

Heat Loss and Cost Reduction of Insulation Materials on Geothermal Pipes

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ABSTRACT

Power plant in X field has 6 production wells with steam dominated reservoir type. Fluid flowing in pipe from the well to the plant experienced heat loss that occurred due to difference in the temperature of the flowing steam and the outside that caused heat transfer from inside the pipe to the outside. Minimizing heat transfer can be done by using an insulator installed on the outside of the pipe, in this case, Foamglas W+F Insulation. The method to assess the heat loss is by calculating material properties as well as fluid properties to determine heat transfer rate for one well as representation of all wells. From the calculation, it can be concluded that the use of Foamglas W+F Insulation material provides reduction in heat loss of 113,61 kWh for one well with significant reduction in costs of 1.035 billion IDR per well per year. By comparing the heat loss reduction value which is almost the same, the option to replace the materials to Foamglas W+F insulation material is cheaper than adding the existing insulation thickness.

Keywords: heat loss; geothermal; surface facilities

I. INTRODUCTION

Geothermal is one of the largest sources of low-cost energy in many regions in Indonesia. This is due to the fact that Indonesian territory is located in vicinity of the colliding plates of the earth. Geothermal fluid is generally used as a power plant which is used to rotate generators in turbines. Geothermal energy potential that is produced by Indonesia reaches around 29,000 MW with potential resources of 13440 MW and reserves of 14,473 MW spread across 265 locations throughout Indonesia. Of this potential, 4% or 1,189 MW of energy has been utilized for power generation with the largest installed capacity in West Java, which is 1057 MW (20% of reserves), followed by Central Java 60 MW, North Sulawesi 60 MW and North Sumatra 12 MW (ESDM, 2015).

The flowing fluid in pipe on its way from the geothermal well to the plant will experience heat loss. This heat loss occurs due to the temperature difference of flowing steam and temperature of outside air, so that heat transfer will occur from the pipe to outside. Heat loss can also cause condensation in pipe, and can reduce fluid pressure which can reduce turbine efficiency.

Theoretically, thicker insulation in pipe will make smaller heat loss, resulting in good heat delivery and electricity generation. However, the insulator cost is getting bigger and less economical. In terms of cost, the thinner the insulation installed on the pipe, the cheaper the cost will be. Of course, it still does not consider to the aspect of environmental safety. The thinner the insulation, the higher the pipe wall temperature and it is not safe for the environment.

The objectives of this research are to determine the total heat loss along the steam pipe which supply the power plant. From the value of the lost of opportunities due to the total heat loss of the steam pipe using old materials, the new material is introduced and is assessed whether it can be more economical.

The assumptions used for calculation and data analysis in order to make it easier to carry out calculations, are calculation of heat loss in a steady state, using the one-dimensional (1D) heat transfer method. The pipe configuration is considered to be entirely horizontal cylinder. For a vertical cylinder pipe, it can be thought of as a vertical flat plate. Fluid flow in the pipe is considered fully developed. The surface temperature of the outer pipe is 40 °C. The air temperature around the power plant is 20 °C with RH ranging from 70% - 80%. The air velocity around the steam pipe is considered to be uniform at 3 m/s.

II. METHODS

2.1. Pipe Heat Loss

Heat loss is heat that is wasted into the environment due to several factors, such as poor pipe insulation, high pipe surface temperature, pipe material and pipe insulation selection, thickness of insulation, etc. High heat loss of pipe pressure can lead to high pressure drop, so at steam pipe will have a lot of steam turns into condensate. In addition, the

temperature around the environment will gradually increase over time if heat loss is large enough that can disrupt natural ecosystems. From this heat loss pipe too, a power plant can experience loss potential steam to make electricity, so that the electric power generated cannot be maximized. The section of the steam pipe is a cylinder which can be seen in Figure 1.

