A suitable heat duct shape for a thermoelectric generator cooling system

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Abstract

In this research, heat ducts of a gasifier system were designed for power generation from waste heat using the thermoelectric generator (TEG). The commonly used heat duct has a circular shape which is impossible to install a flat thermoelectric module (7×7 cm^2). Therefore, a heat duct has to be modified into a circular, a triangular and a square cross-sectional ducts. The cross-sectional area of these three geometries were A'=7.07 cm^2, 43.5 cm^2 and 100 cm^2 for a circular, a triangular and a square cross-sectional ducts, respectively. Power generation by using different heat duct shapes, effect of turbulent flow on the efficiency of heat transfer and directions of a cooling system were observed. In conclusion, a square cross-sectional duct is the most suitable shape for power generation using the thermoelectric devices. Even though temperatures along all duct shapes steadily decreased, the temperature profile of a square cross-sectional duct was more homogenous than the other shapes. Installation of a swirl core could create turbulent flow, increased the average temperature for approximately 16-22% compared with a heat duct without a swirl core. A counter flow of a water cooling system also created higher contrast of the temperatures on the surface of hot and cold sides compared with a parallel flow. These solutions can improve the efficiency of heat transfer inside a heat duct.

Keywords: *Thermoelectric generator (TEG), Heat duct, Duct shape, Water cooling system*

1. Introduction

Most of the biomass gasifier system uses a circular cross-sectional duct to deliver hot gas from a kiln to a cyclone unit. The synthetic gas of syngas has to be cooled by a water cooling system. To employ the benefits of temperature differences, the thermoelectric power generation system can be integrated into the original biomass gasifier system. Even though there is no any major modification, a suitable heat duct shape has to be designed since the commonly used heat duct has a circular shape which is impossible to install a flat thermoelectric module (7×7 cm^2). Therefore, a heat duct has to be modified into a circular, a triangular and a square cross-sectional duct.

This study has an objective to investigate power generation from waste heat of the biomass gasifier system by using the thermoelectric power generation. The three different duct shapes were designed in a circular, a triangular and square cross-sectional duct. The performances such as heat transfer and thermal conductivity of these ducts were observed. Installation of a wedge and a swirl core was operated to investigate whether which core can create turbulent flow. Flow directions of a water cooling system which are a counter and a parallel flow were considered. These solutions were studied to find the suitable conditions for power generation of the integration between the original biomass gasifier system and the additional thermoelectric power generation system.

2. Materials and methods

2.1 Gas flow in a pipe

Rough internal surface can increase flow resistance in a pipe. The smooth internal surface made of glass, copper, brass and ethylene contributes less resistant than a pipe made of concrete, steel and iron. In the case that the system requires a lot of turbulence, a pipe can be designed to have rough surface.

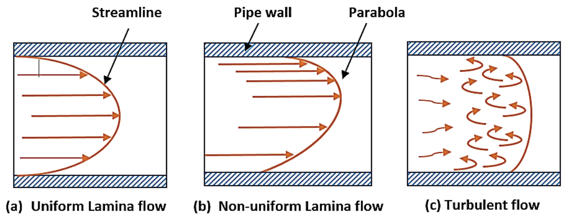


Figure 1. Types of flow in a pipe [1]

There are several types of flows inside a pipe as shown in the Figure 1. The internal surface of a pipe can create frictional forces that lower the velocity of the flow near the surface. Therefore, gas at the center of a pipe can flows at higher velocity. However, the rough internal surface of a pipe will not affect abrasion resistance in a case of high viscosity liquid. This phenomenon is known as laminar flow, which can be determined by the Reynolds's number (Re) [2].

2.2 Thermoelectric generator (TEG)

A thermoelectric device is a solid-state material that can convert thermal energy (temperature difference) into electricity. The thermoelectric effect was known as the Seebeck effect because it was discovered by Thomas Seebeck in 1821. The temperature differences between the hot and cold junction of the two dissimilar materials (P-type and N-type semiconductors) results in generating electric potential as shown in the Figure 2.

