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Experimental Analysis and Optimization of Power Generation by Waste Heat Thermoelectric Module of Biomass Dryer for Lighting

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ABSTRACT

The goal of this study is the application and optimization of electricity generation in lighting systems. There are five steps for examining model optimization as follows: 1) design the thermoelectric module to generate electricity, 2) study the influence of variables through experimental design, 3) analyze variance and mathematical modeling, 4) simulation and surface mapping, and 5) optimize the model to find the optimal condition. A thermoelectric device was used and removed in hybrid circuits. A full factorial design is used for the experimental study of a Light-Emitting Diode (LED) bulb load (5 to 25 W) and a temperature difference (ΔT) between the hot and cold sides from 5 to 30 ˚C. The analysis of variance and mathematical modeling found that the modeling as a function of ΔT and load was non-linear. The model can then be used for surface plots and results can be predicted, and experimental data showed good agreement (R^2 = 97.13%). The yield power generation increased with increasing ΔT. Finally, a LED bulb load of 13.68 W and a temperature of 30 ˚C was found to be the optimum condition.

Keywords: Biomass dryer; Mathematical modeling; Lighting; Power generation; Thermoelectric modules

1. Introduction

In power generation, a generator is a device that converts mechanical energy into electrical energy. Water turbines, steam turbines, gas turbines, electric motors and wind turbines can convert sources of

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mechanical energy. The case system for generating electricity with non-moving parts starts with the most popular solar cell technology [1, 2]. Fuel cell technology is an electrochemical device that continuously converts chemical energy into electrical energy [3, 4]. Thermoelectric technology is a device that uses thermal energy to generate electricity [5-7]. Thermoelectric devices can be applied in 2 modes: 1) thermoelectric devices are intended to be applied in cooling systems [8-10] or heating systems [11], and 2) thermal energy is converted to electricity by controlling the temperature difference between the hot and the cold side of the thermoelectric device. Thermoelectric genera-tors contain no moving parts and are silent. These generators offer great potential for utilizing waste heat. The charcoal production technology, known as a 200-liter furnace [12], is easy to build, inexpensive and produces high quality charcoal. One production step is waste heat, waste gas and losses in the 200-liter furnace. Chunkaew et al. [13] retrofitted a hot air dryer using waste heat from a 200-liter furnace. A hot air dryer was then developed to dry bananas using the waste heat from a 200-liter oven to reduce heat loss in the structure and exhaust air heat exchanger [14]. Eventually, biomass dryer technology was transferred to rural communities not connected to the grid. Dryers can be used to dry bananas and other fruits using only biomass [15]. From the research on drying technology using biomass, it can be seen that more waste heat is generated during the drying process. The thermoelectric module power generation using the waste heat power generation of the biomass dryer is checked and analyzed to find the optimal conditions. The main steps of this research process are the development of thermoelectric modules for power generation using waste heat from biomass dryer, experimental design, mathematical modeling analysis, model verification, and model optimization.

2. Research Process

For most research processes, the ultimate research lies in finding the optimal research conditions. The research process of this study includes a 5-step design of con-structing a thermoelectric module for lighting power generation with waste heat from a biomass dryer. The research is an experimental design to study the effect of temperature difference between hot and cold sides (ΔT) and LED bulb load, analysis of variance and mathematical modeling, model and surface plots, model validation and optimization responses as shown in Fig. 1.

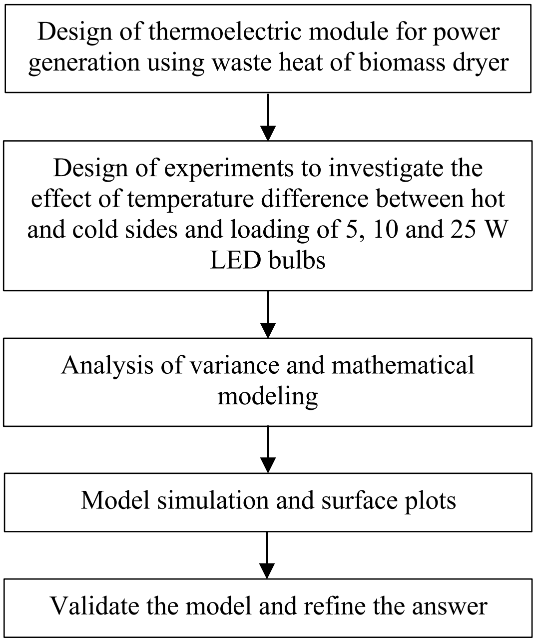


Fig. 1. Five steps to generate electricity from biomass dryer waste heat lighting thermoelectric modules.

