AMTEC CLUSTERS AS ADD-ON SYSTEM FOR POWER GENERATION IN A CONCENTRATED SOLAR POWER PLANT

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Abstract: The present study reports a first estimation of the number of Alkali Metal Thermal Energy Converter (AMTEC) cells required for an AMTEC-Concentrated Solar Power (CSP) hybrid power plant in the 100 MWth class envisaged in [3]. Furthermore, numerical results obtained for the structural analysis of an experimental AMTEC cell developed at the Karlsruhe Institute of Technology (KIT) are reported.

1. Introduction

Due to the changes in the German energy policy, a shortfall can possibly appear in the energy coverage when the availability of the fossil resources will decrease to the extent that they cannot be used to deliver the electrical demand. This scenario is further aggravated by the worldwide increased energy demand and motivates the search for other environmental-friendly energy sources. In parallel, it is also essential to increase the efficiency of the present “green” energy technologies, such as wind power and solar power.

In this context, the Alkali Metal Thermal Energy Converter technology together with a thermal storage device represents a promising solution for the extension of the global efficiency and of the total electrical output of a thermal power plant. AMTEC devices are based on the unique property of β-alumina ceramics, such as β”-alumina solid electrolyte (BASE), to allow the transport of alkaline (sodium) ions, while having a high electric resistivity. On the anode side of an AMTEC cell, characterized by high temperature (~800 °C) and relative high pressure (~1 bar), the sodium ionizes, with ions being transported through the BASE and electrons directed towards an electric load to produce electricity. On the cathode side of the cell, characterized by low temperature (250 – 500 °C) and low pressure (10 – 100 Pa), the ions recombine with the electrons to form neutral sodium molecules in vapor state that is further condensed and circulated back to the anode side, so that the cycle can be repeated. For a detailed description of the AMTEC operating principle we refer to the paper of Heinzel et al. [1].

The use of liquid metals such as sodium for thermal power plants has been recently identified as the best heat transfer fluid, delivering the largest electrical energy to the grid and achieving the largest efficiency of the ideal delivered electricity, according to Liu et al. [2]. At the same heat capacity rate, liquid sodium has the highest average heat transfer rate compared with air, compressed air at 10 bar, super critical CO_2 at 100 bar, steam at 10 bar and molten salt. This is due to its extremely high heat conduction coefficient and hence the best heat transfer value.

Recently a concept of using liquid metals such as sodium for a hybrid thermal solar plant using AMTEC technology has been proposed by Hering et al. [3].

As an alternative for delivering the electrical base load, this new concept envisage the use of a heat storage tank that will allow the continuous operation of the facility during night and will also compensate the heat fluctuations that can occur during day operation. Further, the peaks in the thermal energy that can appear during day operation can be used by employing the AMTEC technology as an add-on system for direct generation of electricity. The low temperature side of the AMTEC devices operates at temperatures < 500 ^{0}C and it is connected to the storage tank. By this solution the "cold" sodium from the storage tank at ~200 °C is heated by the "waste" heat generated by the AMTEC devices. A concept design for a compact, small size solar thermal receiver using AMTEC converters generating has been proposed by Tanaka [4]. It is reported that the system conversion efficiency in maximum mode can reach 20 % at 1050 K and generate ~12 kWe, while in maximum output mode reaches 18 % and generates almost 23 kWe.

2. Preliminary layout of the AMTEC system for CSP

For the hybrid system AMTEC and Concentrating Solar Power (A&CP), the AMTEC system envisaged should be dimensioned in the range 1-10 MW, for a total system thermal output of about 100 MWth. The ratio can be optimized to meet the needs of the projected power plant. The yearly averaged thermal energy potentially available for AMTEC system, which is location dependent, should be correlated with the size of the base plant, receiver and of the thermal storage tank in order to properly dimension the AMTEC system.

For an AMTEC cell, the power vs. amperage curve has an inverted U-shape, defining therefore the voltage and amperage at the peak of the profile for maximal electrical power. Typically the maximum power density has been compared in literature. Underwood et al [5] proposed that the comparison should be made in terms of the AMTEC figure of merit Z_A, defined as the ratio of the measured maximum power density:

$$P_m = V_m I_m / A_e \ , \qquad (1)$$

where V_m is the applied voltage at maximum power, I_m is the total measured current at maximum power and A_e is the area of the electrode, to the theoretical maximum power density P_t:

$$Z_A = P_m / P_t \qquad (2)$$

The theoretical maximum power is the maximum power density produced minus the ohmic power losses occurring in the electrolyte, the resistances occurring in the current lead, BASE/electrode contact and sheet resistance. For the preliminary layout of the AMTEC system, the focus is on the maximum power density P_m that can be achieved by different configurations. Consideration of the figure of merit for a preliminary layout is still premature at this stage. A rough estimation of the number of BASE elements coated with electrodes for the output power required is performed in this study.

For this purpose it is considered as a reference configuration an AMTEC cell consisting of a single cylinder with one end closed and a surface of 30 × 200 mm^2 (diameter × length) covered by a structured electrode.