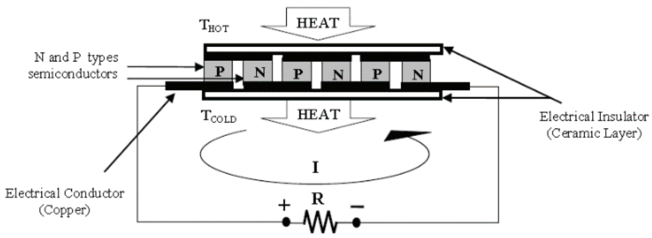


Figure 2. Power generation of a thermoelectric device [3]

In 1834, Jean Charles Athannase Peltier found that the electric current could be generated at the hot-cold junction of the two dissimilar metals. The proportionality constant is shown as the Peltier coefficient. Twenty years later, William Thomson proposed a comprehensive explanation of the Seebeck and Peltier effects, and described their inter-relationship through thermodynamics which is a phenomenon known as the thermoelectric effect. These three effects can describe as follows.

$$dE = \alpha(h\text{-}c)\ dT$$

$$dQ = \pi(h\text{-}c)\ dI$$

$$dQ = \beta(h\text{-}c)\ dI\ \partial T/\partial x\ dx$$

Where the Seebeck coefficient (α (h-c)), Peltier coefficient (π (h-c)), Thomson coefficient (β (h-c)), conductor length(x), electric current (I), electrical potential (E), hot-cold junction's temperature (h, c). [3]

In 1910, Altenkirch provided a theoretical explanation of the thermoelectric effect. In 1948 Loffe proposed a new theory. That was thermoelectric generating material needs to have a high Seebeck coefficient (α), high electrical conductivity (σ), and low thermal conductivity (κ). The efficiency of thermoelectric material is defined as shown in the Figure 3.

$$\text{Figure of merit } (Z) = (\alpha^2 \sigma)/k$$

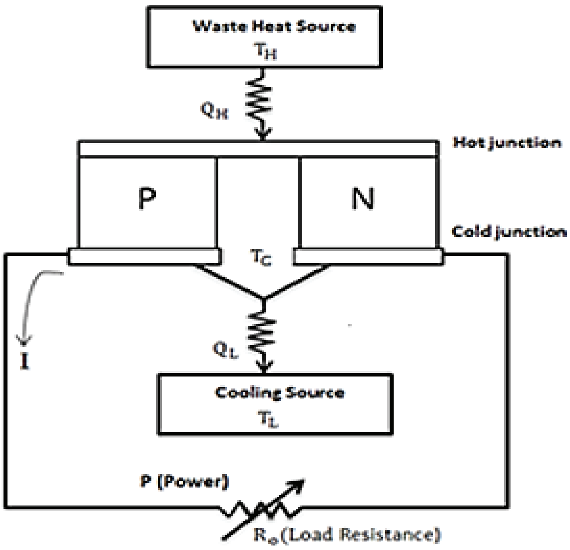


Figure 3. Schematic diagram shows basic concept of thermoelectric generation. [4]

3. Experimental setup

In this research, three different duct shapes which are a circular, a triangular and a square cross-sectional duct were designed. The performance of a thermoelectric power generation system, the effects of a turbulent flow on the efficiency of heat transfer and the effects of flow directions of a cooling system were observed in the experiment. The experimental setup and the operating procedures were described as follows.

3.1 Heat duct design and fabrication

The commonly used heat duct has a circular shape which is impossible to install a flat thermoelectric module (7×7 cm^2). Therefore, a heat duct has to be modified into a circular, a triangular and a square cross-sectional duct. In this experiment, a heat duct was design to have smooth surface and sufficient spaces for 5 thermoelectric devices.

The thermoelectric device model HZ-14 which requires 7×7 cm space was used in the experiment. To measure temperatures on surface of a heat duct at the positions where the thermoelectric devices will be installed as shown in the Table 1. The HZ-14 model is made from bismuth, telluride alloys and 98% of couple. The thermoelectric device requires a heat flux of about 8 Watt per cm^2, the temperature differences of 200˚C to convert 5% of the thermal energy into electricity. It can generate the maximum amounts of electricity at 13 Watt. When properly installed, it can operate for tens of thousands of hours [4]. The specification of the thermoelectric devices is shown in the Table 1.

Table 1 Characteristics of heat ducts

Duct type	Radius (cm.)	High (cm.)	Width (cm.)	Deep (cm.)	Long (cm.)	Volume (cm^3)	Cross-sectional area (cm^3)
1. Circular	1.5	-	-	-	40	282.8	7.07
2. Triangular	-	8.7	10	-	40	1750	43.5
4. Square	-	-	10	10	40	4000	100

To select a suitable material as shown in the Table 2 for the fabrication of heat ducts, thermal conductivity, corrosion resistance, heat resistance and price should be considered. In this study, carbon steel was selected, because it has the most suitable thermal conductivity and can withstand temperatures used in the experiments. Moreover, carbon steel is easy for fabrication and modification such as cutting, drilling, welding and bending.

