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Comparative assessment of a porous burner using vegetable cooking oil–kerosene fuel blends for thermoelectric and thermophotovoltaic power generation

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HIGHLIGHTS

- Effects of fuel–air equivalence ratios on TE and TPV systems were elucidated.
- Three blends of high viscosity kerosene–VCO fuels were examined experimentally.
- CO emission for TE system is lower than the TPV system.
- Electrical efficiencies for TE and TPV systems improved at rich mixtures.

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ABSTRACT

This paper presents an experimental evaluation of combustion-driven thermoelectric (TE) and thermophotovoltaic (TPV) power systems using several blends of vegetable cooking oil–kerosene (VCOK) fuels. The TE and TPV systems were integrated with a porous burner, and the combustion characteristics and system performance were evaluated. Three blends of fuel mixtures were tested: 95%/5% VCO–kerosene (9505 VCOK), 90%/10% VCO–kerosene (9010 VCOK), and 80%/20% VCO–kerosene (8020 VCOK). Experiments were conducted to assess the effects of the fuel–air equivalence ratio on the temperature distributions, emission profiles, electrical power output, and electrical efficiency. For both the TE and TPV systems, the asymmetrical temperature distributions were highly insensitive to the fuel–air equivalence ratio and the fuel blends. The emissions of carbon monoxide (CO) and nitrogen oxide (NOx) were largely unaffected by the fuel blends. The CO emission exhibited a minimum value at a fuel–air equivalence ratio of 0.60 for the TPV system, and the level of NOx emission gradually decreased with mixture enrichment. It was also observed that the general trend of electrical efficiency tended to be similar for both the TE and TPV systems, and the electrical efficiency markedly improved at a rich fuel–air equivalence ratio.

1. Introduction

Combustion-driven thermoelectric (TE) and thermophotovoltaic (TPV) systems have been extensively researched as power sources in diverse fields of applications. TE systems receive commendable attention in microcombustors [1], stoves [2,3], domestic heating systems [4], and cogeneration [5]. TPV systems, alternately, have been demonstrated in powering electronic devices [6], terrestrial devices [7], and cogeneration [8]. Both TE and TPV power systems show excellent compatibility for operating on varieties of liquid fuels, such as JP8 fuel [9], methanol [10], and liquid heptane [11]. The energy density of these liquid fuels spans the range from 45 to 50 MJ/kg [12,13] and far surpasses the energy density of gaseous fuels. However, aside from JP8 fuel, other fuels are relatively volatile and permit easy adaptation with combustion-driven TE and TPV systems. Fuel spray is commonly created to produce a large ratio of liquid surface area to liquid volume for adequate vaporization because heavier liquid fuels exhibit poor volatility and aggravate fuel clogging [14]. The approach is convenient but would be impractical in combustion-driven systems, given the requirement of an external pumping device, which inevitably results in reduced efficiency. Conversely, a non-spray method for blends of kerosene–vegetable cooking oil (VCO) holds

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the logical promise because it offers the exploitation of the renewability of VCO and can overcome issues related to the combustion of high viscosity fuels.

Both TE and TPV systems are primarily output-driven, which in turn impinges on the specific range of performance characteristics of these devices. A microcombustor TE system yielded a maximum power output of merely 160 mW [15], as opposed to the 889 W of a much larger combustor [9]. The measured power in a TE system is governed by the voltage difference, which is usually a function of the temperature gradient [16]. To induce a sufficient temperature difference, a few investigators have achieved a combustor temperature between 900 °C and 1000 °C [9,17], but a lower temperature of 450–680 °C was also reported [18]. Jiang et al. [17] performed the analysis at a lean fuel–air equivalence ratio, as opposed to Ismail et al. [18], who carried out the experiment at a rich fuel–air equivalence ratio. In a TPV system, a maximum range of power output between 4 and 8 W was attained at rich fuel–air mixtures [19], but it was drastically diminished to 0.83 W when the system was operated leaner than stoichiometric [20]. The efficiency of the TPV system is equally varied, from as low as 0.3% [21] to a maximum theoretical efficiency of 24.5% [22]. Although these aforementioned studies provided satisfactory performance of the TE and TPV systems, the discussions were specifically individual-based. Thus, it is difficult to make fair comparisons between TE and TPV systems because the assumptions for a particular system may be open to question, given that the operating conditions and geometrical parameters are predominantly different. The results from these investigations [17–21] showed a certain degree of correlation between the thermal aspects of the burner and the fuel–air equivalence ratio. However, knowing that the fuel–air equivalence ratio plays a critical role in the combustion-driven power systems, previous studies did not produce consistent trends to provide a meaningful understanding when the range of the fuel–air equivalence ratio was subsequently broadened.

