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Optimization of the TIEC/AMTEC cascade cell for high efficiency

M.A.K. Lodhi *, V.R. Malka

Department of Physics, MS 1051, Texas Tech University, Lubbock, TX 79409, USA

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Abstract

A mathematical modeling of a system consisting of a cascade of a thermionic energy conversion (TIEC) device and an alkali metal thermal to electric converter (AMTEC) device has been performed to optimize the efficiency of the cell. The TIEC is heated by electronic bombardment, which converts heat partially into electricity and rejects the remaining heat. The AMTEC utilizes the rejected heat of the TIEC. Cascading these two cells provides lots of advantages. A mathematical model for the cascade converter has been developed to analyze the effects of key parameters such as power level, heat fluxes and temperatures. In this effort, a 12-node system of non-linear simultaneous equations has been constructed which is solved by MATCAD and a locally optimized efficiency has been derived. Thus, efficiency of the cascaded cell is improved, so that it is greater than the highest efficiency among the TIEC and AMTEC and lower than the sum of their individual efficiencies.

Keywords: TIEC; AMTEC; Cascade; Efficiency; Optimization

1. Introduction

The conversion of thermal and/or mechanical energy to electrical energy has been historically the mainstay for power systems. With the advent of Faraday's law of electromagnetic induction and steam engine, dynamic conversion systems evolved rapidly and were perfected with the engineering details mostly for terrestrial and aircraft devices. As a potential alternative to the dynamic conversion systems, static thermal to electrical conversion systems have been investigated, particularly for space power systems. With the discovery of the Seeback effect, the thermo-electromotive force, which occurs in materials under the effect of a temperature gradient, has been the driving force for static thermo-electric generators. A large number of static devices have been evolved and studied [1–9]. The goal for static conversion systems has been to identify static converters with efficiencies that are competitive with dynamic systems. Two compatible static devices may be linked together in a tandem form to increase the overall efficiency. The objective of this work is to optimize the efficiency of a device that cascades two static devices, namely TIEC and AMTEC.

A thermionic energy converter (TIEC) is a static device (see Fig. 1), which converts heat energy through the surface emission of electrons. It consists of an emitter (cathode), which receives heat from a suitable source and emits electrons from the other side. A collector (anode) collects these electrons and is cooled to a lower temperature than that of the emitter to limit the back emission of electrons [2]. The anode and the cathode are connected by external electrical leads to supply the generated power to the load.

An alkali metal thermal to electrical converter (AMTEC) is a device for the direct conversion of heat to electrical energy with no moving parts (see Fig. 2). It has the potential to produce electrical power with much higher efficiency and power density than current devices such as the radioisotope thermo-electric generator (RTG), general purpose heat source modules (GPHS) [3]. AMTEC uses a beta-alumina solid electrolyte (BASE) to separate electrons from ions in a high-pressure and high-temperature region of liquid metal at 900–1300 K [10]. It converts the work of the isothermal expansion of sodium vapor directly to electrical power. AMTEC has many advantages for terrestrial and space power

* Corresponding author. Tel.: +1 806 742 3778; fax: +1 806 742 1182.
E-mail address: a.lodhi@ttu.edu (M.A.K. Lodhi).

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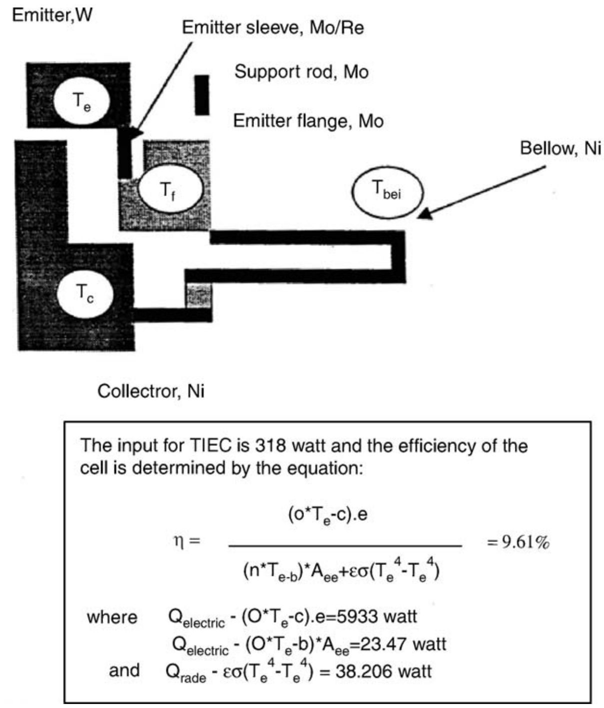

