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The Chimney Heat Potential to be Converted into Electrical Energy with Thermoelectric Generator: Dimensionless Analysis

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ABSTRACT

The gas-steam power plant combines a gas power plant and a steam power plant, where Heat Recovery Steam Generator (HRSG) is a unit for generating steam. The waste heat from this system is channelled to the chimney with a Thermoelectric Generator (TEG) module to generate electrical energy. TEG uses the waste heat from the thermal conduction process from the chimney wall, where the height, diameter, and velocity variables are considered for analysis. To optimize this analysis, we used dimensional analysis to get a laboratory-scale system, and the method used the matrix dimensionless of the balance energy equation. As a result of the investigation, the calculation of chimney heat potential is obtained; the condition temperature will increase when velocity increases and the value of diameter and height decrease, then there is have an error about 14% from laboratory-scale design of chimney.

1. Introduction

There is an energy crisis in several countries, it will seriously impact daily life and economic activity. Therefore, many countries are changing their energy policies in a way that does not depend on fossil energy sources and starting to utilize the available renewable energy such as bioenergy, wind energy, solar energy, and others [1-4]. Indonesia has much renewable energy sources (RES), where PV energy is more potential as an electrical power source, and the residual energy is mostly neglected [5].

Residual energy utilization is a solution to increase the efficiency of the energy source, and a Gas-Steam Power Plant (GSPP) produces hot steam that produces waste thermal energy from the chimney's wall of the HRSG (Heat Recovery Steam Generator). Thermoelectric Generator (TEG) module is a proper solution to overcome the residual heat of the HRSG process on the chimney's wall, and this heat can be converted into electricity.

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Other researchers applied TEG to the waste heat dissipation, presenting 60-65% wasted in automotive engines [6]. TEG is mounted on exhaust surfaces and the results show an increase in thermal efficiency but non-uniform temperature across the TEG module, which affects the performance of the TEG module [7]. The same research has been carried out by researchers regarding the applications of this TEG module by utilizing the waste heat from the engine block [8]. Almost all TEG research is applied to the small components to facilitate the installation process, collect data on power output or efficiency, and determine cooling methods [9-11]. An unknown scaling method in heat exchanger chimney studies by utilizing waste heat using TEG modules was carried out [12,13].

Incorrect scaling will affect the actual experiment size results, there are some researchers have used modeling and numerical study using the Pi-Buckingham theorem for scaling, such as modeling the heat load for an air-conditioned room, or investigation the effect of surface roughness on wet steam flow [14,15]. This study is a preliminary research of waste heat utilization on the HRSG chimney wall, which focus on the mathematical modelling of laboratory-scale with dimensionless analysis using Pi-Buckingham theorem to determine the heat output, efficiency and cooling methods on TEG installation.

2. Method and Dimensional Analysis

The research method is descriptive analysis, starting with a survey of the field on the industrial power plant GSPP, then continuing for analyzing dimensions with laboratory-scale test equipment. Buckingham's pi theory is the basis of dimensional analysis, the dimensions are expressed in these dimensions. The basic dimension is length (L), and the area is symbolized as (L^2). The second basic dimension is time as (T), and the magnitude of speed is symbolized by (LT^{-1}). The third basic dimension of mass is (M), the density is symbolized by (ML^{-3}), mass flow is symbolized by (MT^{-1}), and temperature is (θ) [16,17].

According to the system schematic shown in Figure 1, we assume the dimensionless analysis used the energy balance equation, as shown in Eq. (1) below.