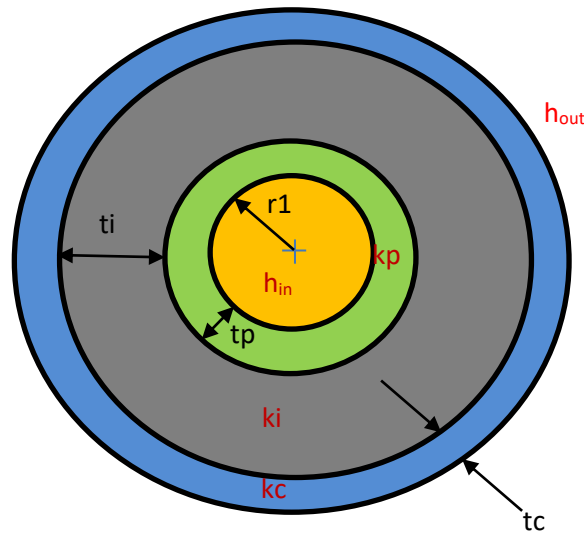


Figure 1. Steam Pipe Section

In conduction in pipe cylinders to reduce heat flux, an insulating material has a large thermal conductivity is needed so the thermal resistance is large. The basic principle calculating pipe heat loss to calculate thermal resistance each layer or layer of a pipe, which usually consists of:

- Convection thermal resistance ($R_{th,conv}$), for the flow in pipe which is considered to moving which naturally transfers heat by convection and for the flow outside the pipe (both forced convection and / or free convection) by first looking at the comparison between the values Gr_D dan Re_D .
- Thermal conduction resistance ($R_{th,cond}$), for pipe thickness layer, insulation layer, and insulation cover layer.

After calculating thermal resistance, then we can calculate how much heat loss from the pipe, which is also based on the temperature difference function. The equations for this heat loss:

$$q_{loss,total} = \frac{\Delta T}{R_{th,total}} = \frac{T_{\infty,in} - T_{\infty,out}}{R_{th,total}} \quad (1)$$

If radiation factor is not neglected, heat loss due to radiation must also calculated using following equation :

$$q_{loss \text{ by radiation}} = \varepsilon \sigma A_s (T_s^4 - T_{surr}^4) \quad (2)$$

- ε = emissivity factor of an object,
- σ = Stefan-Boltzman constant ($5,67 \times 10^{-8} \text{ m}^2\text{-K}^4/\text{W}$)
- A_s = pipe area [m^2],
- T_s = pipe surface temperature [K]
- T_{surr} = temperature around pipe [K]

Another impact of the heat loss is pressure drop, which results in phase change from steam to condensate (liquid) therefore mass flow rate entering the turbine to produce electricity is reduced. Equation in calculating the mass flow rate of steam that turns into condensate:

$$\Delta \dot{m} = \frac{q_{loss}}{h_{fg}} \quad (3)$$

The h_{fg} value is obtained from Refprop with the state level that is reviewed only in header, which is temperature and pressure, because the header is a place where all the mass flow rates of steam from each production well are

accumulated. From the calculation of the mass flow rate of the condensate, the amount of electrical energy that the steam should generate can also be calculated. The equation for calculating the electrical power that should be generated is as follows

$$\Delta \dot{W} = \Delta \dot{m} \times (h_1 - h_2) \quad (4)$$

h_1 = enthalpy of steam enters to turbine [kJ/kg],

h_2 = enthalpy of steam out from turbine [kJ/kg]

2.2. Loss of Revenue (Loss of Opportunities)

Loss of opportunities is a very important factor in seeing amount of loss experienced by a generator due to loss factors, one of which is heat loss. As previously explained, heat loss can reduce the amount of mass of steam that should enter the generator to drive the turbine, but it is reduced due to a part of which is condensed, which also causes a reduction in the electrical power that can be generated. The reduction in electric power can cause income losses which are calculated based on the value of the electricity price per unit kWh. The similarities are as follows:

$$LO = \Delta \dot{W} \times \text{electricity price} \quad (5)$$

III. RESULTS AND DISCUSSION

Based on piping and instrumentation diagram (PID) of power plant, there are 6 (six) geothermal wells that supply generation unit plus one header as the accumulation of steam from the six wells, but the calculation is done for one well as representation of other wells. Properties of pipe material, pipe insulation, and fluids will be explained as follows :

3.1. Pipe Material Physical Properties

Data on the physical properties of materials for pipes and the type of pipe material used in the power plant can be seen at Table 1.