Fig. 1. Schematic of thermal model of thermo-ionic converter (TIEC).

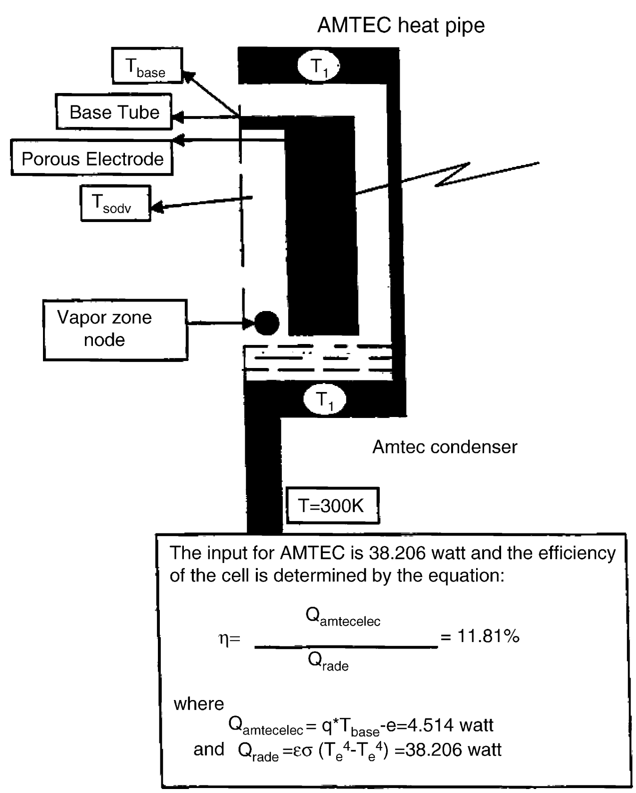

Fig. 2. Schematic of thermal model of alkali metal thermal to electrical converter (AMTEC).

applications including no moving parts with the resulting potential for low maintenance and high durability and efficiency.

An assembly of TIEC and AMTEC has been cascaded with a transition piece between the collector of TIEC and the heat input region of AMTEC (see Fig. 3). The transition piece is surrounded by a trim collar (heater/cooler), which can be heated by a resistance heating element, or cooled by water or by air, in order to maintain the desired temperature in the transition piece. The heat rejected by the collector of the TIEC is picked up by the heat input region of the AMTEC through the transition piece and thus both the TIEC and AMTEC are operated.

Lodhi et al. [1] had developed a model by writing nine nodal equations (using conservation of energy) at strategic locations within the cascaded cell. The number of nodal points has been increased from 9 to 12. The new nodal points included were at the insulator between the transition piece and the AMTEC evaporator, base tube, vapor zone (in the low-pressure region between the base tube and the condenser). The variable identified in this cell is temperature at various points of the cell. Mathematical equations for the energy balance and heat fluxes have been developed. Through this mathematical model the optimized efficiency of the cell is to be achieved. When we are cascading two cells, the efficiency of the cascaded cell is expected to be between the highest efficiency of the individual cells and less than the sum of the efficiencies of the two cells. For this process, a mathematical model has been written in Mathcad, Version 7.0.

2. Thermionic energy converter

A thermionic energy converter is a device, which converts the thermal energy to electrical energy. There are two types of TIEC, one which works in vacuum and the other works with a plasma.

