Integration of Water-Lithium Bromide Absorption Refrigeration System with Diesel engine: A Thermodynamic Study

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Abstract
This paper examines through a thermodynamic analysis the feasibility of using waste heat from Diesel engines to drive an ammonia-water absorption refrigeration system. An energy balance of a diesel engine shows that sufficient waste heat is provided. The results illustrate that higher performance of the system is obtained at generator temperature in near 361K for single effect and then starts decreases till 371K.

Nomenclature
COP Coefficient of performance
H Enthalpy, kJ/kg
m Mass flow rate, kg/s
p Pressure, MPa
Q Heat quantity, kW
T Temperature, K
v specific volume
w Work, kJ/kg
W Power, kW
x Li-Br mass fraction

1. Introduction
As fuel prices soar, diesel engines manufacturers are beginning to scout for more energy efficiency solutions. This can be achieved by increasing the engine efficiency and developing technologies with low pollutant emissions. The increase of the diesel engine efficiency can be achieved by valorizing the waste thermal energy. In diesel engine, a considerable amount of primary energy may be saved by valuing the waste heat rejected during the operation of the main systems. Indeed, a large amount of waste heat energy is released into the environment.

Therefore, an increased attention is being paid for the utilization of this waste energy. This valorization can be intended using absorption refrigeration systems in which the surplus waste heat from the main engine is used to separate a refrigerant vapor from a binary solution.

Traditionally, vapour compression systems are the common in automobile refrigeration systems. These systems are powered using electric energy produced through burning of increasingly more expensive fuel. The challenges of environment protection and energy economy have led to a growing interest in non-conventional refrigeration systems such as absorption refrigeration. In fact, in an absorption refrigeration system, the refrigeration effect is produced through the use of two fluids and a heat source rather than electrical input as in the more familiar vapor compression system. Therefore, energy recovered from waste heat streams can provide a considerable part of refrigeration and air conditioning needs at no additional cost. As a result, the use of surplus heat rejected by the main engine provides substantial fuel savings, involving the reduction of pollutants. The performance of this system affects the attainable amount of energy savings. Improving their performance can be only performed using thermodynamic analysis. While several investigations have been devoted to absorption refrigeration systems [1-18], only few past studies have addressed the...
concept of driving absorption refrigeration systems by waste heat from internal combustion engines [19-27].

It is clear from the literature survey that absorption refrigeration systems have received a considerable interest among the research society during the last years and a substantial amount of work has been published on the subject. Nevertheless, in the above mentioned work, there seems to be only few attempts to integrate absorption refrigeration systems with marine diesel engines.

Hence, following the above mentioned studies, this paper presents a thermodynamic analysis of an absorption refrigeration system driven by waste heat from a Diesel engine. The calculation and analysis of an absorption refrigeration system require the availability of simple and reliable mathematical model for the determination of thermodynamic properties of the working fluids. Combined to fundamental thermodynamic relations, it can generate all the properties required to carry out a thermodynamic analysis of the cycle.

2. Approximate Diesel Engine Energy Balance

Although the great technological development of modern Diesel engines, only a part of the energy contained in the fuel is converted to power output. The maximum efficiency remains lower than 45%. The main losses are dissipated as heat in the exhaust gases, coolants, and transferred to the environment. An energy balance of a Diesel engine indicates how the energy contained in the fuel is used or lost. Indeed, the injection of a mass of fuel in the hot air in the combustion chamber produces a large amount of heat. However, the mechanical work requires only a fraction of the energy produced. The residual energy is, in fact, discharged at various places during his stay in the cylinder. For a Diesel engine, a first-law analysis yields

\[ (Q_{\text{in}}) = W + (Q_{\text{c}}) + (Q_{\text{r}}) + Q_{\text{ex}} \]

Where, in \((Q_{\text{in}})\) is the heat supplied to the Diesel engine, \(W\) the mechanical energy output, \((Q_{\text{c}})\) the heat transferred to the cooling systems, \((Q_{\text{r}})\) the heat rejected in exhaust gases, \((Q_{\text{ex}})\) the heat transferred to the environment by radiation.

Figure 1 shows an example of an energy balance of a modern Diesel engine. The heat transferred to coolants includes charge air cooling (17.8%), jacket water cooling (4.8%) and lubricating oil cooling (3.2%). In addition, 25.1% of the total energy is lost, released into the atmosphere during the exhaust outlet. Finally, a small part of the energy (0.6%) is released by radiation. At first glance, the analysis of heat flows shows that there are three engine waste heat streams, at different temperature levels, that have potential to be recovered: exhaust gas (300-600°C); charge air (200°C); jacket water (80-100°C).

![Fig: 1. Typical heat balance of a marine Diesel engine](image)

3. Description Of Proposed Cycle

In this system waste heat required to drive cycle is obtained from the heat available from radiation in the temperature range of 800°C to 1000°C. Various components are arranged according to their pressures and temperatures. The compressor work is replaced by heat supplied in the generator plus pump work. Cooling must be done in the absorber to remove the latent heat of refrigerant vapor as it changes into liquid state by absorption by the weat solution.