2.1 Design of thermoelectric module for power generation using waste heat of bio-mass dryer

In the past research on biomass dryers to dry bananas [13-15], the temperature of the hot air on the furnace surface and the heat exchange area was relatively high. Therefore, the concept of harnessing this heat to generate electricity using thermoelectric devices [16-18] emerged.

The purpose is to generate voltage suitable for a standard 6 V light bulb.

Initially, we selected the thermoelectric model SP1848 27145 SA of the element, and tested it by the temperature difference (ΔT) between the hot end and the cold end, as shown in Fig. 2. The voltage is 0.34 ± 0.005 V at 15 °C and 0.61 ± 0.012 V with a temperature difference of 30 °C between the hot and cold sides (ΔT). Secondly, the hybrid power generation circuit should be designed from the thermoelectric modules, as shown in Fig. 3. There are two groups of 17 thermoelectric devices. Each set should be connected with a series circuit to raise the voltage to 10.37 V when the circuit is opened. Thirdly, the two sets should be connected in parallel to increase the current. The hot end of the thermocouple is fixed with a 600 × 300 mm^2 finned aluminum plate. The cold end is fixed with a 400 × 300 mm^2 ribbed aluminum plate and immersed in a 400 × 300 × 200 mm^3 aluminum water tank. Fig. 4 shows the working principle of the biomass dryer. The hot air from the 200-liter furnace increases by heat conduction, then moves through the heat process to form heat convection, and ambient air enters the bottom of the dryer. After that, the hot air enters the drying chamber through heat treatment and flows out the top of the drying chamber. The temperature of the drying room can be controlled by controlling the amount of wood and the ambient air in the 200-liter furnace. For this purpose, a thermoelectric module for generating electricity is attached to the side wall of the biomass dryer. The hot end of the aluminum plate thermoelectric is installed inside the dryer, while the cold end is installed outside the dryer and submerged in the water tank. The temperature in the dryer can be controlled by using an inlet valve. The drying materials can use bananas for reducing the moisture content in this dryer.

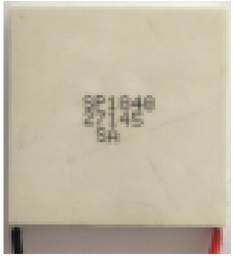


Fig. 2. Thermoelectric model of SP1848 27145 SA.

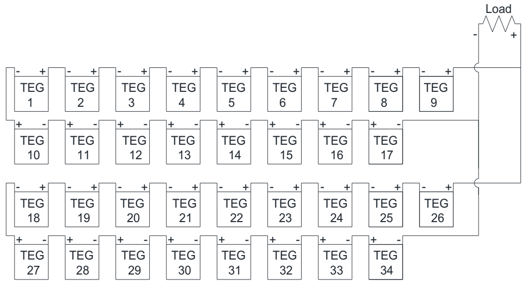
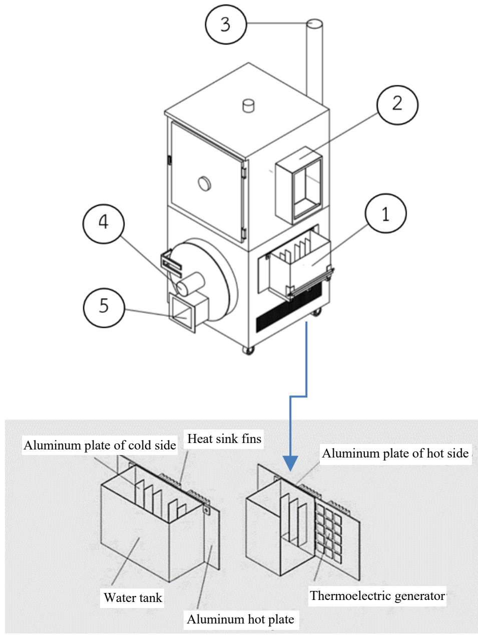


Fig. 3. Hybrid circuit for generating electricity from thermoelectric modules.