Table 1. General Physical Properties of Steam Pipes

Type of Material	Schedule	Thermal Conductivity, k
Low Carbon Steel / Plain Carbon	40	60,5 W/m-K

Based on the API standard Pipe Table [3], it can be seen that pipe thickness, pipe diameter, and others have been converted into international units (SI). The amount and value of pipes for each production well can be seen in Table 2, while the pipe insulation material specification of Foamglas W+F Insulation material can be seen in

Table 3.

Table 2. Steam Pipe Specifications from each production well

Parameter	NPS [m]	Do [m]	t [m]	Di [m]	L [m]
Well 1	0,30	0,32	0,02	0,30	850

Table 3. Pipe Insulation Material Specifications and Pipe Insulation Covers

Insulation Material	Calcium Silicate
k, Isolation [W/m-K]	0,075
Insulation thickness [m]	0,05
Cover Material	Aluminium
k, cover	200
Thick cover [m]	0,002
Emissivity, ε	0,05

3.2. Fluid Properties Data

Based on P&ID and PFD of the power plant it can also be seen that physical properties of vapor fluid, such as vapor mass rate, temperature, pressure and others at each state level can be seen in Table 4. The value of the fluid properties can be seen in Table 5 for each production well, while for air properties it can be seen in

Table 6.

Table 4. Level of Steam State of Each Production Well

Param	m dot steam [kg/s]	Temp. Steam [°C]	Steam Pressure [bara]	Temp. Pipe Cover [°C]	Temp. Air [°C]	Temp. Film [K]
Well 1	23,36	185	11,14	40	20	303

Table 5. Physical Properties of Vapor Fluid

Param	ρ [kg/m ³]	μ [$\cdot 10^{-05}$ Pa-s]	ν [$\cdot 10^{-06}$ m ² /s]	Pr	k_f [W/m-K]
Well 1	5,73	1,5	2,6	1,12	0,04

Table 6. Physical Properties of Air at a Certain State

Air rate [m/s]	3
Temp. Film [oC]	303
β [K-1]	0,0033
air pressure [bara]	0,8
ρ [kg/m ³]	0,95
μ [Pa-s]	1,82E-05
ν [m ² /s]	1,9E-05
k_f [W/m-K]	0,0263
Pr	0,707

From data in Table 1 to Table 6, the next step is processing of these data. The calculation of these data is to calculate how much total heat loss of steam pipe in good or normal conditions. Here are some calculations made to calculate heat loss.

3.3. Calculation of Reynold's Number (Re)

Based on data in Table 5 and Table 6 using equation (6),

$$Re_D = \frac{\rho u_{\infty} D}{\mu} = \frac{4\dot{m}}{\pi D \mu} \quad (6)$$

where:

ρ is the density of the fluid

u is the flow speed

L is a characteristic linear dimension

μ is the dynamic viscosity of the fluid

ν is the kinematic viscosity of the fluid

It can be calculated the Reynold number for steam and ambient air. Reynold's calculation is useful for knowing type of flow of fluid, whether laminar or turbulent. The following are the results of calculating the Reynold number for each steam in six wells and air which can be seen in Table 7 for steam and Table 8 for air.

