



Design and Fabrication of a Thermoelectric Waste Heat Recovery System for Industrial Flue Gas Ducts

Guided by

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Abstract—Industrial processes release a considerable amount of thermal energy through exhaust gases and flue gas systems, and a significant portion of this energy is discharged into the surroundings without further utilization. Thermoelectric generators (TEGs) provide a direct method for converting a temperature difference into electrical energy through the Seebeck effect. This paper presents the design and fabrication of a thermoelectric waste heat recovery module intended for installation on a vertical industrial flue gas duct. The system consists of a mild-steel vertical duct, copper thermal collector plates, TEG modules, aluminium heat sinks with cooling fans, thermal insulation, and an electronic monitoring system built around an Arduino UNO, K-type thermocouples with MAX6675 modules, voltage and current sensing circuits, a DC-DC converter and an LCD display. The primary objective is not high-power generation but the recovery of otherwise wasted thermal energy and its conversion into useful electrical energy. In a prototype test at a pipe temperature of 140.8 °C, a temperature difference of 38.5 °C across the TEG modules gave an output voltage of 10.96 V and an output power of about 9 W. The developed prototype provides a platform for studying thermoelectric energy harvesting from industrial exhaust systems and for evaluating the influence of thermal gradients, heat transfer, cooling conditions and electrical loading on TEG performance.

Keywords—Thermoelectric Generator, Waste Heat Recovery,

Seebeck Effect, Flue Gas, Sustainable Energy, Energy Harvesting, TEG, Industrial Waste Heat.

I. INTRODUCTION

Energy demand has continuously increased with industrial development. At the same time, a considerable amount of energy supplied to industrial processes is ultimately rejected as waste heat. Exhaust gases, furnaces, boilers, engines and industrial heating systems are common sources of this rejected thermal energy, and waste heat recovery therefore represents an important approach for improving overall energy utilization [1], [7].

Thermoelectric generators are solid-state energy conversion devices capable of directly converting a temperature difference into electrical energy. Unlike conventional mechanical power generation systems, TEGs have no moving parts and can be integrated with heat sources where conventional recovery systems may be difficult to install [2], [5].

The electrical generation capability of a TEG is strongly dependent on the temperature difference between its hot and cold surfaces. Therefore, effective heat transfer from the waste-heat source to the hot side and efficient removal of heat from the cold side are important design considerations [3], [4].

Previous research has investigated thermoelectric generators for waste-heat recovery in industrial and automotive applications [1], [6]. Literature has also examined system integration, heat-transfer enhancement, converter circuits and thermal management for improving thermoelectric performance [3], [8].

In this work, a compact thermoelectric waste heat recovery module is designed for a vertical flue gas duct. The system combines thermal collection, thermoelectric conversion, cooling, electrical conditioning and real-time monitoring in a single prototype.

II. PROBLEM STATEMENT

Industrial flue gas systems continuously release thermal energy into the environment. Conventional systems generally focus on removing the exhaust gases safely, while a portion of their available thermal energy remains unused.



The main problem addressed in this research is the development of a simple and practical system capable of collecting a portion of this waste heat and converting it into electrical energy using TEG modules. The major technical challenges include:

- efficient transfer of heat from the flue gas duct to the TEG hot side;
- maintaining a suitable temperature difference across the TEG modules;
- effective cooling of the TEG cold side;
- minimizing thermal contact resistance;
- conditioning the generated electrical output; and
- monitoring thermal and electrical parameters during operation.

III. OBJECTIVES

- To design a thermoelectric waste heat recovery system for a vertical industrial flue gas duct.
- To fabricate a thermal collection arrangement using copper plates.
- To integrate multiple TEG modules with the heat collection system.
- To provide suitable heat sinks for cold-side cooling.
- To develop an Arduino-based monitoring system.
- To measure hot-side, cold-side and duct temperatures.
- To monitor voltage and current generated by the TEG system.
- To investigate the relationship between temperature difference and electrical generation.
- To demonstrate the utilization of otherwise wasted thermal energy.
- To explore the potential of TEG technology for sustainable energy recovery.