(1) Thermoelectric modules generate electricity
(2) Control box
(3) Exhaust gas
(4) Inlet air
(5) Biomass intake pocket

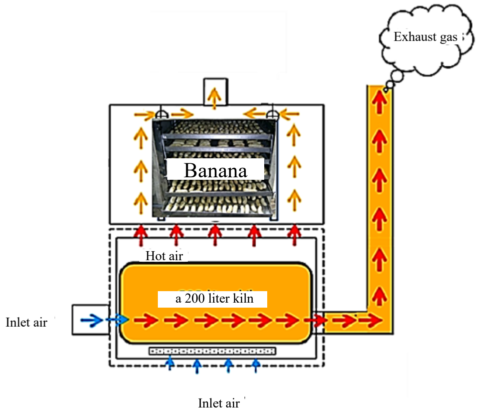


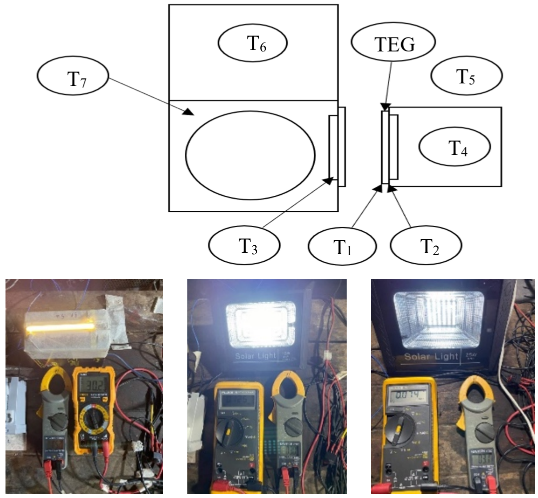
Fig. 4. Biomass dryer waste heat thermo-electric module power generation experimental device.

2.2 Experimental design to study the influence of the temperature difference between the hot and cold ends and the load of LED bulbs

The experiments were performed under loads of 5, 10 and 25 W LED bulbs (as shown in Fig. 5) and temperature differences (ΔT) between hot and cold sides of 5, 10, 15, 20, 25 and 30 °C, respectively. The 5, 10 and 25 W LED bulbs are available in online marketplaces. The 10 and 25 W LED bulbs have resistance of 14.5 M and 3.99 K, respectively. The resistance of the 5 W LED bulb is high, and the resistance cannot be measured. In the experiment, the temperature of the hot end of the aluminum plate is controlled at the highest temperature of 60, 65 and 70 °C. The cold side of the aluminum plate is controlled by changing the low temperature water in the sink. The temperature of the aluminum plate is 28 to 38 °C. All experiments were performed in triplicate.

Fig. 5. The 5, 10 and 25 W LED bulbs.

A multi meter model Fluke 78 automotive meter was used to measure voltage in function DC voltage mode and a KT200 clamp tester was used to measure the DC electrical current. A temperature recorder (TM-1947SD) is used to measure the temperature in the experiment, as shown in Fig. 6.



(T1) Thermoelectric device hot end temperature
(T2) The temperature at the cold end of a thermoelectric device
(T3) The temperature of the hot side of the aluminum plate
(T4) Water temperature
(T5) Ambient temperature
(T6) Drying room temperature
(T7) Hot air room temperature
(TEG) Thermoelectric module for power generation

Fig. 6. Temperature recorded on the experimental setup.

In the experiment, heat can be transferred from the aluminum plate to the cold side of the aluminum plate at the temperature of the hot side, so this experiment uses a water supply system with a flow rate of 5.4 liters per minute to control the temperature of the cold side. The hot side temperature can then be increased to add biomass and open the intake valve wider for intense combustion.