The working principle of vacuum TIEC involves in conversion of a gas of free electrons in the inter-electrode space, in a vacuum. These electrons create a negative space charge between the electrodes, and as a result, a retarding field develops which deflects some of the emitted electrons back to the cathode. The gas chosen in TIEC is cesium (Cs). Cesium has the lower ionization-potential among candidate substances and its adsorption reduces the surface work function of the electrodes below that of liquid cesium or any metal [11].

The cell operates at a temperature of 1800–2000 K at the emitter end, T (see Fig. 1). It has been designed to work independent of the heating source. The heat from emitter zone is either radiated or conducted to the other parts of the cell. A portion of the heat is radiated to the surroundings, T_{amb}. The heat gained by the flange from the emitter is in two-fold, one through radiation and the other through conduction. The temperature at flange is T_f. The gas uses some amount of heat to get ionized and to dissipate the electrons. The electrons get accelerated and travel through the electrodes towards the

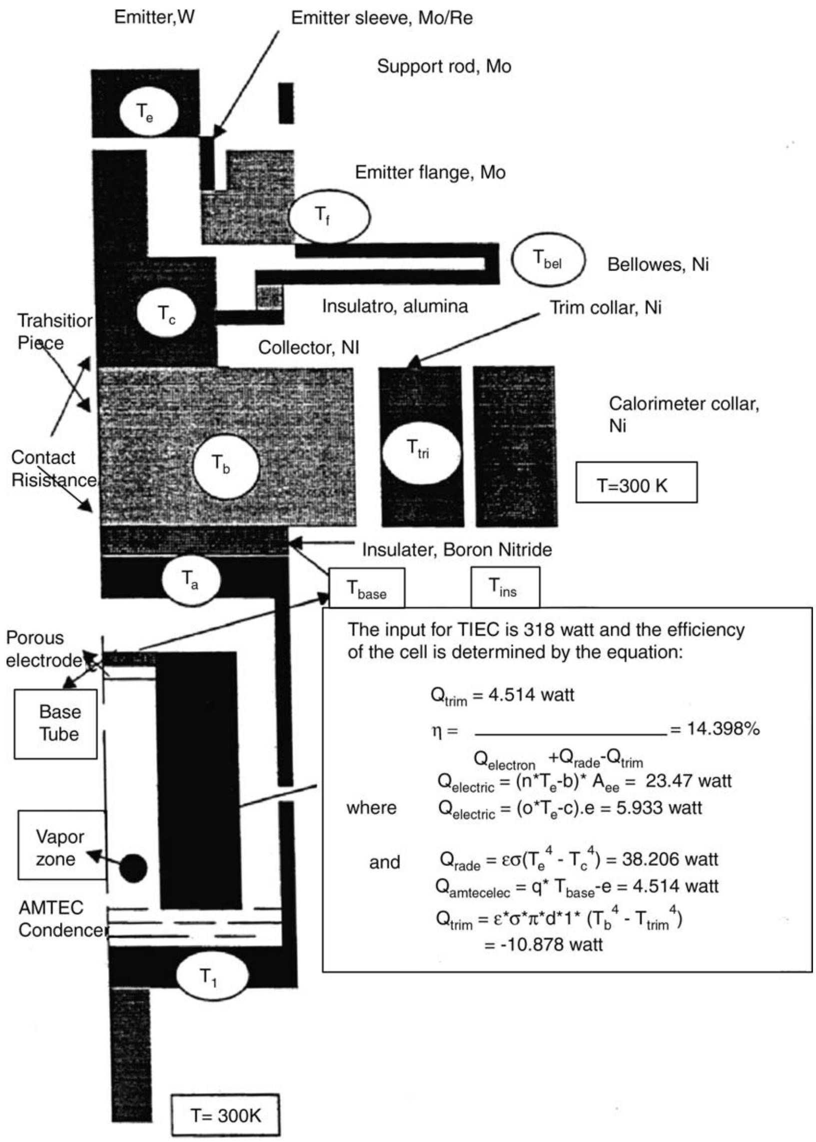

Fig. 3. Schematic of thermal model of cascaded TIEC/AMTEC converter.

collector. The electricity is drawn from the electrodes at this point. The heat energy is also radiated to the collector.