Table 7. Steam Reynold Number (Steam)

Well	Re	Flow Type
Well 1	$6,5 \cdot 10^6$	Turbulent

Table 8. Reynold Number of Ambient Air

Well	Re _D
Well 1	$6,7 \cdot 10^4$

3.4. Comparison of Reynold and Grashof Numbers

In free convection, a new number is known to replace the Reynolds number, which is the Grashof number (Gr), because the Reynolds number can only be used for forced convection in and out of pipes. The equation of the Grashof number for pipes is:

$$Gr_D = \frac{g\beta(T_s - T_\infty)D^3}{\nu^2} \quad (7)$$

where:

- g = gravitational acceleration due to Earth
- β = the coefficient of thermal expansion
- T_s = the surface temperature
- T_∞ = the bulk temperature
- L = the vertical length
- D = the diameter
- ν = the kinematic viscosity

Calculation of heat transfer by convection for cases of combined effects between free and forced convection must be considered, therefore several conditions are made to facilitate calculations, including:

- If $Gr_D/Re_D^2 \approx 1$, then both free and forced convection must be considered and calculated
- If $Gr_D/Re_D^2 \ll 1$ then free convection can be neglected
- Jika $Gr_D/Re_D^2 \gg 1$, then forced convection can be neglected

Based on theoretical on free convection, which states that the results of Reynold's calculation (Re, D) must be compared with the Grashof number (Gr, D), so that it can be seen what type of convection is dominant (Smith, 2013). However, it is necessary to calculate the Grashof number (Gr, D) beforehand. The results of the calculation of the Grashof number and the results of its comparison with the Reynold number can be seen in **Table 9**.

Table 9. Ratio of Grashof Number and Reynold Number

Well	Re _D	Gr _D	Gr _D /Re _D ²	Remarks
Well 1	$6,7 \cdot 10^4$	$1,4 \cdot 10^8$	0,031	Free convection neglected

From Table 9 it is known that the dominant convection that occurs between the steam pipe and the air is forced convection because the symptoms are less than one. Due to forced convection, to calculate the Nusselt number, we can directly use Equation 9 below:

$$Nu_D = \frac{h.L}{k} \quad (8)$$

where,

- h = coefficient of convection heat transfer, W/m² k
- L = length, m
- k = material conductivity, W/m K

3.5. Nusselt Number Calculation

After calculating the Reynolds number in Table 3.7 and Table 3.8, it is known that the type of flow in the pipe is turbulent with the assumption of fully developed, so the equation used must be the equation for turbulent flow, which are equation (7) for flow in the pipe (internal flow) and equation (9) for forced convection flow. Based on Hamdan (2018), if the flow is laminar, then $Nu = 3.66$, and if the flow is turbulent then

$$Nu = 0.023Re^{0.8}Pr^{0.3} \quad (10)$$

where,

Re = Reynolds Number

Pr = Prandtl Number

The results of calculating the Nusselt number (Nu_D) can be seen in Table 10.

Table 10. Nusselt Number Result

Param	Nu_D inside	Nu_D outside
Well 1	6779,1	184,3

3.6. Calculation of Convection Coefficient (\bar{h})

Based on the calculation of the Nusselt number in Table 10, the value of the convection coefficient (h) can be calculated, both inside and outside the pipe flow. The results of the calculation of the convection coefficient can be seen in Table 11.

Table 11. Convection Coefficient

Coefficient	[W/m ² -K]	[W/m ² -K]
Well 1	1662,5	22,7

3.7. Calculation of Thermal Resistance (R_{th})

Before calculating pipe heat loss, it is necessary to calculate the thermal resistance of a pipe which can be said to be composite or layered with different thermal conductivities. The calculation of thermal resistance is divided into 2 types, namely thermal resistance due to conduction ($R_{th,cond}$) and thermal resistance due to convection ($R_{th,conv}$). The results of the calculation of the thermal resistance can be seen in Table 12.

