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Use of waste heat of TIEC as the power source for AMTEC

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Abstract

In this investigation, the heat rejected by one heat conversion device has been utilized as the source of power input for another device. A mathematical model has been developed to cascade the two devices under investigation consisting of a thermionic energy converter (TIEC) and an alkali metal thermal to electrical converter (AMTEC) cell. The latter uses the waste heat of the former as the energy input. This cascade system employs a different type of AMTEC, which is a vapor anode system rather the liquid anode used in an earlier work. Also, it uses a more involved algorithm with increased number of nodes than simulated previously. The efficiency of the new cascade has been optimized by solving 16 non-linear equations by MATHCAD. Because of the limitation of MATHCAD the solution is performed in two loops. Nevertheless, the efficiency of this new cascade is thus improved by 28% over the previous one.

Keywords: Waste heat utilization; TIEC; AMTEC; Cascade; Node; Improved efficiency

1. Introduction

Utilization and recycling of waste energy have been the mainstay in the recent past along with the conservation of energy. In this work, we are addressing this problem by directly utilizing the waste energy of a fuel cell as an input power source for an energy conversion device. The concept may not be confined just to this simulation; it may be extended to any kind of waste heat, from any source in any form, to be converted for some practical use. In a recent paper [1], hereinafter called Paper I, two cells thermionic energy converter (TIEC) and alkali metal thermal to electrical converter (AMTEC) were cascaded for an improved efficiency. The AMTEC was employed to utilize the heat rejected by TIEC [2]. In this work, we have adopted the same approach, in principle, as taken by Paper I, i.e. cascading the two cells: one utilizing the rejected heat of the other. However, the receiving cell, AMTEC is of different type and efficiency. The algorithm developed is somewhat different and little more involved but provides much higher efficiency. The problem is divided into two segments and combined again giving rise to a set of 16 non-linear equations including 16 nodal points, to be solved by MATHCAD. Also, in this analysis the AMTEC vapor anode is used instead of liquid anode, used in the simulation of Paper I. In this paper, we avoid the duplication of the details in describing the devices used in this work since they have been described in Paper I. However, for this paper to be self consistent, we describe TIEC briefly in Section 2 but explain the AMTEC structure and its working in detail in Section 3 as it is a different type than what was used in Paper I. The detail of the algorithm developed for this work will be published in a different journal catering the computational techniques. The basic algorithm used for solving a set of 16 non-linear equations is MATHCAD version 7.

2. TIEC

TIEC is a static energy conversion device. It converts heat energy to electrical energy. The work on the thermionic energy converters began in the 1960s. The focus on the TIEC increased greatly because of one of its great potential advantages of converting thermal energy to electrical energy without going into any intermediate mechanical energy step [3]. Some of its other attractive properties include high temperature heat rejection in comparison to other devices for energy conversion and high specific power. As there is no moving part in the cell, there is no vibration. Its compactness adds another reason to focus on this

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Nomenclature

A_{ec}	area of the collector in cm^2
A_{ee}	area of the emitter in cm^2
A_{er}	area of the emitter in cm^2
b	$58.6\ W\,cm^{-2}$
c	power per unit area in $W\,cm^{-2}$
e	8.9 W
n	$0.0423\ W\,K^{-1}\,cm^{-2}$
O	$0.0135\ W\,K^{-1}\,cm^{-2}$
q	$0.012\ W\,K^{-1}$
$Q_{amtecelec}$	electric power output of AMTEC (W)
$Q_{electric}$	electric power output of TIEC (W)
$Q_{electron}$	input energy for the TIEC
Q_{input}	input energy for the AMTEC
Q_{rade}	input energy for the TIEC in radiation form
Q_{trim}	radiation energy stored in trim collar
r	$0.02\ A\,K^{-1}$
T_b	temperature at the transition piece
T_{basewh}	temperature at the BASE tube wall horizontal node
T_{basewv}	temperature at the BASE tube wall vertical node
T_{bel}	temperature at the bellows
T_c	temperature at the collector
T_{cal}	temperature at the calorimeter
T_{con}	temperature at the condenser
T_e	temperature at the emitter
T_{eva}	temperature at the evaporator
T_f	temperature at the emitter flange
T_{hot}	temperature at the hot plate
T_{plenum}	temperature at the plenum plate
T_{trim}	temperature at the trim collar
T_{wallc}	temperature at the cell wall cold zone
T_{wallh}	temperature at the cell wall hot zone
T_{wick}	temperature at the wick

