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WASTE HEAT RECOVERY WITH THE USE OF THERMOELECTRIC GENERATORS – A RESEARCH STATION

Key words: thermoelectric generator, waste heat, heat energy recovery.

Abstract: Closing technological cycles by means of reducing the amount of waste and its management is one of the main issues addressed in manufacturing companies. Low temperature heat is an example of technological waste which may take the form of hot flue gases, cooling liquids from industrial processes, or hot water from heating vents or operating installations. One of the methods of managing low temperature heat from the above sources is converting it into electricity using thermoelectric generators (TEG). The article presents an experimental research station for heat energy recovery. The paper includes a description of a control system which enables adjustment and control of the parameters of generated electricity. Moreover, proprietary software to analyse, archive, and create databases of heat exchange parameters and electronic converters are discussed. The station has a modular structure, enabling its further expansion, both through the use of various heat sources and different cooling systems.

Stanowisko badawcze odzysku ciepła odpadowego z wykorzystaniem termogeneratorów

Słowa kluczowe: termogenerator, ciepło odpadowe, odzysk energii cieplnej.

Streszczenie: Zamykanie obiegów technologicznych poprzez redukcję ilości odpadów i ich zagospodarowanie są jednymi z głównych zagadnień podejmowanych w przedsiębiorstwach produkcyjnych. Przykładem odpadu technologicznego jest energia cieplna o parametrach niskotemperaturowych w postaci: gorących spalin, gorących lub ciepłych cieczy chłodniczych procesów przemysłowych, ciepłej wody z upustów ciepłowniczych czy instalacji eksploatacyjnych. Jedną z metod zagospodarowania energii tego typu źródeł niskotemperaturowych jest przetworzenie jej na energię elektryczną z zastosowaniem termogeneratorów (TEG). W artykule przedstawiono opracowane eksperymentalne stanowisko do badań eksperymentalnych takich układów. Opisano system sterowania, umożliwiający regulację i kontrolę parametrów generowanej energii elektrycznej. Omówiono autorskie oprogramowanie umożliwiające analizę, archiwizację i tworzenie baz danych parametrów wymienników ciepła oraz przekształtników elektronicznych. Stanowisko posiada konstrukcję modułową, umożliwiającą jego dalszą rozbudowę, zarówno poprzez wykorzystanie różnych źródeł ciepła, jak i różnych układów do wytwarzania chłodu.

Introduction

Reduction of CO2 emissions and improvement of the energy balance of production processes are the main two factors that influence the generation of new methods for energy recovery and waste management, specifically the waste heat energy [1]. Low temperature heat [2] is a product of a technological or production processes, and it is also a result of the exploitation of natural heat sources as well as forced heating processes. It is considered a waste heat, and it is currently used to a minimal extent, because waste heat management, in general, faces two major obstacles, i.e. low thermal parameters and diverse physicochemical properties of the waste in question. Most often it is returned to the environment, thus deteriorating the environmental conditions. Therefore, a number of waste heat utilization projects are being undertaken. The approach is to transform the hot waste heat into cold or useful heat [3, 4]. Experts also work on the use of waste heat from hot flue gases generated in the process of pellet combustion in low-power boilers, to produce electricity using a thermoelectric power generation system [5]. Solutions that use heat recovery processes from hot exhaust gases are still being developed, e.g., by using innovative segmental thermogenerator modules, whose efficiency is estimated at about 9% [6]. Electricity generated from such cells can be used directly as direct current or converted into alternating current with DC/AC converters [7]. The research station presented in the article enables the testing of waste heat energy recovery systems in which the final product is electricity. The device generates electricity through the conversion of thermal energy into direct current. Moreover, it converts DC into AC.

1. Construction of the research station

The research station has a modular structure (Fig. 1) which enables its rapid modification and further development through the use of various low temperature heat sources, different cooling systems, and thermoelectric generators. The basic elements of the station are modules which allow the storage and exchange of high temperature thermal energy *(B_{HT})*, storage and exchange of low temperature thermal energy *(B_{LT})*, heat exchangers hot *(W_{HT})* and cold *(W_{LT})*, and a set of thermoelectric generators (TEG).

