Abstract: Day after day, stricter environmental regulations and rising operating costs and fuel prices are forcing the shipping industry to find more effective ways of designing and operating energy-efficient ships. One of the ways to produce electricity efficiently is to create a waste heat-driven liquid metal–water binary vapor power plant. The liquid metal Rankine cycle systems could be considered topping cycles. Liquid metal binary cycles share characteristics like those of the steam Rankine power plants. They have the potential for high conversion efficiency, they will likely produce lower-cost power in plants of large capacity rather than small, and they will operate more efficiently at design capacity rather than at partial load. As a result, liquid metal topping cycles may find application primarily as base-load plants onboard ships. In this study, a waste heat-driven liquid metal–water binary vapor power plant onboard a ship is designed and thermodynamically analyzed. The waste heat onboard the vessel is the exhaust gas of the LM2500 marine gas turbine. Mercury and Cesium are selected as liquid metals in the topping cycle, while water is used in the bottoming cycle in binary power plants. Engineering Equation Solver (EES) software (V11.898) is used to perform analyses. For the turbine inlet temperature of 550 °C, while the total net work output of the binary cycle system is calculated to be 104.84 kJ/kg liquid metal and 1740.29 kJ/kg liquid metal for mercury and cesium, respectively, the efficiency of the binary cycle system is calculated to be 31.9% and 26.3% for mercury and cesium as liquid metal, respectively. This study shows that the binary cycle has a thermal efficiency of 26.32% and 31.91% for cesium and mercury, respectively, depending on liquid metal condensing pressure, and a binary cycle thermal efficiency of 25.9% and 30.9% for cesium and mercury, respectively, depending on liquid metal turbine inlet temperature, and these are possible with marine engine waste heat-driven liquid metal–water binary vapor cycles.

Keywords: binary cycle; liquid metal; waste heat; ship; marine engine

1. Introduction

With the increasing world population, global trade volume has also expanded. The first step of trade is manufacturing. Since countries with a population above the world average are seen as cheap labor, many large companies have manufacturing centers in Southeast Asian countries. After manufacturing electronic, automotive, and textile products, they are sent to different parts of the world. A large part of the logistics network of global trade uses maritime vehicles [1]. This is because the cheapest commercial transportation is by sea [2]. The dimensions of cargo ships used at sea vary depending on the materials they carry. As the size of ships increases, the amount of fuel they consume also increases. The economic instability experienced after the COVID-19 pandemic also impacted fuel prices [3]. Growing costs are reflected directly on consumers. This situation sometimes causes trade disruptions. This chain reaction is one of the leading causes of inflation.

Fuel oil, used as an energy source in ships, helps to move on water and operate the electronic circuits on the ship. There are many electronic systems on ships. An uninterrupted energy source is required for all of these to work. Since this needed energy is provided...
from fossil fuels, both economic and environmental damages occur. In recent years, there have been many projects with different approaches to reduce the fuel consumed to obtain the energy used on ships [4].

This study also offers suggestions on energy efficiency for ships with a different approach. This approach is a liquid metal–water binary steam power plant. This system’s energy is obtained using evaporation reactions between liquid metal and water. Liquid metals can be used in steam production because they have efficient high-temperature heat-transport fluids [5]. This steam power plant aims to provide economical and environmentally friendly energy production by replacing traditional fuels. The interest in such sustainable energy solutions in the maritime industry is aligned with achieving energy independence and increasing environmental sustainability. Additionally, such innovative power systems could significantly benefit the marine industry by allowing ships to be more efficient and environmentally friendly during long-distance voyages.

Liquid metal–water steam power plants consist of two cycles. These are the liquid metal cycle and the water cycle. The reason for using liquid metal is its high temperature resistance and conductivity properties. The liquid metal heats up when it encounters the high-temperature exhaust gas in the waste heat boiler. Energy is produced from high-temperature liquid metal through a turbine and generator. The liquid metal passing through the turbine transfers its remaining energy to the water through a heat exchanger without encountering the water. In this system, a heat exchanger located between the two fluids serves as both a condenser for the fluid with high temperature and low vapor pressure and as a boiler for the fluid at low temperature with high vapor pressure. Metals such as sodium, mercury, potassium, or cesium can be used in this cycle. The second part of the power plant is the water cycle. Using the high-temperature energy that it receives from the liquid metal, the evaporated water produces energy through a turbine or generator. Thus, energy is made twice in this power plant [6].