Greek letters

ε	emissivity (=0.18)
η_{amtec}	efficiency of AMTEC
$\eta_{cascade}$	efficiency of TIEC and AMTEC
η_{tiec}	efficiency of TIEC
σ	$5.67 \times 10^{-12}\ W\,cm^{-2}\,K^{-4}$

cell. The primary parts of TIEC are an emitter, an emitter flange, an emitter sleeve, bellows and a collector, see Fig. 1. The emitter receives heat from one side and emits electrons from the other side. The rate of the electron emission from the hot metal surface is a function of the metal's temperature and work function. The kinetic energy of electrons within the bulk metal increases with increasing temperature, allowing a higher fraction of them to escape from the metal surface. The collector receives these electrons at a lower temperature. The emitter acts as a cathode and the collector acts as an anode. The anode and cathode are connected by the electrical leads, which supply the power to the external load.

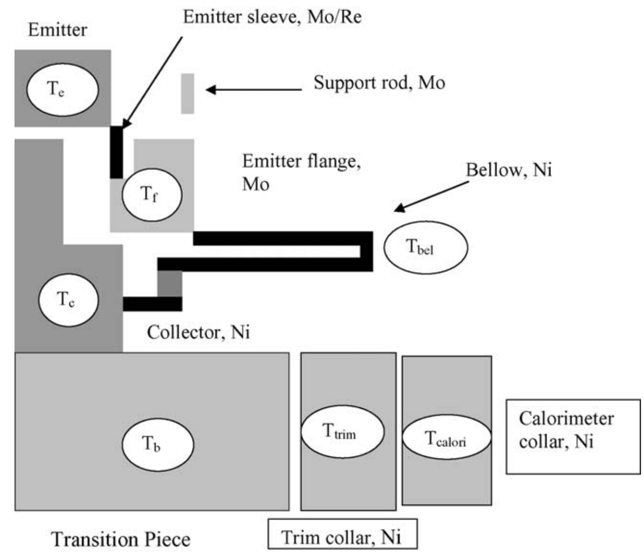

Fig. 1. TIEC with nodes.

TIEC converts a gas of free electrons in the inter-electrode space. These electrons may thus create a negative space charge between the electrodes. As a result, a retarding field develops which deflects some of the emitted electrons back to the cathode. To reduce the space charge effect, the gap between the emitter and the collector is filled with some plasma. The most commonly used substance for this purpose is cesium (Cs) vapor. Cesium has lower ionization potential among candidate substances and its absorption reduces the surface work function of the electrodes below that of liquid cesium or any metal [2]. The high temperature is localized within the emitter and moderate temperature resides elsewhere in the cell. The points of different temperatures are called nodes, which in TIEC are T_e, T_{bel}, T_f, T_b, T_c, T_{trim}; see Fig. 1.

The TIEC cell operates between temperatures of 1800–2000 K at the emitter end. The cell has been designed to work independently of the heat source. The heat from emitter zone is transported by means of radiation and conduction to the other parts of the cell. A portion of the heat is radiated to the surrounding. The flange receives heat from the emitter through radiation and conduction. The cesium gas, to get ionized and to dissipate the electrons uses some amount of heat. The electrons get accelerated and travel through the electrodes towards the collector. Some of the heat energy is also radiated to the collector. The heat from the flange is conducted to the bellows, radiated to surroundings and to collector. The bellows temperature is considerably less than the temperatures at other nodes because the heat is radiated to the surrounding from the bellows node. The collector temperature is usually between 1000 and 1250 K. Thus, most of the heat energy is given out to the surroundings. This heat energy can be used to generate more electricity. The efficiency of TIEC is calculated as the ratio of the contact potential difference which is equal to the voltage on the load to the sum of the energy carried away by the electrons from the cathode and the radiation heat transferred from emitter to collector.

