A MATHEMATICAL MODEL OF AN ABSORPTION REFRIGERATION SYSTEM FOR A REFRIGERATED STORAGE FOR FISHING BOATS

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ABSTRACT

The objective of this paper is to determine if it is possible to refrigerate an area by means of a heat source. Theory determines that an absorption refrigerator can work as a possible solution through a refrigeration fluid. According to it, the system works by the evaporation or condensation of the working fluid. The traditional process consists of using engine fuel to run an electric compressor and by its means achieve refrigeration. That process has its toll on fuel economy and engine efficiency and the refrigeration fluid damages the ozone layer or is based on the transportation of ice previously bought on shore. The technological improvement will be equipped on fishing boats, in order to make the trip last longer due to the possibility of not needing to buy and transport ice and for the purpose of lowering the fishing industry cost. Absorption refrigeration can augment engine efficiency by using heat energy that is normally wasted and the system could reach temperatures of freezing water, meaning that it could be possible to follow Brazilian and international standards. The methodology of this work consists of an energy analysis of an absorption refrigerator, which is the determination of the heat transfer equations on the ammonia evaporator, condenser and exhaust/ammonia. Furthermore, it should be analyzed if it's possible to determine to which working parameters the system will have an optimum operation. From the mathematical analysis, the system shows that with the equations it is possible to operate an absorption refrigeration based on the exhaust gases of fishing boats. Furthermore, the process can be operated on a wide range of temperatures, being possible to determine according to a few dimensionless parameters to which temperature levels the process of refrigeration shows the best removal of heat.

Keywords: absorption refrigeration; mathematical model; renewable energy; thermodynamics systems

NOMENCLATURE

B dimensionless equation of heat from the exhaust gas
c_p fluid specific heat at constant pressure, J * kg^{-1} * K^{-1}
$\dot{M}$ mass flux from hot gasses into refrigerator, kg * s^{-1}

Q_H heat transfer rate from hot gasses to the refrigerant, W
Q_L heat transfer on the evaporator, W
Q_O heat transfer on the condenser, W
$\tilde{Q}_H$ dimensionless heat transfer from hot gases to the refrigerant
$\tilde{Q}_L$ dimensionless heat transfer on the evaporator
$\tilde{Q}_O$ dimensionless heat transfer on the condenser
T_H working temperature of exhaust-ammonia, K
T_{HC} internal reversible compartment temperature in the exhaust heat exchanger, K
T_L working temperature of the evaporator, K
T_{LC} internal reversible compartment temperature in the cold heat exchanger, K
T_O reference ambient temperature, K
T_{OC} internal reversible compartment temperature in the ambient heat exchanger, K
T_{ST} temperature of the hot gasses entrance, K
UA product between the convection heat coefficient and area of the system
$(UA)_H$ product between the convection heat coefficient and area of exchange of exhaust gases, W * K^{-1}
$(UA)_L$ product between the convection heat coefficient and area of exchange of the evaporator, W * K^{-1}
$(UA)_O$ product between the convection heat coefficient and area of exchange of the condenser, W * K^{-1}

Greek Symbols

γ dimensionless value corresponding to the ammonia heating
ζ dimensionless value corresponding to the evaporator
τ_H dimensionless working temperature of exhaust-ammonia
τ_{HC} dimensionless internal reversible compartment temperature at the hot heat exchanger
τ_L dimensionless working temperature of the evaporator
τ_{LC} dimensionless internal reversible compartment temperature at the evaporator
τ_{OC} dimensionless internal reversible compartment temperature at the heat exchanger in contact with the ambient
τ_{ST} dimensionless temperature of the hot gases entrance

Subscripts

$_C$ used as a reference to Carnot it indicates a reversible cycle

INTRODUCTION

Fishing whether as a commercial profession or as a hobby, has the potential to generate many dividends, as an economic resource, and as an entrepreneurial sector it requires an initial investment on boats, nets or fishing rods, among other things, the costliest being the fuel expenses and the fish refrigeration process.