IV. SUSTAINABLE ENERGY AND ENVIRONMENTAL SIGNIFICANCE

Waste heat recovery is an energy-efficiency approach in which thermal energy that would otherwise be rejected to the surroundings is utilized for another useful purpose. The proposed system supports sustainable energy utilization by converting part of the available thermal gradient into electrical energy without requiring additional fuel for electricity generation, since in an actual installation the heat source is the existing flue gas. In the prototype, an LPG burner represents the flue gas and the cooling fans are powered from a separate supply, so the reported output is not net of the fan consumption.

The system is particularly suitable for low-power energy harvesting applications where the waste heat source is already available, such as sensors, monitoring systems, low-power electronics and auxiliary electrical systems.

The proposed approach does not directly eliminate industrial emissions. Its environmental significance lies in improved utilization of existing thermal energy and the

possibility of reducing the requirement for externally supplied electrical energy for suitable low-power applications. Studies on industrial waste heat have identified waste heat recovery as a relevant approach for energy conservation and sustainable development [7].

V. LITERATURE REVIEW

Thermoelectric generators have been studied extensively for converting waste heat into electrical energy [1], [2]. The basic principle is the Seebeck effect, in which a temperature difference across a thermoelectric material produces an electrical potential.

Research in automotive applications has investigated the integration of TEG systems with exhaust systems and the influence of thermal conditions on electrical output [6]. Various studies have also addressed the modelling and design of TEGs for waste heat recovery, emphasizing thermal resistance, temperature distribution, module characteristics and system configuration [3]–[5].

Recent research has further considered power-conditioning circuits such as boost converters, because TEGs can produce relatively low voltage depending on the available temperature gradient. Converter systems can make the generated electrical energy more suitable for practical loads and energy storage [8]. Work on the commercialization of TEGs for low-temperature waste heat recovery [9] and on waste heat potential [7] highlights the importance of recovering thermal energy from industrial processes.

VI. WORKING PRINCIPLE

The proposed system operates according to the Seebeck effect. When two sides of a TEG experience different temperatures, an electrical potential difference is generated across the module. For a string of N modules connected in series, the open-circuit voltage is

$$V = N\alpha\Delta T \quad (1)$$

where V is the open-circuit voltage of the string, N is the number of series-connected modules (ten in the prototype), α is the effective Seebeck coefficient of one module and ΔT is the temperature difference between the hot and cold sides. Under load, the terminal voltage is lower than this value.

The hot side of the TEG is thermally connected to the copper plates attached to the flue gas duct. Heat transferred from the hot exhaust gas raises the temperature of the collector plates. The opposite side of the TEG is connected to an aluminium heat sink, which transfers thermal energy to the surroundings and helps maintain a lower cold-side temperature. The resulting temperature difference generates electrical energy, which is supplied to the electrical conditioning and monitoring circuit.

VII. SYSTEM DESIGN AND FABRICATION

A. CAD Model and Overall Layout

The prototype was modelled in SolidWorks before fabrication. Fig. 1 shows the isometric, front and top views of the assembly with the main dimensions in millimetres. An insulated vertical duct of 900 mm height stands on a square

base of approximately 400 mm × 400 mm. The TEG modules with their heat sinks and fans are mounted around the duct at

two levels, and the top view shows how the units are distributed around the duct circumference.