3. AMTEC

AMTEC, like TIEC, is also a relatively new type of static energy conversion device. Its working is, however, based on the principle of an appropriate metal concentration cell, which converts heat to electrical energy. Since the middle 1960s, a number of programs in developing the operating principle, design and technology of AMTEC has been evolving rapidly. In a patent assigned to Ford Motor Company in 1968, Kummer and Weber [4] demonstrated the conversion of heat through the sodium cycle, into electricity by the use of beta″ alumina solid electrolyte (BASE). Weber [5] described the operating principle of AMTEC with a liquid anode in 1974. There are some informative papers on the working principle of AMTEC [6–9]. The use of nuclear power for AMTEC perhaps provided another motivation for further investigation into AMTEC [10–12]. Some brisk activities about AMTEC began around the world at the beginning of 1990s. The research and development at Jet Propulsion Lab (JPL) included studies, which address both overall device construction and AMTEC components [13–28]. Advanced Modular Power Systems (AMPS) have been focusing on designing and manufacturing AMTEC cells supposedly for intended Pluto Express mission [29–32]. Air Force Research Lab (AFRL) had also been testing the AMTEC cell performance for the same mission [33–39]. Orbital Science Corporation has been conducting a series of studies of radioisotopes power system based on general purpose heat source (GPHS) for potential deep space missions [40,41]. Off late, University of New Mexico has been engaged in modeling and analysis of AMTEC performance and evaluation [42–45]. Kyushu University in Japan has also done some research [46,47]. A number of efforts are underway to develop practical and high efficiency of AMTEC cells [48–51].

AMTEC consists of mainly hot plate, plenum plate, wick, evaporator, BASE tube, electrodes and condenser. The number of BASE tubes may vary from a single to several. The input energy can be obtained from any kind of source. AMTEC has better efficiency compared to radioisotope thermoelectric generator (RTG), general purpose heat source (GPHS) modules [52]. The BASE tubes are in the high pressure and high temperature sodium (Na) vapor and the condenser is in the low pressure and low temperature regions. The liquid–vapor interface is in the evaporator. AMTEC has low maintenance cost and high durability for terrestrial and space power applications [53].

The static nature of static converters achieves close to the Carnot efficiency [3] at relatively low operating temperatures. An optimized AMTEC can potentially provide theoretical conversion efficiency between 20 and 40% with no parasitic losses. The operation of AMTEC cell involves several heat and mass transfer processes. AMTEC operates at a temperature of 1000–1200 K at hot side and 400–700 K at the cold side. There are two types of AMTEC cell based on the working principle, the liquid-anode sodium AMTEC and vapor-anode sodium AMTEC. The former type was used in Paper I whereas the latter type is simulated in this work. In a vapor-anode AMTEC, as the name suggests, the metal gas vapors are introduced into the BASE tube, carrying an anode at the inner surface. The conductivity of the BASE is much larger for ions than the electronic conductivity [54,55].

