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Effect of liquid saturated porous medium on heat transfer from thermoelectric generator

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ABSTRACT

Low-temperature heat sources are widely available in nature, they are considered to be unusable, even though the conversion of such low-grade energy into electricity (high-grade energy) is highly desirable. Thermoelectric generators (TEGs) are achieving increasing interest in converting low temperature heat into electricity. TEG suffers from low performance, improving the performance of TEG will allow there use in huge engineering applications. In this paper the effect of heat transfer rate on the performance of TEGs will be analysed under both steady and transient conditions. Enhancing heat transfer from the TEG surface will be studied using a liquid saturated porous medium. Aluminium and copper particles are used and their influences are compared to forced convection heat transfer from TEG surfaces with and without liquids. The experimental results showed that power generated with Cu particles exceeds that of Al particles with 14%. The free to forced convection power generation ratio was 26.5% for Al,36% for Cu and the enhancement of TEG performance reached 149% for liquid saturated Cu particles.

1. Introduction

Solar energy, wind energy, chemical energy, and high-temperature geothermal energy are all sources of high-grade energy (HGE) that are easy to exploit for generating mechanical and electrical power [1]. Low-grade energy (LGE) harvesting is a challenge, low-temperature heat and low-velocity wind are rarely employed to generate electrical power [2]. Low-grade energy harvesting devices have recently received much attention for their contribution to transferring LGE into electricity [3–5]. Thermoelectric devices (TEs) are direct conversion devices that use a combination of three different phenomena to convert heat to electricity [6]: the Seebeck effect, Peltier effect, and Thomson effect. In recent years, TEGs have received a lot of interest in the field of low-grade energy harvesting, with engineering applications ranging from small to large devices. Thermoelectric generators (TEGs) are widely used in a variety of applications due to their appealing characteristics, which include energy efficiency, low maintenance and manufacture from a variety of materials such as silicon, ceramics, and polymers, being a suitable option for low-power systems with limited electrical grid access, and having a long lifespan [7,8]. Even though current TEGs have generally a low efficiency [9], a newly manufactured TEG has a promising efficiency as reported by Appadurai et al. [10].

TEG efficiency is influenced by different factors, including: (i) thermoelectric properties of the material in terms of thermal conductivity K, Seebeck coefficient α, and resistivity ρ, (ii) temperature gradient, which is affected by the sink and source capacities and heat transfer rate, (iii) the figure of merit (ZT) which is a non-dimensional metric that represents TEG overall performance [11,12].

Several experimental and theoretical studies [13–16] examined heat transfer from the TEG surface in order to improve its performance and its power generation. TEG with heat pipe heat sink has been investigated

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Nomenclatures

Al	Aluminum.
Cu	Copper.
DAS	Data Acquisition System.
HGE	High Grade Energy.
I	Current [Ampere].
K	Thermal Conductivity [W/m K].
LGE	Low Grade Energy.
n	Negative
p	Positive.
P	Power [W].
PM	Porous Medium.
PV	Photo-Voltaic.
Q	Heat [W].
R	Resistance.
T	Temperature [K].
TE	Thermoelectric.
TEG	Thermoelectric Generator.
Z	Figure of Merit.

Greek Letters

α	Seebeck Coefficient..
ρ	Electrical Resistivity.
η	Efficiency.
τ	Thomson Coefficient.
Δ	Difference.

Subscripts

c, cold	Cold Side
car	Carnot.
h, hot	Hot Side.
in	Internal.
out	out.
Load	System Load
m	Mean or average.
max	Maximum.
oc	open circuit.
r	Ratio.

Superscripts

	Rate [per time].

with variable fin space, fin length, fin height, fin materials for both natural and forced convection to enhance the TEG performance [17,18]. For the importance of heat transfer the impact of a squared shape fin perforation was tested to increase heat transfer from fins [19–21]. Increasing heat transfer rate will expand the range of applications for TE devices, recently a TE device was used in a high productivity distiller by Mohammad Nasir et al. [22], moreover, by substituting PV panels with thermoelectric devices, hydrogen could be generated 24 h a day [23,24]. Enhancing the TEG performance requires faster heat transfer rate from the cold surface; it lowers the cold surface temperature and increases the temperature difference between hot and cold surfaces, thus creating higher power [25]. The TEG has limited power generation capacity because as the hot surface temperature increases the cold surface temperature increases as well, this will restrict the power generated from the TEG. To have a high-power generation from TEG the heat transfer from the cold surface should be increased. This could be done by fins or forced convection as performed in [13,26] and many other researches. Such methods require fans and extra volume for fins which may not be available in many applications specially the medical or built-in application. This limitation of the TEG applications may be overcome by implementing porous layer of a suitable material such as Cu or Al, and/or using the high heat transfer rate in phase change regime.