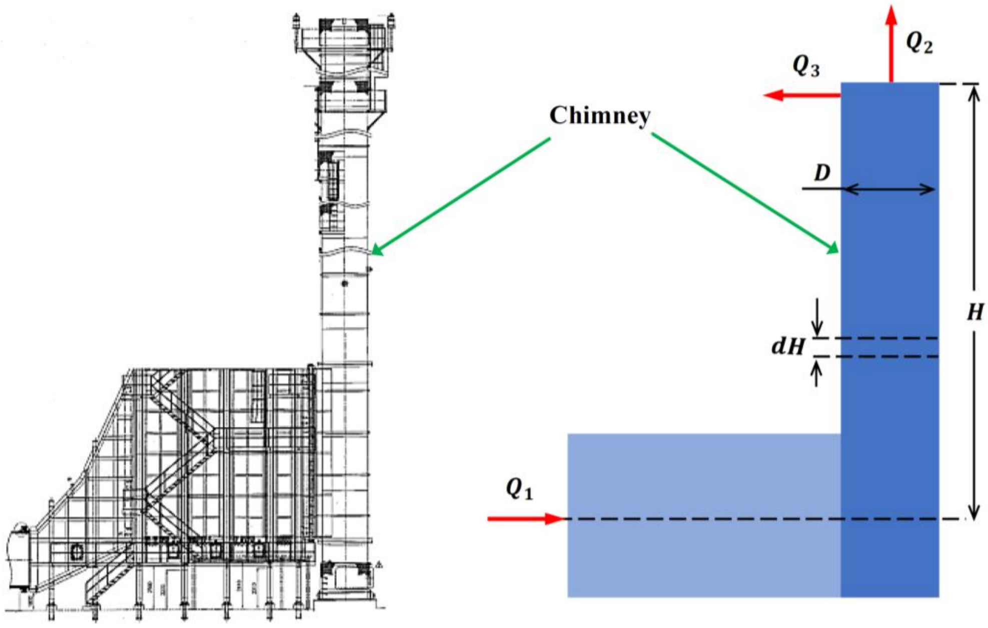


Fig. 1. Dimensionless analysis schematic of the steam chimney

$$Q_1 = Q_2 + Q_3 \tag{1}$$

The value Q_1 is the input heat that enters the plant chimney from the residual heat source of the HRSG. The value Q_2 is the heat out of the chimney and Q_3 the residual heat in the wall. H is denoted as the height of the chimney and D is the diameter of the chimney [18,19].

$$Q_1 = \dot{m}_2 \cdot c_p \cdot T_{out} - k \cdot A \cdot \frac{\Delta T}{\Delta x} \tag{2}$$

$$Q_1 = \dot{m}_2 \cdot c_p \cdot T_{out} - k \cdot (\pi D H) \cdot \frac{(T_s - T_a)}{\Delta x} \tag{3}$$

where T_s is the wall temperature of the system, T_a is the ambient temperature, and T_{out} is the outside temperature of the system.

$$T_s = T_{out} \tag{4}$$

We assumed the value of T_s is equal to $T_s = T_{out}$, where the value of the $dH = H$ at the chimney's peak.

$$Q_1 = Q_2 - k \cdot (\pi D H) \cdot \frac{(\Delta T)}{\Delta x} \tag{5}$$

The list variables of the dimensionless equation

$$Q_1, Q_2, k, D, H, \Delta T, \Delta x \tag{6}$$

where

$$Q_1 = \dot{m}_1 \cdot c_p \cdot T_{in} \tag{7}$$

$$Q_2 = \dot{m}_2 \cdot c_p \cdot T_{out} \tag{8}$$

$$\Delta T = T_s - T_{out} \tag{9}$$

k is the thermal conductivity, the temperature difference ΔT, and Δx the chimney's thickness. After all list variables are determined in Eq. (6), then continue to define the dimensional matrix as shown in Table 1.

Table 1
Dimensional matrix

Dimensional	Q_1	Q_2	k	D	H	ΔT	Δx
M	1	1	1	0	0	0	0
L	2	2	1	1	1	0	1
T	-3	-3	-3	0	0	0	0
θ	0	0	-1	0	0	1	0

Then the formation of matrix two non-dimensional groups on Eq. (10) to (13).

$$\begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 2 & 2 & 1 & 1 & 1 & 0 & 1 \\ -3 & -3 & -3 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} a & h \\ b & i \\ c & j \\ d & k \\ e & l \\ f & m \\ g & n \end{bmatrix} = [0] \tag{10}$$