Table 2 Thermal conductivity of metal. [7]

Material	Thermal conductivity (cal/sec)/(cm^2 C/cm)	Thermal conductivity (W/m K)
Copper	0.99	385.0
Brass	-	109.0
Aluminum	0.50	205.0
Iron	0.16	79.5
Steel	-	50.2

All heat ducts must have equal width (10 cm) and length (40 cm), and also have sufficient spaces for the installation of 5 thermoelectric devices. The characteristics of heat ducts are shown in the Table 1 and Table 2.

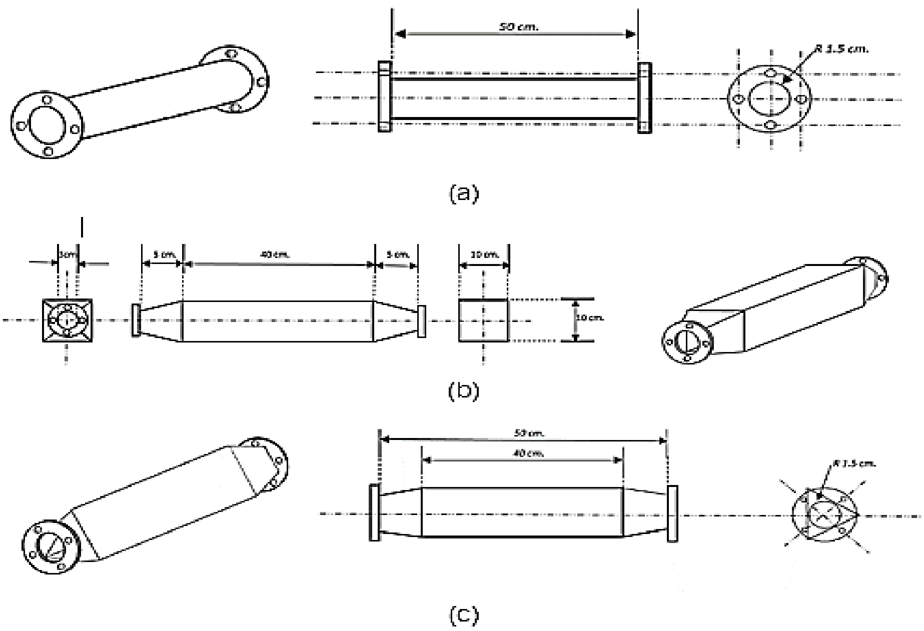


Figure 4. Heat duct design (a) Circular cross-sectional duct (b) Square cross-sectional duct and (c) Triangular cross-sectional duct.

To investigate the efficiency of heat transfer of different duct shapes, liquid petroleum gas was used as a heat source (LPG). Heat ducts were placed on above a gas stove. These thermoelectric devices will be placed on the surface of heat ducts, the appropriate distance between each thermoelectric device is necessary to calculate. The suitable distance between each device was 7.5 cm. Temperatures along the length of heat ducts were measured on the positions that the thermoelectric devices will be installed as shown in the Figure 5.

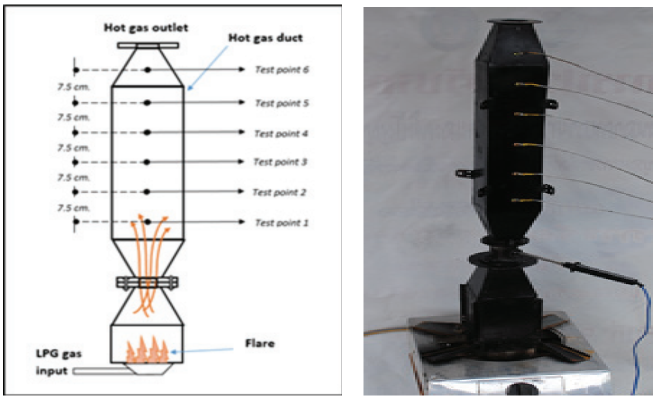


Figure 5. Thermal conductivity of different duct shapes.

