.36576	16.552

The adiabatic combustion temperature (T_{ad}) is determined using eq. (3) and Fig. 4, which shows the enthalpy of the combustion gases as a function of temperature. When burning marine gas oil (with *LHV* = 42000 kJ/kg) with an excess air of 15%, for a thermal efficiency of the combustion chamber of 92%, an adiabatic temperature of 1681°C results.

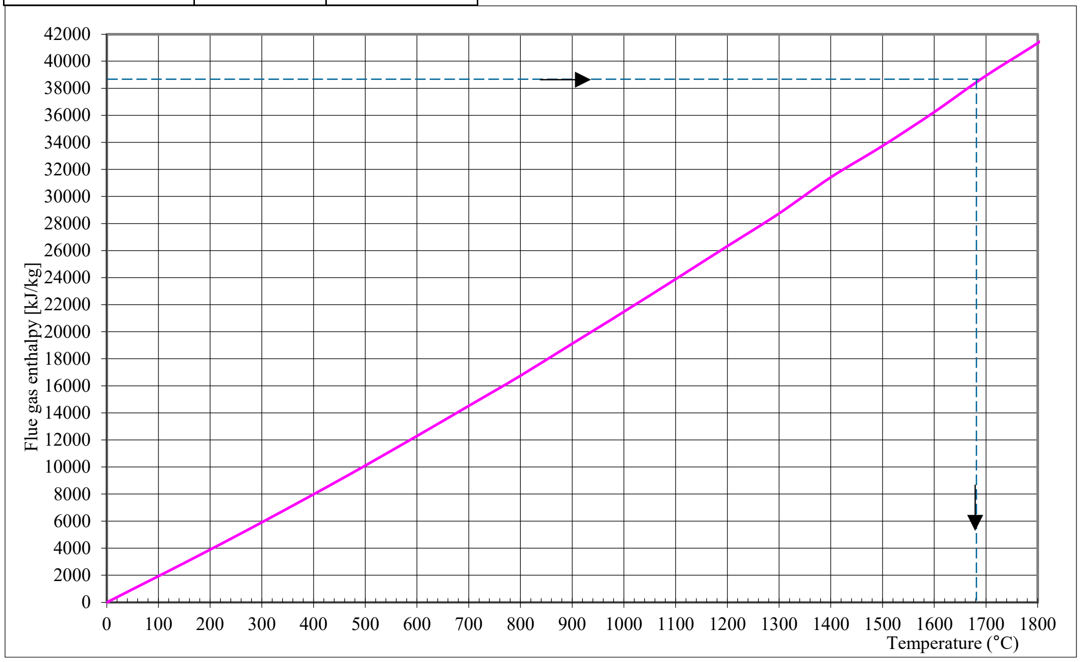

Figure 4. Flue gas enthalpy as function of temperature.

To cool the inert gas with a mass flow rate of 0.172 kg/s from 50°C to 15°C, a flow rate of 1.63 kg/s of cold water at 5°C is required (for a heat exchanger thermal efficiency of 0.8 [10]). A lithium bromide absorption chiller requires a flow rate of 1.7 kg/s of hot water at 90°C at the generator (desorber) to cool the inert gas. This hot water is generated by cooling the inert gas from the adiabatic combustion temperature (1681°C) to 140°C in the combustion chamber of the IGG. The simulation of the lithium bromide absorption chiller was performed by using the Sorption Simulation (SorpSim) software developed by the

Oak Ridge National Laboratory [11, 12]. The operating parameters of the absorption refrigeration plant are presented in Fig. 5. Seawater is used to cool the absorber and condenser. As can be seen in Fig. 5, the cooling capacity of the chiller is 70.7 kW and the COP is 0.671.

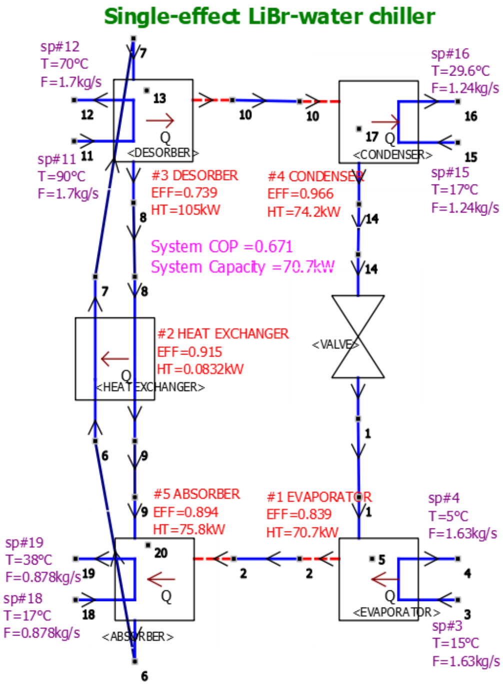

Figure 5. Design parameters predicted by using the SorpSim software.

If an absorption refrigeration system with ammonia solution is used to cool the inert gas, more intense cooling would be achieved, but this would require a higher temperature of the liquid feeding the chiller generator. Instead of the cooling water of the combustion chamber, thermal oil can be used, which allows heating to temperatures higher than 100°C.

By using the residual heat in an absorption refrigeration plant with lithium bromide solution to cool the inert gas, electrical energy savings of approximately 1.7 MWh can be achieved when the system is operated for 24 hours. In addition to the energy savings, the quality (absolute humidity) of the inert gas is also improved.

4. Conclusions

The regulatory measures introduced by the International Maritime Organization (IMO) to reduce greenhouse gas emissions promote, in addition to operational improvements, advanced propulsion systems and the adoption of cleaner fuels and the use of energy-saving devices [13].

This paper aligns with the IMO strategy by proposing a solution to increase the performance of combustion inert gas generators by recovering waste heat and using it in an absorption refrigeration plant for further cooling of the inert gas.

For an IGG consuming 240 kg/h of marine gas oil, 132 kW can be recovered to drive a lithium bromide-water absorption chiller, which can cool the inert gas to 15°C, a temperature at which the water vapor content of the inert gas is 12.79 g/m^3, much lower than if the inert gas is only cooled to 50°C (82.5g/m^3) as is done in most IGGs. The refrigeration plant has a capacity of 70.7 kW and can achieve an electricity saving of 1.7 MWh, when the IGG is operated for 24 hours.

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