EXPERIMENTAL STUDY AND OPTIMIZATION ON THERMOELECTRIC GENERATOR COMBINED WITH HEAT PIPE-HEAT SINK

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ABSTRAK

Thermo-Electric Generator (*TEG*) pada ketika ini adalah antara teknologi penjanaan tenaga dari haba buangan yang paling banyak dikaji oleh para penyelidik. Namun demikian, pengunaan *TEG* hanya digunakan pada skala kecil disebabkan oleh kecekapan tenaga yang sangat rendah. Kekurangan rekabentuk *heat sink* adalah salah satu sebab yang mengurangkan prestasi *TEG*. Jika dibandingkan dengan sistem *TEG* yang biasa digunakan, gabungan sistem *TEG* bersama *Heat Pipe -Heat Sink* (*HP-HS*) adalah kombinasi yang terbaik. Walaubagaimanapun, prestasi *TEG* yang digabungkan dengan *HP-HS* adalah bergantung kepada bentuk geometri, bahan serta optimisasi *HP-HS*. Matlamat kajian ini adalah untuk mengkaji melalui eksperimen kesan bahan, kesan geometri *HP-HS*, kesan konveksi semulajadi dan konveksi paksa, kesan suhu di sebelah panas *TEG* kepada prestasi penjanaan tenaga, serta optimisasi parameter *HP-HS*. Eksperimen telah dilaksanakan dengan dimensi ukuran jarak fin, panjang fin, ketinggian fin yang berbeza, serta perbezaan bahan fin iaitu dari tembaga dan aluminium. Analisis eksperimen dan statistikal telah dilaksanakan dengan kaedah satu-faktor-disatu-masa untuk mendapatkan kesan bahan dan kesan geometri *HP-HS*, kesan kaedah pemindahan haba untuk konveksi semulajadi dan konveksi paksa, serta kesan suhu panas *TEG* yang dipilih pada 250 ^{o}C dan 300 ^{o}C. Tambahan pula, optimisasi objektif-multi menggunakan kaedah *Response Surface Method* (*RSM*) yang telah digunapakai untuk menentukan geometri optimum dari *HP-HS* serta bahan untuk memaksimakan output kuasa *TEG* (*P*), kecekapan *TEG* (η), dan meminimumkan kos ($\$_{HP-HS}$). *HP-HS* dari bahan tembaga telah didapati sebagai pilihan utama dibandingkan dengan bahan aluminium bagi semua kes eksperimen. Ketinggian fin telah didapati mempunyai kesan terbesar bagi tembaga dan aluminium terhadap *P* dan η, diikuti dengan panjang fin dan jarak fin. Sementara itu bagi $\$_{HP-HS}$, ketinggian fin telah didapati mempunyai kesan terbesar, diikuti dengan jarak fin dan panjang fin. Eksperimen juga telah menunjukkan prestasi *TEG* adalah lebih baik di bawah konveksi paksa pada 300 ^{o}C. Tambahan pula, dapatan menunjukkan peningkatan dari segi prestasi *TEG* apabila dibandingkan dengan kajian-kajian lain. Perbezaan peratusan kecekapan *TEG* (η) apabila dibandingkan dengan hasil kajian-kajian lain adalah 40.6 % bagi kelajuan angin udara luar, dan 23.4 % bagi konveksi paksa. Dari segi perbezaan bahan, tembaga didapati menghasilkan prestasi yang lebih baik daripada aluminium disebabkan oleh $\$_{HP-HS}$ yang lebih rendah terhadap *P*, iaitu USD 8.75/W, sedangkan untuk aluminium adalah USD 10.13/W, bagi kaedah kelajuan angin udara luar. Bagi konveksi paksa pula, USD 7.57/W untuk tembaga, dan USD 8.74/W untuk aluminium. Penyelidikan ini juga telah menunjukkan peningkatan pengurangan kos *HP-HS* setinggi 17.9 % bagi kelajuan angin udara luar, dan 29.0 % bagi konveksi paksa jika dibandingkan dengan kos *HP-HS* dalam kajian-kajian lain. Hasil kajian selepas optimisasi juga menunjukkan peningkatan prestasi, dan ia menunjukkan gabungan *TEG* dan *HP-HS* boleh digunakan untuk pelbagai jenis haba buangan.

