Waste Heat Recovery from Exhaust Gas and Cooling Water as Water Heater on Domestic System of a Cruise Ship 48 meters

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Abstract—Cruise ship is a ship used for recreational and entertainment purposes. As a means of vacation and entertainment, the design of this transportation requires more attention. The design of the ship itself must be able to make it comfortable for the passengers. One of them, to increase comfort for cruise ship passengers is by adding heating water to the domestic system. Will need a large amount of electrical energy if using an electric heater. While in the engine room there is exhaust heat that can be utilized. The purpose of this research is to plan the utilization of waste heat contained in the exhaust gas and cooling water system (high temperature) as a water heater on the domestic system. The method used is the analysis of calculations. From the results of the calculation analysis, it was found that the hot water requirements of this ship were 3409 liters/day and needed a heat 167.12 kJ/s to increase the water temperature from 25°C to 66°C. From the calculation results, the 50% load engine has a heat 469 kJ/s, 75% load engine has a heat 645 kJ/s, 80% load engine has a heat 729 kJ/s, 100% load engine has a heat 781 kJ/s, while in cooling water system (high temperature) has a heat 252 kJ/s. Tank insulation using glass wool with a thickness of 610 mm. While the insulation on the pipe uses glass wool with thickness 50 mm. By replacing the electric water heater by utilizing waste heat can minimize the cost up to Rp.245,211.833/day or Rp.7,356,355.008/month.

Keywords—Domestic system, waste heat recovery, water heater.

I. INTRODUCTION

The cruise ship is a ship that is used specifically for recreational and entertainment purposes. As a means of vacation and entertainment, the design of this transportation requires more attention. The design of the ship itself must be able to make it comfortable for the passengers. One of them, to increase comfort for cruise ship passengers is by adding heating water to the domestic system. In obtaining hot water on domestic systems on ships there are several ways by using electricity, gas, and solar power.

Electricity consumption for the operation of electric water heaters on ships requires a large amount of energy and costs are expensive. Whereas if using solar power the cost that must be spent is far more expensive than using an electric water heater.

While in the engine room there is waste heat formed from the engine and other components. At present day there are many technologies that utilize waste heat energy to be used as the turbocharger, refrigeration, and desalination. So to obtain hot water without using electric water heater and solar power, it is a planned system that exploits waste heat for a domestic system in a ship. By utilizing this waste heat indirectly we can reduce the need for electricity usage [1-4].

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Convection is the transfer of heat that occurs to a silent fluid to a fluid that flows, and vice versa which occurs due to differences in temperature.

3) Radiation
Radiation heat transfer can be said to be the process of transferring heat from one medium to another due to temperature differences without the need for intermediate media.

![Figure 1. Conduction](image1)

![Figure 2. Convection](image2)

![Figure 3. Radiation](image3)

C. Heat Exchanger
The heat exchanger is a device used to exchange heat between two fluids, both of which have different temperatures. In general, heat exchangers used in various applications, for example, are used as heating and air conditioning systems in homes, used as chemical processes and as power plants [11].

Heat transfer in a heat exchanger usually involves two heat transfer processes, namely convection in each liquid and conduction through a wall separating two liquids [12]. The heat transfer rate between two fluids in a heat exchanger depends on the amount of temperature difference that varies along the heat exchanger. The types of heat exchangers vary greatly and can be classified as follows [13-15]:

1) Number of streams
Most processes of heat transfer between fluids involve only two different types of fluid. Such as water with water, steam with water, steam with seawater, and so forth

2) Transfer Process
According to the transfer process, the heat exchanger is divided into two, namely direct contact and indirect contact. The definition of direct contact itself is the transfer of heat
transferred between the cold fluid and hot fluid through direct contact, between these fluids there is no dividing wall. While the understanding of indirect contact heat transfer process between these two fluids is limited by a dividing wall. Hot fluids and cold fluids flow simultaneously while heat energy is transferred through the separation wall.

4) Heat transfer mechanism
Basically, the heat transfer mechanism is used to transfer heat energy from the fluid that is on one side of the heat exchanger to the separation wall. There are several types of heat transfer mechanisms, namely:

3) Construction geometry
The geometry of construction for the heat exchanger is divided into three types, namely tubular, plate, and extended surfaces.