The fish on board refrigeration process normally consists of ice purchase, before leaving the docks, and keeping the ice and fish in insulated materials or by means of electrical engines that compress refrigerant fluids (vapor compression refrigeration system) to achieve the refrigeration effect. Normally refrigerant fluids contain chemical compounds such as HCFC and CFC, which can be harmful to the ozone layer in case of leakage (Xu et al. 2017).

The transport sector currently uses an energetic matrix whose source is based on fossil fuels. The fuel is used in internal combustion engines which are responsible to change the chemical energy of fuels into mechanical energy. According to Wang (2005) the maximum efficiency of energy conversion for internal combustion engines reaches 40%, and the leftover energy is wasted as thermal energy.

Fernández-Seara et al. (1997) built an absorption refrigeration prototype meant to work with ammonia-water mixture on a trawler fishing vessel, the cost of the prototype was 50% higher than the equivalent size compression refrigerator. The main function of the refrigerator is to keep water in a solid state (ice), so the temperature in the refrigerated space averages between 0 ºC and -10 ºC. The refrigerator is driven by the exhaust of a four-stroke diesel engine and saves fuel from 2% to 4% with an expected coefficient of performance (COP) of 0.5 (Fernández-Seara et al, 1997).

A hardship faced by the implementation of absorption refrigeration on open seas is associated with the undulatory movement, which can make the absorber fluid on an ammonia-water absorption refrigerator go into the heat exchangers, lowering the efficiency of the process (Ni et al. 2011 and Xu et al. 2017). The same idea was presented by Táboas et al. (2014) which implied that technical problems could be evident due the shaking, for example, damaging the heat exchangers or at least resulting in a lower heat and mass exchange in the system.

One of the goals of the Paris agreement, signed by a large number of nations, is to keep global warming to a maximum of 2 ºC (Gunfaus, 2021). To achieve that goal is necessary to improve the efficiency of fuel usage, and one of the possible methods is to raise the energetic efficiency of the already operating systems, or the mixture of renewable sources of fuel (Jacob-Furlan et al, 2020).

Along these ideas, we propose a change of the refrigeration process in engine fishing boats that use vapor compression refrigeration, suggesting a mechanical equipment that uses the absorption refrigeration process, meant to refrigerate the protein load. The refrigeration process is more ecological because the energy matrix is different from the conventional vapor compression process, due to the use of thermal energy, which is less noble when compared to electrical energy, and because it is a source normally wasted.

Thus, the present work proposes an analysis of the absorption refrigeration cycle using thermal energy, obtained from the boat exhaust determining the mechanical components used, as well as the heat transfer equations of the system, allowing the modelling of the absorption refrigeration. The model is then implemented computationally to determine the refrigeration effect, which would be destined to the production of cold air for the fish refrigeration.

ABSORPTION REFRIGERATION

Physical System of Refrigeration

The absorption refrigeration process uses a mixture of two fluids, commonly water and ammonia. The working principle is based on the change of the vaporization pressure of the mixture, thus achieving evaporation at lower temperatures, the process can reach boiling temperatures at -70 ºC (Jiang et al, 2019). Water acts as an absorbing fluid and ammonia as a refrigerant.

The main advantage of the absorption refrigeration process is that it utilizes thermal energy, which is not a noble source when compared to electricity. The energy comes from the exhaust pipes from the engines, choosing for the very exit so it does not affect the temperature needed to execute the removal of harmful elements such as NO_X and SO_X.

Figure 1 represents the physical system from the entrance of exhaust gases to the flow of ammonia.

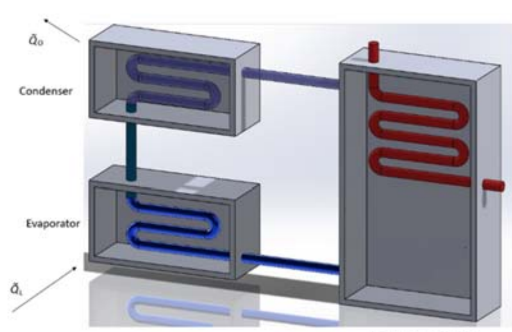

Figure 1. Physical representation of absorber refrigeration

Ammonia is a gas that can cause damage to the respiratory systems which can lead to death, so a good management of the process is important. To have a better control of the ammonia gas the refrigerator will be located near the engine room, which can only be accessed by maintenance crew, minimizing the people in direct access to the gas.