For calculation π_1

$$\pi_1 = \frac{b}{a} = \frac{Q_2}{Q_1} \tag{11}$$

According to the balance energy equation $Q_1 > Q_2$

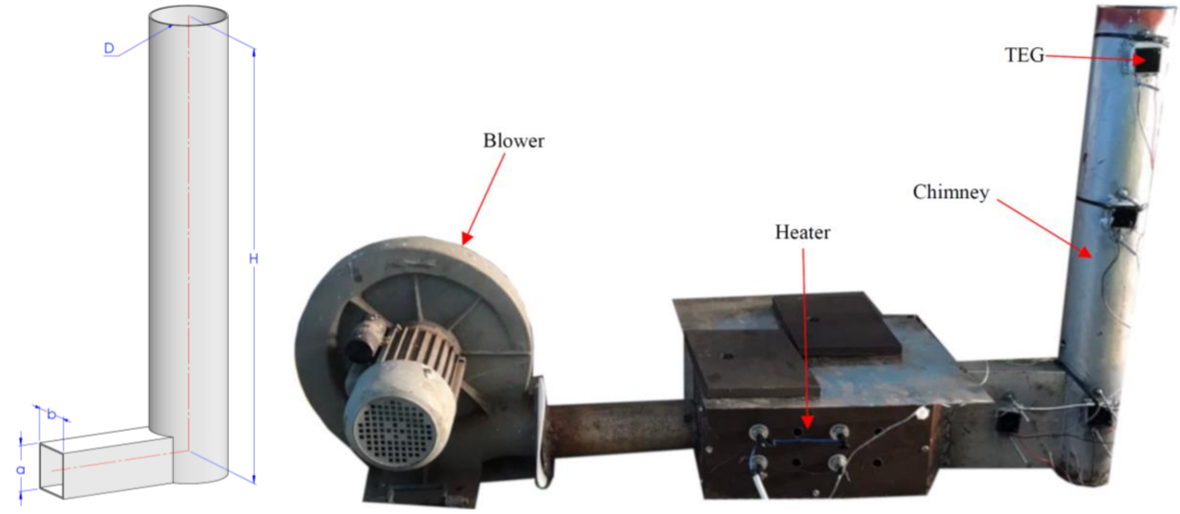
$$0 < \frac{Q_2}{Q_1} < 1 \tag{12}$$

For calculation π_2

$$\pi_2 = \frac{j \cdot k \cdot l \cdot m}{i \cdot n} = \frac{kDH}{Q_2} \cdot \frac{\Delta T}{\Delta x} \tag{13}$$

Based on the field survey, the chimney height is 40 m, the chimney diameter is 2.6 m, the chimney exit temperature is 118 °C, the thermal conductivity is 46 W/m.K and the hot air mass flow rate is 83.2 kg/s.

As shown in Figure 2(a), the laboratory scale dimension of HRSG with diameter 4 inches, a = 201.4 mm, and b = 40 mm, then the value of H is from the dimensionless calculation. The experiment setup is depicted in Figure 2(b), the HRSG chimney used a black iron pipe with thermal conductivity from 26-37.5 W/m.K, where the TEG is attached to the outer wall, then a blower to produce inlet velocity and a heater to produce inlet temperature. More details on the experimental parameter setup values are given in Table 2 below.



(a) (b)

Fig. 2. Laboratory scale of HRSG chimney (a) Dimension parameters (b) Experimental setup

Table 2
Comparison of the actual size HRSG chimney and laboratory scale size

Parameters	Actual size	Laboratory scale size
Height (m)	36.05	0.765
Diameter (m)	26	0.1143
Thickness (m)	0.05	0.002
Inlet area (m^2)	23.750	0.008
Outlet area (m^2)	2.042	0.090
Thermal Conductivity (W/m.K)	46	31.7
Inlet velocity (m/s)	2.86	1.2
Inlet temperature (°C)	300	100
Outlet temperature (°C)	118	-
Ambient temperature (°C)	27	-

In Table 2, the value of the outlet and ambient temperature will be obtained in the experimental result and will be compared with the actual size in the dimensionless calculation result.

3. Results

The result of the dimensionless energy balance calculation on the chimney shows a trend between π_1 and π_2, where the value π_2 will increase while the value π_1 decreases, as shown in Figure 3. The value π_1 is set from 0.1-1 because it Q_2 will not be greater than Q_1. The value Q_2 will decrease while through the chimney's wall as thermal conduction.