4) Heat transfer mechanism
Basically, the heat transfer mechanism is used to transfer heat energy from the fluid that is on one side of the heat exchanger to the separation wall. There are several types of heat transfer mechanisms, namely:

5) Flow settings
Based on the flow, heat exchangers can be divided into three types, namely Parallel flow, Counterflow, and Crossflow. The definition of parallel flow is where working fluids in the heat exchanger flow parallel and have the same flow direction between fluid one with the other fluid. While the notion of counterflow where the fluids flowing in the heat exchanger has the direction of the flow opposite between one fluid with another fluid. Crossflow two fluids flowing in this type of heat exchanger have perpendicular or crossing directions.

6) Compact surface
The next classification of heat exchangers is based on the area of the contact area between inter-fluid heat transfer. The parameters used in this classification are the large unit surface area of contact in each heat exchanger volume. The more surface area of the contact area of heat transfer per unit volume, the greater the heat transfer efficiency obtained. But this must also pay attention to the type of working fluid used. The greater the particle content in the fluid, the lower the need for the surface area of the heat transfer contact area in the heat exchanger.

D. Selection of Heat Exchanger
There are many criteria in choosing a heat exchanger, but the main criteria are the type of fluid that must be handled, operating pressure and temperature, heat energy, and cost. While the fluid involved in heat transfer can be categorized into temperature, pressure, phase, physical properties, toxicity, corrosivity, and fouling tendency. The operating conditions for heat exchangers vary in a very wide range, and a broad spectrum of requests is imposed for their design and performance. All of this must be considered when assessing the type of unit to be used. When choosing a heat exchanger the following points must be considered [14].

1. Construction material
2. Pressure and temperature during operation
3. Flow rate
4. Flow arrays
5. Parameters for the effectiveness of heat and pressure drop
6. Fouling
7. Type and phase of the fluid
8. Maintenance, inspection, cleaning, and repair
9. Overall costs
10. Fabrication techniques
11. Applications

E. Calculation of Heat Exchanger
The research method is based on the following calculations [11, 12]:

1) Heat duty
To find out the amount of heat that can be transferred from hot fluids to cold fluids in a heat exchanger, calculations are carried out based on the following equation.

\[ Q = m_h C_p \] .......................................................... (1)

2) LMTD (Log Mean Temperature Difference)
To calculate the average temperature of a fluid flowing in a heat exchanger can be calculated by the following equation.

\[ \text{LMTD} = \frac{(\text{th} - \text{tc})}{\ln \frac{\text{th}}{\text{tc}}} \] ........................................... (2)

3) Caloric temperature
Is the temperature that corresponds to each stream or stream. Calorific temperature can be calculated by the following equation. For hot fluids
\[ T_c = T_2 + Fc (T_1 - T_2) \] ........................................... (3)
For cold fluids
\[ T_c = t_1 + Fc (t_2 - t_1) \] ........................................... (4)

4) Flow area
Flow area is the area passed by each fluid and can be calculated by the following equation.
For hot fluids
\[ as = (IDt.CB) / (144 Pt) \] ........................................... (5)
For cold fluids
\[ at = (NLt.At) / (144 n) \] ........................................... (6)

5) Mass velocity
That is the mass velocity of each fluid, which can be calculated by the following equation.
For hot fluids
\[ Gs = ms / at \] ...................................................... (7)
For cold fluids
\[ Gt = mt / at \] ...................................................... (8)

6) Reynold number
For hot fluids
\[ Re = (DGs) / \mu \] ............................................. (9)
For cold fluids
\[ Ret = (Drt.Gt) / \mu \] ............................................ (10)

7) Dimension factor for a heat exchanger (JH)
To determine the dimension factor can be seen in the diagram.

