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Seebeck Generators and Their Performance in Generating Electricity

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Abstract- *Nowadays, renewable energy sources are considered better choices in the field of energy generation. It is possible to replace traditional energy sources (i.e., petroleum oil and gases) with more attractive alternatives. This presents several advantages, such as low emissions of greenhouse gases and reduction of climatic change along with associated global warming. In the current paper, a comprehensive review is done introducing thermoelectric generation (TEG). These are applications of renewable energy sources that use the Seebeck effect to generate electricity. In this type of system, two different materials melt at their ends. One is on the hot side, while the other is used as a cold side. The present paper is a survey that includes applications and hybrid systems (based on renewable energy sources) that are integrated with a thermoelectric generator. Also, investigations of the effects of including thermoelectric generation in hybrid systems on the overall performance of such systems are reviewed. These systems can be viewed as an investment in recovery of waste heat from devices such as water pipes, photovoltaic panels, and vehicle exhaust to produce extra power in a hybrid system.*

Keyword—Hybrid systems, Power, Seebeck effect, Survey, Thermoelectric generation.

1. Introduction

In electricity generation, there are many kinds of energy sources. Some of them are dependent on fossil fuels to generate electricity such as in thermal power plants and diesel generators, among others. In such systems, electricity generation is accompanied by pollution and greenhouse gas emissions [1]. Other energy types depend on renewable energy sources such as wind and solar energy, which employ wind turbines or photovoltaic (PV) cells, respectively. These alternative energy generation facilities need maintenance and their electricity production is affected by variations solar radiation, temperature and wind speed [2]. Regardless of the type of electricity generation, energy is lost as heat when it is applied to a load or even through energy transmission [3]. If this heat is exploited as another source of energy and used for further electricity generation, the generation efficiency of the entire system will be increased. Thermoelectric generators (TEG) are of great interest to researchers at present in their attempts to maximize energy conversion efficiency. TEGs work on a principle known as the Seebeck effect, first explored by the scientist, Thomas J. Seebeck, in 1821 [4]. This effect is created by two types of semiconductors working together, p-type and n-type semiconductors. These semiconductors are electrically connected through a conductive strip. When heat is applied to a thermal generator, the charge carriers, which are holes in the p-type and electrons in the n-type, will move from the heat source to the cold area. This diffusion can cause an electric current to flow and create a voltage potential at the terminals of a TEG [5]. TEGs are widely utilized in civil and military applications [6].

There are many research studies that consider TEGs. S. Travadi and J. Dabhi [7] reviewed TEG designs and presented an analytical model. Their study investigated the role of TEG dimensions, length and cross-sectional area, as well as their relationship in determining TEG power and efficiency. A study using TEGs under various thermal conditions, employing heat from diesel engine exhaust, was done by B.D. In et at. [8]. Their study examined optimization of a TEG layout and its configuration. Another study of TEG performance was done by G. Rohit et al. [9]. They examined the relationships between current, voltage and TEG power. Their study showed that when the temperature of a hot surface was increased, the power output increased as well.

This paper surveys Seebeck generator technology and its performance in generating electric current. It considers various TEG studies and their designs with experimental investigations. An introduction is first presented. Then, the paper continues to present thermal electric generator principles, review thermoelectric generators, and ends with some conclusions.

2. Thermoelectric Generator Principles

Thermoelectric generators (TEG) are instruments that are employed to convert thermal energy into electricity based on the Seebeck effect, which defines a Seebeck coefficient. TEGs use a temperature difference (ΔT) between disparate materials, the ends of which have melted. Consequently, an electromotive force is generated resulting in a current flow in a circuit. TEGs have numerous benefits. These include simple design, equipment that requires no moving parts and is consequently quiet and maintenance free [10].

The Seebeck coefficient (α) can be defined as:

$$\alpha = \frac{\Delta V}{\Delta T} \tag{1}$$

where ΔV is a voltage difference in (V) and ΔT is the temperature difference in (K). The Seebeck coefficient is different for various materials. Semiconductor materials have high Seebeck coefficients.

There are two types of thermoelectric processes, thermoelectric generation and thermoelectric cooling. TEGs produce power when two disparate materials are joined at their ends, as depicted in Fig. 1.