The purpose of this study is to improve the heat transfer rate from the TEG's cold surface, attempting to increased power output. Therefore, the TEG cold surface is embedded in a liquid saturated porous medium and tested for different heat flux conditions (100, 356 and 445 W/m^2) and different porous medium particles (Al and Cu). Steady-state conditions will be validated and compared. Finally, the transient behaviour of the TEG when the heat transfer medium changes is discussed.

2. Thermoelectric generator

The Thermoelectric Generator TEG encounters different energy conversion phenomena between temperature difference and energy; Seebeck voltage, Joulean, Peltier, Conduction and Thomson heat flow as shown in Fig. 1.

Fig. 1 is used to derive the equations governing the TEG. Performing an energy balance for the heat source portion of the TEG yields:

$$\dot{Q}_h + \frac{1}{2} R\, I^2 - K(T_h - T_c) - \alpha\, T_h I = 0 \tag{1}$$

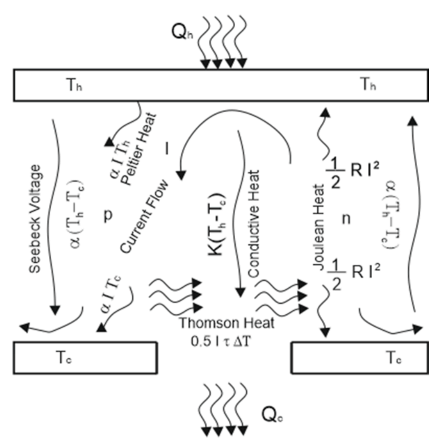

Fig. 1. Schematic Diagram of the TEG working Principle.

and for the heat sink portion of the TEG as

$$-\dot{Q}_c + \frac{1}{2} R\, I^2 + K(T_h - T_c) + \alpha\, T_c I = 0 \tag{2}$$

Because the TEG module is side-wise insulated and in beten ht represents a small value, the Thomson heat was ignored. In such configuration the TE represents a heat engine that generates power (TEG) equal to the difference between supplied and rejected energy [27]:

$$P = \alpha\, I\, (T_h - T_c) - R\, I^2 \tag{3}$$

From this equation its clear that in case the temperature difference increases the power of the TEG will be increased. If this could be done passively (without fans) and with minimum volume (without fins), the main purpose of this work is satisfied.

3. Experimental setup

An experimental setup has been developed to conduct TEG experiments utilizing a porous material. The experimental setup consists of a variable power supply, a multi-meter, a thermoelectric generator (TEG1-12611-08), a fan, thermocouples, a variable heat flux supplying plate, Al and Cu particles (as a porous medium) and electric wires for connections as shown in Fig. 2

TEG1-12611-08 can produce up to 13 W at 300°C temperature difference, withstand a high-temperature differential of up to 350°C, and generate 3 A at maximum power Table 1. Fig. 3 illustrates the concept of the TEG with a porous layer on the top surface to assist in heat removal. When a heat flux is applied to the TEG, a temperature differential is produced along the TEG, this temperature difference is converted into power via the TEG

The open voltage resulted from this temperature difference can be calculated from [29]:

$$V_{oc} = \alpha\ (T_h - T_c) \tag{4}$$

A hotter surface temperature T_h, a colder surface temperature T_c, and a voltage differential will result from the delivered heat at the bottom of the TEG. To boost the output voltage, heat transfer from the colder surface is required.