The heat energy from the flange is conducted to the bellows, radiated to surroundings and to the collector. The temperature at the bellows, T_{bel}, is considerably less than the temperatures at other nodes. Most of the heat is given out to surroundings from bellows. The temperature at the collector, T_c, is expected to be between 1000 and 1250 K. Release of heat energy at such high temperatures makes the cell inefficient.

The converter 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 electrons from the cathode and the radiation beat transfer from emitter to collector. Thus, the efficiency, η_{TIEC}, is:

$$\eta_{TIEC} = \frac{Q_{electric}}{Q_{electron} + Q_{rade}}$$

where $Q_{electric} = (O \times T_e - c) \times A_{ee}$, O = constant = 0.0135 $W\,K^{-1}\,cm^{-2}$, T_e = emitter temperature in K, A_{ee} = area of the emitter in cm^2, c = power per unit area in $W\,cm^{-2}$; $Q_{electron} = (n \times T_e - b) \times A_{ee}$, n = constant = 0.0423 $W\,K^{-1}\,cm^{-2}$, b = 58.6 $W\,cm^{-2}$; $Q_{rade} = \sigma \times \varepsilon \times (T_e^4 - T_c^4)$, $\sigma = 5.67 \times 10^{-12}\,W\,cm^{-2}\,K^{-4}$, ε = emissivity = 0.18, T_c = collector temperature in K.

3. AMTEC

AMTEC is a high-temperature regenerative concentration cell for an appropriate alkali metal, which converts thermal energy directly into electrical energy (see Fig. 2). In this study, liquid sodium is selected as the working fluid. The efficient operation of the AMTEC cell involves several heat and mass transfer processes. AMTEC is a relatively new type of device, based upon the principle of an alkali metal concentration cell, conceived in late 1960s. This is a static conversion device, which can provide efficiency close to the theoretical Carnot efficiency. AMTFC operates at a temperature of 900–1300 K at hot side and 400–600 K at the cold side.

There are two types of AMTEC cells based on their working principle. One is liquid anode type and the other is vapor anode type. In this study, we are simulating the liquid anode type. To understand the working of AMTEC, its operating cycle is illustrated in Fig. 2 schematically. A closed vessel is divided into a high-temperature (T_a) region in contact with a heat source and a low-temperature (T_l) at the cooler region. The critical material in the operation of the AMTEC is the beta-alumina solid electrolyte, a sodium ion conductor whose ionic conductivity is much larger than its electronic conductivity. In an AMTEC cell, the BASE separates the hot (high-pressure) region filled with a small quantity of liquid sodium in contact with the heat source, from the cold (low-pressure) region occupied with sodium vapor. A porous electrode covers the low-pressure (outer) side of the BASE. Electrical leads in contact with the porous electrode and the high-temperature liquid sodium exit through the wall of the device and is connected to an external load. The pressure differential across the BASE forces ionization of sodium atoms on the hot side. The ions diffuse through the BASE towards the low-pressure side in response to the pressure differential gradient of free Gibbs energy while the electrons circulate through the external load, producing electrical work. Electrons and sodium ions recombine at the interface between the BASE and the porous electrode. The resulting sodium ions absorb their heat of vaporization, move through the electrode and the vapor space, then release their heat of vaporization at the low-temperature side of the condenser surface. A wick structure or an electromagnetic pump brings the liquid condensate to the high-temperature side of the BASE tube to complete its circulation.

The heat distribution in the AMTFC is as follows: the temperature at the hotplate, T_a, should be between 900 and 1300 K. The heat source for AMTEC may be radioactive materials, solar, heat rejected from other devices or any other heating source. The heat energy from this point is given out to the sodium liquid. Because of convective heat transfer, the sodium starts boiling and slowly gets converted to vapor. The heat energy allows the sodium to move towards the low-pressured BASE. As the sodium approaches the BASE it gets ionized. The temperature at the BASE, T_{base}, is approximately equal to that of the boiling point temperature of sodium. Hence some part of heat energy is used in transporting sodium, some in generating electricity and some of the heat energy is wasted as parasitic losses. Also some part of heat energy is transferred to the sodium vapor in convection mode. The heat passed onto the vapor zone from the BASE is linearly distributed to the condenser and to the surroundings through the wall of the cell. The temperature at the condenser, T_l, is expected to be above 400 K.