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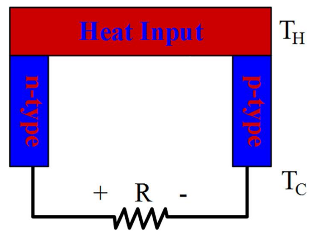

Fig. 1: A schematic showing a thermoelectric generator [11]

Whilst thermoelectric cooling occurs when a voltage is produced by two different materials as shown in Fig. 2.

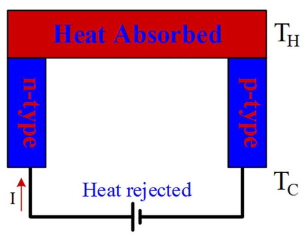

Fig. 2: A schematic showing thermoelectric cooling [11]

TEGs are most often manufactured using many thermopiles to increase output. Each thermopile is fabricated of many thermocouples connected in parallel and electrically in series [12].
After that, it was found that various conductor materials absorb or expel heat at their ends. This phenomenon is known as the Peltier effect.
The properties of the two different conductor metals and their joint temperatures determine the heat absorption or heat expelled. These concepts can be used to define the well-known Figure of Merit (Z). This is a dimensionless parameter that can be used to determine thermoelectric performance of a specific material. Every metal has its own Figure of Merit. It is defined as:

$$ZT = \frac{\alpha^2}{K}\sigma T \tag{2}$$

where σ and T represent electrical conductivity and temperature respectively. K is thermal conductivity of the material.
The efficiency and coefficient of performance of TEGs can be calculated as

$$\eta_{max} = \frac{T_H - T_C}{T_H} \times \frac{\sqrt{1+Z\overline{T}} - 1}{\sqrt{1+Z\overline{T}} + \frac{T_H}{T_C}} \tag{3}$$

where T_H and T_C are the temperatures of the hot and cold sides, respectively $\overline{T}$ is the mean temperature.

$$COP_{max} = \frac{T_C}{T_H - Tc} \times \frac{\sqrt{1+Z\overline{T}} - \frac{T_C}{T_H}}{\sqrt{1+Z\overline{T}} + 1} \tag{4}$$

TEGs are theoretically based on the Carnot engine, but the working medium consists of electrons [11].
Let the temperature difference be given by $\Delta T = T_H - T_C$, and ΔT is as given above, and the Seebeck coefficients for the p-type and n-type semiconductors are αp and αn, respectively. Then, the Seebeck open circuit voltage can be given as [11]:

$$V_{open} = (\alpha\text{p} - \alpha\text{n})\,\Delta T \tag{5}$$

3. Thermoelectric Generators Reviewed

This section presents a review of thermoelectric generators and their integration with heat sources. S. Addanki and D. Nedumaran [13] designed, simulated, synthesized, analysed and fabricated a micro electric generator, as depicted in Fig. 3, that consists of two sides. One is a heated sided with a tradition cold side. In this paper, the proposed design was first simulated via COMSOL Multiphysics to model the temperature distribution and heat transfer in the device. After that, the proposed thermoelectric generator was manufactured considering information learned about the design parameters. The TEG was tested with electronic devices and its performance determined by attaching it to various positions on a human body. From their results, the suggested thermoelectric generator was successful in generating power for handheld electronic devices. This application has many advantages as it is less costly and easily applied to many devices.

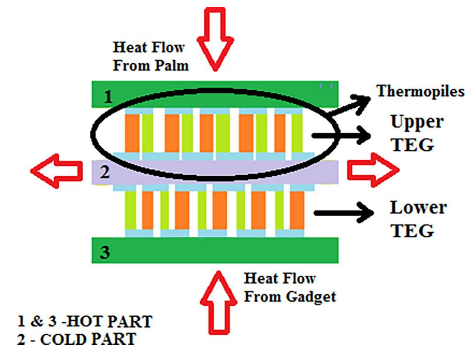

Fig. 3: Schematic diagram of the proposed micro-electric generator [13]

A thermoelectric generator with a half ring shape employing polymer-based composite materials was fabricated by Jizhe Wang et al. [14]. It was used to recover waste heat from hot water pipes, as depicted in Fig. 4. The proposed TEG generates an open-circuit voltage of 3.4 mV and a maximum output power of 126 nWatt under a temperature difference (ΔT) of 10.5 K. In this paper, a COMSOL Multiphysics finite element method was used to investigate relevant parameters (i.e., the effect of the area of the heat sink, thickness, and number of thermocouples, and convective heat transfer coefficient of air) on TEG performance. From their results, it can be seen that the simulation was in good agreement with experimental data. This suggests applications can be manufactured to develop thermoelectric generators for use to recover waste heat from hot water pipes.
Sohel Rana et al. [15] developed an optimized thermoelectric generator to use low grade waste heat (see Fig. 5). They estimated gross power, net power, parasitic power, where the dimensions of a channel (i.e., gap height, length, and width) and mass flow rate were considered as variable parameters, while the number and efficiency of the TEGs were fixed. Also, the work in this study optimized channel dimensions and flow rate for best operating conditions.