Table 12. Thermal Resistance

R_{th}	R1 = $R_{th,conv}$ [K/W]	R2 = $R_{th,cond}$ [K/W]	R3 = $R_{th,cond}$ [K/W]	R4 = $R_{th,cond}$ [K/W]	R5 = $R_{th,conv}$ [K/W]	$R_{th, total}$ [K/W]
Well 1	$7,4 \times 10^{-7}$	$2,0 \times 10^{-7}$	$6,7 \times 10^{-4}$	$8,8 \times 10^{-9}$	$3,9 \times 10^{-5}$	$7,1 \times 10^{-4}$

3.8. Calculation of Heat Loss (q_{loss})

Based on the results of the calculation of thermal resistance in Table 12, the calculation of heat loss can be carried out where the calculated heat loss still ignores the radiation factor. The results of calculating heat loss along the pipe without radiation effects can be seen in Table 13

Table 13. Heat Loss without Radiation

Well	Heat loss [kW]
Well 1	231,7

with a total heat loss of each steam pipe is 231.7 kW (without radiation effect).

If the effects of radiation are considered, according to equation (2), the results of calculating heat loss due to radiation can be seen in Table 14.

Table 14. Heat Loss due to Radiation

Well	Heat loss [kW]
Well 1	7,2

with a total heat loss due to radiation is 7,2 kW.

From the results of the calculation of heat loss in both Table 13 and Table 14, where the radiation factor is considered, the result of the sum of the two total heat loss values is 238,9 kW. The percentage of the radiation effect on total heat loss is 3%.

As a result of the heat loss, some of the condensed steam mass becomes liquid, so that the steam entering the turbine will also be reduced. The equation for calculating how much steam turns into condensate ($\Delta\dot{m}$) is in accordance with equation (3).

$$\Delta\dot{m} = \frac{q_{loss}}{h_{fg}} \quad (9)$$

with the h_{fg} value on the T and P header: 1983.9 kJ/kg, so the equation becomes:

$$\Delta\dot{m} = \frac{238,9 \text{ kW}}{1983,9 \text{ kJ/kg}}$$

$$\Delta\dot{m} = 0,12 \frac{\text{kg}}{\text{s}}$$

Based on the calculation of the mass rate of condensed steam ($\Delta\dot{m}$), the amount of electricity that cannot be generated ($\Delta\dot{W}$) can also be calculated due to the reduction of the mass of steam into condensate. The calculation is in accordance with equation (4), which is:

$$\Delta\dot{W} = \Delta\dot{m} \times (h_1 - h_2) \quad (10)$$

where the enthalpy values of each state level are known from the P&ID of the power plant:

$$h_1 = 2761.3 \text{ kJ/kg}$$

$$h_2 = 2220.4 \text{ kJ/kg}$$

assuming losses at the state level before entering the turbine are ignored, the calculation is: $\Delta\dot{W} = 0,12 \frac{\text{kg}}{\text{s}} \times (2761,3 - 2220,4) \frac{\text{kJ}}{\text{kg}}$

$$\Delta\dot{W} = 113,61 \text{ kW} = 0,113 \text{ MW}$$

3.9. Calculation of Loss of Opportunities

Based on the calculation of the loss of electric power due to steam condensation, the loss of revenue for the generator can also be calculated. The electric power that seems "wasted" is then multiplied by the price of electricity so that the result of calculating the loss of the generator is obtained. According to PLN, the current electricity price is 8 cents USD/kWh or IDR 1,040 per kWh. In accordance with equation (2.20), the calculation results are:

$$\text{Loss of Opportunities} = \Delta W \times \text{electricity price}$$

$$\text{Loss of Opportunities} = 113,61 \text{ kWh} \times \text{IDR } 1040 /\text{kWh}$$

$$\text{Loss of Opportunities} = \text{IDR } 118,154 \text{ per hour}$$

If we want to find out per day, we only need to multiply it by 24 hours to become IDR 2,835,705 per day. If we want per year, we only have to multiply it by 24x365 assuming the plant is fully operational within a year without experiencing an overhaul, so it becomes IDR 1,035,032,544 per year.

IV. CONCLUSION

It can be concluded from the calculation above that The use of Foamglas W+F Insulation material provides a significant reduction in costs and with considerable reduction in heat loss.

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