On the refrigerator the ammonia will be located on closed spaces, such as pipes or on the reservoir, only in case of mechanical damage such as holes or cracks leakage of ammonia could occur. And as a last means of safety in case of leakage the refrigerator will not work properly, meaning the refrigerated area will heat up, and that can be seen by the ship captain or the one responsible for maintenance through a thermometer set on deck, allowing for protective measures.

System Equations

The refrigerator is based on three heat exchangers, one of them responsible to transfer heat to ammonia from the exhaust, and the other two, called condenser and evaporator, responsible to change the fluid phase. On the condenser energy is transferred to the ambient by the liquefaction process, and on the evaporator, it absorbs energy from the ambient, in this case the fish storage, and it flows back to the first exchanger to do another cycle.

Vargas et al, (1996) presented a mathematical analysis to understand how the heat exchanger areas change the results of the model solution, and they suggest that a total heat exchanger area inventory can be considered as a realistic constraint, as it is represented in Eq. (7).

Based on the conservation of energy and considering the facts that changes in kinetic energy and potential energy are negligible, and the change in the pressure of exhaust gas will not influence the gas enthalpy then the heat transfer rate from the hot gases can be simplified to terms of Eq. (1).

The mathematical modelling presented herein was previously introduced by Vargas et al, (1996) and used by Gonçalves et al, (2020) and we will present below its main concepts, being equations (2)-(7) the heat transfer equations.

$$Q_H = \dot{M} * C_P * (T_{ST} - T_H) \tag{1}$$

$$Q_H = (UA)_H * (T_H - T_{HC}) \tag{2}$$

$$Q_O = (UA)_O * (T_{OC} - T_O) \tag{3}$$

$$Q_L = (UA)_L * (T_L - T_{LC}) \tag{4}$$

$$\frac{Q_H}{T_{HC}} + \frac{Q_L}{T_{LC}} = \frac{Q_O}{T_{OC}} \tag{5}$$

$$Q_H + Q_L = Q_O \tag{6}$$

$$UA = (UA)_H + (UA)_O + (UA)_L \quad (7)$$

In this model, the three heat exchangers of the absorption refrigerator connect the hot (T_H), cold (T_L), and ambient (T_O) reservoirs to an internal reversible compartment that is correspondingly at T_{HC}, T_{LC}, and T_{OC}. The "c" sub index is used as a reference to Carnot, since the internal compartment is considered reversible (see Equation (5)).

Q_H is the heat transfer rate from hot gases to the refrigerant, W; $\dot{M}$ is the mass flux from hot gases into the refrigerator, kg * s^{-1}; c_p is the specific heat at constant pressure of diesel, J * kg^{-1} * K^{-1}; T_{ST} is the temperature of the hot gasses entrance, K; $(UA)_H$ is the product between the convection heat coefficient and area of exchange of exhaust gases, W * K^{-1}; T_H is the working temperature of exhaust-ammonia, K; T_{HC} is the internal reversible compartment temperature in the cold heat exchanger, K; Q_O is the heat transfer in the condenser, W; $(UA)_O$ is the product between the convection heat coefficient and area of the condenser, W * K^{-1};T_{OC} is the internal reversible compartment temperature in the ambient heat exchanger, K; T_O is the reference ambient temperature, K; Q_L is the heat transfer on the evaporator, W; $(UA)_L$ is the product between the convection heat coefficient and area of the evaporator, W * K^{-1}; T_{LC} is the internal reversible compartment temperature in the cold heat exchanger, K; T_L is the working temperature of the evaporator, K.