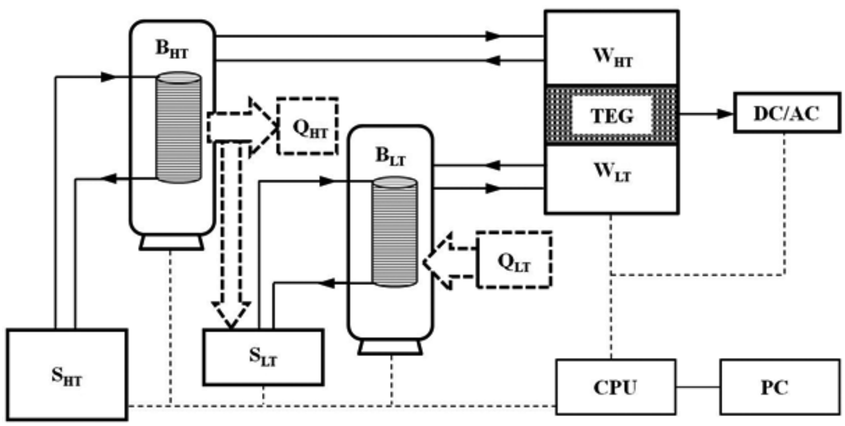


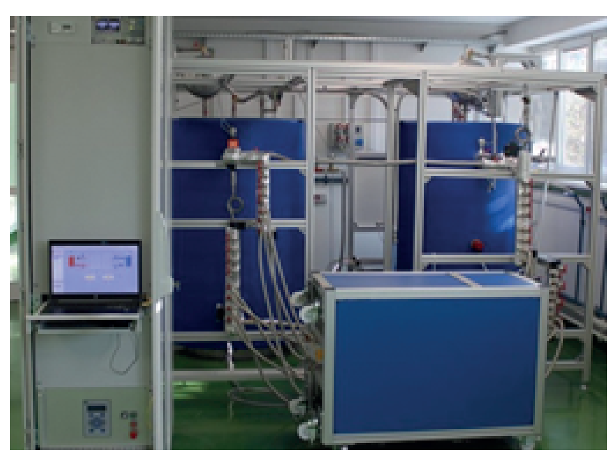
Fig. 1 Block diagram of the research station

Further modules of the research station are a DC/AC converter module (DC/AC), a storage module with high thermal parameters *(S_{HT})*, a storage module with low thermal parameters *(S_{LT})*, a control system module *(CPU),* and PC computer *(PC)*. High temperature heat exchange module *(Q_{HT})* and low temperature heat exchange module *(Q_{LT})* can be added to the system if necessary.

2. Construction of the research station

Figure 2 presents the construction of the research station. Storage and heat exchange modules with high and low temperature parameters (Figs. 2.2 and 2.3) were developed as cylindrical tanks of a capacity equal to *800 dm³* and a spiral coil placed inside, which has a heat

a)



b)

Fig. 2 Model of the research station in 3D (a) and its realization (b): 1) frame, 2) B_{LT}, 3) modules B_{HT}, 4) control cabinet of CPU, DC/AC and PC modules, 5) modules W_{HT}, W_{LT}, and a TEG module se

transfer area of $3\ m^2$. The coils forbid direct contact of liquids in the exchangers; hence, the possibility of using liquids with different freezing and evaporation temperatures is possible. Consequently, it can be used to extract heat from sources with different temperatures.

The maximum temperature for heating the liquid in the tank is set at 95°C for water, which stores heat energy while the minimum temperature for cooling the liquid is 4°C. Similarly, the storage and heat exchange modules with low thermal parameters are adapted to cooperate with different heat collection systems, an example of which is a dry or wet cooling tower [8], a fanless cooling tower, or an adsorption aggregate [9–11]. The research station is also equipped with a block of modules, i.e. a set of thermoelectric generators (Fig. 3) with hot and cold side heat exchangers.

The design of the block of modules allows testing of one to four individual units placed inside a thermally insulated case (Fig. 4).

The case is made of bolted aluminium profiles that enable extension and modification.