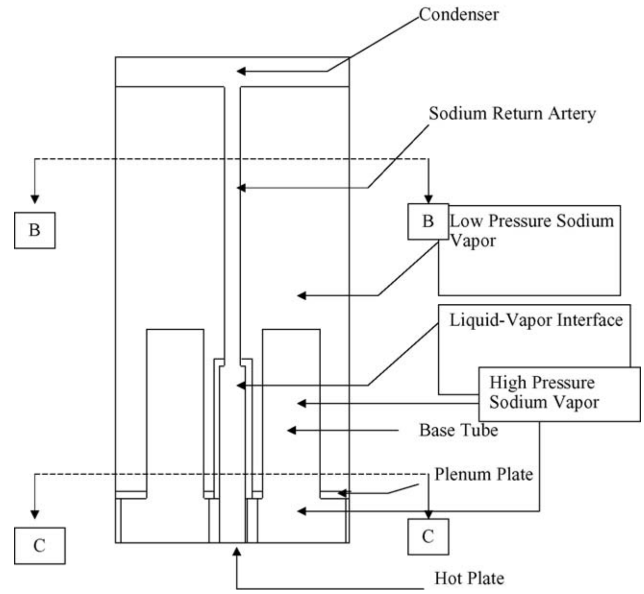

Fig. 2. ‘Vapor anode AMTEC (SEC A-A).

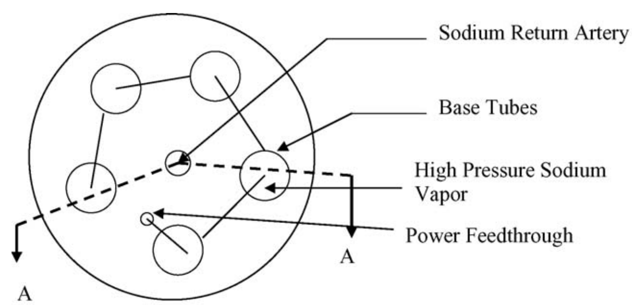

Fig. 3. Vapor anode AMTEC (SEC B-B).

In an AMTEC, see Figs. 2–4, the liquid sodium in the condenser is at 550–700 K, from where it is administered to the high-temperature, high-pressure evaporator. The BASE tubes are insulated from each other and from the cell wall, too, which is not possible in liquid-anode cells, because sodium is good electrical conductor. It utilizes a capillary wick structure, such

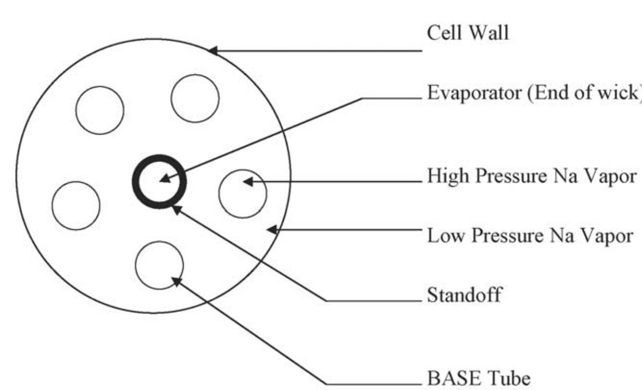

Fig. 4. Vapor anode AMTEC (SEC C-C).

as sintered, felt metals or cable arteries, to circulate the liquid sodium from the condenser to the evaporator [56]. In the wick structure, a thin film of liquid sodium is there on its surface, which reflects thermal radiation toward the interior thus reducing parasitic losses. The wick for AMTEC used in simulating the cascade under investigation, is of a stainless steel mesh pad condenser or a Creare condenser wick. The stainless steel pad develops dry patches and increases parasitic losses. The Creare wick forces liquid sodium to spread uniformly on the surface of the wick, which helps the flow of condensed liquid sodium to the underlying thin stainless steel felt wick structure [57]. The amount of working fluid returned to the evaporator is self-regulating. As the liquid sodium evaporates, the increase in capillary forces at the liquid–vapor interface pulls more fluid to the evaporative surface. The heat input is given to the hot plate. It can be from any source. The plenum plate is on the standoffs. The space between the plenum plate and the hot plate is filled with high-pressure sodium vapor. The condenser is in the low-pressure and low-temperature zone. The sodium vapor is condensed in the condenser. Then it is again circulated through the wick (return artery). The return artery is between the condenser and the evaporator. The liquid–vapor interface is in the wick-evaporator junction.

