Chapter 8
Concluding Remarks and Future Scope

8.1 Concluding remarks

The research focuses on enhancing waste heat recovery through thermoelectric generators (TEGs) by systematically investigating all three critical components: the hot side, the TEG module, and the cold side. The study further optimized the heat transfer enhancement technique on the hot side to identify the most efficient configuration. Finally, a solar-TEG hybrid system was developed, integrating the optimized vortex generator configuration, to comprehensively evaluate its performance. At each stage of the study, the main inferences can be summarized as follows:

- The maximum heat transfer coefficient improvements on the hot side for envelope, delta, and fishtail VGs were observed to be 45.16%, 51.85%, and 56.18% respectively, over the smooth channel. The maximum pressure drop increases by 1.3, 1.47, and 1.17 times for envelope, delta, and fishtail VGs respectively over the smooth channel.
- The value of TEF for all the VG configurations remains above 1, which showcases the thermohydraulic effectiveness of the VGs. The highest value of 1.32 is exhibited by FVG at $D/H=4$ and $\theta=30°$. The power output of the TEG increases with the installment of VGs. The highest power output obtained is 1.62W at $D/H=2$, $\theta=60°$ for the fishtail vortex generator.
- The distance-to-height ratio and angle of inclination angle of the VGs for obtaining the highest thermohydraulic performance of the hot side of the TEG were $D/H=2$ and $\theta=60°$ for fishtail VG.

- Vortex generators (VGs) enhance heat transfer by creating longitudinal vortices that disrupt the thermal boundary layer and improve fluid mixing. This mechanism brings higher-temperature fluid into direct contact with heat exchange surfaces, leading to a more uniform temperature distribution. Consequently, VGs significantly improve the hot-side performance of a TEG, which can increase power output and enable the design of more compact waste heat recovery systems.
- Multistaging, novel materials, and variable cross-section give an improved performance with MVS-TEG-2 as the best-performing TEG. It produces the highest voltage (165.1V), power (31.1W), and conversion efficiency (18.75%).
- The highest second law efficiency is exhibited by MVS TEG-3 with a value of 24.49%. MVS TEG-2 exhibits the best-normalized performance when row numbers are considered, while MVS TEG-3 exhibits the best-normalized performance when exhaust inlet temperature and coolant flow rate are considered.
- The novel multi-variable strategy (MVS) TEG design demonstrated superior conversion efficiency. This performance enhancement is a direct result of implementing key modifications: multi-stage architecture, tapered leg geometry, and the use of dissimilar materials with advanced thermoelectric properties, which collectively optimize thermal impedance matching and energy conversion.
- Among the different coolants studied, the best thermal performance is exhibited by the cylindrical-brick (MWCNT-Fe_3O_4) blend, and the best exergetic performance by the blade-cylindrical (Al_2O_3-MWCNT) blend.
- The cylindrical-brick (MWCNT-Fe_3O_4) blend improves the heat transfer coefficient by 79.27% and the blade-cylindrical (Al_2O_3-MWCNT) blend exhibits the highest FOM value of 0.9841 at φ=0.001 and flow rate =7 x$10^{-6}m^3/s$.

- The highest TEG power and conversion efficiency is exhibited when a cylindrical-brick (MWCNT-Fe_3O_4) blend is used. The highest values obtained are 6.085W and 5.47% respectively.
- Hybrid nanofluids serve as advanced coolants with the potential to significantly improve heat extraction on the TEG's cold side due to their superior thermal properties. For practical implementation, future work must address inherent challenges such as increased pumping power demands, nanoparticle precipitation, and long-term stability to ensure viability.
- The highest values of heat transfer coefficient, pressure drop, and TEF obtained are 554.17W/m^2K at ambient h=5W/m^2K for FVG, 12.93Pa for DVG, and 2.258 for FVG at h=25W/m^2K.
- With 20 neurons in the hidden layer and 1 in the output layer, predicting fit quality (R^2) of 1, 0.99994, 0.99962, and 0.99991.
- Analyzing heat transfer performance under a wide range of ambient and operating conditions is critical for assessing real-world applicability. Furthermore, employing optimization algorithms and artificial neural networks is recommended to efficiently determine the statistically optimal configuration for a vortex generator-enhanced TEG system, moving beyond a parametric study to a definitive design solution.
- The TEG power is improved with the installment of the fishtail VGs in the EUSWH-TEG hybrid system. The maximum voltage, current, power, and conversion efficiency increase by 3.57%, 3.62%, 7.49%, and 3.25% respectively for channels equipped with fishtail VGs, at mass flow rate=0.01kg/s and inlet temperature=303K.

- The maximum improvement hybrid system efficiency obtained is 7.39% at mass flow rate=0.01kg/s and inlet temperature=303K with fishtail VG.
- The integration of a TEG with a solar water heater presents a viable co-generation system for the simultaneous production of electricity and domestic hot water. The overall efficiency of this hybrid system can be substantially increased by incorporating performance-enhancing structures like vortex generators on the thermal side, maximizing the utilization of captured solar energy.

Based on the studies conducted in this thesis, the overall performance of a thermoelectric generator (TEG)-based waste heat recovery system can be significantly enhanced. This improvement is not attributable to a single factor, but rather to the synergistic optimization of all major aspects associated with a TEG module. These include maximizing the temperature difference across the hot and cold sides, as well as optimizing TEG device specifications such as staging, leg geometry, and material properties. Furthermore, the findings indicate substantial potential for refining these TEG enhancements and integrating them with other energy systems to develop efficient co-generation applications.