The first facility of this type was established in 1917. In the facility where mercury was used as the liquid metal, the maximum steam temperature was 315.5 °C and the steam absolute pressure was 3.1 MPa. In this facility, built in 1923, mercury was used as liquid metal. The 20 tons of mercury were heated at 241.3 kPa pressure and 433.3 °C. The mercury in the cycle is concentrated at 10.3 kPa and 251.6 °C. More than 1.3 MPa of steam was produced to drive the steam turbine. Following this facility, only mercury was used as liquid metal in all other power stations established between 1928 and 1947. However, the mercury temperature was never raised above 510 °C in any facility established in those years. The danger of corrosion of the pipes and the release of mercury vapor into the environment have always been considered. In the following years, with composite pipe materials with high thermal resistance, systems operating at higher temperatures began to be used [7]. The number of studies on this subject is not satisfactory. The subject of a small number of academic research has been facilities that produce large amounts of power. Some of the following examples include those.

Pesar analyzed the potassium-steam binary cycle thermodynamically. In his study using numerical methods, he determined the potassium turbine inlet temperature and condensation pressure as variable parameters. As a result, it was determined that the most important parameter for potassium-steam binary cycles is the turbine inlet temperature [5]. Simmons’ research aimed to determine the high-efficiency potential of the cascade Rankine cycle systems. In his work, he used mercury as the liquid metal for the high-temperature stages and water for the low-temperature stages. As a result, it was determined that the maximum system efficiency was at peak temperatures between 482.2 °C and 1648.8 °C [7]. Gutstein and his colleagues thought that using liquid metal Rankine cycles at high temperatures along with traditional steam cycles at low temperatures would increase the efficiency of the systems. They made separate calculations for mercury and potassium and examined the conditions under which these liquid metals should be used. As a result, they determined that the use of potassium at high temperatures is more advantageous [8]. Barak and his colleagues used six different power conversion systems in their studies to measure
the energy efficiency of the systems. As a result, they found that the most efficient system was the liquid metal–water binary steam cycle. They stated that in the binary steam cycles in which they used sodium as the liquid metal, they achieved 15% more efficiency than the Rankine cycle [9]. Prisnyakov and his colleagues investigated parallel feed evaporators of alkali metals in space power systems, which used solar power conversion according to the Rankine cycle as their source. They determined the conditions for creating the highly efficient evaporators of space power systems under consideration [10]. Angelino and Invernizzi considered that the temperature potential of solar energy was much greater than the amount obtained from standard conversion cycles. For this reason, they examined liquid metal–vapor cycles. During their investigations, they made calculations using potassium and rubidium as liquid metals. As a result of the different analyses they made, they found that the efficiency obtained from the liquid metal–steam binary cycle they had designed using potassium was higher than others. They stated that if the turbine inlet temperature is 800 °C, the efficiency of the system increases up to 57% [11]. Bombarda and Invernizzi stated that adding a liquid metal cycle to the organic Rankine cycle increased the total thermal efficiency. The alkali metal and steam binary cycles, however, are only suitable within a convenient power range. In the small power range, their suitability is restricted by the steam’s intrinsic thermodynamic properties (high enthalpy drops, high maximum pressures). In contrast, in the very high power range, their suitability is limited by the extremely low condensation pressure typical of alkali metals (0.017 bar at 450 °C for potassium) [12]. Lorenzin and Abanades stated that liquid metals should be used to increase the efficiency of Concentrated Solar Energy (CSP) systems, which they think will play an important role in future energy scenarios. In their studies, where they calculated structural compatibility and thermal efficiency using CFD software (Fluent V.12), they accepted the ideal operating temperature as 1000 °C. As a result, the best liquid metals that can be used in CSP systems are identified as tin, gallium, lithium, sodium, and lead-bismuth [13].