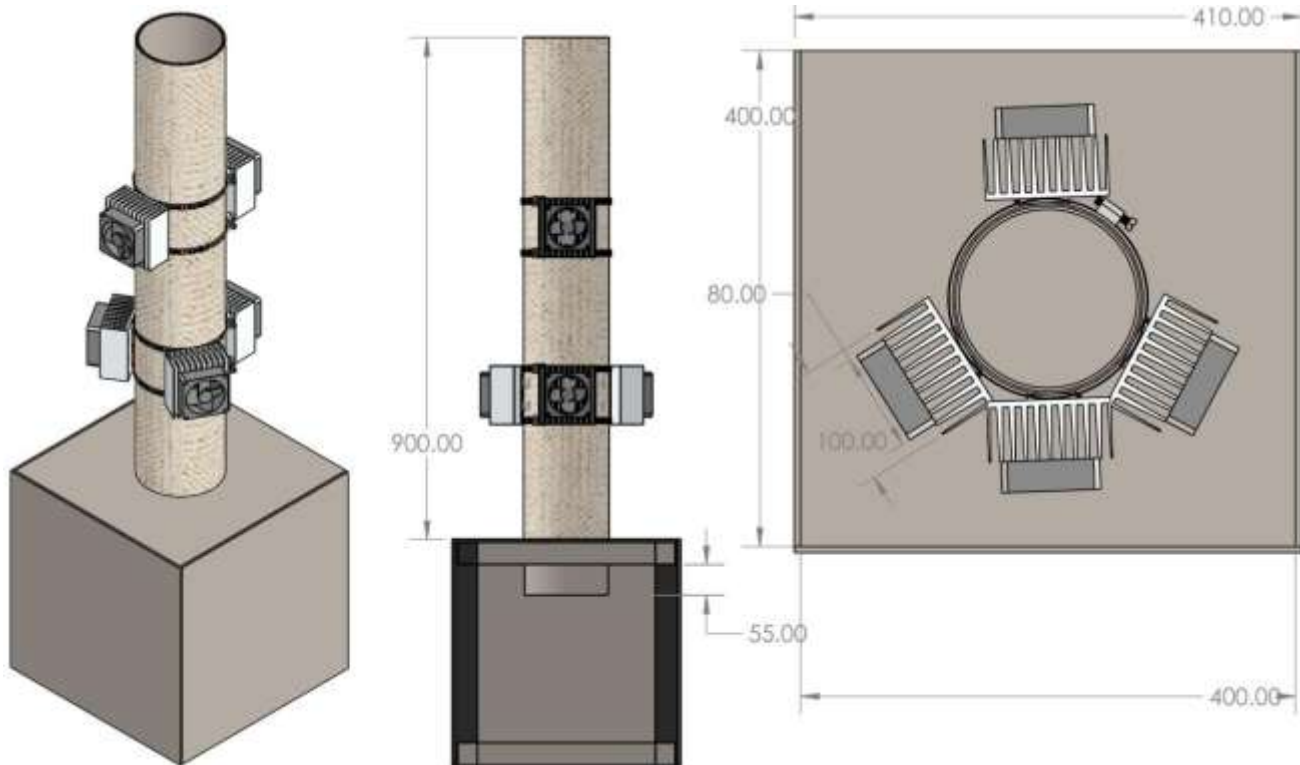


Fig. 1. CAD model of the prototype: isometric view (left), front view (centre) and top view (right). Dimensions are in mm.

The heat-flow path through the assembly is shown in Fig. 2(a). Heat from the hot flue gas passes through the duct wall and the copper collector plates to the hot sides of the TEG modules, and is rejected from their cold sides through aluminium heat sinks cooled by DC fans. Thermal paste is applied between the TEG modules and the heat sinks to reduce the contact resistance. As shown in Fig. 2(b), the duct is covered with glass wool insulation and an aluminium foil cover.

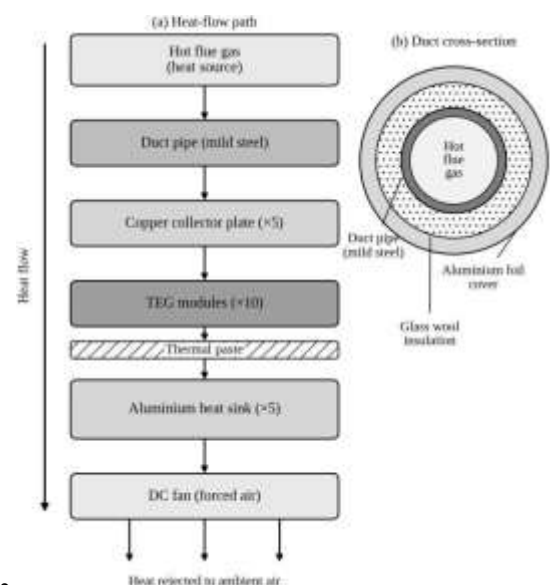


Fig. 2. Thermal and mechanical arrangement. (a) heat-flow path from the hot flue gas to the ambient air and (b) cross-section of the insulated duct.

