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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 25ºC to 66ºC. 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 heat waste 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 wasted 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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II. METHOD

A. Waste Heat

Waste heat recovery is one example of energy savings which aims to improve the efficiency of fuel use. In diesel engines, there are 3 main heat sources that can be utilized, including exhaust heat generated from jacket water, exhaust gas, and also from cooling water [1-4]. Factors affecting Waste Heat Recovery as follows:

1) Heat Quantity
   Heat quantity is the amount of heat energy contained in waste heat.
2) Waste Heat Temperature
   Waste heat temperature is a factor that determines whether the temperature of the exhaust heat can be utilized.
3) Waste Stream Composition
   Waste stream composition is a chemical content found in waste heat, which can affect the material and recovery process.
4) Minimum allowable temperature limit

B. Heat Transfer

Heat transfer is the process of transferring heat or heat caused by temperature differences. Where heat will move from high temperatures to lower temperatures. This transfer process will continue until there is a temperature balance in both media [5-10]. The process of heat transfer can be divided into three, namely as follows:

1) Conduction
   Conduction heat transfer is heat transfer that occurs on a solid medium, or on a silent fluid. Conduction occurs due to temperature differences between one surface and another on the media.
2) Convection

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.

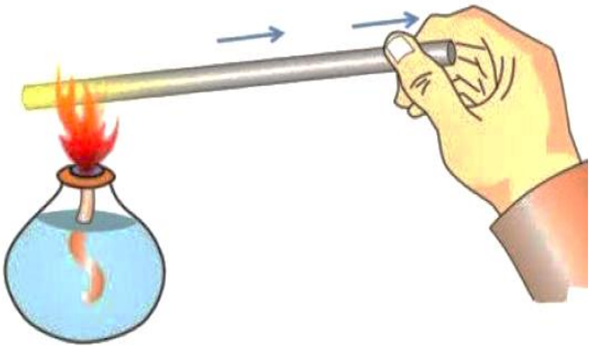

Figure. 1. Conduction

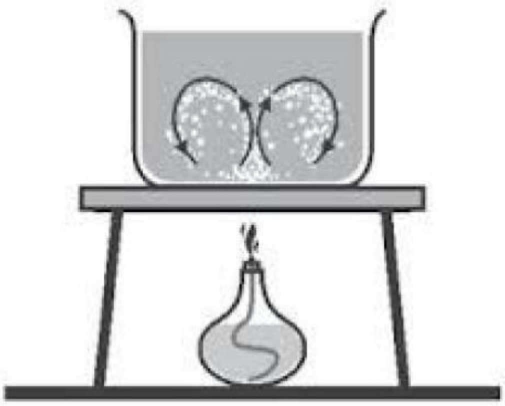

Figure. 2. Convection

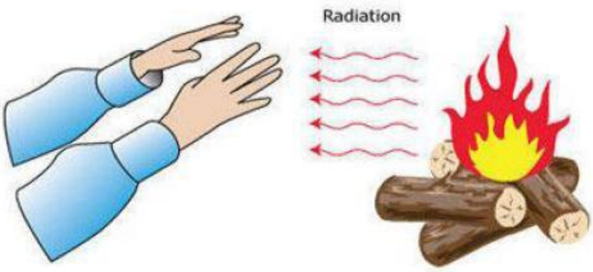

Figure. 3. Radiation

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 sea water, 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.

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:

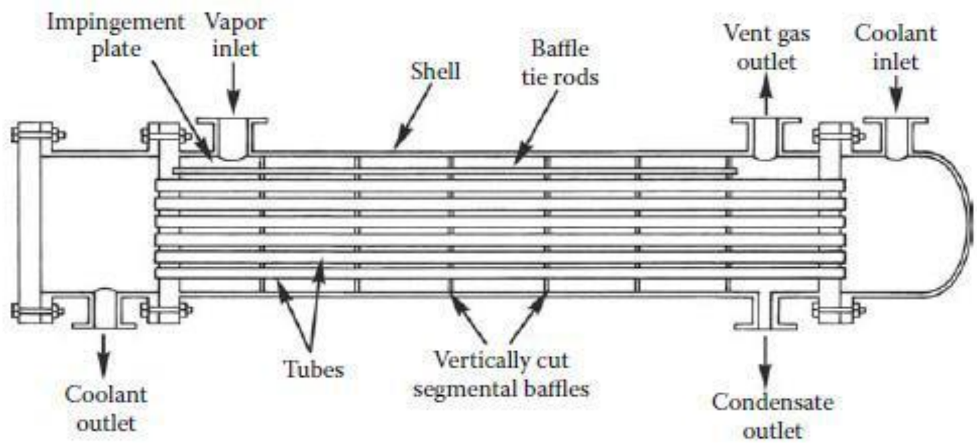

Figure. 4. Shell and tube

1. Single phase convection on both sides.
2. Single phase convection on one side, the other two-phase convection on phase.
3. Two-phase convection on both sides.

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.