To examine and compare thermal conductivity of each geometry, three types of heat ducts were placed on a gas stove. Thermocouples were connected to positions that the thermoelectric devices will be installed as shown in the Figure 5. Thermocouples were used to measure temperatures along the length of heat ducts.

The temperatures used in the experiments were also change by adjustment of gas levels from level 1 to 2 and 3. The experiments were performed several times by changing the order of gas levels from 1-2-3 to 3-2-1 in order to eliminate the influence of the external temperature. The ambient temperature was 37˚C and only changed less than 1˚C during the experiment. The results of this experiments are shown in the Figure 6.

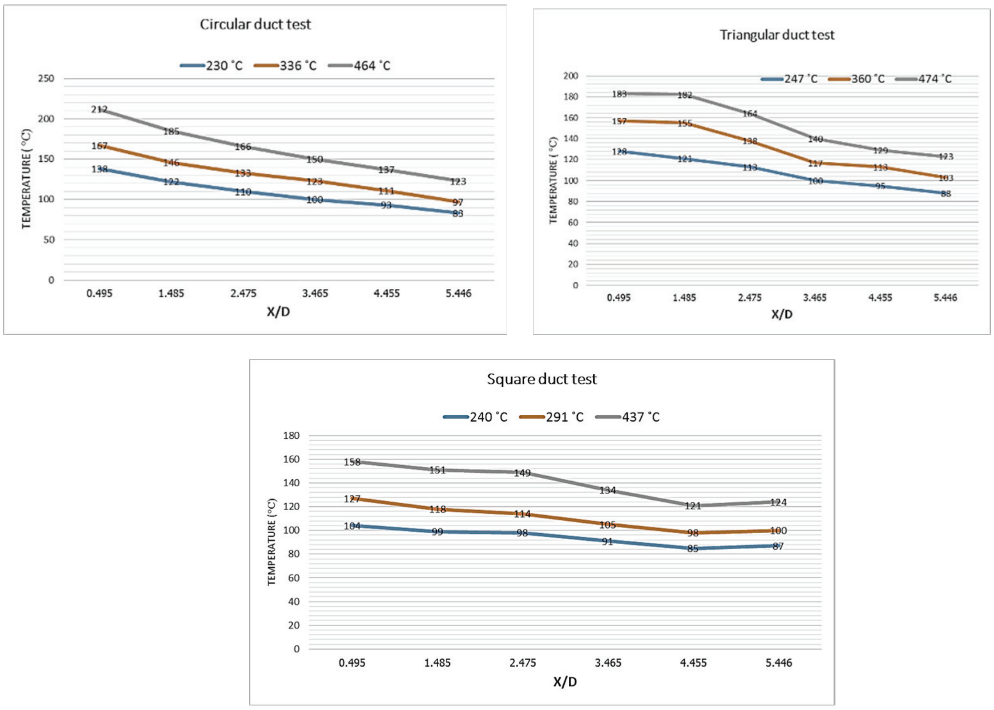


Figure 6. Temperature profiles of different duct shapes.

The temperature profiles of all geometries shares the same feature that the temperatures at the inlet were the highest and linearly decrease to the temperature at the outlet. The temperature profile of a square cross-sectional duct as shown in the Figure 7 was the most stable.

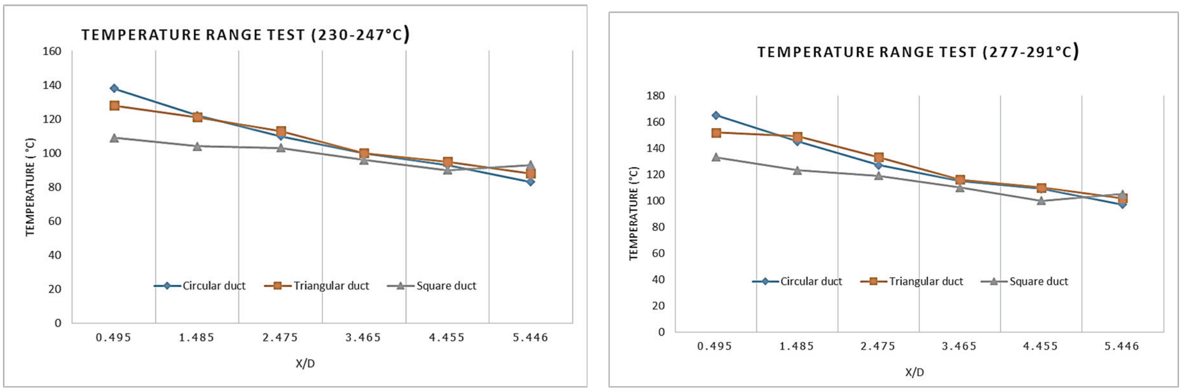
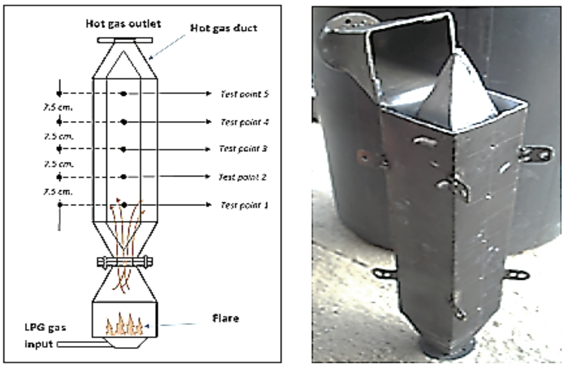