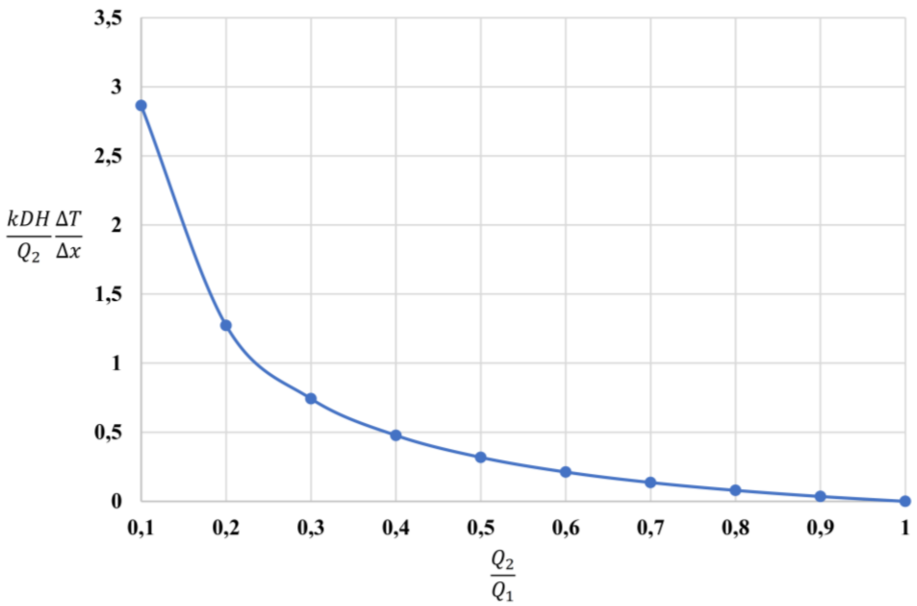


Fig. 3. Two non-dimensional groups π_1 and π_2 for the energy balance of the steam chimney

The value of π_1 has relation to the efficiency of output temperature, wall temperature and TEG power output, when π_1 increases will make the efficiency high and vice versa. Furthermore, for the calculation result of the output temperature is obtained from ΔT in π_2, where the T_{out} will be used in TEG as hot side and cold side from T_a with assisted by aluminum fins.

Figure 4 to Figure 6 shows the relation between π_1 and T_{out}, where temperature decreases when the π_1 increases, then the outlet temperature increases when the head of the chimney, outlet diameter, and inlet velocity decreases respectively. According to the experimental setup in Figure 2(b), the value of diameter is difficult to change because it has been determined from fabrication, but we can change the value of the chimney height (black iron pipe height) and inlet velocity from the blower.