B. Flue Gas Duct

The main structure is a vertical mild-steel duct designed to represent an industrial flue gas passage. The duct provides the thermal source for the thermoelectric system. Copper thermal collector plates are positioned around the duct to collect heat from the duct wall.

C. Copper Thermal Collector Plates

Copper is used because of its high thermal conductivity. Five copper plates are incorporated into the system. Each plate acts as a thermal interface between the duct and the thermoelectric modules, providing a comparatively low thermal resistance path for heat transfer toward the TEG hot sides.

D. Thermoelectric Generator Modules

A total of ten TEG modules are incorporated into the prototype. Two TEG modules are mounted on each copper thermal collector plate. This arrangement increases the total thermoelectric conversion area and allows multiple modules to operate simultaneously.

E. Heat Sinks and Cooling Fans

Aluminium heat sinks are mounted on the cold side of the thermoelectric modules to dissipate heat and maintain a temperature difference across the TEG modules. A DC axial fan is fitted on each heat sink to enhance forced-air cooling, as shown in Fig. 3. The fans are powered from a separate DC supply and not from the TEG output. The effectiveness of the heat sink directly influences the thermal gradient available for thermoelectric conversion.

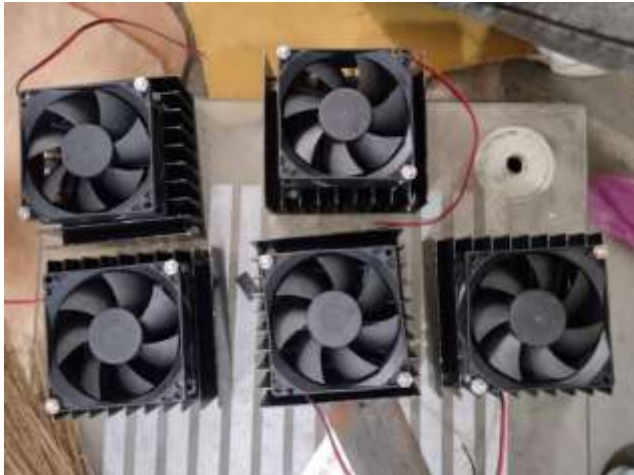


Fig. 3. Aluminium heat sink and DC fan assemblies used for cold-side cooling of the TEG modules.

F. Thermal Insulation

Thermal insulation is provided around appropriate sections of the duct to reduce unwanted heat losses to the surroundings. As shown in Fig. 4(a), a glass wool insulation blanket and an aluminium foil cover are wrapped around the duct, which helps direct a greater portion of the available thermal energy toward the intended heat-transfer path.



(a)



(b)

Fig. 4. Fabricated prototype: (a) assembly of the insulated vertical duct with heat sink and fan units; (b) prototype under test, with the bulb load illuminated by the generated electrical output.

G. Design Specifications

The main specifications of the fabricated prototype are summarised in Table I.