The electrodes for AMTEC use should have low contact resistances and good bonding with the BASE tube. The permeability to sodium vapor has to be high, and good corrosion resistance to sodium vapor. They ought to have low material loss rate due to chemical reaction with metallic and gaseous impurities and should have slow grain growth and material migration [58]. The metal electrodes used are porous. The anode and cathode cover inner and outer surfaces of the BASE, respectively. They provide a path for the external load when connected. If the AMTEC cell is liquid-anode type, as used in Paper I, the metal anode is not needed, because liquid sodium being a good conductor acts as anode also.

Some aspects, not considered in Paper I, are taken care of in this investigation. For example, low conductivity materials for the cell walls can reduce the heat loss between the hot and cold ends of the cell. Materials such as stainless steel can be used [60]. The heat conduction losses are dependent on the cross-sectional area. So, reduction in the cross-section area of the leads could increase the efficiency. On the other hand, the reduction of the cross-sectional area of the leads would increase the resistance. An optimum value for the lead cross-section is also considered for higher cell efficiency.

The number of BASE tubes can also vary in an AMTEC cell. When there are more than one BASE tubes, the tubes are connected in series. Other tubes receive a portion of the radiation from each tube, which is advantageous. The temperature of the BASE tubes and the evaporator are very important. The BASE tube temperature has to be higher than the temperature of the evaporator. This is done to prevent the condensation inside the tubes and potential electric shorting of the cell [59]. The BASE tube actually divides the cell in to two separate regions. One side is high-pressure and high-temperature sodium vapor (10–1000 kPa, ∼1200 K) [61,62], and the other side is a cooled low-pressure sodium vapor region. This pressure differential causes the expansion of sodium ions (Na^+) the electrons circulate through the external load to the cathode and recombine with the sodium ions. The multi-tube vapor anode cell has relatively low specific mass than single tube cells [61]. It is a characteristic that makes it more attractive for space applications. The radiation shield is used to reduce parasitic heat losses. Parasitic heat losses are significant to decrease the efficiency of AMTEC.

The number of nodes considered for this AMTEC simulation is nine, namely, T_{hot}, T_{plenum}, T_{wallh}, T_{wallc}, T_{basewv}, T_{basewh}, T_{eva}, T_{wick}, T_{con}.

4. Cascade

The typical operating temperatures of TIEC are 1000–2000 K at the emitter and 800–1100 K at the collector [63]. It has an efficiency of about 10–15% [64]. The operating temperatures of AMTEC are 900–1200 K at the hot plate and 400–700 K at the condenser [65]. It has an efficiency of about 15–20% [66]. The operating temperatures of the TIEC and the AMTEC make it plausible to cascade for utilizing the heat rejected by TIEC as the input for AMTEC.

To cascade TIEC and AMTEC a transition piece is used between collector of TIEC (see Fig. 1) and hot plate of AMTEC. The transition piece is surrounded by trim collar which can be heated by resistance heating element and cooled by water or air to maintain the desired temperature. The heat rejected by the collector of TIEC is used by the hot plate as the input energy for the AMTEC through the transition piece.

The purpose of cascading TIEC and AMTEC is to utilize the waste heat of TIEC by deriving an optimum power output with minimum heat energy wasted. Cascading of direct energy conversion devices when the waste heat of a high temperature device is used to operate a bottoming low temperature device would allow the development of a highly efficient, compact, light weight power source and a bimodal system to address future civil and defense missions [67]. The emitter converts a portion of heat energy into electricity and rejects the rest from the lower end of the collector, into the transition piece. The heat rejected at the bottom of the collector is picked up by the AMTEC hot plate via the transition piece. In case of excess amount of heat supplied to the transition piece, the heat is passed to the trim collar. On the other hand if the transition piece does not get enough heat the trim collar will supply the required heat to the transition piece. To measure the amount of heat energy passing though the transition piece, a calorimeter is used (Fig. 1).

