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Design, empirical modelling and analysis of a waste-heat recovery system coupled to a traditional cooking stove

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ABSTRACT

In this work, a waste-heat recovery (WHR) system was designed and implemented to utilise the waste heat from a cooking stove. The WHR system was designed to preserve maximum thermal energy efficiency, use passive cooling, and produce a system that did not alter the body of the cooking stove. The thermal energy from the cooking stove was converted into electrical energy by a thermoelectric generator (TEG) and used in a waste-heat hot water boiler. The cold side of the TEG was cooled by heat pipes immersed in a water box that offers a high heat transfer rate. The heated water can be used for domestic purposes. Dependent variables were the heater temperature and the volume of water. The heater temperature was varied between 130 and 271 °C, and 4.2–9.5 L of water was investigated. At equilibrium, response surface methodology based on a central composite design was used to empirically model the influence of the heater temperature and the volume of water on the electrical power generation and the hot water temperature. Experimental results of the system efficiency showed that the heater temperature was more influential than was the volume of water. The total efficiency of the WHR system was more than 80%. Thermal contact resistance was analysed to improve the WHR system performance. Finally, the thermal efficiency of a cooking stove, both with and without the WHR system, was measured. Results showed that the thermal efficiency of the cooking stove decreased by less than 5% when the WHR system was attached.

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1. Introduction

A serious problem for people in the rural areas of developing countries is a lack of reliable access to electricity. A sustainable solution to this problem is the ability to independently generate electrical power, preferably from routine activities, such as using a cooking stove. Various types of cooking stove have been widely used, and 90% of people in rural areas of developing countries use a biomass cooking stove [1]. Several countries in Southeast Asia, such as Thailand, Lao, Cambodia, Malaysia, the Philippines, and Vietnam, use a similar mechanical form of the cooking stove [2]. For example, the Thai cooking stove comprises a galvanised iron bucket and an inner ceramic firebox. The bucket has an opening cut into its side from the bottom and an integrated grate with equally distributed holes 15–20 mm in diameter [2]. Wood or charcoal can be burned on the grate. Thermal energy from the cooking stove can be converted to electricity by the thermoelectric module contained in a thermoelectric generator (TEG). Thermoelectric has long been too inefficient to be cost effective in energy conversion application compared with solar cells and wind turbines. The application is not currently available for people in developing country. However, theoretical predictions suggested that thermoelectric efficiency could be greatly enhanced through nano-structural engineering and low-dimensional system [3,4]. Thermoelectric generator looks very promising and can contribute to applying the application. Energy conversion of a part of waste heat from stoves using TEG system has been developed. Efforts are already underway to combine a thermoelectric generator on various types of stove in many countries. The TEG has the advantages of being a maintenance-free system, containing no moving or complex parts, and being compact in size [1,5–11]. Although photovoltaic solar and wind systems are more efficient than TEGs, they depend on favourable natural conditions. Lertsatitthanakorn [10] analysed the electrical performance of the Thai cooking stove with an integrated TEG system. The side wall of the cooking stove was removed and a TEG system was installed. The system had a power output of 2.4 W at a temperature difference of

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Nomenclature

WHR	waste-heat recovery
TEG	thermoelectric generator
RSM	response surface methodology
CCD	central composite design
T_H	heater temperature (°C)
V_W	water volume (L)
P_{avg}	average electrical power generation from the TEG (W)
P_{max}	maximum electrical power generation from the TEG (W)
T_w	hot water temperature (°C)
T_{wi}	initial hot water temperature (°C)
T_{we}	boiling water temperature (°C)
$T_{w(max)}$	maximum hot water temperature at equilibrium (°C)
T_1 and T_2	temperatures inside the copper block (°C)
T_3	cold side temperature of the thermoelectric module (°C)
T_a	ambient temperature
$q_h^{\bullet}$	heat rate into the waste-heat recovery system (W)
$q_C^{\bullet}$	heat rate leaving the thermoelectric module (W)
$q_w^{\bullet}$	heat rate leaving the heat pipes and transferring to the water in the box (W)
$q_L^{\bullet}$	heat loss rate from the water box (W)
$q_{C2}^{\bullet}$	heat rate leaving the thermoelectric module and transferring to the aluminium block (W)
K_{cu}	thermal conductivity of copper (W/m K)
K_{Al}	thermal conductivity of aluminium (W/m K)
A_{Cu}	surface area of the copper block (m^2)
A_{Al}	surface area of the aluminium block (m^2)
x	distance between the T_1 and T_2 measurements (m)
m_{wi}	initial mass of water (kg)
C_p	specific heat capacity of water
R_c	thermal contact resistance between the thermoelectric module and apparatus (°C/W)
R_{chp}	thermal contact resistance between the heat pipe and aluminium block (°C/W)
R_{TE}	thermal resistance of the thermoelectric module (°C/W)
R_{hp}	thermal resistance of the heat pipe (°C/W)
R_{Al}	thermal resistance of the aluminium block (°C/W)
UA_s	heat loss rate from the water box per unit of temperature difference (W/°C)