TABLE I
DESIGN SPECIFICATIONS OF THE PROTOTYPE

Component	Specification
Flue gas duct	Mild steel; 6 in (152.4 mm) outer diameter, 3 mm wall thickness, 900 mm height
Insulation	Glass wool insulation with aluminium foil cover
Copper collector plates	5 nos.; 100 × 50 × 5 mm each
TEG modules	SP1848-27145SA, 40 × 40 × 3.4 mm; 10 nos. (2 per copper plate)
TEG connection	All 10 modules electrically in series
Heat sinks	Aluminium; 5 nos.; 100 × 105 × 44 mm
Thermal interface	Thermal paste between TEG modules and heat sinks
Cooling fans	80 × 80 mm, 12 V DC axial fan on each heat sink; separate DC supply
Thermocouples	K-type, 3 nos., with MAX6675 modules
Controller and display	Arduino UNO; 20×4 I2C LCD
DC-DC converter	Step-up (boost) type; input 10–32 V, output 12–35 V (adjustable)
Electrical load	12 V, 9 W bulb
Heat source	LPG gas burner

VIII. ELECTRONIC MONITORING SYSTEM

An Arduino UNO is used as the main controller for monitoring the thermoelectric system (Fig. 5). The monitoring system consists of an Arduino UNO, three K-type thermocouples, three MAX6675 thermocouple modules, a 20×4 I2C LCD, a voltage sensor, a current sensor, a DC-DC converter and an electrical load.

Three temperature locations are monitored: the pipe temperature, the TEG hot-side temperature and the TEG cold-side temperature. The Arduino receives the temperature signals from the MAX6675 modules and displays the values on the LCD. Electrical parameters such as voltage and current

are also monitored, and the electrical power is determined from

$$P = VI \quad (2)$$

where P is the electrical power, V the voltage and I the current.

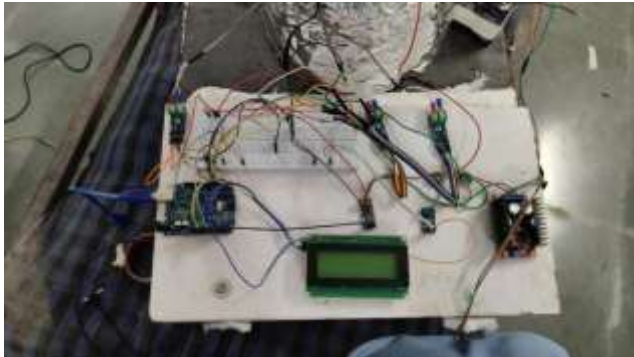


Fig. 5. Arduino-based monitoring and conditioning board: Arduino UNO, 20×4 LCD, MAX6675 thermocouple modules, voltage/current sensing modules and DC-DC converter.

IX. ELECTRICAL SYSTEM

The TEG modules generate electrical energy when a temperature difference exists across their hot and cold sides. The ten TEG modules are connected electrically in series so that their individual voltages add, and the generated output is connected to the electrical monitoring and conditioning circuit. A DC-DC converter is incorporated to regulate or condition the generated voltage according to the requirements of the connected load.

The current sensor is connected in series with the electrical path so that the load current can be monitored, and the voltage sensor is connected across the electrical output to measure the generated voltage. The Arduino processes these signals and displays the system parameters on the LCD.

The circuit of the system is shown in Fig. 6. The series string of ten TEG modules feeds the current sensor and the DC-DC boost converter, which supplies the load, a 12 V, 9 W bulb, and the return path closes at the negative terminal of the TEG string. The voltage sensor is connected across the TEG output. The outputs of the voltage and current sensors are read at the analogue inputs A0 and A1 of the Arduino UNO, while the pipe, TEG hot-side and TEG cold-side temperatures are read from three K-type thermocouples through MAX6675 modules. All readings are displayed on the 20×4 I2C LCD.