LMTD = (th- tc) / (ln th / tc).......................... (2)

3) Caloric temperature

Is the temperature that corresponds to each stream or stream. Caloric temperature can be calculated by the following equation. For hot fluids

Tc = T2 + Fc (T1 - T2) ....(3)

For cold fluids

Tc = t1 + Fc (t2 - t1) ....(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 = (IDs.CB) / (144 Pt) .... (5)

For cold fluids

at = (Nt.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 / as .... (7)

For cold fluids

Gt = mt / at .... (8)

6) Reynold number

For hot fluids

Res = (De.GS) / μ .... (9)

For cold fluids

Ret = (IDt.Gt) / μ .... (10)

7) Dimension factor for a heat exchanger (JH)

To determine the dimensional 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.

hi / Øt = ∂H x K / IDt Pr1 / 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 / $_{\varphi}$S) / (hio / $_{\varphi}$t + ho / $_{\varphi}$S) (Tc - tc) ....(13)

hio / Øt = (hio / Øt x IDt) / ØtODt .... (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

$_{\varphi}$s = μ / (μw) .... (15)

12) The corrected heat transfer coefficient

The corrected heat transfer coefficient can be calculated using the following equation.

On the tube side

hi = Øt x ∂H x K / IDt Pr1 / 3 ....(16)

On the tube wall

hio = Øt + (hi / Øt x ODt) / ODt .... (17)

On the shell side wall

ho = Øs x ∂H x K / De Pr1 / 3 .... (18)

13) Clean overall coefficient

The clean overall coefficient is that the heat transfer conductors in the heat exchanger are clean, clean overalls can be calculated using the following equation.

Ud = Qt / (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.

ΔPs = (f.Gs ^ 2 (N + 1)) / (5.22 x 〖10〗 ^ 10.Dc.SG Øs) ….(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 pumps 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 (ºC)**	**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

3) 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

4) 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 (66^0C)
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	**Shell**			**Tube**		
	Notation	**Unit**	**Dimension**	**Notation**	**Unit**	**Dimension**
Outside diameter	OD	inch	15.25	OD		
Inside diameter	ID	inch		ID	l	
Number of baffles	N	unit	4			
Number of passes	n	unit	1			2
Type of fluid			Gas			Water
BWG			13			
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	ft^2	0.085	0.060
Mass velocity	$lb/hr.ft^2$	12235.3	5250
Reynold number		14002	2883
Heat transfer factor		50	7
Specific heat		0.8	
Heat transfer coefficient	$BTU/hr.ft^2$ F	30	688.5
Clean overall coefficient (Uc)	$BTU/hr.ft^2$ F		43.4
Design overall coefficient (UD)	$BTU/hr.ft^2$ 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		Tube	
		Notation	Dimension	Notation	Dimension
Flowrate	lb/hr	W	1040	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/ft^2 h F
Wet wall (hFw)	550	BTU/ft^2 h F
Roof (hFr)	700	BTU/ft^2 h F
Bootom (hFb)	550	BTU/ft^2 h F
Thermal conductivity	**Value**	**Unit**
Galvanized steel (kM)	24.5	BTU/ft^2 h F
Glasswool insulation (kI)	0.029	BTU/ft^2 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/ft^3
Specific heat	1	BTU/ft^2 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/ft^3
Specific heat	0.234	BTU/ft^2 h F
Viscosity	0.12	lb/ft h
Coefficient of volume metric expansion	0.002	/F

TABLE. 6.
AREA OF EACH WALL

Wall	Area (ft^2)
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/ft^2 h F)	A (ft^2)	q (Btu/h)
Dry wall	0.1032	1.58	10.21
Wett 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)

Heat loss = total Q x 24
= 463.68 x 24
= 11128.32 Btu / day
= 11128.32 x 1.055
= 11740.38 kJ / hr

2) Temperature after 24 hours

Q = m x c x ΔT
m = 3409 kg / day
c = 4.2 kJ / kg C

ΔT = Q / (m x c)
= 11740.38 / (3409x 4.2) = 2.84

C Initial temperature = 66 C

ΔT = Initial temperature - Final temperature
2.84 = 66 - Final temperature
Final temperature = 66 - 2.84 = 63.16 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 (kin) = 0.05 W / m C
- Insulation heat transfer coefficient (hout) = 6.5 W / m2 C
- The temperature of fluid in the pipe (Tin) = 660C
- Ambient temperature (Tout)=250C

2) The overall heat transfer coefficient

$$U = \frac{1}{\frac{D3 \ln\left(\frac{D3}{D2}\right)}{2.kin} + \frac{1}{hout}}$$

$$= \frac{1}{\frac{0.05 \ln\left(\frac{0.05}{0.034}\right)}{2.0.05} + \frac{1}{6.5}} = 5.31 \text{ W/m}^2 \text{ C}$$

3) Heat loss per one meter of insulated pipe Q / L = π.D3.U (Tin – Tout)
= 3.14 x 0.05 x 5.31 (66 - 25)
= 34.18 W
= 123048 J / hr

4) Heat loss (24 hours)

Heat loss = Q / L x 24 hours
= 123048 x 24
= 2953152 J
= 2953.15 kJ

5) Temperature after 24 hours

Q = m x c x ΔT
m= 3409 kg / day
c= 4.2 kJ / kg C
ΔT = Q / (m x c)
= 2953.15 / (3409x 4.2) =0.86^{0}C

Initial temperature = 66 C

ΔT = Initial temperature - Final temperature
0.86 = 66 - Final temperature
Final temperature = 66 - 0.86 = 65.14 C

E. Cost Analysist

From the previous calculations obtained the heat requirements needed to heat water from a temperature of 250C - 660C 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
= 167.12 kWh

Price of Electricity Industry per kWh = Rp. 1467.28

Usage Operating Costs = Rp. 245,211,833 per day
= Rp. 7,356,355,008 per month
= Rp. 88,276,260,096 per year

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^{0}C to 66^{0}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^{0}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^{0}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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