ABSTRACT

Thermo-Electric Generator (TEG) is presently the most pursued thermal energy harvesting technology from waste heat. In spite of that, TEG devices have been used only on a small scale, because of their low conversion efficiency. Heat sink lack of design is one reason that negatively affects the performance of TEG. As compared to conventional cooling systems which use TEG principle, Heat Pipe Heat Sink (HP-HS) has the best performance with TEG. However, the performance of TEG with HP-HS could be affected by geometry, materials and optimization of HP-HS of the TEG cold side, which are still unknown. Thus, the objective of this study is to investigate experimentally the effect of materials, the geometry of HP-HS under outdoor air speed (ODAS) in Kuala Pahang, Malaysia and forced convection (FC) at 250℃ and 300℃ hot side temperatures on the performance of TEG, as well as to optimize the parameters of HP-HS. Experimental and statistical analysis by one-factor-at-a-time method has been done to find out the effects of materials and geometry of HP-HS under ODAS and FC and TEG hot side temperature on the TEG performance. Furthermore multi-objective optimization using response surface methodology (RSM) is applied to determine the optimum geometry of HP-HS and materials in terms of maximizing the TEG power output (P), TEG efficiency (η), and minimizing HP-HS cost ($\$_{HP-HS}$). The Cu HP-HS was found to be preferable over Al for all cases. The fin height has the highest effect for both materials on P and η followed by fin length, and then fin space. It was also found that the TEG performance was better under FC, and at 300℃. Compared with the literature, improvement of η achieved was 40.6 % for ODAS and 23.4 % for FC. Additionally, Cu HP-HS was found to be preferable over Al because of its lower cost per P ($\$_P$), at 8.75 USD/W; whilst Al was 10.13 USD/W under ODAS. The cost effectiveness for FC was 7.57 USD/W and 8.74 USD/W for Al. The current research also shows an improvement in HP-HS cost reduction by 17.9 % for ODAS and 29 % for FC, compared with estimated HP-HS cost in the literature. The results found after optimization were unique as they positively indicated that with combined use of HP-HS and TEG as a system, waste heat can be used as a heat source generating clean energy without emitting harmful emissions.

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LIST OF SYMBOLS

Al	Aluminium
Cu	Copper
C_{Ep}	Experimental TEG current
C_{Man}	Manufacturer's TEG current
f_h	Fin height
f_{No}	Fin number
f_l	Fin length
f_s	Fin space
P	Thermo-Electric Generator power output
P_{Ep}	Experimental TEG power output
P_{Man}	Manufacturer's TEG power output
R_L	Load resistance
TEG_C	Cold side temperature of Thermo-Electric Generator
TEG_H	Hot side temperature of Thermo-Electric Generator
TEG_{IR}	Internal resistance of Thermo-Electric Generator
V_{Ep}	Experimental TEG voltage
V_{Man}	Manufacturer's TEG voltage
Z	Dimensionless figure of merit
ZT	Non-dimensionalize figure of merit
η	Thermo-Electric Generator efficiency, HP-HS cost
$\$_{HP-HS}$	Heat Pipe-Heat Sink cost
$\$_M$	Metal price per mm^2
$\$_{Mb}$	Metal block price
$\$_P$	Cost per power
$\$_{\mathrm{TEG}}$	Thermo-Electric Generator price.
$\$_{HP}$	Heat pipe price

LIST OF ABBREVIATIONS

APC	Auxiliary Power Consumption
BBD	Box–Behnken Design
Bi2Te3	Bismuth telluride
CCD	Central Composite Design
DoE	Design of Experiments
Ca3Co4O9	Ceramics material
CaMnO3	Ceramics material
EIA	Energy Information Administration (of the United States)
FC	Forced Convection
HP-HS	Heat Pipe-Heat Sink
HP	Heat Pipe
HP-HS -TEG	Heat Pipe-Heat Sink with Thermo-Electric Generator
HSTE	Solar Thermo-Electric
Nu	Nusselt number
NaCo2O4	Ceramics material
OFAT	One-Factor-At-Time
ODAS	Outdoor Air Speed
PbTe	lead telluride
PTH	Polythiophene
PEDOT	Polyethylene dioxythiophene
PPY	Polypyrrole
PEDOT	Poly carbazole
PEDOT:PSS	Polystyrenesulfonate
PEM	Proton Exchange Membrane
P_r	Prandtl number.
RSM	Response Surface Methodology
R_a	Rayleigh number
SiGe	Silicon-Germanium
SSRes	Sum Of Square of error
SST	Total Sum of Squares
SD	Standard Deviation

STECG	Solar Thermo-Electric Cogeneration
TIM	Thermal interface material
TE	Thermo-Electric
TEG	Thermo-Electric Generator
TEGs	Plural of TEG
TWT	Traveling-Wave Tube

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