4. Working principle

The system receives a specified amount of heat flow $\dot{Q}_h$ from the heating plate, increasing the hot surface temperature and creating a temperature difference between the hot and cold surfaces. This temperature difference creates a voltage difference V_{oc} between n and p junctions. If the system is connected to an external load with electrical resistance R_{load} and the ratio of the load resistance to the TEG module resistance is considered $R_r = R_{load}/R_{in}$, and $R_p = R_r + 1$ then the produced voltage, current and power of the TEG are:

$$V_{out} = V_o\ (R_r / R_p), \tag{5}$$

$$I_{out} = \frac{V_o}{(R_{in}\ R_p)} \tag{6}$$

$$P_{out} = \frac{V_o^2\ R_r}{\left(R_{in}\ R_p^2\right)} \tag{7}$$

spectively.

For optimizing the results achieved from the experiment the efficiency of the TEG can be calculated as:

$$\eta = \eta_{car}\left[\frac{R}{\left(R_p + \frac{R_p^2}{ZT_h} - 0.5\eta_{car}\right)}\right] \tag{8}$$

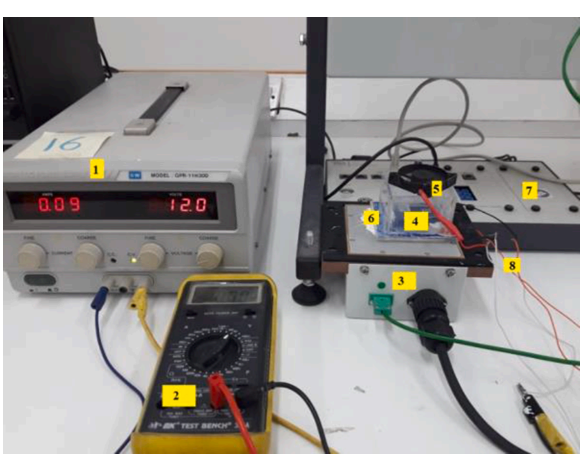

Fig. 2. Actual Setup used to perform the experiments with parts (1- Power Supply, 2- Avometer, 3- Heater, 4- Container, 5-Fan, 6-TEG, 7- DAS and 8-Sensors).

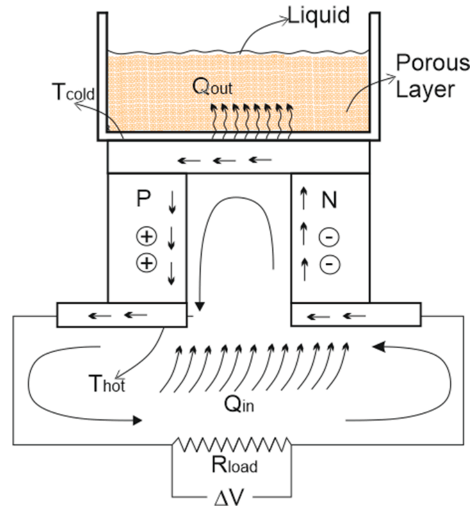

Fig. 3. Schematic Diagram of the Thermoelectric Generator Module.

where $\eta_{car} = \frac{T_h - T_c}{T_h}$ is the Carnot efficiency of the heat engine, compared to the maximum TEG efficiency:

$$\eta_{max} = \eta_{car}\left[\frac{\sqrt{1 + Z\ T_m} - 1}{\sqrt{1 + Z\ T_m} + \frac{T_c}{T_h}}\right] \tag{9}$$

where the figure of merit is $Z = \frac{\alpha^2}{K\ R}$ *with dimension* $[K^{-1}]$, and T_m is the mean TEG temperature.

5. Results and discussion

To perform the experiments, the cold surface container is filled with porous material and has been tested with and without liquid (Ethanol C_2H_6O) foboth free and forced convection, as shown in Fig. 3, in order to improve heat transfer, produce greater voltage differences and therefore higher power.