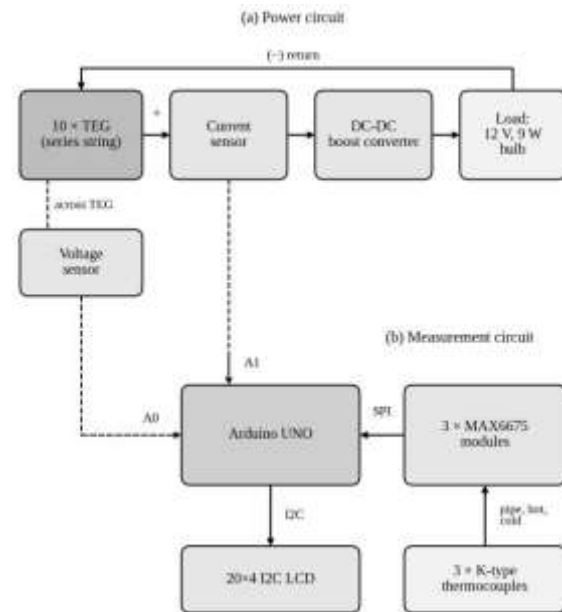


Fig. 6. Circuit diagram of the system: (a) power circuit and (b) Arduino-based measurement circuit.

X. EXPERIMENTAL METHODOLOGY

Step 1: System fabrication—The vertical duct, copper plates, TEG modules, heat sinks and insulation are assembled to form the thermoelectric recovery module.

Step 2: Thermocouple installation—Three thermocouples are positioned at the pipe, the TEG hot side and the TEG cold side.

Step 3: Electrical connections—All ten TEG modules are electrically connected in series, and the string is connected to the voltage/current monitoring circuit.

Step 4: Arduino monitoring—The Arduino UNO receives signals from the thermocouple, voltage and current sensors.

Step 5: Heat source application—An LPG gas burner is used as the heat source to heat the duct and simulate the thermal conditions of an industrial flue gas system.

Step 6: Thermal stabilization—The system is allowed to reach a relatively stable thermal condition before electrical parameters are evaluated.

Step 7: Electrical loading—A 12 V, 9 W bulb is connected as the electrical load at the output of the DC-DC converter.

Step 8: Parameter monitoring—Pipe temperature, TEG hot-side temperature, TEG cold-side temperature, temperature difference, output voltage, output current and electrical power are monitored.

XI. PERFORMANCE EVALUATION

The performance of the system can be evaluated using the temperature difference across the TEG modules, calculated as

$$\Delta T = T_h - T_c \quad (3)$$

where T_h is the hot-side temperature and T_c is the cold-side temperature. The electrical power is calculated from (2). The experimental investigation can be used to study the influence of heat-source temperature, hot-side temperature, cold-side



temperature, temperature difference, cooling effectiveness, electrical load and thermal contact resistance. The measured values are presented in Section XIII.

XII. EXPECTED PERFORMANCE BEHAVIOUR

The electrical output of a TEG is expected to increase when the temperature difference between its two sides increases. However, the actual output depends on several factors, including TEG module characteristics, temperature difference, heat-transfer rate, thermal resistance, contact resistance, cold-side cooling, electrical configuration, load resistance and converter efficiency. Therefore, increasing the heat-source temperature alone does not necessarily result in proportional electrical power generation.

XIII. RESULTS AND DISCUSSION

Table II lists the readings recorded during a test of the prototype. With the pipe wall at 140.8 °C, the TEG hot-side and cold-side temperatures were 83.0 °C and 44.5 °C, respectively, giving a temperature difference of $\Delta T = 38.5$ °C from (3), and the output voltage was 10.96 V. Since the ten modules are connected in series, this corresponds to an average of about 1.10 V per module.

TABLE II
MEASURED PROTOTYPE READINGS

Parameter	Reading	Unit
Pipe (duct wall) temperature	140.8	°C
TEG hot-side temperature, T_h	83.0	°C
TEG cold-side temperature, T_c	44.5	°C
Temperature difference, ΔT	38.5	°C
Output voltage, V	10.96	V
Output current, I	0.82	A
Output power, P	8.99	W

As shown in Fig. 7, the pipe-to-hot-side temperature drop was 57.8 °C, more than half of the pipe temperature. A considerable part of the available temperature difference is therefore lost in the heat collection path, which consists of the duct wall, the copper collector plates and the contact interfaces: only 38.5 °C of the 96.3 °C difference between the pipe and the cold side appears across the TEG modules. This confirms the importance of thermal contact resistance noted in Section XIV and supports the planned improvement of the copper plate geometry and the thermal interface materials.