The immense contribution of mercury and cesium binary cycles to thermodynamics is the increase in energy conversion efficiency. Increasing energy efficiency reduces fuel consumption, waste heat emissions, and pollutants. Apart from the advantages of this type of cycle, they also have some disadvantages. Examples of these include higher capital and increased maintenance costs. Before the designed systems are installed, the efficiency of their essential components should be examined in detail. In recent years, binary conversion has been studied in different branches of industry. However, there is no history of using liquid metal topping cycles in utility onboard ships. This article aims to fill this gap in the literature.

In this study, numerical calculations have been made using different parameters for liquid metal–water steam power plants. Mercury and cesium have been chosen as liquid metals in the binary cycle. Calculations have been made under the same conditions for each liquid metal. In cases where the condensing pressure and turbine inlet temperature are changed, the efficiency of the power plant and the total network output are calculated. The resulting values have been compared with each other. The study aims to see the difference in the parameters affecting the efficiency obtained from liquid metal–water steam power plants onboard ship.

**Working Fluids**

Liquid metals are used primarily in specific industrial applications and environments requiring high heat conduction. Liquid metals have higher heat conduction coefficients than other fluids. Thanks to these properties, liquid metals can conduct heat faster. Liquid metals can generally operate stably over a wide range of temperatures. This means they can be used in high-temperature applications that are unsuitable for many fluids [14]. Liquid metals have low viscosity due to their physical state. This allows liquid metals to lose energy due to less friction while circulating in the system [15]. The thermal expansion coefficient of liquid metals provides an advantage for their use in thermodynamic systems.
Especially at high temperatures, materials’ expansion can be controlled. These advantages mean liquid metals can be preferred for industrial applications [16].

Mercury and cesium have been chosen as the liquid metals for this study. Mercury is a metal element, but its liquid form differs from most other metals because it is liquid at room temperature [17]. Cesium is a chemical element found in the alkali metal group in the periodic table. Alkali metals are generally reactive, soft, and low melting point elements [18]. In this study, mercury and cesium are preferred because the boiling temperature of liquid metals is lower than the maximum gas temperature of the LM2500 gas turbine onboard the ship. Table 1 compares the properties of mercury, cesium, and water because water is so widely used as a working fluid.

**Table 1.** Properties of working fluids.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Working Fluids</th>
<th>Mercury</th>
<th>Cesium</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular weight</td>
<td></td>
<td>201</td>
<td>132.9</td>
<td>18</td>
</tr>
<tr>
<td>Critical temperature (°C)</td>
<td></td>
<td>~1540</td>
<td>~1770</td>
<td>~374.2</td>
</tr>
<tr>
<td>Critical pressure (MPa)</td>
<td></td>
<td>105.82</td>
<td>13.37</td>
<td>22.11</td>
</tr>
<tr>
<td>Latent heat (MJ/kg)</td>
<td></td>
<td>0.294</td>
<td>0.491</td>
<td>2.438</td>
</tr>
<tr>
<td>Specific volume of vapor (m³/kg)</td>
<td></td>
<td>1.30</td>
<td>0.55</td>
<td>39.52</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td></td>
<td>~38.83</td>
<td>28.4</td>
<td>0</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td></td>
<td>13.55</td>
<td>1.93</td>
<td>1</td>
</tr>
<tr>
<td>Specific heat of liquid (J/kg·K)</td>
<td></td>
<td>138</td>
<td>239</td>
<td>4187</td>
</tr>
<tr>
<td>Thermal conductivity of liquid (W/m·K)</td>
<td></td>
<td>13.3</td>
<td>18.5</td>
<td>0.606</td>
</tr>
</tbody>
</table>

Figure 1 plots the vapor pressure of liquid metals and water as a function of temperature. From these and other data, specific generalizations about mercury and cesium may be made. The latent heat of vaporization of mercury is roughly one-tenth that of water. The vapor pressure of mercury at 500 °C is about 823.6 kPa. At about 200 °C, the vapor pressure of mercury falls to about 2.325 kPa, and the vapor-specific volume at this condition is nearly 7.36 m³/kg. This represents the lower limit on practical mercury condensing temperature. Due to its high molecular weight, mercury exhibits a low sonic velocity. This property imposes low turbine tip speeds that might result in the need for multiple-flow turbines. The vapor pressure of cesium is relatively low; at 500 °C, it is 14.98 kPa, and at about 200 °C, the vapor pressure of cesium falls to about 0.01805 kPa. As a result, over this temperature range, the wall thickness of the cesium boiler tubes will likely be determined by consideration of stresses other than those arising from internal pressure.