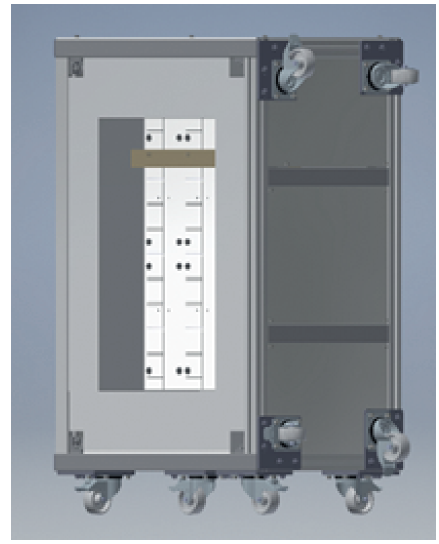
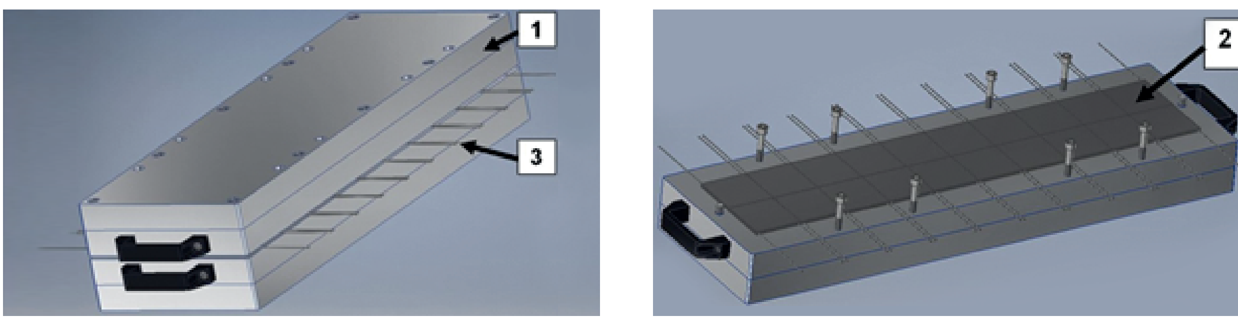


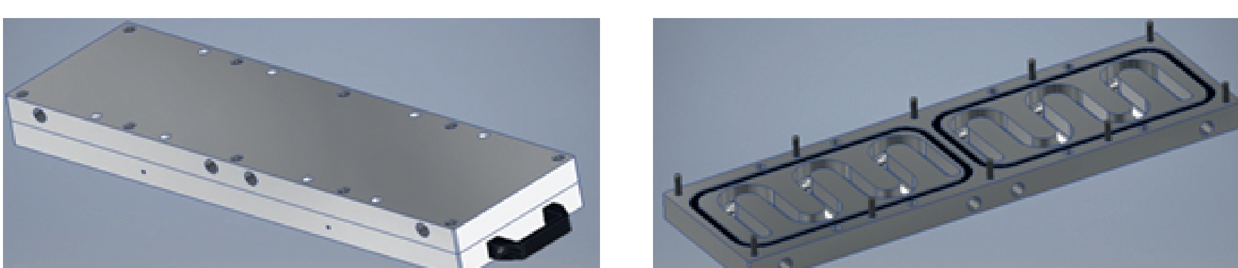
Fig. 3. Construction diagram of a thermally insulated case with a single block of heat exchanger modules for testing thermoelectric generators.



a) b)

Fig. 4. Construction diagram of a single set of heat exchanger modules with a water circuit for testing thermoelectric generators: a) unit drawing, b) location of thermoelectric generators inside the unit, 1) hot side exchanger, 2) thermoelectric generators, 3) cold side exchanger

The design of the block makes it possible to assemble the modules vertically or horizontally. The entire unit is also mobile. A unit placed in the block consists of aluminium heat exchangers and liquid thermoelectric generators (Fig. 4). The modules of exchangers have the same design for both hot and cold sides of the thermoelectric generators. A single heat exchanger module is a two-section heat exchanger (Fig. 5) in which the heating or cooling liquid flows inside, depending on the function of the module.



a) b)

Fig. 5. Construction diagram of a single hot/cold side exchanger module with a water circuit for testing thermoelectric generators: a) unit drawing, b) two-section water exchanger circulation

In a single set of heat exchanger modules, space has been provided to accommodate a set of twenty individual thermoelectric generators. The construction is designed to enable the reconfiguration of electrical connections of individual thermoelectric generators. The station is operated using a control system containing a measuring and control system, a DC/AC converter, and a PC computer, placed in the control cabinet (Fig. 2).