Cascading the TIEC and AMTEC is basically done to maximize the use of input energy source by achieving a high efficiency and power density [68]. The cost effectiveness of the cells also depends on the weight of the conversion cells. Cascading the cells also helps to effectively reduce the weight of the converters combined. A thermal model for the nodal analysis has been developed. This model considered four nodes in TIEC, one node each in trim collar, transition piece, and calorimeter and nine nodes in AMTEC. The temperatures of these nodes are the variables. The optimized efficiency is accomplished by evaluating the temperatures at these nodes of the thermal model. The node in the hot plate receives the rejected heat of TIEC, which is

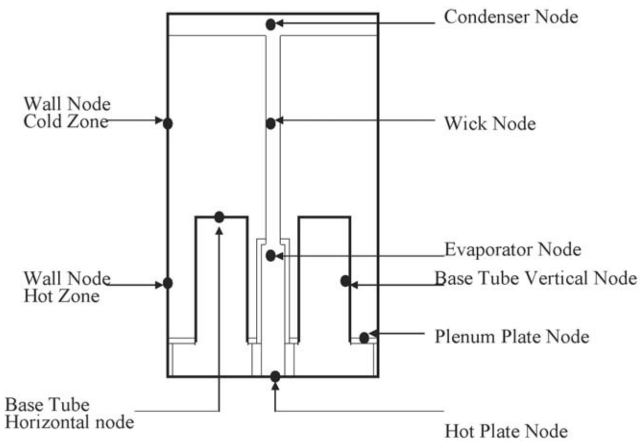

Fig. 5. AMTEC thermal model nodes.

represented as Q_{input}. This energy is transported to other nodes in AMTEC, namely the plenum plate node, node in the BASE tube vertical wall, node in the BASE tube horizontal wall, node in the evaporator, wick node, condenser node and nodes in cell walls in hot and cold regions. These nodes are shown in the thermal model schematic diagram in Fig. 5.

5. Calculations and results

We have developed a set of 16 non-linear equations to be solved in this investigation. As it turned out that the MATHCAD version, chosen for solving them has some limitation. It is designed to handle up to 12 equations at the most at one time. We, therefore, solved a set of seven equations including four nodes of TIEC and one node each at transition piece, trim collar and hot plate in one loop. The other set of nine equations including all AMTEC nodal points was solved as another loop. This means that the solution for the cascade thermal model is divided in to two separate models, one for the standalone TIEC and the other for standalone AMTEC. They are then combined into one. The TIEC and AMTEC have one common node at the hot plate. In order to determine the temperature at various points in different regions of the cascade a criterion is set up. In that the energy balance at each node is considered, i.e. the total amount of heat entering into a node must be equal to the energy leaving the node. As the energy flows from one node to the next the temperature goes on decreasing. The temperature profile of the nodes of TIEC and AMTEC is given below.

The first part of the solution is:

$$\begin{bmatrix} T_{\text{e}} \\ T_{\text{c}} \\ T_{\text{f}} \\ T_{\text{bel}} \\ T_{\text{b}} \\ T_{\text{hot}} \\ T_{\text{trim}} \end{bmatrix} = \begin{bmatrix} 1.808 \times 10^3 \\ 1.101 \times 10^3 \\ 1.208 \times 10^3 \\ 1.058 \times 10^3 \\ 1.063 \times 10^3 \\ 1.04 \times 10^3 \\ 1.048 \times 10^3 \end{bmatrix} \text{(K)}.$$

The second part of the solution with nine nodes of AMTEC is obtained as:

$$\begin{bmatrix} T_{\text{hot}} \\ T_{\text{plenum}} \\ T_{\text{wallh}} \\ T_{\text{wallc}} \\ T_{\text{basewv}} \\ T_{\text{basewh}} \\ T_{\text{eva}} \\ T_{\text{wick}} \\ T_{\text{con}} \end{bmatrix} = \begin{bmatrix} 1.103 \times 10^3 \\ 1.081 \times 10^3 \\ 966.641 \\ 677.865 \\ 1.044 \times 10^3 \\ 1.042 \times 10^3 \\ 861.491 \\ 679.312 \\ 547.67 \end{bmatrix} \text{(K)}.$$