Liquid–liquid heat exchanger is used in between generator and absorber where heat from the absorbent is given to the refrigerant that increases the temperature of refrigerant entering into generator thus increases coefficient of performance. In lithium bromide absorption system lithium bromide salt solution is used as the absorbent and water as the refrigerant. A concentrated solution of lithium bromide has a great affinity for water. Since water is the refrigerant, the refrigerant operating temperature in the evaporator has to be above the freezing point of water (0°C) of water.

The absorption system considered uses lithium bromide as the absorber and water as the refrigerant to create a continuous cycle for the water. Figure 2 shows a schematic of a basic lithium bromide-water absorption refrigeration system. It consists mainly of a generator, a condenser, an evaporator, an absorber, a solution heat exchanger and a circulation pump. The generator uses waste heat from the Diesel engine to separate water vapour from the concentrated ammonia solution. In the condenser, high pressure ammonia vapours are cooled and condensed to liquid state.
Liquid ammonia leaves the condenser and flows to the evaporator through an expansion valve. The refrigerant then enters the evaporator, where it receives heat from the cold source. Then, ammonia vapour enters the absorber, where a weak solution of water and low concentration ammonia absorbs the refrigerant and, at the same time, releases heat to the neighborhood. The ammonia-water solution flows back to the generator through a circulation pump to undergo a new cycle.

![Fig: 2. Block diagram of proposed system](image)

**4. Thermodynamic Analysis**

In order to carry out a thermodynamic analysis, the conservation laws of mass and energy have been applied to each component of the system. Every component has been considered as a control volume exchanging heat, work and in flow and outflow streams with its surrounding. To simplify the theoretical model, the following assumptions have been considered:

- The analysis is carried out under steady state conditions and assuming thermodynamic equilibrium at all points of the cycle;
- Li-Br at the generator and evaporator outlets is assumed as saturated vapour;
- Li-Br at the condenser outlet is saturated liquid;
- Pressure losses in the pipes and all heat exchangers are negligible;
- Heat exchange release to surroundings does not occur.

**Table: 1. Main parameters considered for the analysis**

<table>
<thead>
<tr>
<th>Component</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator temperature</td>
<td>80°C-100°C</td>
</tr>
<tr>
<td>Condenser temperature</td>
<td>40°C</td>
</tr>
<tr>
<td>Chilled-water temperature</td>
<td>10°C</td>
</tr>
<tr>
<td>Absorber temperature</td>
<td>40°C</td>
</tr>
</tbody>
</table>

![Fig: 3. Absorption cycle on ln p -1/T diagram](image)

Based on the above assumptions, the governing equations for mass and energy conservation are given by the following expressions:

- Mass balance: \( \sum m = 0 \)
- Material balance: \( \sum m x = 0 \)
- Energy balance: \( \sum Q + \sum m h = 0 \)

Specific weak solution circulation is given by:

\[
 f = \frac{F-D}{x_r-x_d} = \frac{x_a-x_r}{x_r-x_d} \\
 f = \frac{1-x_r}{x_r-x_d} \\

\]

**State: 1.** a energy balance of liquid–liquid heat exchanger gives

\[
 f (h_{1a} - h_4) = (f-1) (h_2 - h_3) 
\]
**State: 5.** at these condition superheated space

\[ h = (2501 + 1.88t) \]

The energy required to pump the solution from the low pressure (absorber) to the high pressure (Generator) is:

\[ q_p = f \nu_4(p_k - p_0) \]

Where \( \nu_4 \) is the specific volume of the strong solution?

**State: 6.** saturate water at condenser temperature

\[ h_6 = 4.1868(40) \]

**State: 7.** \( h_7 = h_6 \)

**State 8** At saturated vapor and evaporator pressure

\[ h_8 = 2501 + 1.88(10) \]

Finally, the mass and energy balance equations applied to the absorber, the condenser and the evaporator give the following expressions:

- Heat rejected in condenser,
  \[ Q_c = \frac{D}{v_6}(h_5 - h_6) \]
- Heat rejected in the absorber,
  \[ Q_a = D [ (h_9 - h_3) + f(h_3 - h_4) ] \]
- Heat supplied in the generator,
  \[ Q_h = D [ (h_5 - h_2) + f(h_2 - h_{1a}) ] \]
- Heat added in generator per unit mass of vapor distilled,
  \[ Q_{h} = (h_5 - h_2) + f(h_2 - h_{1a}) \]
- Refrigerating effect,
  \[ Q_o = h_8 - h_7 \]

The performance of refrigeration systems are usually measured using the coefficient of performance (COP). This parameter is defined as the ratio of the useful effect produced to the energy input of the system:

\[ \text{COP} = \frac{Q_o}{q_h} \]

**5. Results and Discussions**

**References**