Thermogenerator of the TEC1-12730 type were used in the research station for waste heat recovery [12]. It is supplied with energy from the high temperature parameters storage and the heat exchange module, which is fed with waste heat energy. The heat exchange medium used in this circuit is water and its thermal parameters in the B_{HT} module are monitored by temperature, pressure, and level sensors. The water flow in the circuit between B_{HT} and W_{HT} modules is implemented using a *Yonos ECO* pump [13]. The measuring elements of the WHT module circuit are DUK ultrasonic flow meter [14], TP-375 temperature sensors [15], and a SEN pressure sensor [14].

Fig. 6. Elements dispersing thermal energy located outside: 1) external coolant tank, 2) external fanless cooler

The energy of the W_{LT} module of the cold side of the thermoelectric generator is discharged to the low temperature parameters storage and the heat exchange module, in which the heat is collected using elements of heat energy dissipation. The heat exchange medium used in this circuit is also water. The components and measuring elements in this circuit are the same as in the W_{HT} module circuit. The heat dissipating element in this system is a fanless external fin exchanger together with an external coolant container (Fig. 6). The heat transfer from the B_{LT} module to the S_{LT} module is carried out by the flow of the coolant in an additional circuit. Ethylene glycol (*Ergolid A with 35% concentration*) was used as the cooling liquid [16].

3. The control system

The research station is equipped with a control system monitoring its components using information provided by the measuring system. The cDAQ-9189 [17] controller with a set of analogue and digital I/O modules was used here. The controller allows the measurement of both slow-changing signals (temperature, flow) as well as high-amplitude waveforms associated with the generation of 230 V, 50 Hz electricity.

The controller works with a PC on which the proprietary control and measurement software, developed in the LabVIEW environment, has been implemented. The software enables the visualization of the work of the entire research station (Fig. 8). It allows the operator to change the controllers of individual components, on-line analysis of measurement data, as well as archiving and creating databases from the acquired measurement data, which relates to the conversion of generated electricity. The main supervisory functions of the software include the monitoring of the station's parameters, setting the parameters of its components, recording the measured parameters, and detecting and alarming in case of emergency. These functions are implemented in seven windows of the system software.

The *INSTALLATION* window (Fig. 8) contains a schematic illustration of all the station's elements with characteristic temperatures, flows, and pressures in the system. The window enables the activation of hot and cold water circulation pumps and the control of valves in their circuits. The voltage, current, and power of the waveform generated in individual sets with thermoelectric generators are also monitored here. The software enables forcing automatic operation of thermoelectric generators in conditions without electrical load, but also with electronic resistance load *Rigol DL3021A* [18]. The system also works with the load of the proprietary *DC/AC* converter and with the load of the commercial *DC/AC* converter.

The next software windows shown in the program tree are *DETAILS, Temperatures, TEG, DC, AC,* and *ALARMS* windows. The *DETAILS* window allows for reading and setting parameters related to the deeper layer of the station's control. The *Temperatures* window illustrates the temperature waveforms and allows the operator to select and preview any waveform, automatically or manually scale the chart axis, and save it as a text file. The *TEG* window enables 3D imaging of temperature distribution in units with thermoelectric generators and their scaling. The *DC* window visualizes the parameters of the DC output (current, voltage, power) from thermoelectric generators modules and enables the collection of discrete data for determining the current-voltage characteristic and power characteristic of the thermoelectric generators module. The *AC* window presents current, voltage, and power waveforms of *DC/AC* converters operating without load or connected to the power grid. The *ALARMS* window records emergency situations occurring during the functioning of the station, such as errors in communication between the computer and the controller, errors in reading the input signals of the controller, or exceeding the permissible values of the station parameters.