Figure 7. Comparison of temperature profiles in different duct shapes.

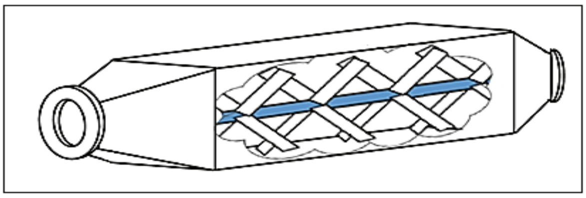
The temperature were increased to the range of 230 - 247°C and 277 - 291°C as shown in the Figure7. However, the experimental results presented feature of temperature profiles of low temperatures. A square cross-sectional duct was still the most suitable duct for power generation by using thermoelectric devices.

3.2 Effects of two type cores insertion in the duct

To increase the efficiency of heat transfer in a square cross-sectional duct, a wedge and a swirl core were installed to examine whether which type of cores can create a turbulent flow. A turbulent flow can improve the efficiency of heat transfer. The schematic and the installations of a swirl and a wedge cores into a square cross-sectional duct are shown in the Figure 8.



(a)



(b)

Figure 8. The schematic and the installation of a wedge core (a) and a swirl core (b).

A square cross-sectional duct was selected for this experiment. The heat transfer of the laminar flow was lower than the turbulent flow. The average temperature could improve by creating a turbulent flow. The experiment was performed at two temperatures of 180℃ and 280℃. The ambient temperature was 34°C. A wedge and a swirl core were inserted to create a turbulent flow. A wedge core could not create the turbulent flow because the length of the heat duct was not enough, while the swirl core could create the turbulent flow and increased the average temperature of a heat duct as shown in the Figure 9.

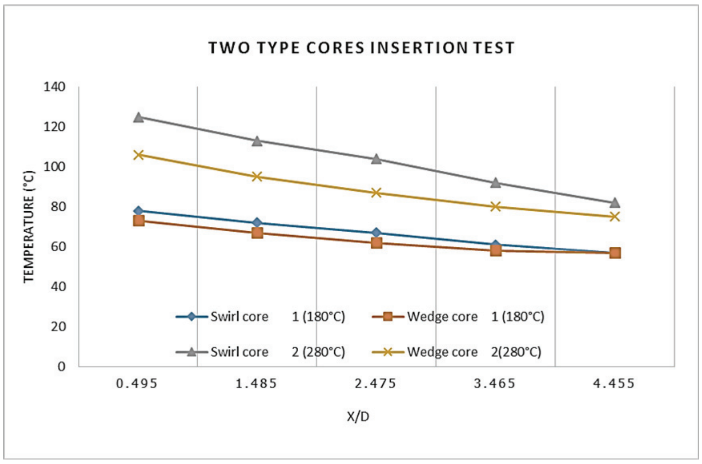


Figure 9. Comparison of temperatures in a wedge core and a swirl core insertion.

3.3 Cooling system design for thermoelectric devices

A biomass gasifier system uses a cooling system to lower temperature of hot gas. A cooling system can be integrated to the gasifier system by simply attaching a water cooling pipe on one side of the thermoelectric devices. Another side of the thermoelectric devices must attach to a heat duct in order to create temperature difference according to principles of the Seebeck effect. The installation details are shown in the Figure 10.