The resulting optimization model can be used to analyse heat exchangers for any inlet temperature, operating condition, and number of TEGs. In this study, a channel design was found to affect the net power. A new hybrid photovoltaic-thermoelectric system was investigated and improved by Omid Farhangian Marandi et al. [16]. They designed and fabricated a TEG and then conducted a practical assessment of their novel system (a solar cavity receiver joined with a PV–TEG that directly utilized solar radiation as shown in Fig. 6). From this study, effective capture of solar radiation and a remarkable reduction of re-radiation losses were observed. The TEG was fixed on the back side of a solar panel. This was done to exploit the temperature difference between the back side of a PV module and the ambient temperature based on the Seebeck effect.
From their investigation, generation of extra power by the TEG modules and rejection of the heat produced by PV modules was

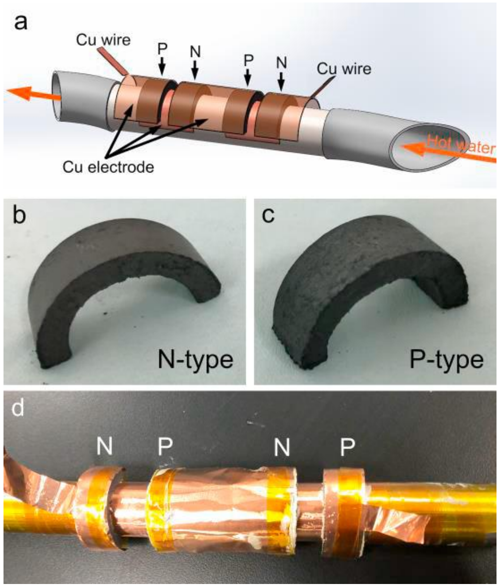

Fig. 4: TEG on a hot water pipe [14]

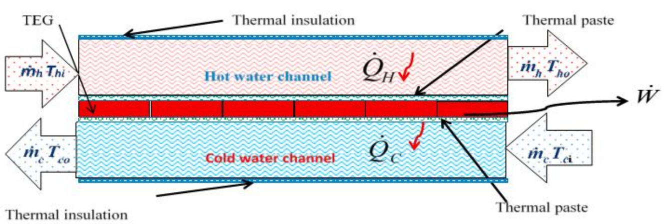

Fig. 5: Design principles of thermoelectric generators [15]

accomplished. Also, the overall performance of the hybrid PV-TEG system was higher than for the PV modules alone. This system was tested experimentally under two environmental conditions. The first was done under laboratory conditions (i.e., constant ambient temperature, no wind, and fixed radiation of a light simulator at 1000 W/m^2). The second test involved direct exposure to sunlight, where PV panels and TEGs assemblies were placed in a cavity receiver. This cavity hybrid PV-TEG system is considered optimal.

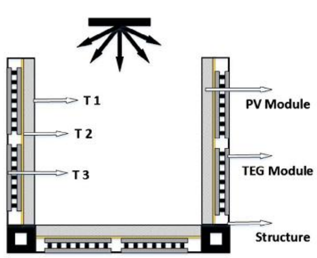

Fig. 6: Schematic diagram of the novel hybrid PV-thermoelectric system [16]

Krishnadass Karthick et al. [17] introduced a thermal system (see Fig. 7) for a thermoelectric generator employing a heat sink combined with a thermal energy storage system for solar power generation using thermoelectric modules. In this study, a phase change material (PCM) for thermal energy storage was integrated with a heat sink to provide energy at night. Two conditions were used in this study, open and closed circuit voltages. Concurrently, TEG modules were exposed to both heating and cooling phases. The heat exhausted from the TEG was stored as thermal energy in a container of PCM. This stored energy was employed as a heat source for power production through a cooling phase. From their experiments, the cooling process used a heat exchanger with copper tubes. In this paper, various heat fluxes and electrical currents were used to analyse the thermal and electrical parameters of open and closed circuit voltages during heating and cooling processes. From these results, it can be seen that the power generation in both the heating and cooling processes is similar, with a net power production from the heating cycle of 0.39 W, while, 0.31 W was generated during the cooling cycle. Unfortunately, the experimental setup showed that the reversible operation of the TEG modules is optimal during the night cycle operation.