5.1. Porous medium variation

Two different metallic particles were used as a porous medium to study the effect of porous media on the TEG performance. The particles used were coarse Al chips from a turning machine, the Al parts were 2 mm long by 2 mm wide and 0.2 mm thick. The other Cu particles used were fine spherical particles of 0.5 mm diameter. The thermal conductivity of pure Cu is about 400 W/m K, and that for pure Al is about 200

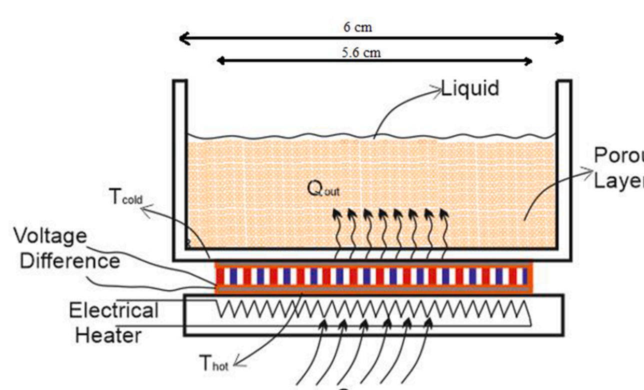

Fig. 4. Schematic of the device used for experimentation.

W/m K [30]. Fig. 4 illustrates a schematic diagram of the device used: the heat flux source, TEG Module, horizontal flat plate surface, and porous medium. The container is 6 cm by 6 cm by 6 cm cubic shape, and the liquid ethanol layer starts from 1 cm until fully evaporation. The hot surface temperature, cold surface temperature, ambient temperature, and open-circuit voltage were registered as indicated in Table 1.

Table 1a shows a sample of data from the experiments.

Many researchers have studied power generation using PV generators or Stirling engines [30–34] others studied the heat transfer from a flat plate embedded in a porous medium [35–37]. It was clear from research that adding a high thermal conductivity porous layer on a flat plate increases the heat transfer from the plate [38]. As TEG performance is negatively affected by the heat transfer to the sink [39,40] researchers should seek methods of enhancing heat transfer. enhanced micro-energy harvester to transform ambient thermal fluctuations into electricity has been performed [41]. Mahgoub [31] investigated the effects of particle diameter and particle thermal conductivity on heat transfer from a horizontal flat plate, for a smooth flat plate without a porous medium he reported,

$$\widetilde{Nu}_L = h\frac{L}{k_f} = 0.0475\ Re_L^{0.78} \tag{11}$$

The averaged Nusselt number governing the effect of particles size and thermal conductivity is reported as [29],

$$\widetilde{Nu}_L = 0.36\left(\frac{d}{L}\right)^{0.27}\left(\frac{k_m}{k_f}\right)^{0.43} Re_L^{0.68} \tag{12}$$

for the range of Reynolds numbers 10^5 to 10^6, particle diameter to plate length ratio from 0.0054 to 0.022 and stagnant effective thermal conductivity-to-fid thermal conductivity ratio from 6 to 17.

Experiments have been performed and results compared for the three different cases with/without porous medium, with and without liquid ethanol and for free and forced convection.

Fig. 5 shows the performance of the TEG if a porous medium is added to the surface, Aluminum and Copper Particles have been tested. The results in Fig. 5 demonstrate that Cu particles are better than Al particles, as expected. This result is due to the higher conductivity of Cu compared to Al. Free and forced convection for both particles are also shown in the figure, it is clear that forced convection is better than free convection, but this is not the important result. The important result is noted from the limited increment between free and forced convection, which reflect the resistance of the particles to airflow, and the airflow does not fully penetrate through the porous particles.

5.2. Air saturated porous medium, and flat plate

The first action taken to analyse the addition of a porous medium to the cold surface of the TEG was to study the heat transfer with forced convection accompanied with porous media for both Al and Cu particles and then to compare the data with the flat plate results.

Table 1
TEG1-12611-08 Technical Specifications [28].

Hot Side Temperature	300 °C
Cold Side Temperature	30 °C
Open Circuit Voltage	9.5 V
Matched Load Resistance	1.8 ohms
Matching Load Output Voltage	4.8 V
Matching Load Output Current	2.7 A
Matching Load Output Power	13 W
Seebeck Coefficient	0.031 V/K
Thermal Conductivity	20.85 W/K
Heat Flow across the Module	325 W
Heat Flow Density	10.4 W/cm^2
AC Resistance at 27 °C and 1000Hz	0.7-1.0 ohms
Width	56 mm
Length	56 mm
Thichness	3 mm

The results of this experiment performed with porous media are shown in Fig. 6, which shows that free convection heat transfer with a porous medium (PM) is slightly higher than the heat transfer rate from the flat plate without PM. This increment in heat transfer rate is reversed with forced convection, which reveals that the porous medium added a thermal resistance to the TEG surface. It should be noted that this reduction is due to the way airflow is supplied (from the top) which reduces the air velocity reaching the inside particles (if the air is forced through a porous medium these results are expected to change).