The efficiency of AMTEC, η_{AMTEC}, is defined as the ratio of the amount of electric energy generated to the amount of heat supplied to the AMTEC.

Thus, the efficiency of AMTEC is:

$$\eta_{AMTEC} = \frac{Q_{amtecelec}}{Q_{rade}}$$

where $Q_{amtecelec} = q \times T_{base} - e$, $q = \text{constant} = 1.2 \times 10^{-12}$ W K^{-1}, T_{base} = BASE tube temperature in K, $e = 8.9$ W; $Q_{rade} = \sigma \times \varepsilon \times (T_e^4 - T_c^4)$, $\sigma = 5.67 \times 10^{-12}$ W cm^{-2} K^{-4}, ε = emissivity = 0.18, T_c = collector temperature in K.

4. Cascade of TIEC and AMTEC cell

The purpose of cascading TIEC and AMTEC is to derive an optimum power output with less heat energy wasted. A schematic diagram of such a cascade is shown in Fig. 3. Cascading of direct energy conversion devices has been designed for the waste heat of a high-temperature device used to operate a bottoming low-temperature device. It would allow the development of a highly efficient, compact and light weight power to address future civilian and defense missions [5]. This system uses a cesium-TIEC to operate a bottoming sodium-AMTEC [12]. This combination is most suitable because the optimum collector temperature, T_c, of TIEC is typically in the 1000–1200 K ranges and AMTEC hot pipe temperature, T_a, falls well within this range.

The construction of such system involves using a transition piece between the collector of TIEC and the heat pipe of AMTEC. The transition piece is surrounded by a trim collar (heater), which can be heated by a resistance heating element, or cooled by water or air, to maintain the desired temperature and heat flux in the transition region. The TIEC is heated up by the electron bombardment on the upper end of the emitter, which converts a portion of heat energy into electricity and rejects the rest from the lower end of the collector, into the transition piece. The remaining heat rejected at the bottom of the collector is picked up by the AMTEC via the transition piece.

The heat rejected from the collector of TIEC is absorbed by the transition piece. Some portion of the heat energy may be used to heat the trim collar. The heat energy supplied to trim collar will be through radiation. If an excess amount of heat is supplied to the transition piece, then some heat is passed onto the trim collar. If the collector of TIEC does not supply sufficient amount of heat energy to the transition piece, the trim collar will supply the required heat energy. Hence, the heat contribution by the trim collar to the total cell may be included or excluded. A calorimeter is used for the transition piece to measure the amount of heat energy passing through it. Thus, certain amount of heat energy is radiated from the trim collar to the calorimeter, and part of it from the calorimeter to the surroundings. A certain amount of heat energy is supplied to the AMTEC heat pipe. The heat flow of the cascaded cell is illustrated in Fig. 4.