Prior works on low volatility and high viscosity fuels were limited, and the issues remain persistently challenging. Very recently, kerosene–vegetable cooking oil (VCO) blended fuels were introduced in TE [23] and TPV [24] systems. These preliminary investigations [23,24] covered up to a 50/50 blend of kerosene–VCO fuel, and the techniques adopted offer remarkable opportunities for future progress. There is a potential for further enhancement by increasing the VCO portion in the fuel mixture, given that the VCO could alleviate the detrimental effects on the environment. It is also obvious that a completely satisfactory evaluation and comparison of similarly configured TE and TPV systems using a high viscosity liquid is not yet available. Indeed, the sporadic works by many authors do not even clearly elucidate the combustion and performance characteristics of these systems. Part of the difficulty in explicating published results is the insufficient characterization of the burner. The general performance characteristics of the systems are generally well understood, but the integrated thermal and combustion characteristics are still openly debated. This work attempts to elaborate on the principle in our previous works [23,24] and explore the suitability of wider fractions of VCO content in a manner that is amenable to power both TE and TPV systems. The thermal characteristics of the burner are discussed in detail, and a direct comparison of similarly configured TE and TPV systems is presented.

2. Methodology

2.1. Fuel preparation and thermodynamics of combustion

Three blends of VCO and kerosene were prepared prior to the tests. These blends were 9505 VCOK (95% VCO with 5% kerosene), 9010 VCOK (90% VCO with 10% kerosene), and 8020 VCOK (80% VCO with 20% kerosene). These fuels were blended in an ultrasonic homegenizer (UH FS-1200, Life Scientz, China). The detail experimental procedure can be consulted with Mustafa et al. [23,24] of the present authors. These fuels were analyzed to determine the thermophysical properties and the chemical components in the fuel blends. The ultimate analysis was carried out to determine the stoichiometric combustion equation for 9505 VCOK, 9010 VCOK, and 8020 VCOK to find the stoichiometric air–fuel ratio from the combustion equation. An elemental analyzer (EA Perkin Elmer CRIESII 2400, Perkin Elmer, USA) was used for this analysis and the results are shown in Table 1. The stoichiometric combustion equation can be written as follows:

$$C_xH_{2y}O_{2z} + a(O_2 + 3.76N_2) \rightarrow xCO_2 + yH_2O + (3.76a)N_2 \quad (1)$$

where "a" can be expressed in terms of x, y, and z to obtain the following equation:

$$a = x + \frac{y}{2} - z \quad (2)$$

The stoichiometric air–fuel ratio A/F_s on a mass basis can be written as follows:

$$A/F_s = \frac{a[32 + 3.76(28)]}{12x + 2y + 32z} = 34.32\left(\frac{2x + y - 2z}{6x + y + 16z}\right) \quad (3)$$

where the molecular weight M for O_2 and N_2 is 32 and 28, respectively.

2.2. Experimental setup and procedure

A schematic diagram of the experimental setup is shown in Fig. 1. It is fundamentally similar to the previously developed systems that have been detailed by the present authors [23,24]. Major hardware components were maintained and consisted of a combustion chamber, a porous alumina, a supply system for fuel and air, and measuring and data processing equipment. The dimensions of the combustion chamber are shown in Fig. 2. The axial temperatures of the burner were recorded by thermocouples T_1, T_2, and T_3. Two additional thermocouples were added to measure the asymmetrical temperature distributions in the burner, and they are denoted as T_4 and T_5. The precise locations of all thermocouples are shown in Fig. 3. The filtered and dried air was supplied from a laboratory compressor, and it was continuously adjusted during the experiment to achieve the desired air flow rates. All types of fuel blends were manually regulated by a needle valve and supplied to the combustion chamber though a 5-mm-diameter fuel line. A range of the fuel–air equivalence ratio was achieved by simultaneously manipulating the air and fuel flow rates. The concentrations of CO and NOx in the exhaust gas were continuously sampled at the top of the burner and were measured using a CA-6203 CA-CALC combustion analyzer. For the TE system experiment, ten bismuth-telluride TE cells were attached to a 1-mm-thick stainless steel plate to form a ten-sided polygon. The hot side of the plate was exposed to the hot gases of the combustion products, and the cold side was thermally glued to the finned dissipaters to create a sufficient temperature gradient [23]. For the

Table 1
Ultimate analysis and calculated stoichiometric air–fuel ratio.

Fuel	Ultimate analysis (weight %)					Stoichiometric air–fuel ratio
	C	H	O	N	S	
9505 VCOK	70.93	12.09	15.83	0.17	0.98	11.7
9010 VCOK	70.90	13.45	14.29	0.22	1.14	12.3
8020 VCOK	72.14	16.15	10.45	0.21	1.05	13.5