Table 1 shows the temperature results for seven locations under dry conditions from 60 to 70 ˚C. Biomass has started to burn. The hot air chamber temperature (T7) is the heat transferred from the surface of the oven to increase the temperature. Heat is then transferred from the the hot air chamber to the hot side of the aluminum plate (T3). Finally, the temperature of the hot end of the thermoelectric device (T1) is high temperature, and the drying condition control conditions are 60, 65 and 70 ˚C. The temperature at the cold end of the thermoelectric device (T2) is controlled to a low temperature by transferring heat to the water (T4). The temperature of the oven (T6) is higher than the temperature of the hot end of the thermoelectric device (T1). The ambient temperature (T5) is approximately 25 to 32 ˚C.

Table 1. Temperature results for seven locations under dry conditions.

Control of drying conditions (˚C)	T_1 (˚C)	T_2 (˚C)	T_3 (˚C)	T_4 (˚C)	T_5 (˚C)	T_6 (˚C)	T_7 (˚C)
60	61±1.7	34.3±1.6	72.7±1.2	28.8±0.8	25±0.8	74.3±3	121.7±15.5
65	64.7±0.6	37.7±2.4	79.7±1.5	29.2±1.0	29.2±7.3	79.4±8.6	161.3±21.2
70	69.3±0.6	37.3±1.2	84±2.6	28.8±0.3	32±4.4	88.3±3	231.3±14

Table 2. Experimental design parameters.

Factor	Variation Levels					
	1	2	3	4	5	6
Load (Watt)	5	10	25			
Different temperature (ΔT, ˚C)	5	10	15	20	25	30

Table 3. Arrangement of experimental plan

Test Number	Variables (Coded value)		Variables (Real value)	
	Load (Watt)	Different temperature (ΔT, ˚C)	Load (Watt)	Different temperature (ΔT, ˚C)
1	1	1	5	5
2	1	2	5	10
3	1	3	5	15
4	1	4	5	20
5	1	5	5	25
6	1	6	5	30
7	2	1	10	5

Table 3. Arrangement of experimental plan (cont'd).

Test Number	Variables (Coded value)		Variables (Real value)	
	Load (Watt)	Different temperature (ΔT, ˚C)	Load (Watt)	Different temperature (ΔT, ˚C)
8	2	2	10	10
9	2	3	10	15
10	2	4	10	20
11	2	5	10	25
12	2	6	10	30
13	3	1	25	5
14	3	2	25	10
15	3	3	25	15
16	3	4	25	20
17	3	5	25	25
18	3	6	25	30

In the experimental study of thermo-electric module power generation, a general full factorial design was used for two factors. Table 2 shows the stress of the LED bulb and the temperature difference between the hot and cold ends of the thermoelectric (ΔT). The multiple regression model used to fit the response surface in this experimental analysis is shown in Eq. 2.1. There are 18 experimental points in total, as shown in Table 3:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_1^2 + \beta_3 x_2 + \beta_4 x_2^2 + \beta_5 x_1 x_2 + \beta_6 x_1 x_2^2 + \beta_7 x_1^2 x_2 + \varepsilon \tag{2.1}$$

where y is the response variable (Power), β_0 is the constant, ε is the residual (error) term, β_1, β_3 are the linear coefficients, β_2, β_4 are the quadratic coefficients, $\beta_5, \beta_6, \beta_7$ are the interaction coefficients, x_1, x_2 are the independent variables.

Table 4 shows the experimental results of a general full factorial design for power gene- ration under different variations of thermoelectric module settings, with three iterations. The performance at 5, 10, and 25 W loads is nonlinear with the temperature difference (ΔT) between the hot and cold ends of the thermoelectric.

Table 4. Experimental setup and results of thermoelectric module power generation.