5.3. Ethanol C_2H_6O saturated porous medium,

As been noted from the previous results of air not permeating through the particles, Ethanol has been used as the heat transfer fluid. Fig. 7 shows the results of using Ethanol with a porous medium for both free and forced heat transfer modes.

The heat transfer mechanism associated with the liquid saturated porous medium is as interesting as with an air-saturated porous medium. The heat transfer from the surface is governed by [24],

$$\dot{Q}_c = \dot{m}_{ev}\ h_{fg} = h_{T-ph}A\ (T_s - T_\infty) \tag{13}$$

where $\dot{m}_{ev}$ is the liquid evaporation rate, h_{fg} is the latent heat of vaporization, and h_{T-ph} is the two-phase flow heat transfer coefficient.

The liquid thermal conductivity (0.33 W/m K) [42,43] is lower than the porous medium thermal conductivity which will lead to a lower heat transfer as shown in Fig. 7a. When forced convection is used with liquid, higher values of voltage differences were noted in Fig. 7b. Here the forced heat transfer by liquid is dominant, the porous medium seems to assist the heat transfer by liquid evaporation. At high heat flux, the effect of the porous medium is demolished.

Fig. 8 shows the power generation from the TEG with liquid saturated porous medium forced convection, the power increases remarkably when liquid temperature passes through evaporation which increases the heat transfer rate thus the power generated from the TEG.

5.4. Error analysis

Different instruments such as thermocouples, power supply, and a multi-meter to measure current and voltage were used to analyse the errors associated with the experimental values. The accuracy of the instruments used in the tests is shown in Table 2. The percentage error was determined using the following formula [44,45]:

$$\text{Error\%} = \frac{\text{Apparatus accuracy}}{\text{Minimum value of apparatus measured}} \times 100\% \tag{10}$$

6. Conclusion

Thermoelectric generators (TEG) are becoming more advantageous in terms of converting low-grade heat to power. TEGs are ideal for harvesting low-grade energy because of their vast range of applications in electronics and medical devices, as well as their bright future in 24-hour power generation. The performance of TEGs were tested in this research using three distinct modes: clear flat plate surface, porous medium surface (both Al and Cu), and Ethanol saturated porous medium. All modes have been tested for both free and forced convection heat transfer. According to the results, Cu particles outperformed Al particles by 14% for forced convection and 7% for free convection. Finally, by converting an air-saturated porous medium to an ethanol-saturated porous medium, the boost was 149 % for Cu and 185 % for Al. Because the base Al value is smaller, the enhancement for an Al saturated porous medium is larger. Finally, the liquid saturated porous medium had the maximum heat transfer rate as well as the best TEG performance. In liquid saturated situations with high heat transfer rates,