In order to determine the total electric power delivered, the experimental data reported by Fang and Knödler [6] for titanium diboride (TiB_2) electrodes at 700 °C and 800 °C and by Fletcher and Schwank [7] for titanium nitride (TiN) electrodes at the same temperatures have been extrapolated for the AMTEC geometry considered. For all sets of data, the area of the electrode was kept constant, while the current density varies due to the change in operating temperature and electrode material, as displayed in Table 1.

For long time operation of the AMTEC system the power degradation has to be taken into account, in order to eliminate it from the design phase by appropriately setting the AMTEC operating parameters. Richman and Tennenhouse [8] report critical values for the current density below which no power degradation occurs, e.g. a BASE containing 0.25 wt. % LiO_2 should be charged below a current density of 1 A/cm^2 in order to avoid the power degradation. Therefore, for the present calculation are considered only current densities below or slightly above this critical value.

Table 1 Current density and voltage extrapolated on a reference configuration

Electrode	TiB_2	TiB_2	TiN	TiN
Temperature (°C)	700	800	700	800
Current density (A/cm^2)	0.5	0.6	0.81	1.12
Voltage (V)	0.33	0.40	0.27	0.32
Electrode area (m^2) for P_m = 1 MW	612	421	462	278
Nr. BASE elements for P_m = 1 MW	32480	22337	24498	14750
P_m / A_e (W/m^2)	1633	2375	2166	3597
Data source	[6]	[6]	[7]	[7]

The power dependency on the electrode area is displayed in Figure 1. The output electrical power determined is very sensitive to the operating characteristics of the cell. Beside current density and operating temperature, many other issues such as BASE and electrode thicknesses, resistances of the current collector, current lead etc. have to be taken into account and correlated to achieve a robust AMTEC performance able to deliver a large amount of electrical energy without power degradation. The highest power can be obtained at the largest current density of 1.12 A/cm^2 and a temperature of 800 °C. For this system configuration an electric output in the range of 1 MW can be realized with approximately 14750 BASE elements coated with electrodes (total electrode area A_e = 278 m^2). A larger electrical output would impose significant raise in costs due to the increase in the number of BASE elements and is at least for the moment not realistic. In parallel, the task of increasing the critical current density above which power degradation can occur has to be further pursued.

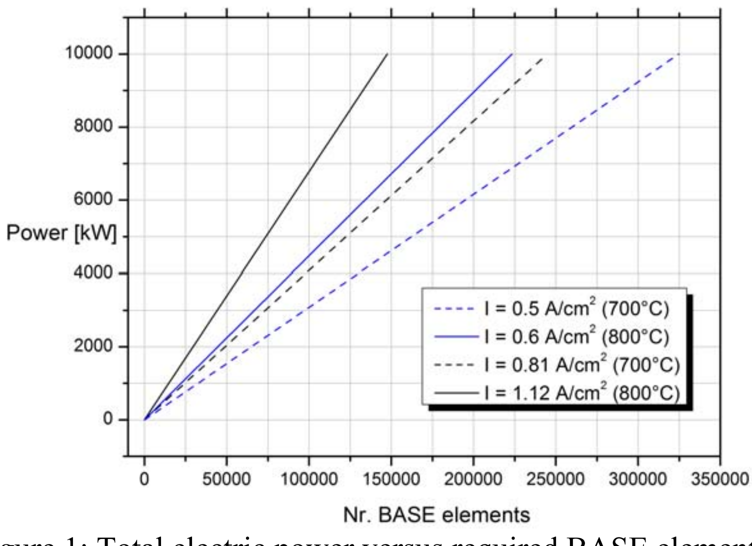


Figure 1: Total electric power versus required BASE elements.

The ratio of the maximum power to the total electrode area P_m/A_e is presented in Table 1. The above calculation is in good agreement with the data reported by Tanaka [4] for the AMTEC-solar receiver, for which in maximum power mode a ratio of $P_m/A_e \sim 3183$ W/m^2 at 1000 K can be calculated. To obtain the balanced optimum between the maximum electric power delivered and constant performances during long-time usage further studies have to be performed for a better estimation of the electrical power, taking into consideration also other AMTEC specific issues such as the small electrode effect.

3. AMTEC test facilities at KIT

The experimental investigation and development of AMTEC cells has been recently restarted at KIT in the frame of two research projects, the Helmholtz alliance on LIquid Metal TECHnology (LIMTECH) and Helmholtz Energy Materials Characterization Platform (HEMCP). The experimental program is focused on short term tests and long term tests of AMTEC cells, as well as tests of innovative materials for AMTEC cells in hot sodium environment. The short term tests are planned to start mid 2014 in the Amtec TEst FAcility (ATEFA) at KIT. For a detailed description of the facility and of the research projects we refer to the paper of Onea et al. [9]. The long term tests are planned to be performed in the 1000 K SOdium Loop to TEst materials and Corrosion (SOLTEC) facility that is presently at the end of the design phase at KIT. The experimental test campaign planned in the ATEFA facility is focused on AMTEC key issues such as the tests of BASE ceramics, electrode materials, new technologies, and stability of ceramic-metal interfaces.