Sunil Kumar et al. [18] fabricated a hybrid power system that consisted of thermoelectric generators and piezoelectric nano-generators, as shown in Fig. 8. This system provides power from two sources, thermal energy and mechanical vibrational energy. From the results, a net power of 1.8 nW was generated from this TEG. Alternatively, piezoelectric nano-generators produced approximately 1.2 μW and could obtained an open circuit voltage approaching 4 V, with a short circuit current of 75 nA. This system is applicable in capturing energy from engine exhaust pipes where thermal energy and mechanical vibrations are present.

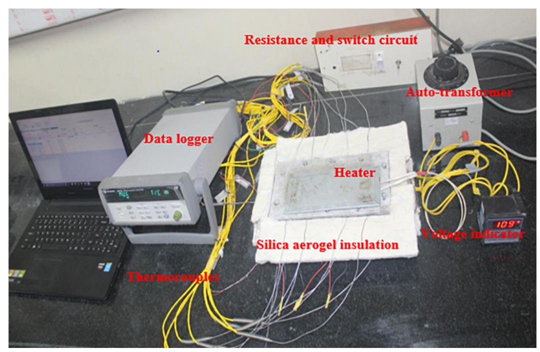

Fig. 7: Experimental test prototype [17]

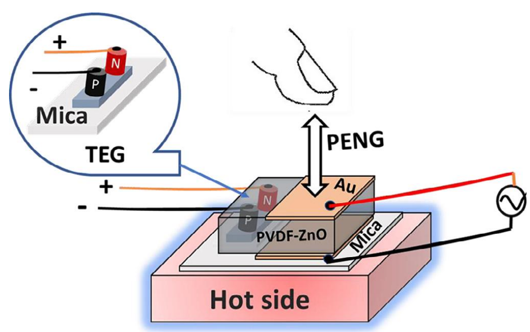

Fig. 8: Schematic of a hybrid instrument comprised of a thermoelectric generator (TEG) and a piezoelectric nano-generator (PENG) [18]

Riahi et al. [19] investigated a concentrated photovoltaic thermal (CPVT) device and a concentrated photovoltaic system combined with thermoelectric generators, as depicted in Fig. 9. A concentrated photovoltaic thermoelectric generator hybrid system prototype was designed, fabricated and tested. Also, a mathematical model was developed and validated with corresponding experimental results. The model was used to optimize both electrical and thermal efficiencies of the concentrated photovoltaic thermoelectric hybrid system, and to compare them with a concentrated photovoltaic thermoelectric system. The results showed that CPVT-TE hybrid system was superior to the CPVT standalone system. An enhanced efficiency of 7.46% was achieved for the CPVT-TE compared with the CPVT-TE system under a solar radiation of 935 W/m^2 and an ambient temperature of 33.

D.N. Kossyvakis et al. [20] combined a photovoltaic cell with a thermoelectric generator in one system, which is known as a PV-TEG hybrid (see Fig. 10). This system was investigated experimentally and validated theoretically. Two types of photovoltaic panels were used, poly-Si and dye-sensitized panels. The results revealed an enhanced performance of poly-Si of 22.5% and 30.20% for the dye-sensitized panels.

A novel low concentrating photovoltaic thermal-thermoelectric hybrid system, as depicted in Fig. 11, was proposed by Chen Haiping et al. [21]. The system consists of a photovoltaic thermal unit and a solar generator. A mathematical model was developed to compare the approach with experiment results. A test stand for the system was used under various operating conditions.

Another novel non-concentrating (flat plate) photovoltaic thermoelectric generator hybrid system was suggested by C. Babu and P. Ponnambalam [22]. It was combined with a commercial multi-crystalline material. Theoretical analysis was employed to predict the performance of a PV-TEG hybrid system while varying the irradiance and ambient temperatures. A MATLAB Simulink environment was used to analyse this PV-TEG hybrid system. It was employed as an optimization tool to improve the operational parameters of the PV. Also, various analytical methods were utilized to estimate the TEG parameters. From the results, 5% excess energy was added to the system with an increase in overall efficiency of about 6%. The TEG generates energy at about 1.3% of the PV rating.