![Figure 1](image-url)
2. Governing Equations

Assumptions are as follows:
1. Steady operating exists.
2. Kinetic and potential energy changes are negligible.
3. Pressure drops and heat losses in piping are negligible.

The mass balance equation for a general steady flow system is expressed as follows:

\[
\sum_{in} m = \sum_{out} m
\]  

(1)

The energy balance equation for a general steady flow system is expressed as the following:

The rate of energy in W

\[
\dot{E}_{in} = \dot{E}_{out}
\]  

(2)

The first law in W

\[
\dot{Q} - \dot{W} = \sum_{out} m \left( h + \frac{V^2}{2} + gz \right) - \sum_{out} m \left( h + \frac{V^2}{2} + gz \right)
\]  

(3)

Mercury cycle:
Pump inlet work in kJ/kg

\[
w_{\text{pump}, Hg} = v_1 (P_2 - P_1)
\]  

(4)

Inlet heat in kJ/kg

\[
q_{\text{in}} = h_3 - h_2
\]  

(5)

Turbine output work in kJ/kg

\[
w_{\text{turbine}, Hg} = h_3 - h_4
\]  

(6)

Net output work in kJ/kg

\[
w_{\text{net}, Hg} = w_{\text{turbine}, Hg} - w_{\text{pump}, Hg}
\]  

(7)

Steam cycle:
Pump inlet work in kJ/kg

\[
w_{\text{pump}, w} = v_5 (P_6 - P_5)
\]  

(8)

Turbine output work in kJ/kg

\[
w_{\text{turbine}, w} = h_7 - h_8
\]  

(9)

Net output work in kJ/kg

\[
w_{\text{net}, w} = w_{\text{turbine}, w} - w_{\text{pump}, w}
\]  

(10)

Heat exchanger:
The ratio of mass flow rates is determined from an energy balance on heat exchanger.
The ratio of energy in W

\[
\dot{E}_{\text{in}} = \dot{E}_{\text{out}}
\]  

(11)

\[
\dot{m}_{Hg} (h_4 - h_1) = \dot{m}_{w} (h_7 - h_6)
\]  

(12)

The ratio of mass flow rates

\[
\frac{\dot{m}_{w}}{\dot{m}_{Hg}} = y
\]  

(13)
Binary cycle:
The total net work output per kilogram of Mercury becomes the following:
\[ w_{\text{net}} = w_{\text{net, Hg}} + yw_{\text{net, steam}} \text{ (kJ/kg)} \]  \hspace{0.5cm} (14)

Thermal efficiency of the binary cycle is determined from the following:
\[ \eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} \]  \hspace{0.5cm} (15)

Exergy balance for a general steady flow system is expressed as follows:
\[ \dot{X}_{\text{in}} - \dot{X}_{\text{out}} - \dot{X}_{\text{destroyed}} = 0 \text{ (W)} \]  \hspace{0.5cm} (16)

The rate of heat transfer from the exhaust gas is expressed as follows:
\[ \dot{Q}_{\text{exh}} = \dot{m}_{\text{exh}}(h_{\text{exh1}} - h_{\text{exh2}}) \text{ (W)} \]  \hspace{0.5cm} (17)

The flow exergy of a flowing fluid is expressed as follows:
\[ \psi = (h - h_0) - T_0(s - s_0) \text{ (kJ/kg)} \]  \hspace{0.5cm} (18)

For steady-flow system, the reversible power is expressed as the following:
\[ \dot{W}_{\text{rev}} = \sum \dot{m}_i \psi_i - \sum \dot{m}_e \psi_e \text{ (W)} \]  \hspace{0.5cm} (19)

\[ \dot{W}_{\text{rev}} = \dot{m}_{\text{exh}}[(h_{\text{exh1}} - h_{\text{exh2}}) - T_0(s_{\text{exh1}} - s_{\text{exh2}})] \text{ (W)} \]  \hspace{0.5cm} (20)

The exergy efficiency of system is expressed as follows:
\[ \eta_{\text{ex}} = \frac{w_{\text{net}}}{\dot{W}_{\text{rev}}} \]  \hspace{0.5cm} (21)

3. Case Study

The liquid metal in the cycle is vaporized by utilizing the heat of the high-temperature exhaust gas of the LM2500 gas turbine onboard the ship. A system to be designed can use this high-temperature fluid in energy production. One of these systems is the liquid metal–water vapor binary cycle. The schematic and T-s diagram for a liquid metal–water vapor power plant is shown in Figures 2 and 3.