8) Prandtl Number (Pr)
Prandtl numbers can be calculated by the following equation.
\[ Pr = (Cp.M) / K \] ............................................ (11)

9) Heat transfer coefficient
The heat transfer coefficient can be calculated using the following equation.
\[ h_i = \Delta H \times K / IDt \times Pr_1 / 3 \] .................................. (12)

10) The temperature on the tube wall
The temperature on the tube wall can be calculated using the following equation.
\[ tw = tc + (h / \phi S) / (hio / \phi t + ho / \phi S) (Tc - tc) \] ................................ (13)
\[ hio / \phi t = (hio / \phi t x IDt) / \phi ODt \] ............................. (14)

11) Fluid viscosity ratio
The viscosity ratio of the fluid can be calculated using the following equation.
On the shell side and tube side
\[ \phi s = \mu / (\mu w) \] ............................................ (15)

12) The corrected heat transfer coefficient
The corrected heat transfer coefficient can be calculated using the following equation.
On the tube side
\[ hi = \phi t x \Delta H x K / IDt \times Pr_1 / 3 \] .............................. (16)
On the wall tube
\[ hio = \phi t + (hi / \phi t x ODt) / ODt \] ............................ (17)
On the shell side wall
\[ ho = \phi s x \Delta H x K / De \times Pr_1 / 3 \] ............................ (18)

13) Clean overall coefficient
The clean overall coefficient is that the heat transfer conductors in the heat exchanger are clean, clean overall can be calculated using the following equation.
\[ Ud = Q / (Nt.La” LMTD) \] ........................................ (19)

14) Fouling Factor / dirty factor
Fouling factors are obstacles to heat transfer due to the presence of deposits in the heat exchanger. Fouling factors are influenced by several things including fluid type, temperature, tube material, and flow velocity during operation.
\[ Rd = (Uc-Ud) / (Uc.Ud) \] ........................................ (20)

15) Pressure drop
Pressure drop is the maximum reduction in pressure allowed in a heat exchanger when a fluid passes through it. The pressure drop will be greater if the value of the fouling factor increases, the pressure drop can be calculated using the following equation.
\[ \Delta Ps = (FGs \times (N + 1)) / (5.22 x 10^10 \times Dc.SG \phi s) \] ...(21)

F. Domestic System
Domestic system is a system that aims to serve the needs of fresh water and sea water for the passengers of the ship during the voyage. Domestic systems are used in some rooms for example:
1. Bathroom
2. Washing place
3. Kitchen
In the domestic system is divided into 2 systems, namely the fresh water supply system, and seawater supply system, where the components of the system are as follows:
1. Sea chest is a place for the entry of seawater for the needs of a seawater supply system on board.
2. Seawater pump functions to move sea water from sea chest to hydrophore.
3. Seawater hydrophore is a place to store seawater before being distributed for domestic purposes on a ship.
4. Freshwater tanks are a place to store fresh water on a ship.
5. Freshwater pump a tool used to move fresh water from the fresh water tank to hydrophore.
6. Freshwater hydrophore is a place to store fresh water before being distributed for domestic system needs.

III. RESULT AND DISCUSSION

A. Data collection
Data collection for this research is the main dimension, the specifications of the engine on the 48-meter cruise ship, the need for fresh water for the domestic system on a 48-meter cruise ship.

1) Main Dimension
- LOA : 48,34 m
- LWL : 43,34 m
- LPP : 42,59 m
- BREADTH : 7,80 m
- HEIGH : 15,11 m
- DRAFT : 1,80 m
- VS : 16 Knot

2) Machinery
- Main Marine Engine : 3 x 1340 KW YANMAR 12
- AYM-WGT. Table 1 is data for load main engine.
Table 1.
FLOWRATE AND TEMPERATURE EXHAUST GAS

| Load (%) | Temperature (°C) | Flow rate (kg/s) | Q (kJ/s) |
|----------|-----------------|-----------------|--------|
| 100      | 323             | 2.3             | 781    |
| 80       | 330             | 2.1             | 729    |
| 75       | 340             | 1.8             | 645    |
| 50       | 358             | 1.2             | 469    |

Cooling Water System (HT)

Based on data from the project guide, it is known that the energy that can be used in the cooling water system (HT) is 252 kW or 252 kJ/s

Amount of fresh water

Data for ship fresh water tank are:
- Freshwater tank portside: 5000 liters
- Freshwater tank starboard: 5000 liters

From the data above, it can be seen that the total volume of 10000 liters of fresh water 60-85% will become domestic liquid waste. 75% of domestic liquid waste is gray water.