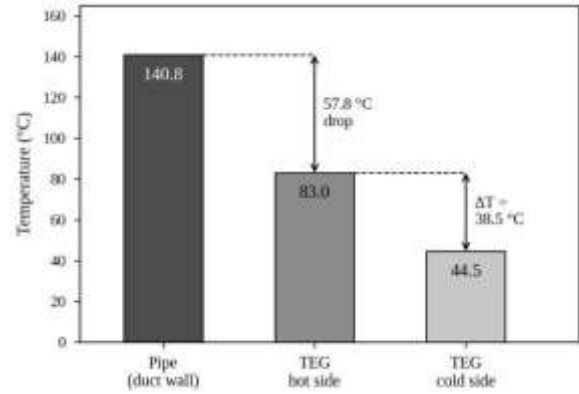


Fig. 7. Measured temperature profile: pipe (duct wall), TEG hot side and TEG cold side, showing the 57.8 °C drop between the pipe and the hot side and the temperature difference $\Delta T = 38.5$ °C across the TEG modules.

The output voltage and current were read directly from the LCD as 10.96 V and 0.82 A. The electrical power from (2) is therefore $P = 10.96 \text{ V} \times 0.82 \text{ A} \approx 8.99 \text{ W}$. This is a single reading at one heat-source condition; further readings at several heat-source temperatures and electrical loads are needed to establish the relationship between temperature difference and electrical power.

In a separate qualitative demonstration, an LED connected to the generated output was illuminated while heat was applied to the duct (Fig. 4(b)), confirming that the temperature difference across the modules is converted into usable electrical energy. The readings in Table II were recorded with the 12 V, 9 W bulb as the load.

XIV. LIMITATIONS

- Thermoelectric conversion efficiency is relatively low compared with some conventional energy-conversion technologies.
- The generated electrical output strongly depends on the available temperature gradient.
- Thermal contact resistance between the duct, copper plates, TEG modules and heat sinks can reduce heat transfer.
- Maintaining a low cold-side temperature can become difficult when the surrounding temperature increases.
- Readings were recorded at a single operating condition, so the variation of electrical power with temperature difference is yet to be established.
- The cooling fans are powered from a separate supply, so the reported output is not net of the fan consumption.
- The prototype is a laboratory-scale system; industrial implementation would require detailed thermal, mechanical, electrical and economic analysis.

XV. FUTURE SCOPE

Future work may include: improvement of hot-side heat collection; optimization of copper plate geometry; improved thermal interface materials; advanced heat-sink designs; improved forced-air or liquid cooling; optimization of the TEG electrical configuration; maximum power point tracking



(MPPT); battery energy storage; wireless data monitoring; long-duration industrial testing; computational fluid dynamics (CFD) analysis; thermal and electrical simulation; scaling the system for larger industrial ducts; and integration with industrial sensor systems.

Power-conditioning circuits are particularly relevant because TEG output depends strongly on the available temperature gradient and operating conditions. Recent IEEE research has investigated converter-based approaches for making thermoelectric output usable for practical loads [8].

XVI. CONCLUSION

This paper presented the design and fabrication of a thermoelectric waste heat recovery module for a vertical industrial flue gas duct. The system combines a thermal collection mechanism, TEG modules, aluminium heat sinks with cooling fans, thermal insulation, electrical conditioning and an Arduino-based monitoring system.

The main purpose of the system is to recover a portion of otherwise wasted thermal energy and convert it into useful electrical energy. The approach demonstrates the potential of thermoelectric technology as a solid-state waste heat recovery method, and its practical performance depends primarily on the temperature difference available across the TEG modules and the effectiveness of heat transfer and cooling. In the reported test, a temperature difference of 38.5 °C across the TEG modules produced an output voltage of 10.96 V and an output power of about 9 W. The prototype can therefore serve as a platform for further investigation of sustainable energy recovery from industrial waste heat and for developing low-power energy harvesting applications.

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