Test Number	Independent Variables		Response (power, Watt)		
	Load (Watt)	Different temperature (ΔT, ˚C)	Replication		
			1	2	3
1	5	5	0.000016	0.000016	0.000018
2	5	10	0.000074	0.000070	0.000066
3	5	15	0.015900	0.005978	0.004214
4	5	20	0.104092	0.054080	0.078599
5	5	25	0.196040	0.157040	0.196560
6	5	30	0.291500	0.265530	0.278510
7	10	5	0.000019	0.000018	0.000019
8	10	10	0.023400	0.014700	0.016200
9	10	15	0.070000	0.053200	0.064400
10	10	20	0.136300	0.098600	0.133400
11	10	25	0.288000	0.186000	0.231000
12	10	30	0.375000	0.362700	0.384400
13	25	5	0.002300	0.002100	0.002300
14	25	10	0.014000	0.020300	0.026100
15	25	15	0.072800	0.060000	0.069000
16	25	20	0.112000	0.105000	0.105000
17	25	25	0.151200	0.151900	0.159000
18	25	30	0.197200	0.254200	0.229400

2.3 Analysis of Variance and Mathematical Modeling

With probability analysis, Analysis of Variance (ANOVA) is used to determine the significance (P-value) of each linear, quadratic, and interactive component in the model. A P-value of less than 0.05 was used to evaluate the significance of all models in Table 5 for all terms. Lack of fit tests were used to confirm that the model fits the purpose and predict variance. A P-value greater than 0.05 indicates that the lack of fit test is not significant. The adjusted coefficient of determination (R-sq (ad-j)) for current production in Table 6 has a value close to 1. In addition, the plot shows the randomness of the residuals compared to the expected plot, normal plot, histogram, and histogram. As shown in Fig. 7, the residuals follow a normal distribution with a constant variance. Overall, the study shows that general full factorial design is a useful technique for optimizing parameters of thermoelectric modules for power generation, and that the resulting models are well suited and satisfactory.

Table 5. Variance analysis of power generation of thermoelectric modules.

Source	DF	Adj_SS	Adj_MS	F-value	*p*-value
Regression	7	0.640676	0.091525	302.07	0.000
Load	1	0.001964	0.001964	6.48	0.014
ΔT	1	0.017347	0.017347	57.25	0.000
Load*Load	1	0.001375	0.001375	4.54	0.039
ΔT*ΔT	1	0.036999	0.036999	122.11	0.000
Load*ΔT	1	0.016586	0.016586	54.74	0.000
Load*Load* ΔT	1	0.012216	0.012216	40.32	0.000
Load*ΔT*ΔT	1	0.007823	0.007823	25.82	0.000
Error	46	0.013938	0.000303		
Lack-of-Fit	10	0.002847	0.000285	0.92	0.523
Pure	36	0.011091	0.000308		
Total	53	0.654614			

Table 6. Estimated power generation coefficient.

Term	Coef	SE_Coef	T-value	*p*-value
Constant	0.1026	0.0326	3.14	0.003
Load	-0.01299	0.0051	-2.55	0.014
ΔT	-0.02168	0.00287	-7.57	0.000
Load*Load	0.000339	0.000159	2.13	0.039
ΔT*ΔT	0.000781	0.000071	11.05	0.000
Load*ΔT	0.002223	0.0003	7.4	0.000
Load*Load* ΔT	-0.000052	0.000008	-6.35	0.000
Load*ΔT*ΔT	-0.000023	0.000004	-5.08	0.000

S = 0.0174067, R-sq = 97.87%, R-sq (adj) = 97.55%, R-sq (pred) = 97.13%

The regression coefficients given in Table 6 describe the effect of the generation value on the uncoded parameters. Based on this, the full model is developed, as shown in Eq. 2.2. The proposed equations for this model are shown below.

$$\begin{aligned} Power = {} & 0.1026 - 0.01299 * Load - 0.02168 * \Delta T \\ & + 0.000339 * Load^2 + 0.000781 * \Delta T^2 \\ & + 0.002223 * Load * \Delta T \\ & - 0.000052 * \Delta T * Load^2 \\ & - 0.000023 * Load * \Delta T^2 \end{aligned} \quad (2.2)$$

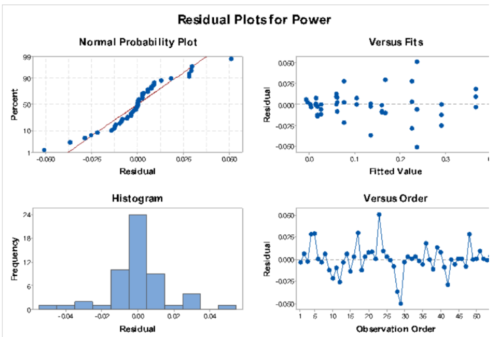


Fig. 7. Residual plots of thermoelectric module power generation.

