Abstract

Thermoelectric generators (TEGs) play a vital role in Waste Heat Recovery (WHR) by directly converting thermal energy into electrical energy through the Seebeck effect. When a temperature gradient is established across the thermoelectric material, charge carriers (electrons or holes) diffuse from the hot side to the cold side, generating an electric voltage. This solid-state energy conversion technology has advantages such as no moving parts, silent operation, and high durability, making it ideal for applications in automotive exhaust systems, industrial processes, and remote power generation. Despite their relatively low efficiency compared to other waste heat recovery technologies, TEGs offer unique benefits in scenarios where conventional methods are impractical. The performance of a TEG is significantly influenced by the temperature difference (ΔT) across its hot and cold sides. A higher temperature difference enhances the thermoelectric voltage and power output due to an increased Seebeck coefficient and thermal gradient. However, excessive temperature gradients can also introduce thermal stresses, leading to material degradation over time. The Seebeck coefficient generally depends on the material's properties and average temperature rather than the temperature difference itself. For most thermoelectric materials, the Seebeck coefficient decreases with increasing average temperature due to increased thermal carrier excitations, which reduce the charge carrier asymmetry. However, in some materials, it may initially increase with temperature before declining. The temperature difference across a thermoelectric generator affects the output voltage and power but doesn’t directly increase the Seebeck coefficient, as the coefficient is primarily a material-specific property tied to its electronic structure. Furthermore, the temperature distribution on the hot and cold sides plays a crucial role in maintaining uniform heat flux. Non-uniform heating can create hotspots, reducing the efficiency and longevity of the thermoelectric material. Effective heat spreading and

cooling mechanisms, such as heat sinks or phase-change materials, can help in maintaining a stable temperature distribution, thereby improving TEG performance. The configuration of a TEG, including its material composition, number of stages, and leg geometry, significantly affects its efficiency. The choice of thermoelectric material determines the conversion efficiency, as materials with high Figure-of-merit (ZT) values exhibit superior performance and organic materials improve the system sustainability. Multi-stage TEGs can be employed to optimize performance across a wide temperature range by using different materials in a cascaded manner. This approach ensures that each stage operates efficiently within its optimal temperature window. The geometry of the thermoelectric legs also plays a crucial role in determining heat transfer characteristics and electrical resistance. Optimizing the leg length and cross-sectional area can enhance the power density and efficiency of the module. Therefore, a balance must be achieved to maximize performance.

The current study discusses three ways to enhance the TEG performance, viz., hot side performance enhancement, TEG device improvement, and cold side performance enhancement. Enhancing heat transfer on the hot side of a TEG can be achieved by incorporating a vortex generator, which disrupts boundary layers and induces turbulence for improved convection. Optimizing TEG performance involves exploring high-ZT sustainable materials, multi-stage configurations, and refined leg geometries. Additionally, replacing conventional coolants with hybrid nanofluids on the cold side enhances thermal conductivity and cooling efficiency, boosting overall power output. These methods, along with optimization techniques and the development of a hybrid system, were examined for their thermohydraulic and electrical performance.

For TEG hot side performance enhancement, an experimental study has been carried out to investigate the influence of novel vortex generators (delta (DVG), envelope

(MVG), and fishtail (FVG)) on the performance of a heat exchanger integrated with a thermoelectric generator (TEG). The effects of the distance-to-height ratio (D/H) and the inclination angle (θ) of the vortex generator configurations on key thermohydraulic parameters— heat transfer coefficient (HTC), pressure drop, and thermal enhancement factor (TEF)—along with their impact on TEG performance metrics, namely power output, have been systematically analyzed. 1-D thermal resistance model analyses heat transport. Vortex generators create longitudinal vortices that enhance fluid mixing. This improves heat transfer by disrupting the boundary layer and bringing hotter fluid closer to the cooler surface. The maximum increment in heat transfer coefficients was 45.16%, 51.85%, and 56.18% for MVG, DVG, and FVG, respectively at D/H=2 and θ=60°. The highest pressure drops obtained are 3.46Pa, 3.72Pa, and 3.27Pa for MVG, DVG, and FVG, respectively at D/H=2 and θ=90°. The TEG output improved due to higher surface temperature in channels equipped with VGs than the smooth channel, owing to better heat transfer. The highest average TEG power obtained is 1.62W.

The focus is then drawn towards modeling a modified TEG based on stages, new sustainable thermoelectric material, and TEG leg geometry. A theoretical study has been carried out that analyses a multistage variable-shaped thermoelectric generator (MVS TEG) for a combination of dissimilar materials. Effect on voltage, power, conversion efficiency, normalized constraints (voltage, power, and conversion efficiency), and second law efficiency with a row number, exhaust inlet temperature, and coolant flow rate were investigated. Results revealed the row number as the most critical input parameter followed by exhaust inlet temperature and coolant flow rate. Also, the work gives optimum values of rows for voltage and power as N_x=19 for MVS TEG-1, MVS TEG-3, and MVS TEG-4 while N_x=18 for MVS TEG-2. The exhaust inlet temperature variation increases the voltage and power output by 54 to 59% and by 53 to 58%

respectively. The coolant flow variation has a greater impact on the conversion efficiency and the average improvement in the efficiency is about 9.23% in the present study. The second law efficiency decreases with the increase in all the input parameters.