Then the statement can be used as a reference for freshwater needs where:

Domestic waste volume = 85% x 10000 liters
= 8500 liters
Gray water = 75% x 8500 liters
= 6880 liters

So that the gray water (freshwater) needed by the ship for per day (for 45 hours or 2 days) is 6880 liters divided by 2. So that freshwater needs are also worth the same, namely 3440 liters per day.

As for the temperature of hot water needed can be seen at MSN 1884 Merchant Shipping Notice (M). So that the mass of warm water needed is as follows:
- Hot water mass = vol. of water x density (66°C)
- Hot water mass = 3440 x 0.991 kg / l
- Hot water mass = 3409 kg / day
= 142 kg / h

B. Heat Exchanger Calculations Result

Table 2 until table 4 are calculation result for a heat exchanger in the domestic system.

Table 2.
HEAT EXCHANGER DESIGN DATA

| Parameter | Notation | Unit | Shell | Tube |
|-----------|----------|------|-------|------|
| Outside diameter | OD | inch | 15.25 | OD |
| Inside diameter | ID | inch | ID | 1 |
| Number of baffles | N | unit | 4 |
| Number of passes | n | unit | 2 |
| Type of fluid | BWG | | Gas | Water |
| Distance between tube | C | inch | 1.25 |
| Tube length | L | ft | 8 |
| Number of tubes | Nt | unit | 68 |
| Distance between baffle | B | inch | 3.05 |

Table 3.
HEAT EXCHANGER CALCULATION

| Parameter | Unit | Shell | Tube |
|-----------|------|-------|------|
| Heat balance | BTU/hr | 22310 | 22310 |
| LMTD | F | 484.5 |
| Caloric temperature | F |
| Flow area | ft² | 0.085 | 0.060 |
| Mass velocity | lb/hr.ft² | 12235.3 | 5250 |
| Reynold number | 14002 | 2883 |
| Heat transfer factor | 50 | 7 |
| Specific heat | 0.8 |
| Heat transfer coefficient | BTU/hr.ft²°F | 30 | 688.5 |
| Clean overall coefficient (Uc) | BTU/hr.ft²°F | 43.4 |
| Design overall coefficient (UD) | BTU/hr.ft²°F | 35 |
| Fouling factor (RF) | 0.005 |
| Max fouling factor | - |
| Pressure drop | psi | 1.6 | 3.4 |
| Max pressure drop | psi | 2 | 10 |
### TABLE 4.

#### HEAT EXCHANGER OPERATING CONDITION

| Parameter               | Unit  | Shell | Notation | Dimension | Tube | Notation | Dimension |
|-------------------------|-------|-------|----------|-----------|------|----------|-----------|
| Flowrate                | lb/hr | W     | W1040    | w         | 315  |          |           |
| Inlet temperature       | F     | T1    | 676      | t1        | 77   |          |           |
| Outlet temperature      | F     | T2    | 583      | t2        | 151  |          |           |
| Temperature different   | F     |       | 93       |           | 74   |          |           |
| Max pressure drop       | psi   |       | 2        |           | 10   |          |           |

C. **Tank Insulation**

In determining the thickness of the insulation the author uses the Jimmy Kumana and Samir Khotari methods in the *Predict Storage Tank Precisely* Heat Transfer paper. Table 5 until table 9 are calculation result in water tank and insulation.

### TABLE 5.

#### TANK SPECIFICATION

| Fouling Coefficient Assumption  | Value | Unit     |
|---------------------------------|-------|----------|
| Drywall (hFd)                   | 700   | BTU/ft² h°F |
| Wet wall (hFw)                  | 550   | BTU/ft² h°F |
| Roof (hFr)                      | 700   | BTU/ft² h°F |
| Bootom (hFb)                    | 550   | BTU/ft² h°F |

| Thermal conductivity           | Value | Unit     |
|--------------------------------|-------|----------|
| Galvanized steel (kJ)          | 24.5  | BTU/ft² h°F |
| Glasswool insulation (kI)      | 0.029 | BTU/ft² h°F |
| Material thickness (tM)        | 0.02  | ft       |
| Insulation thickness (tI)      | 0.2   | ft       |

| Surface emissivity             | Value | |
|--------------------------------|-------|---|
| Wall and roof                  | 0.8   | |