5.1. *Efficiency*

The principal objective of this investigation is to optimize the energy use, which is achieved by maximizing the efficiency of the cascade. Let the efficiencies of TIEC, AMTEC, as they stand alone, and cascade be, respectively, η_{tiec}, η_{amtec} and η_{cascade}, which are evaluated as:

$$\eta_{\text{tiec}} := \frac{Q_{\text{eletric}}}{Q_{\text{electron}} + Q_{\text{rade}}} \times 100$$

$$Q_{\text{electric}} := (o \cdot T_{\text{e}} - c) \cdot A_{\text{ee}}$$

$$Q_{\text{electron}} := (n \cdot T_{\text{e}} - b) \cdot A_{\text{ee}}$$

$$Q_{\text{rade}} := \sigma \cdot \varepsilon_{\text{ti}} \cdot A_{\text{er}} \cdot ({T_{\text{e}}}^4 - {T_{\text{c}}}^4)$$

$$Q_{\text{electron}} = 17.861\,\text{W}$$

$$Q_{\text{electric}} = 3.942\,\text{W}$$

$$Q_{\text{rade}} = 25.177\,\text{W}$$

$$\eta_{\text{tiec}} = 9.16$$

The symbols used for constants are defined as: T_{e}, emitter temperature in K; T_{c}, collector temperature in K; A_{ee}, area of the emitter in cm^2; c, power per unit area in W cm^{-2}; O, $0.0135\,\text{W K}^{-1}\,\text{cm}^{-2}$; n, $0.0423\,\text{W K}^{-1}\,\text{cm}^{-2}$; b, $58.6\,\text{W cm}^{-2}$; σ, $5.67 \times 10^{-12}\,\text{W cm}^{-2}\,\text{K}^{-4}$; ε, emissivity = 0.18.

The efficiency of TIEC as a stand-alone converter is 9.16.

$$\eta_{\text{amtec}} := \frac{q \cdot T_{\text{basewv}} - e}{Q_{\text{input}}} \cdot 100$$

$$Q_{\text{input}} = 26\,\text{W}$$

$$q \cdot T_{\text{basewv}} - e = 3.285\,\text{W}$$

$$\eta_{\text{amtec}} = 12.635$$

The $q \cdot T_{\text{basewv}} - e$ term gives the electricity produced by AMTEC. Hence, we can write: "The efficiency of AMTEC as a stand-alone converter is 12.635".

$$\eta_{\text{cascade}} := \frac{Q_{\text{electric}} + Q_{\text{amtecelec}}}{(Q_{\text{electron}} + Q_{\text{rade}}) - Q_{\text{trim}}}$$

$$\eta_{\text{cascade}} = 18.494\%$$

6. Conclusion

We have established an effective way of utilizing the rejected energy in the form of heat at high temperature by one device as a potential source of input power for another device by selecting the two compatible devices. In this study we employed TIEC and AMTEC to cascade them into one integrated unit. On one hand while this technique provides the efficient use of the waste energy, it suppresses the thermal pollution on the other hand, as a bonus. Considering the fact that the efficiency of the standalone TIEC used for this investigation is only 9.16, but when it is cascaded with AMTEC the final efficiency is raised to 18.5 thus improving by more than 100%. Comparing the outcome of the present work with the previous approaches we notice that the efficiency of this cascade is improved significantly (by 28.5%) over the previous calculation in Paper I which in turn had improved over the result of reference 2 by 7.5%. The improvement is attributed to the selection and the number of nodes. In the earlier work [2] nine nodes were chosen thus obtaining the efficiency of the cascade as 13.4. In Paper I, 12 nodes produced the efficiency of 14.4 whereas the efficiency in this simulation is obtained by increasing the number of nodes to 16. There are some elements in the cascade and particularly in AMTEC where other nodes, different set with more or less number of nodes, could be selected. The solution can thus be improved by selecting the number and position of nodes. One final remark is to set up a program, capable to solve the non-linear equations in an efficient way by considering the cascade as a whole with global optimization.

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