For TEG cold side performance enhancement analysis, the effect of dissimilar-shaped nanoparticles (i.e., graphene-platelet shape, Al_2O_3-blade shape, MWCNT-cylindrical shape, and Fe_3O_4-brick shape), by 50:50 v/v., hybrid nanofluids in a mini channel heatsink (MCHS) with varying volume flow rate and vol. fraction (0.1% - 1%) have been discussed. Comparative thermal performance parameters (COP and figure of merit) and exergetic analysis (inlet and outlet exergy) have been investigated along with the heat transfer rates. The study is carried out with water as the reference fluid. The cylindrical-brick (MWCNT-Fe_3O_4) blend performs the best in terms of thermal properties, with 79.27% enhancement with volume flow rate variation and 1.03% enhancement with the volume concentration in the average heat transfer coefficient. The highest TEG power and conversion efficiency are 6.085W and 5.47% respectively. Cylindrical-brick (MWCNT-Fe_3O_4) hybrid nanofluid gives the best TEG performance.

A numerical study consisting of different geometries of vortex generators (VGs) under different ambient conditions has been studied to find the thermohydraulic effectiveness of the VGs in a rectangular channel and a comparative analysis has been carried out. The shapes of VG examined are delta (D), envelope (M), and fishtail (F). The ambient heat transfer coefficients (HTCs) applied are 5, 15, and 25W/m^2K. Various thermal and fluid flow parameters have been taken into consideration. Taguchi design-of-experiments is used to carry out the combinations of runs required for the analysis. The analysis of variance (ANOVA) and S/N ratios further helps in determining the optimum or the best factors for the outcome. Quantitatively, the heat transfer coefficient value at the outlet increases by 2.797, 2.777, and 2.834 times for DVG, MVG, and FVG respectively as compared to the inlet for h=25W/m^{2}K. Similarly, for h=15W/m^{2}K, h raises by 2.801, 2.783, and 2.838 times at the outlet when compared to the parameter value at the inlet. For h=5W/m^{2}K, these values are 2.785, 2.766, and 2.566 for DVG, MVG, and FVG respectively. The pressure drops by 84.94%, 92.42%, 91.39%, and 89.44% for the smooth-, DVG-, MVG-, and FVG-incorporated channels. Furthermore, the highest value of signal-to-noise ratio is exhibited by the factors A3 (fishtail VG) and B1 (h=5W/m^{2}K) out of the 9 runs. The machine learning ANN model gives the coefficient of determination value (R^2) of 1, 0.99994, and 0.99962 indicating high proficiency of the neural network.

Additionally, an innovative hybrid system comprising an Evacuated U-tube Solar Water Heater (EUSWH) integrated with a TEG has been investigated. To enhance thermal and electrical performance, fishtail vortex generators (FVGs) are strategically implemented on the hot side of the TEG module. The study examines the influence of key operating parameters, including incident solar radiation intensity, water mass flow rate, inlet EUSWH temperature, and the incorporation of vortex generators, on various performance metrics of the EUSWH, TEG, and the overall hybrid system. The analysis reveals that the EUSWH achieves peak performance at the maximum solar irradiance (G). However, increasing the mass flow rate results in a reduction in the outlet water temperature ($T_{out,EUSWH}$), while enhancing the thermal energy output (Q_{EUSWH}) and thermal efficiency (η_{EUSWH}). Conversely, a rise in the inlet EUSWH temperature ($T_{in,EUSWH}$) increases $T_{out,EUSWH}$ but decreases Q_{EUSWH} and η_{EUSWH}. At G=1000W/m^2, η_{EUSWH} increases by 2.63% and 2.62% at mass flow rates of 0.01 and 0.02kg/s, respectively when the $T_{in,EUSWH}$ varies from 303-313K. However, it decreases by 0.45% and 0.46% at $T_{in,EUSWH}$ of 303 and 313K, respectively when mass flow rates are varied from 0.01-0.02kg/s. The hybrid system efficiency (η_{HS}) is enhanced with the application of FVGs on the hot side of the TEG. The hybrid system efficiency increases by 9.12%, and 9.38% for 0.01 and

0.02kg/s mass flow rate, respectively, due to FVGs application. At $T_{in,EUSWH}$=313K, η_{HS} increases by 15.71% and 25.32% for 0.01 and 0.02kg/s.