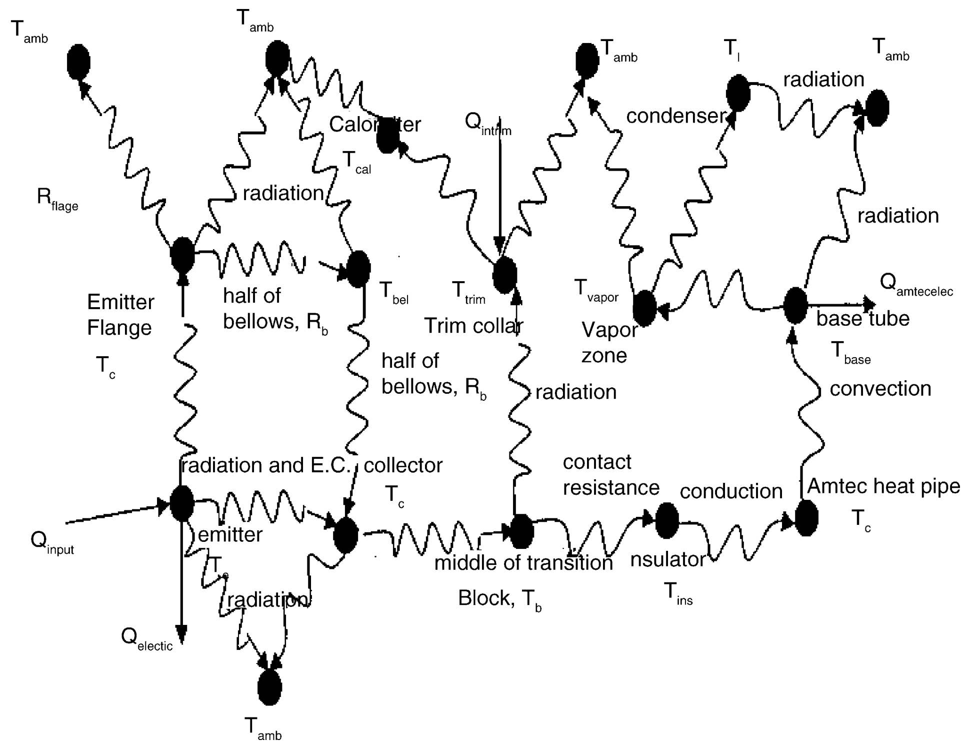

Fig. 4. Thermal circuit for calculating temperatures and power flows in thermo-ionic/AMTEC cascade converter.

The efficiency of the cascaded cell should be larger than the highest efficiency of the individual cells and lesser than the sum of the efficiencies of both the cells. The efficiency of the cascaded cell, η_{cascade}, is:

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

where $Q_{\text{electric}} = (O \times T_e - c) \times A_{ee}$, O = constant = 0.0135 $\text{W}\,\text{K}^{-1}\,\text{cm}^{-2}$, T_e = emitter temperature in K, A_{ee} = area of the emitter in cm^2, c = power per unit area in $\text{W}\,\text{cm}^{-2}$; $Q_{\text{amtecelec}} = q \times T_{\text{base}} - e$, q = constant = $1.2 \times 10^{-12}\,\text{W}\,\text{K}^{-1}$, T_{base} = BASE tube temperature in K, e = 8.9 W; $Q_{\text{electron}} = (n \times T_e - b) \times A_{ee}$, n = constant = 0.0423 $\text{W}\,\text{K}^{-1}\,\text{cm}^{-2}$, b = 58.6 $\text{W}\,\text{cm}^{-2}$; $Q_{\text{rade}} = \sigma \times \varepsilon \times (T_e^4 - T_c^4)$, $\sigma = 5.67 \times 10^{-12}\,\text{W}\,\text{cm}^{-2}\,\text{K}^{-4}$, ε = emissivity = 0.18, T_c = collector temperature in K; $Q_{\text{trim}} = \sigma \times \varepsilon \times \pi \times d_{\text{trans}} \times l_{\text{trans}} \times (T_b^4 - T_{\text{trim}}^4)$, $\sigma = 5.67 \times 10^{-12}\,\text{W}\,\text{cm}^{-2}\,\text{K}^{-4}$, ε = emissivity = 0.2, d_{trans} = diameter of the transition piece in cm, l_{trans} = length of the transition piece in cm, T_{trim} = trim collar temperature in K, T_b = transition temperature in K.

The mathematical model is written for the cascaded cell and is aimed at optimizing the efficiency of the cell.

5. Mathematical model and feasible solution

A mathematical model has been developed in order to maximize the efficiency of the cascaded cell satisfying all the constraints associated with. The cascade cell has been divided into 12 nodal points and at each nodal point the heat balance equations have been written. These heat balance equations are the constraints to the problem. As a general rule heat always travel from hot region to cold, hence the other constraints of the problem are $T_e > T_f > T_c > T_b > T_a > T_{\text{base}} > T_{\text{sodv}} > T_l$.