This system consists of two cycles, as shown in Figures 2 and 3. The fluid of the topping cycle is liquid metal, and the fluid of the bottoming cycle is water. There is no boiler in liquid metal cycles. Instead, liquid metal waste heat boiler and heat exchanger are used. It uses composite pipe materials with high thermal resistance in the topping cycle to protect the pipes from the danger of corrosion and prevent the release of liquid metal vapor into the environment.

Gases, high-temperature combustion products from ship engine exhaust, are directed to the waste heat boiler. The liquid metal fluid passing through the heat exchanger absorbs the heat of the high-temperature exhaust gases, and its temperature rises. Liquid metal that reaches a high temperature enters the steam turbine and turns into mechanical energy. The liquid metal fluid from the steam turbine gives its remaining energy to water, the fluid of the lower cycle, through the other heat exchanger in the system. Water that reaches a high temperature evaporates and enters the turbine. Mechanical energy is obtained from the steam turbine. The water from the turbine gives its remaining heat to the seawater through another cycle heat exchanger. Thus, the water becomes cold. The cooled water is sent through the pump to the standard heat exchanger of the two cycles to receive heat from the liquid metal again. In this way, circulation continues. Energy is continuously
produced throughout the circulation from ship waste heat in two different cycles. The mechanical energy obtained is converted into electricity through the generator. Thus, the energy efficiency of the system increases. The working principle of liquid metal–water steam power plants can be explained in this way.

Figure 2. Liquid metal–water binary vapor power plant onboard ship.

Figure 3. T-s diagram of liquid metal–water binary vapor cycle.

The temperature of the liquid metal increases as it is subjected to compression by a liquid metal pump (1–2). The liquid metal passing through (2–3) the heat exchangers increase in temperature as it absorbs the heat of the ship’s exhaust gases. Liquid metal, which has reached a high enough temperature (3–4), loses some of its energy and its temperature decreases as it enters the steam turbine to provide power. In the (4–1), the liquid metal passes through the standard heat exchanger of the two cycles and gives its remaining heat to the water. Next (5–6), the water temperature increases as the water is subjected to compression by the water pump. As the water passing through the heat exchanger (6–7) and takes the remaining heat of the liquid metal from the steam turbine, its temperature increases. As the water reaches a high temperature (7–8), it enters the steam turbine and provides power, after which it loses some of its energy thus decreasing its temperature. Finally (8–1), the temperature of the water decreases as it is passed through
the heat exchanger, where it gives its remaining heat to the seawater. This process is also shown graphically in Figure 3.

In this study, the exhaust gas of an LM2500 marine gas turbine [19] vaporizes liquid metal via a waste heat boiler in a binary cycle onboard a ship. The maximum power performance of the LM2500 gas turbine is given in Table 2.

Table 2. Maximum power performance for LM2500 gas turbine.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>25,060 kW</td>
</tr>
<tr>
<td>SFC</td>
<td>226.9 g/kWh</td>
</tr>
<tr>
<td>Heat rate</td>
<td>9705 kJ/kWh</td>
</tr>
<tr>
<td>Inlet air flow</td>
<td>69.4 kg/s</td>
</tr>
<tr>
<td>Exhaust gas flow</td>
<td>70.3 kg/s</td>
</tr>
<tr>
<td>Exhaust gas temperature</td>
<td>566 °C</td>
</tr>
<tr>
<td>Power turbine speed</td>
<td>3600 rpm</td>
</tr>
</tbody>
</table>

4. Results and Discussion

Engineering Equation Solver (EES) software was used to determine the thermophysical properties and perform analyses. It was used to calculate the binary cycle efficiency, total net work output, energy supplied to the liquid metal, and binary exergy efficiency depending on liquid metal turbine inlet temperature and condensing pressure. In this study, the condensation temperature in the binary cycle onboard a ship was chosen to be 40 °C since the maximum seawater temperature should be 32 °C, according to Turk Loydu’s rules [20].