| Temperature                    | Value | Unit |
|--------------------------------|-------|------|
| Steam in a tank (TV)           | 144   | F    |
| Water in a tank (TL)           | 151   | F    |
| Environment (TA)               | 95    | F    |

| Size of tank                   | Value | Unit |
|--------------------------------|-------|------|
| Diameter (D)                   | 1.96  | ft   |
| The height of tank (L)         | 3.93  | ft   |
| The height of water (Lw)       | 2.64  | ft   |

| Physical properties            | Value (water) | Unit |
|--------------------------------|---------------|------|
| Density                        | 61.19         | lb/ft³ |
| Specific heat                  | 1             | BTU/ft² h°F |
| Viscosity                      | 2.733         | lb/ft h |
| Coefficient of volume metric expansion | 0.00028 | /F |

| Physical properties            | Value (steam) | Unit |
|--------------------------------|---------------|------|
| Density                        | 0.062         | lb/ft³ |
| Specific heat                  | 0.234         | BTU/ft² h°F |
| Viscosity                      | 0.12          | lb/ft h |
| Coefficient of volume metric expansion | 0.002 | /F |
### Table 6. Area of Each Wall

| Wall          | Area (ft²) |
|---------------|------------|
| Drywall (Ad)  | 1.58       |
| Wet wall (Aw) | 38.25      |
| Roof (Ar)     | 11.4       |
| Bottom (Ab)   | 16.33      |
| Total         | 67.56      |

### Table 7. Total Coefficient Heat Loss

| Coefficient | Drywall | Wet wall | Roof | Bottom |
|-------------|---------|----------|------|--------|
| hVw         | 0.3618  | -        | -    | -      |
| hLw         | -       | 1.449    | -    | -      |
| hVr         | -       | -        | 0.2035 | -  |
| hLb         | -       | -        | -    | 17.66  |
| hAr         | -       | -        | 9.18 | -      |
| hAw         | 955.6   | 955.6    | 955.6 | 955.6  |
| hM          | 1225.5  | 1226.5   | 1227.5 | 1228.5 |
| hI          | 0.1445  | 1.1445   | -    | -      |
| hF          | 700     | 550      | 700  | 550    |
| hR          | 0.964   | 1.054    | 0.964 | 1.054  |
| 1/U         | 9.6875  | 7.4449   | 11.8358 | 7.023 |
| U           | 0.1032  | 0.1343   | 0.0845 | 0.1424 |

### Table 8. Temperature Correction of Each Wall

| Wall      | Temperature (F) |
|-----------|-----------------|
| Tws drywall | 100.05          |
| Tw drywall  | 135.74          |
| Tws wet wall | 100.07          |
| Tw wet wall  | 147.96          |
| Tws roof    | 100.02          |
| Tw roof     | 129.28          |
| Tws bottom  | 100.01          |
| Tw bottom   | 148.43          |

### Table 9. Heat Loss that Occurs on the Tank

| Wall    | U (Btu/ft² h F) | A (ft²) | q (Btu/h) |
|---------|----------------|---------|-----------|
| Dry wall| 0.1032         | 1.58    | 10.21     |
| Wet wall| 0.1343         | 38.25   | 287.67    |
| Roof    | 0.0845         | 11.4    | 47.2      |
| Bottom  | 0.1424         | 16.33   | 118.6     |
| Total   | 67.56          |         | 463.68    |
1) Heat loss (24 hours)

\[
\text{Heat loss} = \text{total Q} \times 24 \\
= 463.68 \times 24 \\
= 11128.32 \text{ Btu/day} \\
= 11128.32 \times 1.055 \\
= 11740.38 \text{ kJ/hr}
\]

\[
\Delta T = \text{Initial temperature - Final temperature} \\
= 66 - 0.86 = 65.14 \text{ C}
\]

Final temperature = 66 - 2.84 = 63.16 C

2) Temperature after 24 hours

\[
Q = m \times c \times \Delta T \\
= 3409 \text{ kg/day} \times 4.2 \text{ kJ/kg C} \\
= 14268.8 \text{ kJ/day}
\]

\[
\Delta T = Q / (m \times c) \\
= 11740.38 / (3409 \times 4.2) = 2.84
\]

\[
\text{Final temperature} = 66 - 2.84 = 63.16 \text{ C}
\]

D. Pipe Insulation

To find out the amount of heat loss in the pipe can be calculated using the equation written by Z. K. Moray, D. D. Gvozdenac in the Applied Industrial Energy and Environmental Management.