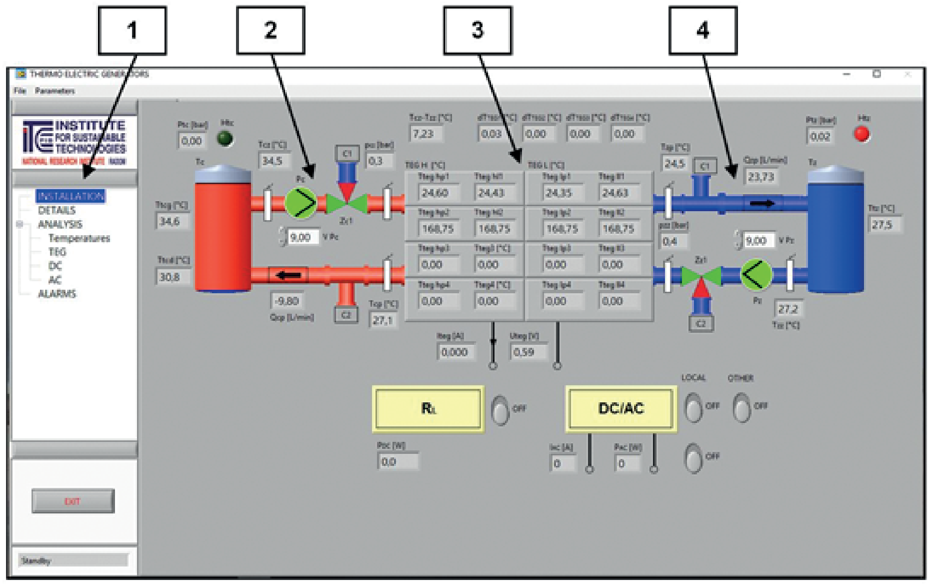


Fig. 7. Main window of the workplace control system software for testing low temperature heat recovery systems: 1) program tree, 2) circulation of the hot sides, 3) block of modules for testing thermoelectric generators, 4) circulation of the cold sides

An important element of the control system is the proprietary DC/AC converter. It can give energy to the power grid (on-grid) or work in a local grid (off-grid). The converter generates electricity up to 1 kW and a constant input voltage range from 10 to 90V.

4. Verification of the station's functionality

The research station allows for carrying out tests of thermoelectric cells with different geometrical dimensions as well as different thermal and electrical parameters. The station also enables the use of waste heat and its conversion into heat with adjustable temperature and flow parameters (Fig. 8). This process takes place in a high temperature heat storage and heat exchange module. On the one hand, the use of water guarantees obtaining and maintaining the maximum temperature (95 ° C) in the B_{HT} module. On the other hand, the use of water as coolant allows for the minimum temperature of 4°C in the system. By using a heat storage and exchange module with low thermal parameters, continuous and stable heat collection is ensured.

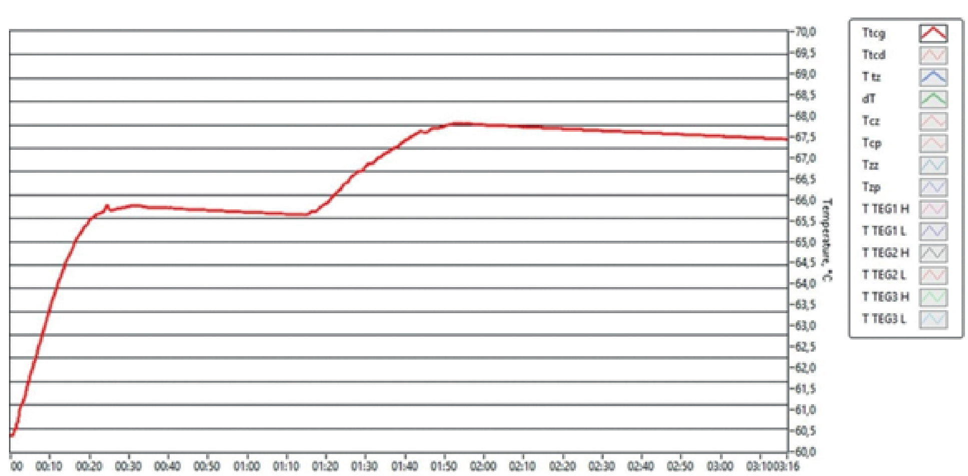


Fig. 8. Graph of temperature changes in the hot water tank obtained under the conditions of the PI controller for two ranges of temperature settings.

The BLT module allows heat collection with adjustable temperature and flow parameters as well as further heat transfer to the heat dissipation system (Fig. 9).