P. Motiei et al. [23] presented a numerical procedure that included introduction of a material that underwent a phase change while serving as a heat sink mounted to photovoltaic thermoelectric generator hybrid system. PCM is sometimes employed to save a great amount of heat through a phase change. This improves energy storage capacity. In this study, an unsteady two dimensional model was used to simulate an entire day (24 hours) in summer and winter. FORTRAN 90 was used to model various parameters (i.e., solar radiation, ambient air temperature, wind speed, and heat losses resulting from convection and radiation), which were embedded in this model. From the results, the performance of the PV-TEG PCM hybrid system was higher than the system with no PCM. Also, this study examined the effects of PCM thickness and melting point temperature to find the best materials and thicknesses.

R. Bjørk et al. [24] investigated the performance of an integrated photovoltaic thermoelectric generator hybrid system using an analytical model. In this study, four commercial types of photovoltaic cells were used, crystalline Si (c-Si), amorphous Si (a-Si), copper indium gallium (di) and cadmium (cdTc). One commercial TEG used bismuth telluride. The results showed the PV-TEG system exhibits improved performance when compared with PVs alone.

K. Teffah and Y. Zhang [25] proposed a system which combined a photovoltaic system (Multi Junction Solar Cell) with thermoelectric cooling and a thermoelectric generator. MATLAB SIMULINK software was used to simulate the behavior of the Multi Junction Solar Cell under various high sun concentration factors. Also, COMSOL MULTIPHYSICS was employed to study the feasibility of utilizing of the entire hybrid system to improve its performance. A finite element approach was chosen for simulating the hybrid system. The results showed good agreement between previous experimental work and the theoretical analysis.

A thermoelectric generator was deployed in shallow hot dry rocks and analysed experimentally by Leyre Catalan et al. [26]. This system is depicted in Fig. 12.

A prototype was built to study the possibilities of utilizing thermoelectric generation in a geothermal application in Timanfaya National Park (Spain). The test rig includes a two phase closed thermosiphon, used as the hot side. Two thermoelectric modules were used as a cold side. They consisted of fin dissipaters supported by a fan and loop thermosiphons, due to their low thermal resistance and low auxiliary energy consumption. It generated a maximum net power of 3.29 W per module with a temperature difference 180. So, this proved to be a good opportunity for geothermal electricity production using shallow hot dry rocks.

B. E. M. Fotso et al. [27] modelled and did thermal analysis of a solar thermoelectric generator with a vortex tube for hybrid vehicles. In this study, three approaches were adopted. The results showed that this system produced lower electrical current in a hybrid vehicle. The power produced from solar TEG with a vortex tube was 147.3 W. Also, electrical current of 1.49 A was produced. They recommended that the performance be enhanced using a high efficiency vortex tube and more recently developed thermoelectric materials.

H. Khalil and H. Hassan [28] suggested heat recovery from chimneys by means thermoelectric generators cooled by natural convection heat sinks. This design included a heat sink equipped with a fixed flap as detailed in Fig. 13. In this study, ANSYS WORKBENCH particular computational fluid dynamics (CFD) was employed to simulate the phenomena, which occurred inside thermoelectric generators. This was done to improve the heat transfer from heat sinks using flaps at the top of the heat sink. Through this study, the dimensions of these flaps (i.e., angles and lengths) were investigated. The results revealed that the modified heat sink provides a 64% enhancement in the thermoelectric generator cooling rate, increasing the output power by 129%.

M. E. Demir and I. Dincer [29] suggested a hybrid system to simultaneously generate electricity and hydrogen using a solar powered gas turbine. The heat from the exhaust of a gas turbine is stored as latent heat in a PCM. Multistage flash distillation is used to produce distilled water from seawater. Then, a proton exchange membrane electolyzer and TEG is employed to produce hydrogen from distilled water. COMSOL Multiphysics was used to predict the performance and behavior of this thermoelectric generator.