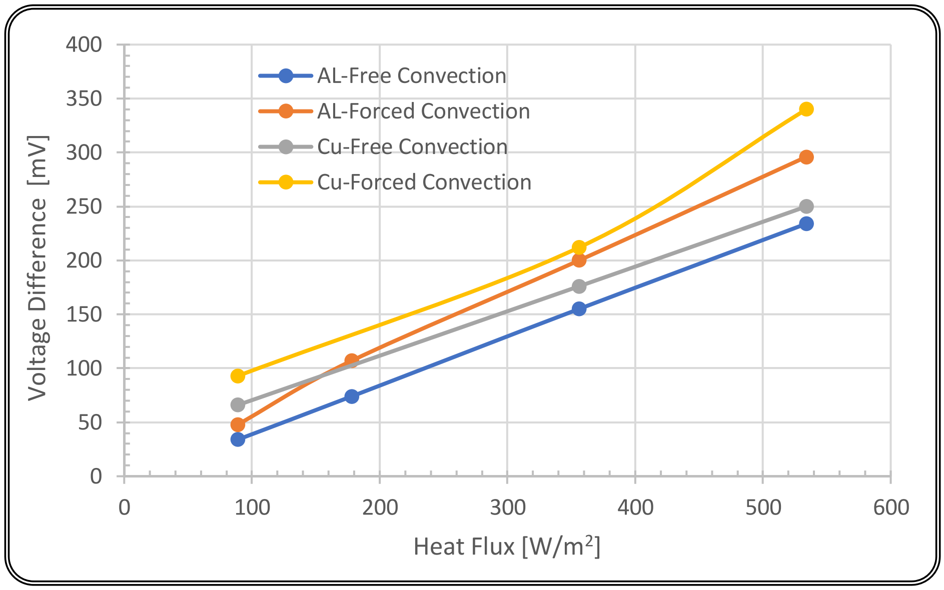

Fig. 5. TEG Performance with porous medium (Al, Cu) under Free and Forced heat transfer.

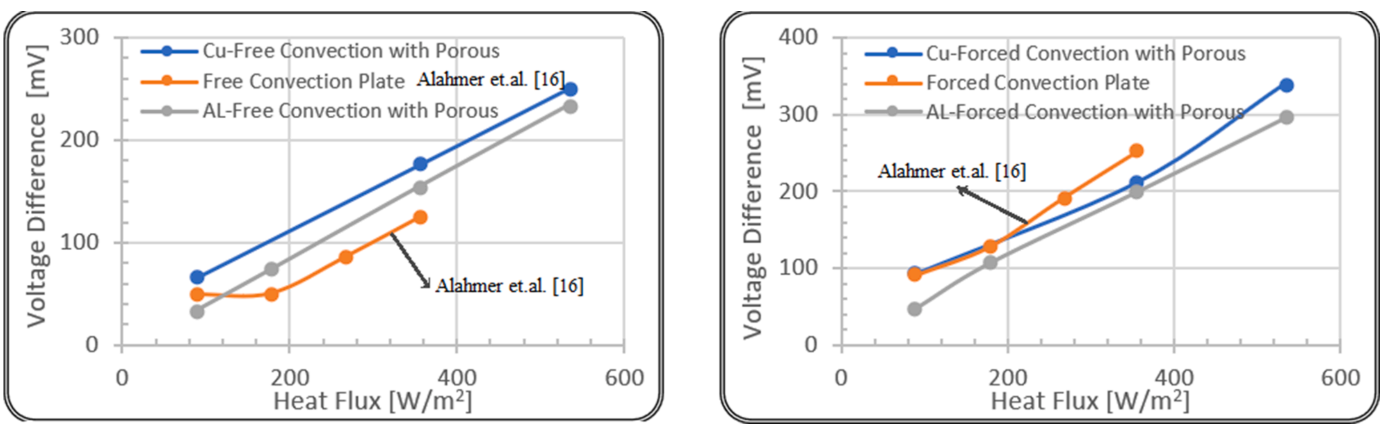

Fig. 6. TEG Performance under Free and Forced heat transfer.