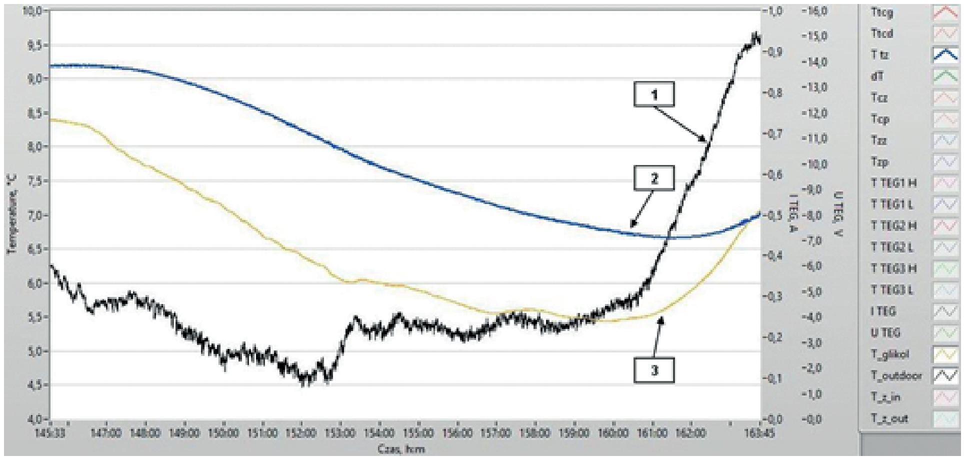


Fig. 9. Graph of temperature changes: 1) outside, 2) in the cold water tank, 3) in the external coolant tank

The prototype research station is used to test not only individual sets of modules, but also large sets of thermoelectric generators. It is designed to test thermoelectric cells of different volumes placed in layers, cascades, and electrically mounted in any configuration – in series and/or in parallel.

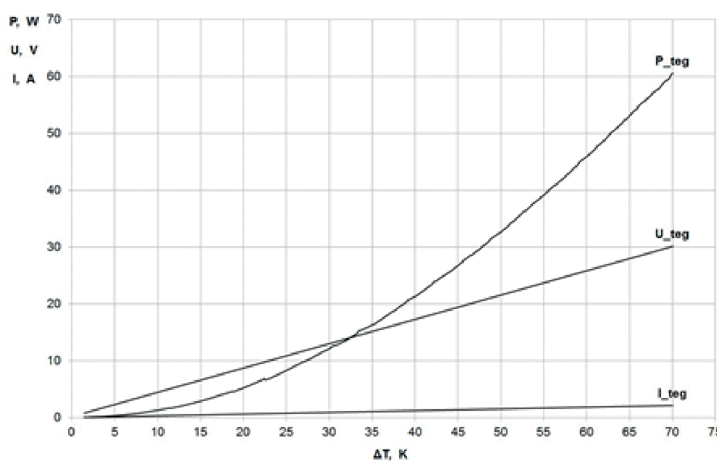


Fig. 10. Changes in electrical parameters at the output of a set of thermoelectric cells: I_teg – current characteristic, U_teg – voltage characteristic, P_teg – power characteristic

The station is equipped with two sets of modules which were separately verified. A single set contains twenty thermoelectric generators. The results from the verification of a single set are shown in Figure 10. During the test, a temperature difference of 70K was induced on the thermoelectric generators. As a result, the response of the system which generated electric power at the average level of 60W was obtained.

5. Summary

The research station for waste heat recovery using thermoelectric generators described in this article allows for the use of lost low-temperature energy and its conversion into electricity. The tests confirmed the correctness of operation of the system and the ability to generate electricity as a result of the temperature difference between the covers of the thermoelectric generators. The research station can be used to verify operation of low power systems that use a small number of thermoelectric cells in which the output product is only DC [5]. It can also be used in research on thermoelectric cells, not only those with single high-efficiency segment modules, but also larger TEG generators with a single generator electrical power of 1kW [6]. The presented solution also enables the conversion of thermal energy from waste heat sources with unstable parameters to thermal energy with utility parameters. The station presented can be used to dissipate thermal energy in the SLT module during a natural fall in temperature at night. As a result, a significant reduction in electricity consumption may be achieved. Furthermore, the adsorption cooling system [19, 20] supplied with heat energy can be used in the developed station to generate supplementary "coolness." This may allow for more efficient use of waste heat energy, and it may also strengthen the heat removal process in the lower heat source and, as a result, increase the temperature difference between the covers of thermoelectric generators. The research station for waste heat recovery may be additionally equipped with systems powered by solar energy, which may affect its autonomy and provide alternative thermal energy in devices with a highly unstable source of waste heat [21].

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