4. CONCLUSION

In this study, we present a comprehensive review of thermoelectric generation. It discusses their applications and integration with other renewable energy sources. The current study revealed that thermoelectric generators can provide extra power. The following are our major findings:

1) The overall performance of electrical systems can be enhanced by using thermoelectric generators.
2) Thermoelectric generation is applicable to a wide variety of fields. Its advantages include the need for minimal maintenance and quiet operation since these processes have no moving parts or vibrations.
3) Heat losses can be recovered from hot water pipes and exhaust gases and then reinvested using thermoelectric generators. This can improve the performance of vehicles and PV panels.
4) Thermoelectric generators can enhance the efficiency of any system by at least 20% in terms of overall performance.
5) Novel materials can be used to improve the performance of a system.
6) TEGs can be used directly in solar energy conversion as a stand-alone system or integrated with other resources.

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Fig. 9: Experimental test prototype [19]

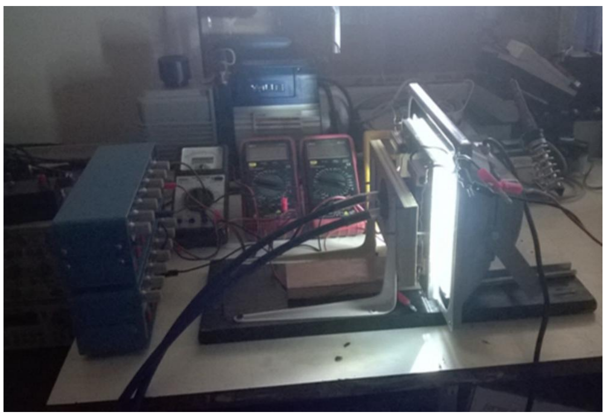

Fig. 10: Experimental test prototype [20]

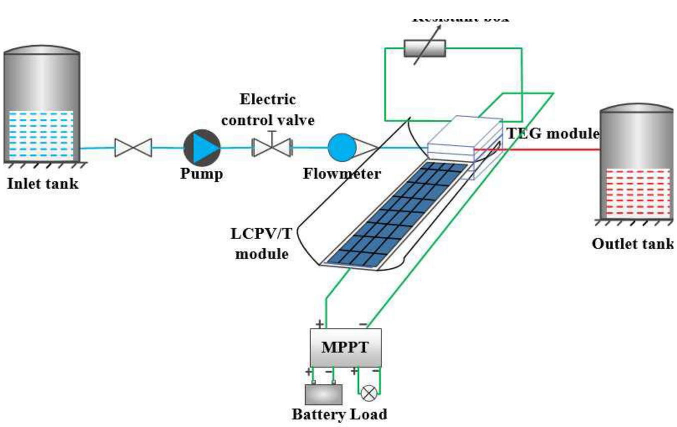

Fig. 11: Schematic diagram of LCPT/T-TEG system [21]

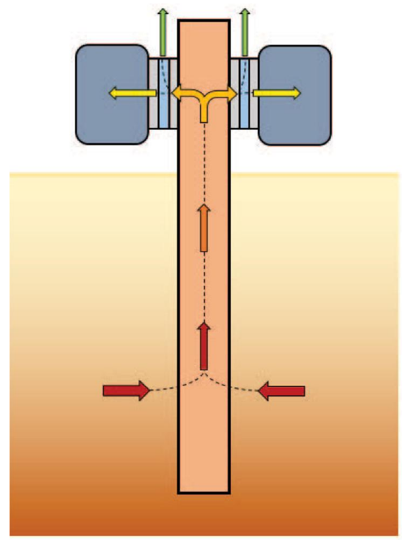

Fig. 12: Schematic diagram of a geothermal thermoelectric generator [26]

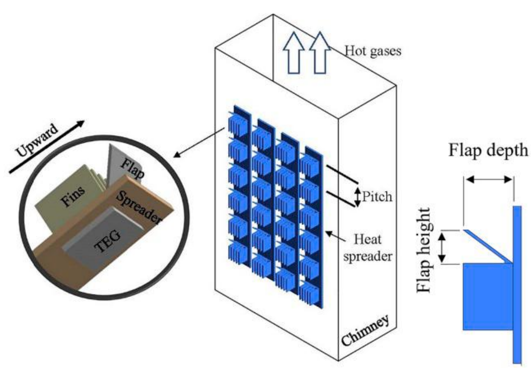

Fig. 13: Schematic diagram of the system of Khalil and Hassan [28]

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