This study provides insights into TEG system enhancement, but its findings should be considered in light of the following limitations:

- Modeling Assumptions and Simplifications: The use of a steady-state model does not capture real-world transient operations, such as varying exhaust flow. The assumption of constant thermophysical properties for all materials ignores their temperature-dependent nature, likely leading to conservative performance estimates.

- Scope of Design Parameters: The study was limited to a predefined set of vortex generator shapes and nanofluid combinations. Performance may be further improved by exploring geometries or materials beyond the selected scope.
- Economic and Practical Viability: The analysis focuses solely on technical performance, omitting economic considerations such as manufacturing costs, nanofluid premium pricing, and cost-per-watt analysis. This limits assessment of real-world feasibility.
- System-Level Integration Challenges: The hybrid system analysis remains theoretical. Practical integration challenges, including control complexity, maintenance, and performance under real weather conditions, were not explored.

8.2 Future scope

The conclusions of this thesis provide a clear foundation for several targeted research directions. Based on the limitations and opportunities identified in this work, the following future studies are recommended to build upon these findings and facilitate practical application:

- Optimization of Novel Vortex Generator Configurations: While this study demonstrated the superior performance of the fishtail vortex generator, future work should focus on its geometric optimization. Drawing from the conclusion that distance-to-height ratio (d/H) is a critical parameter, a multi-objective optimization study should be conducted to determine the ideal d/H, pitch, and angling for fishtail generators specifically, to maximize the trade-off between heat transfer enhancement and pressure drop. This would provide industry with a ready-to-implement optimal design.

- Development of Application-Specific TEG Modules: The models developed here assumed constant material properties. To directly leverage the finding that temperature gradient is the primary driver of power output, future research should involve prototyping and experimentally validating a staged TEG system. This system would use different materials (e.g., Skutterudites on the hot side, Bi_2Te_3 on the cold side) optimized for the specific temperature ranges encountered in automotive exhaust or solar thermal systems, moving from theoretical modeling to practical, high-efficiency module design.
- System-Level Integration and Hybrid Nanofluid Validation: Building on the promising thermohydraulic performance predicted for hybrid nanofluids, a critical next step is to address practical application barriers. Future work must experimentally investigate the long-term stability, dispersion homogeneity, and corrosion impact of these nanofluids on a TEG's cold-side heat exchanger. This is essential for industry adoption, as it assesses durability and real-world maintenance costs alongside performance gains.
- Transient and Real-World Condition Analysis: This study was conducted under steady-state assumptions. To apply this work to real industrial environments like automotive exhaust cycles, future research must develop a transient model. This model would simulate the system's performance under dynamic conditions—such as varying exhaust gas temperature, mass flow rates, and coolant flow—to predict actual energy recovery over a standard driving cycle and validate the system's robustness.

The findings of this thesis provide a foundation for both academic advancement and practical engineering application. The following recommendations are offered to improve upon the present work and to guide its potential implementation.

8.2.1 Recommendations for improving the present work

To enhance the accuracy and robustness of the current models, the following steps are recommended:

- Incorporate Temperature-Dependent Properties: The assumption of constant thermophysical and thermoelectric properties, while simplifying the model, is a source of error. It is recommended to refine the computational model by implementing temperature-dependent properties for exhaust gases, nanofluids, and TEG materials. This will provide a more accurate, quantitative prediction of absolute system performance, especially under high-temperature gradients.
- Develop and Validate a Transient Model: The steady-state assumption limits the model's applicability to real-world scenarios like automotive drive cycles. The immediate next step should be the development of a dynamic, transient model that can simulate performance under varying exhaust and coolant conditions. This model must be validated against experimental data from a laboratory-scale prototype to confirm its predictive reliability.
- Experimental Validation of Key Findings: The superior performance of the fishtail vortex generator and the specific hybrid nanofluids should be confirmed through rigorous experimentation. Building a prototype heat exchanger and TEG setup for bench testing is crucial to move these findings from theoretical promise to proven concept, thereby quantifying any discrepancies between simulation and reality.

8.2.2 Recommendations for application and implementation

The present work offers valuable insights for industry and system designers in the field of waste heat recovery:

- For Automotive Exhaust System Designers: The fishtail vortex generator, particularly at its optimal distance-to-height ratio (d/H) identified in this study, is recommended for integration into the design of new exhaust heat recovery systems. Its design offers a favorable balance between heat transfer enhancement and pressure drop, which is critical for minimizing engine backpressure.
- For TEG Module Manufacturers: This research demonstrates that significant gains can be achieved through system-level design rather than just material science. Manufacturers are recommended to explore the development of application-specific, staged TEG modules tailored to the temperature profiles of different heat sources (e.g., automotive exhaust vs. solar thermal systems), as the analysis shows temperature gradient is the primary driver of power output.
- For Thermal System Engineers: For applications requiring high heat flux dissipation on the cold side of a TEG, the use of the specific hybrid nanofluid combinations analyzed in this work is recommended. However, a parallel focus on solving practical challenges of nanofluid stability, corrosion prevention, and economic viability is essential for successful long-term deployment.
- For Hybrid System Integrators: The successful integration of TEG technology with an Evacuated U-tube Solar Water Heater presents a viable blueprint for developing co-generation systems. It is recommended that this concept be piloted in residential or commercial settings to provide both hot water and auxiliary electricity, thereby improving overall energy sustainability.

By following these recommendations, researchers can build upon the limitations of this work, and industry practitioners can leverage its key findings for practical, efficient energy harvesting systems.