Aiming to analyze a generic system, we dimensionalize the equations in order to ease the interpretation of the data and make the results extensible to a large number of operating conditions.

As the system depends on the heat input, that temperature would be the maximum from the system. Therefore, we can choose the exhaust gas temperature as 653 K (Autier, 2009; Ouadha, 2013, Nolan, 2017).

Considering the dimensionless parameter B on Eq. (11) is based on diesel as fuel, and that the product between convection heat coefficient times area are constant in this analysis, it means that every change on the B parameter will come from a variation on $\dot{M}$, which is the mass flow of exhaust gas that enters the ammonia reservoir.

Equations (8)-(13) present the dimensionless parameters used.

$$\tau_H = \frac{T_H}{T_O}, \tau_L = \frac{T_L}{T_O} \quad (8)$$

$$\tau_{HC} = \frac{T_{HC}}{T_O}, \tau_{OC} = \frac{T_{OC}}{T_O}, \tau_{LC} = \frac{T_{LC}}{T_O} \quad (9)$$

$$\tilde{Q}_H = \frac{Q_H}{U * A * T_O}, \tilde{Q}_O = \frac{Q_O}{U * A * T_O}, \tilde{Q}_L = \frac{Q_L}{U * A * T_O} \quad (10)$$

$$\tau_{ST} = \frac{T_{ST}}{T_O}, B = \frac{\dot{M} * C_P}{U * A} \quad (11)$$

$$\gamma = \frac{(UA)_H}{U * A}, \zeta = \frac{(UA)_L}{U * A}, \frac{(UA)_O}{U * A} = 1 - \gamma - \zeta \quad (12)$$

τH is the dimensionless working temperature of exhaust-ammonia; τL is the dimensionless working temperature of the evaporator; τHC is the dimensionless internal reversible compartment temperature at the hot heat exchanger; τ_{OC} is the dimensionless internal reversible compartment temperature at the heat exchanger in contact with the ambient; τ_{LC} is the dimensionless internal reversible compartment temperature at the evaporator; $\tilde{Q}H$ is the dimensionless heat transfer from hot gasses to the refrigerant; $\tilde{Q}O$ is the dimensionless heat transfer on the condenser; $\tilde{Q}L$ is the dimensionless heat transfer on the evaporator; τ_{ST} is the dimensionless temperature of the hot gasses entrance; B is the dimensionless equation of the heat from the exhaust gas; γ is the dimensionless value corresponding to the ammonia heating; ζ is the dimensionless value corresponding to the evaporator.

Vargas *et al.,* 1996 regarded it possible to evaluate the dimensionless parameters ζ and γ, on each heat exchanger by considering as constants the values of B and τ_{LC}. By sweeping Tst temperature from 1 to 2 Vargas concluded that the values of ζ and γ are almost constant on the entire range so we set the values as 0,25 for each parameter.

By replacing equations (8) - (12) in equations (1) - (6) we obtain the final version on the equation as:

$$\tilde{Q}_H = B * (\tau_{ST} - \tau_H) \quad (13)$$

$$\tilde{Q}_H = \gamma * (\tau_H - \tau_{HC}) \quad (14)$$

$$\tilde{Q}_O = (1 - \gamma - \zeta) * (\tau_{OC} - 1) \quad (15)$$

$$\tilde{Q}_L = \zeta * (\tau_L - \tau_{LC}) \quad (16)$$

$$\frac{\tilde{Q}_H}{\tau_{HC}} + \frac{\tilde{Q}_L}{\tau_{LC}} = \frac{\tilde{Q}_O}{\tau_{OC}} \quad (17)$$

$$\tilde{Q}_H + \tilde{Q}_L = \tilde{Q}_O \quad (18)$$

Due to the need to refrigerate fish and considering the Brazilian standard that for fish refrigeration the temperature must be close to that of freezing water and for frozen fish the temperature has to be -18 ºC in its core (MINISTÉRIO DA AGRICULTURA, 2007). So, we define as the value of the heat exchanger temperature an average between the values of 268 K and 253 K, thus reaching a value of τ_L as 0.875.