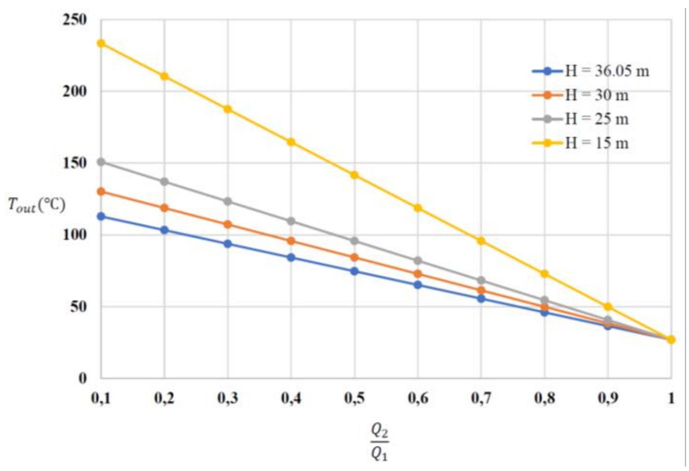


Fig. 4. Effect of height on the ratio π_1 and T_{out}

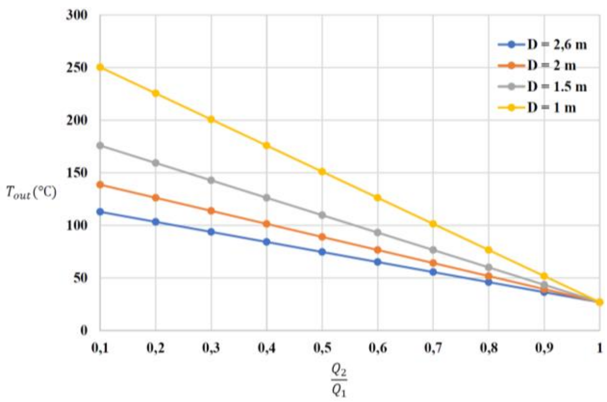


Fig. 5. Effect of diameter on the ratio π_1 and T_{out}

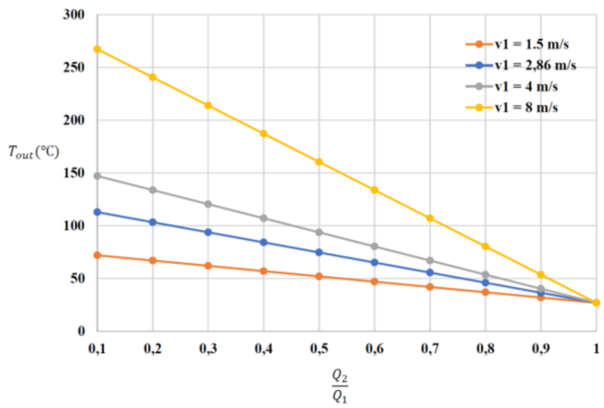


Fig. 6. Effect of velocity on the ratio π_1 and T_{out}

In Figure 7, the output temperature result of the experiment is obtained at 57°C and the ambient temperature is 31.6°C. The result π_1 of the laboratory-scale size is further from the actual size i.e., 0.53 and 0.39, and needs to recalculate the input velocity or height of the laboratory scale, but the output temperature of the laboratory scale is larger than the actual size.

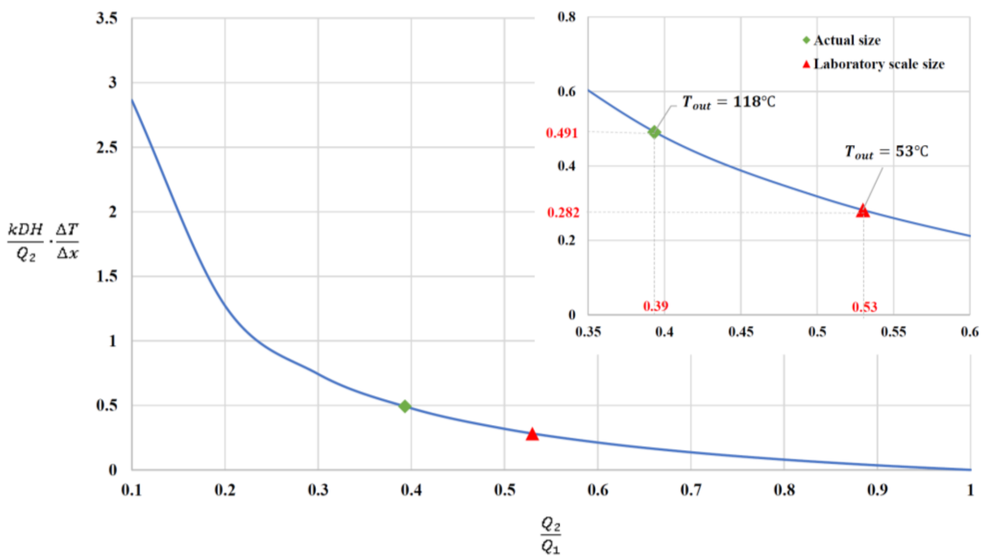


Fig. 7. The comparison results of the actual size HRSG chimney and laboratory scale size on dimensionless calculation

4. Conclusions

The calculation of chimney heat potential in HRSG using dimensionless analysis is obtained. The condition temperature will increase when velocity increases, and the value of diameter and height decrease—the π_1 is heat efficiency of the chimney (made in percentage). Then the π_2 can is considered as the ratio of Q_3 / Q_2 when added by π (phi) as thermal conduction. This dimensionless calculation of the laboratory has been close to the actual size prediction, but there is an error of about 14% from the laboratory-scale design of the chimney, and able to be continued in future studies.

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