Figure 4 illustrates the binary cycle efficiency versus liquid metal turbine inlet temperature.

As seen in Figure 4, the efficiency of the binary cycle using mercury is higher than the system using cesium at every value of the turbine inlet temperature. As the turbine inlet temperature of the liquid metal increases, the cycle efficiency also increases. The efficiency increase is higher at higher temperatures. For the turbine inlet temperature of 500 °C, the efficiency of the binary cycle for cesium and mercury as liquid metal is calculated to be 25.9% and 30.9%, respectively. For the turbine inlet temperature of 550 °C, the efficiency of the binary cycle for cesium and mercury as liquid metal is calculated to be 26.3% and 31.9%, respectively.

The binary cycle efficiency versus liquid metal condensing pressure is illustrated in Figure 5.
Figure 5. Binary cycle efficiency versus liquid metal condensing pressure.

As seen in Figure 5, the efficiency of the binary cycle using mercury is higher than the system using cesium at every value of the condensing pressure. As the condensation pressure of the liquid metal increases, the cycle efficiency decreases. The efficiency decrease is higher at a higher condensation pressure. For the condensation pressure of 7 kPa, the efficiency of the binary cycle for cesium and mercury as liquid metal is calculated to be 26.32% and 31.91%, respectively. For the condensation pressure of 11 kPa, the efficiency of the binary cycle for cesium and mercury as liquid metal is calculated to be 26.07% and 31.52%, respectively. There is not much of a difference between the binary cycle efficiencies of systems at different condensate pressures. However, since this binary cycle is produced for the waste heat of ships, the difference between the efficiency of the cycles is small.

The total net work output versus liquid metal turbine inlet temperature is illustrated in Figure 6.

Figure 6. Total net work output versus liquid metal turbine inlet temperature.

As seen in Figure 6, the total net work output of the binary cycle using cesium is higher than the system using mercury at every value of the turbine inlet temperature. As the liquid metal turbine inlet temperature increases, the total net work output also increases. For the liquid metal turbine inlet temperature of 500 °C, the total net work output of the binary cycle for cesium and mercury as liquid metal is calculated to be 1705.65 kJ/kg and 100.22 kJ/kg, respectively. For the liquid metal turbine inlet temperature of 550 °C, the total net work output of the binary cycle for cesium and mercury as liquid metal is calculated to...
be 1740.29 kJ/kg and 104.84 kJ/kg, respectively. There is not much of a difference between the total net work output of systems at different liquid metal turbine inlet temperatures. The total net work output versus liquid metal condensing pressure is illustrated in Figure 7.

As seen in Figure 7, the total net work output of the binary cycle using cesium is higher than the system using mercury at every value of the condensing pressure. As the condensation pressure of the liquid metal increases, the total net work output decreases. For the liquid metal condensing pressure of 7 kPa, the total net work output of the binary cycle is for cesium and mercury as liquid metal calculated to be 1740.29 kJ/kg and 104.84 kJ/kg, respectively. For the liquid metal condensing pressure of 11 kPa, the total net work output of the binary cycle for cesium and mercury as liquid metal is calculated to be 1721.90 kJ/kg and 102.64 kJ/kg, respectively. There is not much difference between the total net work output of systems at different liquid metal condensing pressure. However, the difference between the total net work output obtained from the liquid metal fluids used in the cycles is very large. If higher net power is desired, cesium should be used instead of mercury.

The energy supplied to the liquid metal versus liquid metal turbine inlet temperature is illustrated in Figure 8.

As seen in Figure 8, the energy supplied to the liquid metal using cesium is higher than that of the system using mercury at every value of the turbine inlet temperature. The difference is very large. If higher net power is desired, cesium should be used instead of mercury.

The total net work output versus liquid metal condensing pressure is illustrated in Figure 9.