The objective function is:

$$\text{Maximize}\ \frac{Q_{\text{electric}} + Q_{\text{amtecelec}}}{Q_{\text{electrn}} + Q_{\text{rade}} - Q_{\text{trim}}}$$

The heat balance constraints are given in Appendix A. The constraints listed in Appendix A are the 12 nodal points which are located at the emitter, flange, bellows, collector, transition piece, trim collar, calorimeter, insulator, AMTEC evaporator (at the high-temperature region), base tube, vapor zone (low-pressure region) and condenser (at the low-temperature region), respectively. At each of these points a detailed study of heat distribution is done and the resulting equations are constrained to the problem.

Apart from these constraints, there are other parameters, which significantly affect the efficiency of the cell. These terms are involved in AMTEC for parasitic losses, electric power output and sodium heat transportation. These parameters affect the AMTEC cells efficiency, and thus the efficiency of the cascaded cell. Once the program has been run and checked for feasible solution, these variables are included and again the program is run. Thus, by applying the search method for the problem with these constraints a local optimal solution is achieved.

The objective function and the constraints are programmed in Mathcad and are allowed to run for several iterations with a minimum error factor of 1.507×10^{-12}.

Table 1
Temperature profile

Norder	Temperature (K)
T_e	1940
T_f	1310
T_{bel}	1036
T_c	1225
T_b	1184
T_{trim}	1229
T_{ins}	1167
T_a	1159
T_{base}	1118
T_{sodv}	635.941
T_l	413.746
T_{cal}	878.045

The constraints for the temperature profile are: (1) $T_e > T_f > T_c > T_b > T_a > T_{base} > T_{sodv} > T_l$; (2) $1100\,K > T_{base} > 1150\,K$; (3) $400\,K < T_l < 500\,K$; (4) $T_f > T_{bel}$; (5) $T_e \leq 2000\,K$.

Mathcad program simultaneously solves for the temperature profile and the search method. Each time the program runs in iterations and solves the problem, the aforementioned parameters are changed in an order. Thus, a feasible solution is achieved which satisfies all the constraints. The model had given a feasible solution of 14.398% satisfying all the constraints. This solution of 14.398% is the efficiency of the cascade, which is greater than the highest of the individual cells where the efficiencies of individual cells are, for TIEC 9.66% and for AMTEC 11.81% and lesser than the sum of the efficiencies of the both the cells, 21.47%. Hence, the solution is acceptable. The temperature profile is given in Table 1.

6. Result and discussion

The Mathcad program gives a locally feasible solution of the mathematical model constructed in this work. For any unconstrained non-linear program there can be several optimal solutions, and for the maximization problem, among these optimal solutions again there can be a maximum valued solution. This maximum valued solution is known as the global optimal solution and the rest of them are the local optimal solutions. In this problem also a solution has been achieved and this solution may or may not be the global optimal solution. It is found that the efficiency of the TIEC is 9.66% and that of the AMTEC is 11.81%. The efficiency of the cascaded cell is obtained to be 14.398. These results have satisfied all the constraints defined in the mathematical model. The heat balance equations have been formed and are allowed to run in iterations, and the result showed that the temperature profile is satisfactory. The temperature profile is given in Table 1.

The results achieved by this project were comparatively better than the results of the previous work, which included nine nodal points [1].

7. Conclusion

The basic purpose of optimizing the cascaded cell is to limit weight, area and material property constraints and finally improve the cost effectiveness. These characteristics have been achieved by predicting a temperature profile in Table 1. The efficiency of the cascaded cell has been obtained as 14.398%. Though the solution is locally optimized still further work needs to be done to globally optimize the efficiency. This project is a good beginning towards the optimization of the cascaded cell. In this direction, the Mathcad program is an acceptable approach for optimization of the cell to the extent that it could not handle any more equations than used in this program. For a program containing more equations than the present work does need some other approach with larger space and capability.