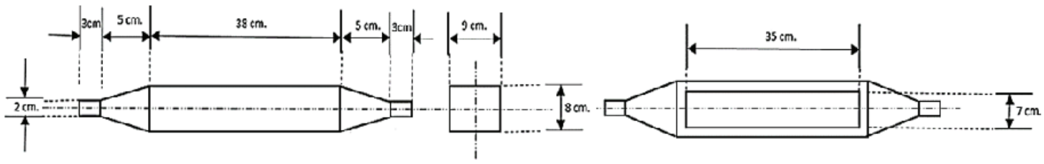


Figure 10. Cooling system design.

Since the temperature of water in a water cooling pipe is not high, a cooling pipe can be made of metal sheet coated with zinc. This makes a cooling pipe light and easy to fabricate. A water cooling pipe is 3/4 smaller compared with a heat duct.

3.4 Flow directions of a cooling system

In this experiment, flow directions of a cooling system were tested whether a counter flow or a parallel flow can improve the efficiency of heat transfer. A parallel flow refers to the flow of cooling water in the same direction of hot gas, while a counter flow refers to the flow of cooling water in the opposite direction of hot gas. The direction of heat pipe and water cooling system used in this experiment is shown in the Figure 11.

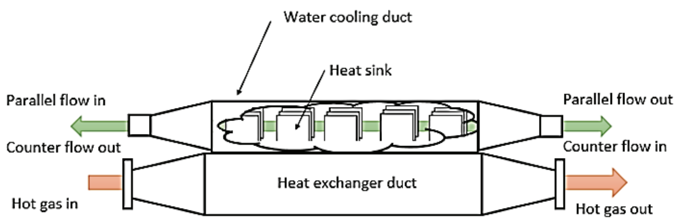


Figure 11. Flow directions of a cooling system.

The thermoelectric devices were installed on the surface of a heat duct and the heat duct was placed over a gas stove. Turn on gas to simulate gas flow as in the biomass gasifier system. Temperature profiles along the heat duct were collected for further analysis. The experimental setup is shown in the Figure 12.

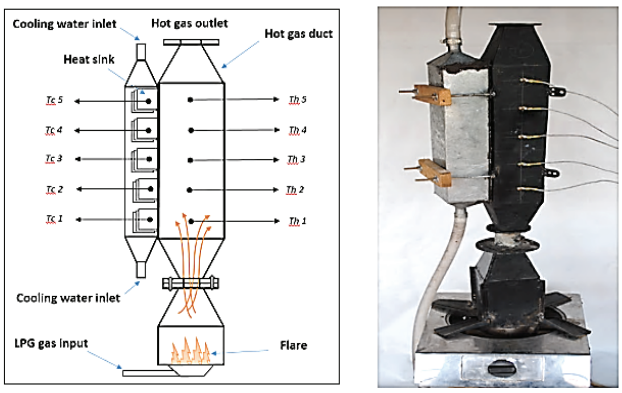


Figure 12. Experiment on flow direction of a water cooling system.

The effect of flow directions of the water cooling system to the temperature profiles of a heat duct is shown in the Figure 12. In the case of a parallel flow which hot gas and water flow in the same direction, temperatures at the positions T1 and T5 were sharply contrast which increased heat accumulation of water. As the average temperature difference along the heat duct of a parallel flow was higher than the counter flow, the thermoelectric module generated unequal amounts of electricity.

A counter flow could lower temperature differences between a heat duct and a cooling pipe, while a parallel flow increased the temperature difference. A small temperature different indicated a good heat transfer. Thus, a counter flow of a water cooling system could improve the efficiency of heat transfer inside a heat duct. Moreover, the thermoelectric devices could generate equal amounts of electricity.