1) Required data:
   - Outside insulation diameter (D3) = 50 mm
   - Pipe outside diameter (D2) = 25A = 0.034 m
   - Pipe material = copper
   - Insulation material = glasswool
   - Thermal insulation conductivity (k_in) = 0.05 W / m°C
   - Insulation heat transfer coefficient (h_out) = 6.5 W / m2°C
   - The temperature of fluid in the pipe (T_in) = 660°C
   - Ambient temperature (T_out) = 25°C

2) The overall heat transfer coefficient

\[
U = \frac{1}{2.05} + \frac{1}{h_out} \\
= \frac{1}{2.05} + \frac{1}{6.5} = 5.31 \text{ W/m²°C}
\]

3) Heat loss per one meter of insulated pipe

\[
Q / L = \pi \times D3 \times U \times (T_in - T_out) \\
= 3.14 \times 0.05 \times 5.31 (66 - 25) \\
= 34.18 \text{ W} \\
= 123048 \text{ J/hr}
\]

4) Heat loss (24 hours)

\[
\text{Heat loss} = Q / L \times 24 \text{ hours} \\
= 123048 \times 24 \\
= 2953152 \text{ J} \\
= 2953.15 \text{ kJ}
\]

5) Temperature after 24 hours

\[
Q = m \times c \times \Delta T \\
m = 3409 \text{ kg/day} \\
c = 4.2 \text{ kJ/kg C} \\
\Delta T = Q / (m \times c)
\]

\[
\Delta T = 2953.15 / (3409 \times 4.2) = 0.86 \text{ C}
\]

\[
\text{Initial temperature} = 66 \text{ C} \\
\Delta T = \text{Initial temperature - Final temperature} \\
= 66 - 0.86 = 65.14 \text{ C}
\]

E. Cost Analysis

From the previous calculations obtained the heat requirements needed to heat water from a temperature of 250°C - 660°C which is equal to 587029.8 kJ / day. With a heat of 587029.8 kJ / day, it can be converted into kWh, where 1 kWh is equal to 1 kJ / s so that the value is 167.12 kWh. Of these values can be calculated the costs required.

Heat needed = 587029.8 kJ / day

Price of Electricity Industry per kWh = Rp. 1467.28

Usage Operating Costs = Rp. 245,211,833 per day

Based on the calculations above it can be concluded that by utilizing waste heat as a substitute for electric water heater can minimize costs of Rp. 245,211,833 per day or Rp. 7,356,355,008 per month.

IV. CONCLUSION

Based on the results of calculations from data analysis in utilizing waste heat like a heater (water heater) for domestic systems, it can be summarized as follows:

1) Fresh water needed for the supply of hot water in the domestic system is 3409 Kg/day and requires heat of 167.12 kJ / s to increase the temperature from 25°C to 66°C.

2) From the calculation results, the heat output from the exhaust gas is 469 kJ / s when the engine loads 50%, 645kJ / s when the engine loads 75%, 729 kJ / s when the engine loads 80% and 781 kJ / s from the 100% load engine. While the heat generated in cooling water (HT) is 252 kJ / s.

3) From the calculation results that have been planned, the heat exchanger used is shell and tube type with the following specifications Shell outer diameter 15.25 in, number of baffle 4, number of pass on shell side 1, while inner diameter on tube side 1 in, number of pass on tube side 2, distance between tubes 1.25in, length of tube 8 ft, number of tubes 68, and distance between baffles 3.05 in.

4) Tank insulation thickness of 0.2 ft or 610 mm using glass wool material, within 24 hours the temperature of fresh water drops to 63.16°C. While the insulation of the pipe is 50 mm with glass wool material, the temperature in 24 hours drops from 66 to 65.14°C.

5) By utilizing waste heat as a substitute for an electric water heater for domestic needs on a 48-meter cruise ship, it can minimize the expenditure of Rp.
245,211,833 per day or Rp. 7,356,355,008 per month.

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