2.4 The surface plot of power generation

Fig. 8 shows the surface plot of the optimized yield generation under loads and different temperatures. It has been observed that the interaction between loads and different temperatures can affect the power generation. Increasing the differential temperature at moderate loads results in an increase in the power generation of the thermoelectric modules. Mathematical modeling of nonlinear functions and loads was able to predict the results, which agreed well with the experimental data (R^2 = 97.13%).

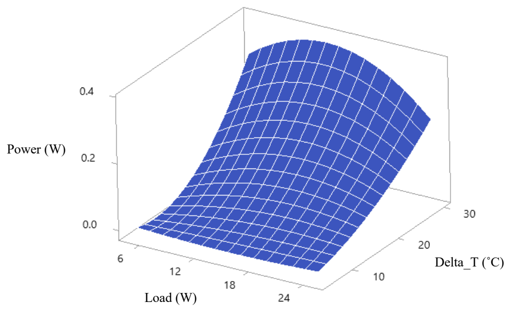


Fig. 8. Surface view of a thermoelectric module for power generation.

2.5 Validate the model and refine the answer

The multiple regression equation (Eq.-2) was used with Minitab software to predict the thermoelectric module's generation optimization. For finding the appropriate level of factors, Minitab's Response Optimizer calculates desirability (d) using a desirability function. Desirability has a range of zero to one. Zero denotes that the response is outside of its allowable bounds, whereas one represents the best-case scenario. In this case, the best combination of predicted variables is 13.6869 W and 30 °C, with a desirability value of 0.99442 and a power of 0.3823 W, as shown in Fig. 9.

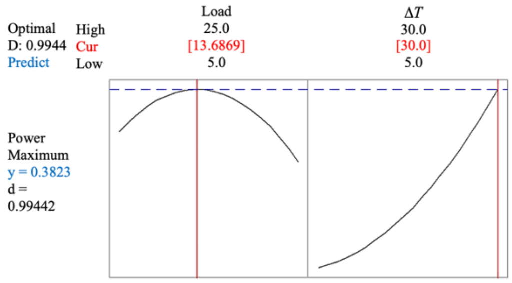


Fig. 9. Optimal conditions for maximum performance development of thermoelectric module.

3. Conclusions

The main components of the biomass dryer waste heat thermoelectric module power generation experimental device are biomass dryer, cold-end aluminum plate water tank, aluminum heating plate heat sink, and 34 models of SP1848 27145 SA thermoelectric equipment for the thermoelectric module to generate electricity. Specific limitations of this designed equipment are that the voltage of the open circuit was not more than 10.37 V and the temperature of the thermoelectric device hot end must not exceed the melting point of the circuit connection, which in this study was about 90 °C. The five steps of designing a thermoelectric module power generation for lighting with the waste heat of a biomass dryer were determined and an experimental design to study the effects of temperature differences of hot side and cold side and of LED light bulb loads of 5, 10 and 25 W was developed. The steps included variance analysis and mathematical modeling, model simulation, and surface plotting. Verification of the model and optimization response were used to find the optimum condition for the maximum power generation of the module. The thermoelectric module power generation was optimized using a general full factorial design. In the analysis of variance, the variable was found to have an effect on the amount of electricity produced. The significant impact on power generation is also attributed to the interdependence between the variables and their interactions. LED bulb load (13.6869 W) and temperature difference (30 °C) proved to be the optimal process parameters for thermoelectric module power generation, and the maximum power generation was 0.3823 W. The suggested material drying applications are bananas, longan and seasonal agricultural fruits. Future research should include studying dryer efficiency with thermoelectric module power generation during drying experiments and designing electrical energy storage equipment.

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