Acknowledgement

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Appendix A

For the objective function,

$$\text{Maximize}\ \frac{Q_{electric} + Q_{amtecelec}}{Q_{electrn} + Q_{rade} - Q_{trim}}$$

The heat balance constraints are:

1. $16.13 \times 10^{-12} \times T_e^4 - 9.348 \times 10^{-12} \times T_{amb}^4 - 3.206 \times 10^{-12} \times T_c^4 - 3.576 \times 10^{-12} \times T_f^4 + 0.1792 \times T_e - 0.1234 \times T_f \leq 239.14$
2. $3.576 \times 10^{-12} \times T_e^4 - 32.022321 \times 10^{-12} \times T_f^4 + 6.5225208 \times 10^{-12} \times T_{bel}^4 + 15.154 \times 10^{-12} \times T_{amb}^4 + 6.7688 \times 10^{-12} \times T_c^4 + 0.123 \times T_e - 0.2298 T_f + 0.01 \times T_{amb} + 0.08 \times T_{bel} + 5.73 \leq 0$
3. $6.5225208 \times 10^{-12} \times T_f^4 - 69.210247 \times 10^{-12} \times T_{bel}^4 + 37.106 \times 10^{-12} \times T_{amb}^4 + 0.086 \times T_f + 0.086 \times T_c - 0.172 \times T_{bel} + 4.153126 \times 10^{-12} \times T_b^4 + 21.4486 \times 10^{-12} \times T_{cal}^4 \leq 0$
4. $4.1626 \times 10^{-12} \times T_e^4 - 16.7148 \times 10^{-12} \times T_c^4 + 6.7688 \times 10^{-12} \times T_f^4 + 5.7834 \times 10^{-12} \times T_{amb}^4 + 0.0423 \times T_e + 0.086 \times T_{bel} - 0.9887 \times T_c + 0.9072 \times T_b \leq 58.6$
5. $0.9027 \times T_c - 3.1807 \times T_b + 2.278 \times T_{ins} - 43.673955 \times 10^{-12} \times T_b^4 + 34.476377 \times 10^{-12} \times T_{trim}^4 + 9.197578 \times 10^{-12} \times T_{bel}^4 \leq 0$
6. $34.476377 \times 10^{-12} \times T_b^4 - 81.304527 \times 10^{-12} \times T_{trim}^4 + 46.82815 \times 10^{-12} \times T_{cal}^4 + 90 \leq 0$
7. $21.4486 \times 10^{-12} \times T_{bel}^4 - 222.3387 \times 10^{-12} \times T_{cal}^4 + 46.8281 \times 10^{-12} \times T_{trim}^4 + 154.06196 \times 10^{-12} \times T_{amb}^4 \leq 0$
8. $1.8224 \times T_b - 7.2992 \times T_{ins} + 34.476377 \times 10^{-12} \times T_{trim}^4 - 37.556844 \times 10^{-12} \times T_{ins}^4 + 5.4772 \times T_a + 2.7930738 \times 10^{-12} \times T_{amb}^4 \leq 0$
9. $5.4772 \times T_{ins} \times T_a^2 + 5.4772 \times T_{ins} \times T_{sod}^2 + 10.9544 \times T_{ins} \times T_{sod} \times T_a - 291829.48 \times T_a^3 + 875499.39 \times T_{sod}^2 \times T_a - 875493.9 \times T_{sod} \times T_a^2 - 291829.48 \times T_{sod}^3 \leq 0$
10. $291829.48 \times T_a^3 - 875488.44 \times T_a^2 \times T_{sod} + 875488.44 \times T_a \times T_{sod}^2 - 291829.48 \times T_{sod}^3 - 2.068977 \times T_{base} + 0.0068977 \times T_{sodv} + 53.2 \leq 0$
11. $0.006977 \times T_{base} - 0.0197813 \times T_{sodv} + 0.0058273 \times T_{amb} + 0.006977 \times T_l \leq 0$
12. $2.05 \times T_{base} + 0.006977 \times T_{sodv} - 0.406977 \times T_l + 0.4 \times T_{amb} \leq 44.3$

The constraints listed above are the 12 nodal points, which are located on the cascade. At each of these points a detailed study of heat distribution is done and the resulting equations are constrained to the problem.

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