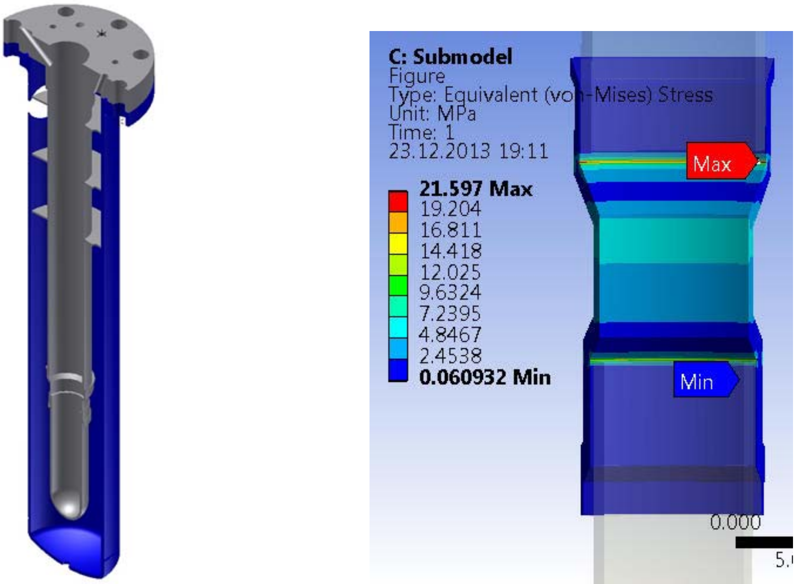
4. Structural analysis of the AMTEC test cell

One of the critical issues related to an AMTEC cell is the BASE-metal interface. During operation, the BASE expands due to a thermal gradient that can reach up to several hundreds of K. Since the BASE is connected to a metallic part, the BASE-metal interface is severely stressed by the thermal and mechanical stresses induced in this region. Many authors, including Heinzel et al. [1], report the crack of BASE occurring rather frequently, and suggest that the demanding operating conditions (high temperature, large temperature gradient across the BASE) induce severe stresses in the BASE that lead to its failure. Unfortunately limited studies can be found in literature regarding the stress distribution in an AMTEC cell. Recently, a structural analysis of the AMTEC test cell developed at KIT has been performed (Palacios et al. [10]) using ANSYS software.

For the AMTEC test cell developed at KIT, the BASE is brazed to a transition piece made of Niobium (Nb) that is brazed on the other side to a metallic tube made of Inconel 617. The choice of Niobium is motivated by the fact that it has a similar coefficient of thermal expansion ($\alpha_{Nb} = 8.5\times10^{-6}$ K^{-1} at 1093 °C) with the BASE ($\alpha_{BASE} = 8.1\times10^{-6}$ K^{-1} at 1000 °C). Since the metallic pipe made of Inconel has a larger coefficient of thermal expansion of ($\alpha_{pipe} = 16.3\times10^{-6}$ K^{-1} at 900 °C), it will expand more, pressing therefore the transition piece.

The numerical model of the one experimental test cell developed at KIT is presented in Figure 2 (a). The braze material for the transition piece was considered to be nickel.

The structural analysis in stationary state has been performed for the nominal operating conditions planned, nevertheless considering the relevant parameters at their extreme range, i.e. the temperature gradient between the hot side and the cold was set to 750 °C, while the pressure gradient on the BASE tube was set to 0.2 MPa. Under these conditions the maximum shear stress in the metal-Nb joint (upper braze) was estimated to reach 9.1 MPa, which corresponds to a safety factor of 4.3, while the maximum shear stress in the Nb-BASE interface (bottom braze) was estimated to be 4.8 MPa, corresponding to a safety factor of 8.2. The maximum von-Mises stress in the transition piece reaches 21.6 MPa (safety factor 6.4), while the maximum principal stresses in the BASE is determined to be 1.83 MPa (safety factor 15). For the stress distribution determined under these operating conditions no material failure should occur in the test cell. The upper brazing between the transition piece and the metallic tube is determined to be the weakest component in the cell.



(a) (b)

Figure 2: a) ANSYS model of the experimental AMTEC test cell b) Stress distribution in the transition piece at $\Delta P = 0.2$ MPa and $\Delta T = 750\ ^0$C.

5. Conclusions

The use of an AMTEC cluster with a reasonable number of elements as an add-on system for a CSP plant coupled with a thermal storage tank can be achieved for an electrical output in the range of about 1 MW if a robust AMTEC design can be attained, able to operate on a long time basis at a current density of ~1 A/cm^2 without power degradation.

Although in good agreement with the data reported in [4], further investigations should be made to appropriately estimate the real electric power delivered by a cluster of AMTEC cells, considering in parallel the long time power behaviour.

Furthermore, the stress distribution in the experimental AMTEC test cell developed at KIT has been numerically investigated and the location of the highest stresses has been identified.

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