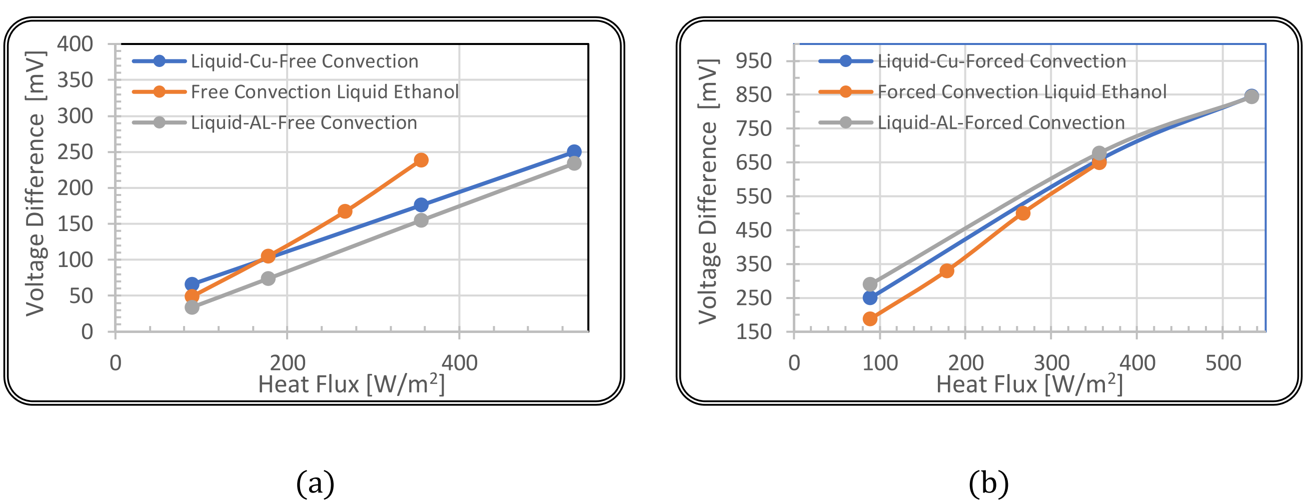

Fig. 7. TEG Performance under Free and Forced heat transfer (Ethanol Saturated Porous Medium).

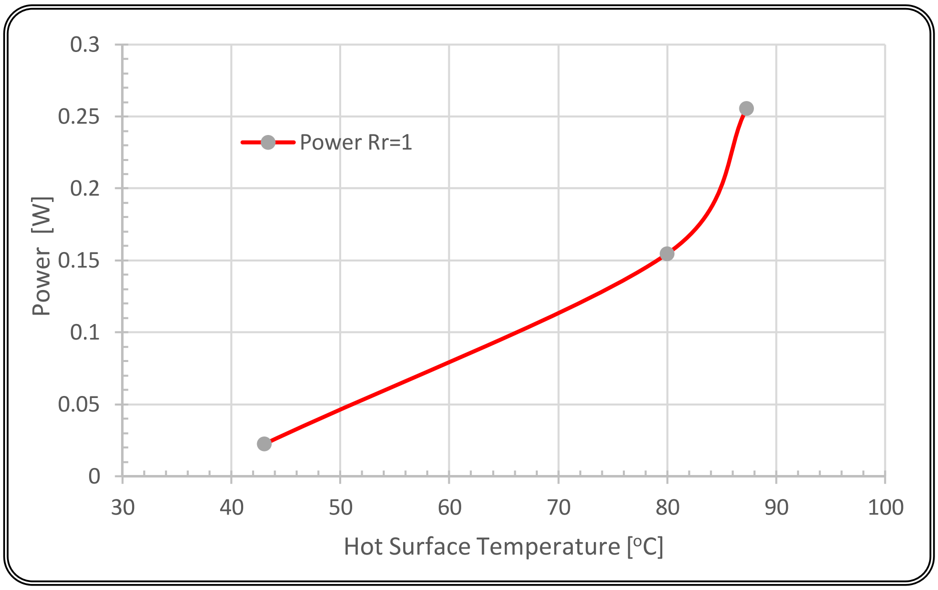

Fig. 8. Power versus hot surface temperature for liquid saturated Cu porous medium with Rr=1.

Table 1a
Data collected for liquid saturated porous medium (Al) experiment, for both free and forced convection (ambient Temp= 19 °C).

LIQUID-POROUS MEDIA -AL				
	Free Convection			
Q (W)	*W/m2*	*T-hot*	*T-cold*	*ΔV (mV)*
5	89	59	44	130
20	356	94.4	70.2	350
30	534	99.4	64.4	489
	Forced Convection			
Q (W)	*W/m2*	*T-hot*	*T-cold*	*ΔV (mV)*
5	89	52	23	290
20	356	87.5	35.2	678
30	534	99.7	37	844

Table 2
Errors calculated for various test equipment.

Apparatus	Accuracy	Range	% Error
Thermocouples	± 1 °C	-200 to 1260°C	0.067
Power Supply Current	+ 3 mV< 10 A	0 to 5 A	0.01
Power Supply Voltage	+3 mV	0 to 120 V	0.01
Multimeter/ Current	±0.1 A	0 to 10 A	± 1
Multimeter/ Voltage	±0.54 V	0 to 600 V	0.09

the impact of the porous medium was eliminated. The results of this work suggest adopting closed system boiling heat transfer from the cold surface to keep cold side temperature constant, and be able to control the power generation directly by the heat input which is a future study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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