![Figure 7. Total net work output versus liquid metal condensing pressure.](image)

![Figure 8. Energy supplied to the liquid metal versus liquid metal turbine inlet temperature.](image)
As seen in Figure 8, the energy supplied to the liquid metal using cesium is higher than the system using mercury at every value of the turbine inlet temperature. As the turbine inlet temperature of the liquid metal increases, the energy supplied to the liquid metal also increases. For the liquid metal turbine inlet temperature of 500 °C, the energy supplied to the liquid metal of the binary cycle for cesium and mercury is calculated to be 6570.97 kJ/kg and 323.34 kJ/kg, respectively. For the liquid metal turbine inlet temperature of 550 °C, the energy supplied to the liquid metal of the binary cycle for cesium and mercury is calculated to be 6609.97 kJ/kg and 328.54 kJ/kg, respectively. There is not much difference between the energy supplied to the liquid metal systems at different liquid metal turbine inlet temperatures.

The energy supplied to the liquid metal versus liquid metal condensing pressure is illustrated in Figure 9.

As seen in Figure 9, the energy supplied to the liquid metal using cesium is higher than the system using mercury at every value of the condensing pressure. As the condensation pressure of the liquid metal increases, the energy supplied to the liquid metal decreases. For the liquid metal condensing pressure of 7 kPa, the energy supplied to the liquid metal of the binary cycle for cesium and mercury is calculated to be 6609.97 kJ/kg and 328.55 kJ/kg, respectively. For the liquid metal condensing pressure of 11 kPa, the energy supplied to the liquid metal of the binary cycle for cesium and mercury is calculated to be 6602.66 kJ/kg and 325.58 kJ/kg, respectively. There is not much of a difference between the energy supplied to the liquid metal systems at different liquid metal condensing pressures. However, the difference between the energies obtained from different liquid metal fluids used in the cycles is very large.

The binary exergy efficiency versus liquid metal condensing pressure is illustrated in Figure 10.

As seen in Figure 10, the exergy efficiency of the binary cycle using mercury is higher than the cycle using cesium at every value of liquid metal condensation pressure. As the condensation pressure of the liquid metal increased, the exergy efficiency of the binary cycle decreased. For the liquid metal condensing pressure of 7 kPa, the exergy efficiency of the binary cycle for cesium and mercury is calculated to be 47.96%, and the exergy efficiency of cesium is 39.57%. For the liquid metal condensing pressure of 11 kPa, the exergy efficiency of the binary cycle for cesium and mercury is calculated to be 47.38% and 39.19%, respectively.
The binary exergy efficiency versus liquid metal condensing pressure is illustrated in Figure 10.

As seen in Figure 10, the exergy efficiency of the binary cycle using mercury is higher than the cycle using cesium at every value of liquid metal turbine inlet temperature. As the turbine inlet temperature of the liquid metal increased, the exergy efficiency of the binary cycle also increased. For the liquid metal turbine inlet temperature of 500 °C, the exergy efficiency of the binary cycle for cesium and mercury is calculated to be 46.58% and the exergy efficiency of cesium is 39.01%. For the liquid metal turbine inlet temperature of 550 °C, the exergy efficiency of the binary cycle for cesium and mercury system is calculated to be 47.96% and 39.57%, respectively.

5. Conclusions

In this study, a waste heat-driven liquid metal–water binary vapor power plant onboard a ship is designed and thermodynamically analyzed. The waste heat onboard the

Figure 10. Binary exergy efficiency versus liquid metal condensing pressure.

Figure 11. Binary exergy efficiency versus liquid metal turbine inlet temperature.
ship is the exhaust gas of the LM2500 marine gas turbine. Mercury and cesium are selected as liquid metals in the topping cycle while water is used in the bottoming cycle in binary power plants.

This study shows the following:

(1) binary cycle thermal efficiency of 26.32% and 31.91% for cesium and mercury, respectively, depending on liquid metal condensing pressure, and

(2) binary cycle thermal efficiency of 25.9% and 30.9% for cesium and mercury, respectively, depending on liquid metal turbine inlet temperature are possible with marine engine waste heat-driven liquid metal–water binary vapor cycles.

Author Contributions: Investigation, H.K.; Formal analysis, C.E.; Methodology, H.K. and C.E.; Project administration, H.K.; Resources, C.E.; Validation, C.E.; Writing—Original Draft, H.K.; Writing—Review and Editing, C.E. All authors have read and agreed to the published version of the manuscript.

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