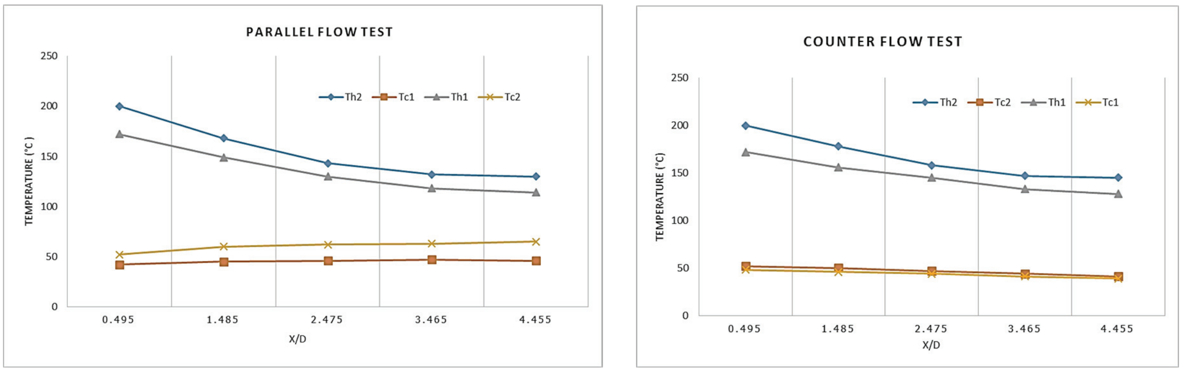


Figure 13. Comparison of temperature profiles in a lamina and a turbulent flows.

3.5 Performance of the thermoelectric devices

A square cross-sectional duct is the most suitable geometry, since the temperatures along its length are nearly equal. Moreover, the thermoelectric devices call be placed on four sides of the heat duct different from other geometries. A turbulent flow which increases the efficiency of heat transfer can be created in a square cross-sectional duct by installation of a swirl core. The experimental setup of the performance analysis of the thermoelectric devices experiment is shown in the Figure 14.

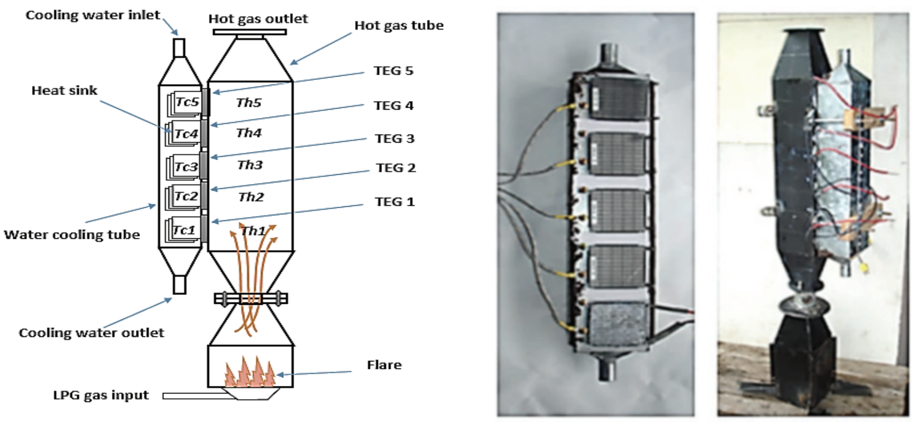


Figure 14. Performance of the thermoelectric devices

The electric current was generated by 5 thermoelectric devices. The temperature differences between the two sides of the thermoelectric devices at the inlet and outlet of a heat duct were 160℃ and 80℃, respectively, and could generate electricity of approximately 6 and 3 Watts under the ambient temperature at 37℃. The electrical resistance of the resistive load was 1.5 Ω 10 Watt. DC voltmeter was used to measure voltage across the resistive load as shown in the Figure 15. The power output of the thermoelectric devices can be estimated as follows.

$$P_{(TEG1 \sim TECG5)} = E_{(R1 \sim R5)} \times I_{(R1 \sim R5)}$$

Where $P_{(TEG1 \sim TECG5)}$ = the power output of each TEG. (Watt), $E_{(R1 \sim R5)}$ = the voltage across the resistive load (V.) and $I_{(R1 \sim R5)}$ = the current in circuit of each TEG (A)

The total output of the thermoelectric devices is the sum of power output of each TEG in the serial circuit and can be estimated as shown in the Figure 15.

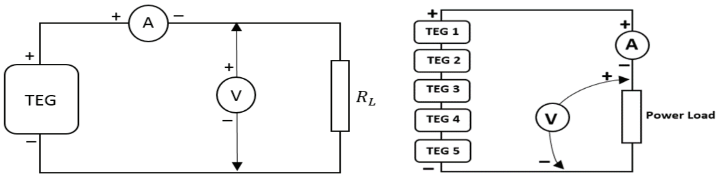


Figure 15. The total power output of thermoelectric devices

$$P_{total} = P_{TEG1} + P_{TEG2} + P_{TEG3} + P_{TEG4} + P_{TEG5}$$

According to the specification of the thermoelectric devices, at the maximum temperature difference of 250℃, a thermoelectric device can generate electricity of 13 Watts. Moreover, if the volume of a heat duct was not high enough, the performance of the thermoelectric devices will be decreased to be low, the thermoelectric devices perform well under high contrast of the temperature differences. The results of this experiment is shown in the Table 3.