approximately 150 °C. However, the best system design was achieved when the TEG was integrated with the cooking stove without changing or damaging the stove body.

The electric power generated by a TEG coupled to a cooking stove depends on the efficiency of the cooling system at the cool side of the TEG, and it has been shown that forced air/water-cooling systems are more efficient than free air/water-cooling systems [1,9]. However, forced cooling systems need electricity to operate and cause some electricity loss from the TEG. All previous applications of coupling the TEG to a stove depended on inefficient natural cooling of the cold side of the TEG. A solution to overcome the low efficiency was introduced by Min and Rowe [12], who combined the generation of heat and power into a symbiotic system, in which the heat released to the cold side is used to heat water for household purposes. The efficiency of the TEG system is equal to that of a conventional heating system, but the TEG system offers the advantage that both electricity and hot water are produced. Similar symbiotic systems were developed by Chen et al. [13] and Goudarzi et al. [14].

Date et al. [15] used concentrated solar energy as a heat source for a thermoelectric power generation system, in which the cooling system was a heat pipe. One end of the heat pipe was embedded inside an aluminium block and installed at the cold side of the thermoelectric module. The condenser of the heat pipe was immersed in a water tank. This technique offers a high heat transfer coefficient for cooling the TEG as well as a way to scavenge heat through water that can then be used for industrial or domestic purposes. Mathematical modelling was used to predict the transient behavior of the water temperature.

In this work, a waste-heat recovery (WHR) system was designed for a traditional cooking stove to preserve maximum thermal energy efficiency, use passive cooling, and produce a system that did not alter the body of the cooking stove. The TEG system, as shown in Fig. 1, consists of a thermoelectric module sandwiched between two heat exchangers; the hot side of the thermoelectric module is installed under the grate. The performance of the cooling system of the TEG was enhanced by using a heat pipe with a water-filled box. The system is used to generate electricity and hot water as a by-product for domestic applications.

The amount of electrical power generated and the hot water temperature depend on both the hot-side temperature and the volume of water being heated. Data acquisition, such as generated electrical power and hot water temperatures a function of time, were analysed for studying the stability and thermal efficiency of the designed system. In addition, we used the response surface methodology (RSM) technique to study the influence of the heater temperature and volume of water on the electrical power generation and the maximum hot water temperature at steadystate. RSM is a statistical method based on a multivariate non-linear model that defines the relationship between parameters and responses and is used to estimate the effect of individual parameters and interactions of parameters on each of the response variables [16,17]. This approach results in improved statistical interpretation of the results, requires less time for analysis, and requires fewer experiments, all of which reduce the cost of system development [18]. The thermal to electrical energy conversion efficiency and hot water production efficiency were calculated. Then, the contact resistances at typical positions were evaluated to improve the WHR performance. Finally, the WHR system was then combined with the cooking stove and tested in realistic operating conditions. The thermal efficiency of the cooking stove, both with and without the WHR system, was determined.

2. Materials and methods

The WHR system constructed for this study is shown in Fig. 2. Three cartridge heaters are embedded in an aluminium block to simulate the waste heat that would be produced by the cooking stove. A copper plate with a thickness of 20 mm is installed under the heater. To calculate the rate of energy ($q_h^{\bullet}$) into the system, K-type thermocouples (accuracy ±0.5 °C) with 1 mm diameter tips are used to monitor the temperatures. NI 9211 (accuracy ±0.05%), NI 9201 (accuracy ±0.04%), and NI 9227 (accuracy ±0.1%) were used as automatic simultaneous data collectors for temperature, electric current, and voltage across match load, respectively. This system was controlled by Labview. T_1 and T_2 are the temperatures at the upper and lower portions of the copper plate. The TEHP12656-0.3 thermoelectric module (Thermonamic, China) was used in this study. This module can work at a temperature as high as 330 °C continuously and up to 400 °C intermittently. The cooling system was designed to use four heat pipes, each with a diameter of

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