SOFTWARE SOLVER

The mathematical model was developed in an open software called Interactive Thermodynamics. It is a very simple software allowing the programmer to set the equations with no need for a programming language.

The software uses C language, which allows the programmer to use loops, conditional programming and also to calculate integral equations. Also, it has thermodynamics tables built in for many types of fluids, which simplifies the interpolation process when programming.

Its main solver uses the Newton-Raphson method, which has a fast convergence process. It is important that the programmer knows what to expect as an answer, because it may be necessary to edit the input data to reach a narrower solution.

The solver has a function called explore which allows the variation of model parameters in a defined interval, giving a depth of perception on the system behavior.

On Figure 2 it shows the process for the development of the computer program.

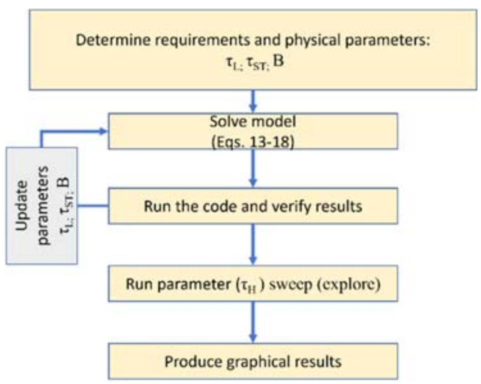

Figure 2. Flowchart about the development process in the program.

The results can be verified by checking the signs of the computed temperatures. Since we are using the temperature in Kelvin, they must not be negative. Also, the magnitudes of the heat transfer interactions must be positive. The negative sign that indicates the direction of the energy transfer is embedded in the energy balance equations.

RESULTS

With the explore function an analysis was conducted to explore the effect of the temperature from the exhaust gas in the refrigeration effect obtained with the system. Based on it we analyzed the τ_H parameter from 1 to 2.19 which is acceptable to the physical system according to the maximum temperature set on τ_{ST}. Also, in the analysis we changed the mass flow of exhaust gas on the system by changing the B parameters, to see if it influences how the refrigeration works. On Figure 3 are the graphical results of the mathematical analysis.

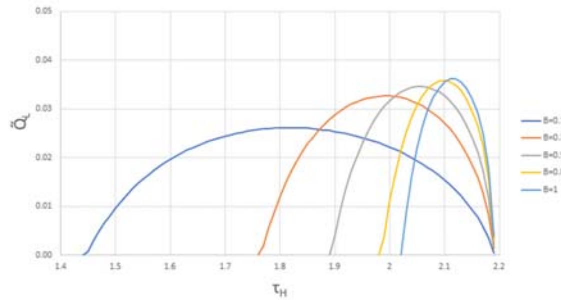

Figure 3. Parametric analysis on τ_H and B.

We can observe that for the analyzed temperature range, the system shows the possibility of optimization, and thus determine an operating temperature at which the system offers the maximum removal of heat from the refrigerated space. Another observation is that the higher the value of the dimensionless parameter B, the greater the capacity to remove heat from the compartment, but even that has a limit due to the heat transfer capacity in the heat energy input heat exchanger, or at the inlet of exhaust gases.

CONCLUSION

Considering the refrigeration process on fishing boats the replacement of the compression system by the absorption refrigeration is recommended due to the absence of HCFC and CFC materials, therefore minimizing the possible damage to the ozone layer, and also by raising the fuel efficiency due to the usage of waste thermal energy leftover from the transformation of chemical energy into mechanical energy.

The analysis shows that the absorption refrigeration is capable of refrigeration according to the dimensionless parameters on equation 16, with the dimensionless temperature of the refrigerated space being τ_L 0,875, which is an acceptable refrigeration temperature according to Brazilian legislation on fish refrigeration. Also, from Figure 3 it is possible to determine the best temperature to operate the refrigerator, based on the type of diesel you use, determined by the parameter B on equation 11, without affecting the removal of harmful substances such as NO_X, and SO_X.

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