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

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ABSTRACT

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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 (L²). 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.

\[ Q_1 = Q_2 + Q_3 \]  

(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].

$$Q_1 = \dot{m}_1 \cdot c_p \cdot T_{in} - k \cdot A \cdot \frac{\Delta T}{\Delta x}$$  \hspace{1cm} (2)

$$Q_3 = \dot{m}_2 \cdot c_p \cdot T_{out} - k \cdot (\pi DH) \cdot \frac{(T_s - T_a)}{\Delta x}$$  \hspace{1cm} (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.

$$T_s = T_{out}$$  \hspace{1cm} (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.

$$Q_i = Q_2 - k \cdot (\pi DH) \cdot \frac{(\Delta T)}{\Delta x}$$  \hspace{1cm} (5)

The list variables of the dimensionless equation

$$Q_1, Q_2, k, D, H, \Delta T, \Delta x$$  \hspace{1cm} (6)

where

$$Q_1 = \dot{m}_1 \cdot c_p \cdot T_{in}$$  \hspace{1cm} (7)

$$Q_2 = \dot{m}_2 \cdot c_p \cdot T_{out}$$  \hspace{1cm} (8)

$$\Delta T = T_s - T_{out}$$  \hspace{1cm} (9)

$k$ is the thermal conductivity, the temperature difference $\Delta T$, and $\Delta x$ 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>
<thead>
<tr>
<th>Dimensional matrix</th>
<th>$Q_1$</th>
<th>$Q_2$</th>
<th>$k$</th>
<th>$D$</th>
<th>$H$</th>
<th>$\Delta T$</th>
<th>$\Delta x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>L</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>T</td>
<td>-3</td>
<td>-3</td>
<td>-3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\theta$</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
Then the formation of matrix two non-dimensional groups on Eq. (10) to (13).

\[
\begin{bmatrix}
1 & 1 & 1 & 0 & 0 & 0 & 0 \\
2 & 2 & 1 & 1 & 1 & 0 & 1 \\
-3 & -3 & -3 & 0 & 0 & 0 & 0 \\
0 & 0 & -1 & 0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
a \\
b \\
c \\
d \\
e \\
f \\
g \\
h
\end{bmatrix}
= [0]
\] 

For calculation \( \pi_1 \)

\[
\pi_1 = \frac{b}{a} = \frac{Q_2}{Q_1}
\] 

According to the balance energy equation \( Q_1 > Q_2 \)

\[
0 < \frac{Q_2}{Q_1} < 1
\]

For calculation \( \pi_2 \)

\[
\pi_2 = \frac{j \cdot k \cdot l \cdot m}{i \cdot n} = \frac{kDH \cdot \Delta T}{Q_2 \cdot \Delta x}
\]

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.
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 $\pi_1$ and $\pi_2$, where the value $\pi_2$ will increase while the value $\pi_1$ decreases, as shown in Figure 3. The value $\pi_1$ 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 $\pi_1$ and $\pi_2$ for the energy balance of the steam chimney.

The value of $\pi_1$ has relation to the efficiency of output temperature, wall temperature and TEG power output, when $\pi_1$ increases will make the efficiency high and vice versa. Furthermore, for the calculation result of the output temperature is obtained from $\Delta T$ in $\pi_2$, 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 $\pi_1$ and $T_{out}$, where temperature decreases when the $\pi_1$ 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 $\pi_1$ 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 \( \pi_1 \) 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.

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 \( \pi_1 \) is heat efficiency of the chimney (made in percentage). Then the \( \pi_2 \) can is considered as the ratio of \( Q_3 / Q_2 \) when added by \( \pi \) (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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