Table 3 Performance of the thermoelectric devices.

Module	Th(˚C)	Tc(˚C)	ΔT1(˚C)	E(V)	I(A)	P1(W)
TEG 1	198	38	160	1.56	3.86	6.02
TEG 2	178	37	141	1.49	3.15	4.70
TEG 3	159	35.6	123.4	1.43	2.69	3.85
TEG 4	147	34.3	112.7	1.38	2.54	3.50
TEG 5	145	34.1	110.9	1.28	2.50	3.20

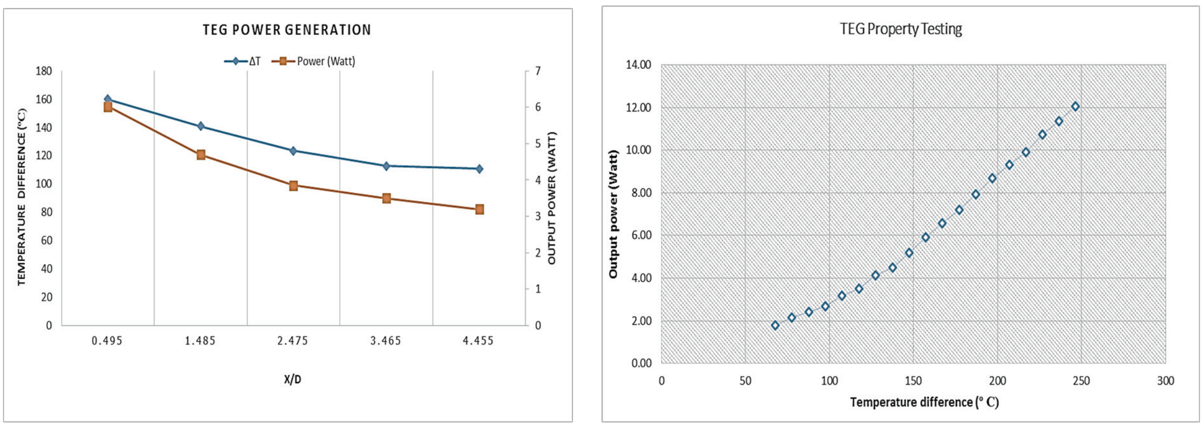


Figure 16. Power generation of the thermoelectric devices.

The maximum temperature of a hot side was approximately 186 - 198˚C, while the temperature at the cold side was approximately 35.6 - 38˚C. Therefore, the temperature difference between these two sides was 150.4 - 160˚C. The system can generate electricity of 5.6-6.02 Watt and can be calculated as follows.

$$q = mC_p\Delta T$$

Where $q =$ the thermal energy sources, m = the mass of the TEG (Hz-14: 82 gm), C_p = the heat capacity of TEG (Bi2Te3: 0.544 joule/gram/°C) and ΔT = the temperature difference. (°C)

The efficiency equation,

$$\eta = \frac{E_2}{E_1} \times 100$$

Where $\eta =$ the energy efficiency of the TEG, E_1 = thermal energy input (source = q) and

E_2 = electricity power output $(P \times t)$.

The power output of the thermoelectric modules (TEG 1-TEG 5) was approximately 5.06~3.8% or 4.34% for the averaged power output.

4. Conclusions

In this study, we found that a square cross-sectional duct was still the most suitable duct for power generation by using thermoelectric devices because the temperatures along a heat duct were nearly equal. Therefore each thermoelectric deices installed on the surface will be able to generate equal amounts of electricity. The integrated system between the thermoelectric power generation and the original biomass gasifier system can generate higher total power output. The installation of a swirl core can create a turbulent flow, which a wedge core could not. The turbulence improves the efficiency of heat transfer inside a heat duct. A counter flow of the cooling system contributes to higher contrast of the hot and cool sides of the thermoelectric devices. Therefore, a square cross-sectional duct with a swirl core and a counter flow of a cooling system can generate the maximum amounts of electricity as specified by the manufacturer. Even though the integrated system has several advantages such as low maintenance, developments of the technology and design have to be made further in order to improve the performance of the system.

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