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Design and Testing of a Heat Pipe cooled Thermionic Energy Convertor

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ABSTRACT

Thermionic Energy Conversion (TEC) has been studied for more than a decade at the Eindhoven University of Technology (EUT). The initial fundamental research on the emitter materials, by the Department of Chemical Engineering, is now followed by design, construction and testing of a flame heated air cooled TEC by the Department of Mechanical Engineering. Air cooling of the collector with a sodium heat pipe has been preferred as to improve the thermodynamical behaviour of the TEC in its prime application area: the electrical generator of a TOTal Energy Module (TOTEM).

In this paper we discuss some results of the characterization of the materials used in the convertor, some design considerations for the air cooled test TEC constructed recently and test results of a sodium heat pipe collector.

1. Introduction

A Thermionic Energy Convertor directly (without moving parts) converts heat into electricity. The TEC is a diode of which one electrode is heated to 1450 °C, so it will thermally emit electrons. A cooled counter electrode (600 °C) collects these electrons and a potential difference develops. The TEC is a high current density (10 Acm^{-2}), low voltage (0.5 V), direct current power source.

Thermionic Energy Conversion has the potential to use the exergy that is lost in the conventional (steam) conversion as the process operates in principal at a higher temperature level. As discussed by Miskolczy [1] and Starr [2] the TEC can be used as topping cycle in power plants, raising the total efficiency. Other terrestrial applications include gas turbine combined cycle systems [3] and cogeneration as discussed in [4]. In a project, starting 1990, in a cooperative European effort of the EUT with ANSALDO, ENEA, Philips, Xycarb, LEVEL and CEMACON the TEC will be integrated in a total energy module for cogeneration of heat and electricity for domestic use in, among others, remote locations.

An important advantage of air-cooling as compared to water-cooling is that heat can directly be resupplied to the process in the form of preheated air for the high temperature burner. Higher flame temperatures and system efficiencies are reached. With air-cooling a TEC can be used to exploit the temperature range from 1700—600 °C, which is not exploited in the conventional steam cycle.

Important requirements for a good efficiency of a TEC are a.o. a uniform temperature field in both collector and emitter and a low flow resistance for the air cooling the collector. These can be realized by using a heat pipe, as discussed by Morris [5,6], to transport the heat from the narrow collector head to an air-duct, allowing for ample heat exchanging area. The collector is part of the heat pipe, which is an isothermal system acting as a superconductor for heat. A heat pipe collector has been constructed and tested at the EUT by Postel [7] and some results are reported in this paper.

A test TEC has been constructed allowing for energy balance measurements. This TEC features an interelectrode spacing adjustment fixture, see Ritz [8], and is fitted with an array of temperature sensors.

The emitter developed at the EUT [9,10,11], consisting of a Cermet electrode surface on a molybdenum plasma sprayed free standing form covered in a CVD process with SiC, is used and will be further optimized.

2. Objectives

In a common effort with the partners mentioned (except for LEVEL & Cemacon) a water cooled TEC has been designed and constructed in a BRITE program of the EEC. In the new proposed BRITE/EURAM project the objective is to develop a thermionic total energy module producing 2 kW electrical power and 18 kWh heat. This concept allows to eliminate moving parts of the system and as a consequence it will be virtually maintenance-free and less noisy than the conventional system.

Aims of the project are:
- to design a thermionic total energy module for the combined generation of heat and electrical power
- to design and build its main components (thermionic energy converters and a ceramic heat exchanger)
- to develop a viable manufacturing technology for the eventual mass production of these components.

Presently the objective was to redesign the water cooled TEC to an air cooled TEC for measurement purposes with a heat pipe collector. With the just finished fully instrumented prototypes of an air cooled TEC a test cycle will yield the data needed for a parameter estimation method used to validate the model of the energy balance.

3. Materials

The first potential material, developed for application as hot shell is a W-TiN-SiC composite material, W (or Mo) serves as the emitter material and will eventually be the substrate for a Cermet emitter, see [9,10,11]. The SiC functions as a high temperature corrosion protection. TiN is used as a diffusion barrier between the W and SiC layer as they would otherwise react at the operating temperature of 1450 °C. TiN is inert towards both SiC and W and adheres well to both materials. Thermal coefficients of expansion of both materials are closely matched: 4.5 10^6 K^{-1} vs. 4.25 10^6 K^{-1}.

The production process of the composite W-TiN-SiC material consists of four consecutive steps. First W is sprayed on a brass mandrel. Subsequently it is reduced at 1600 °C in H_2 and sintered to 96% density at 2200 °C in vacuum. Next a TiN coating is applied by Chemical Vapour Deposition (CVD), by having $TiCl_4$ and N_2 react at the hot shell surface in a hot wall CVD furnace at 900 °C. Finally a SiC coating is applied in a CVD process by pyrolysis of $(CH_3)_2SiCl_2$ in H_2 at 1200 °C.

Thermal conductivity, measured by the laser flash method, was found to be 50 $Wm^{-1}K^{-1}$ at 1400 °C. Thermoshock resistance was proved by quenching from 1000 °C in water. Thermal fatigue was tested by applying 100 cycles from 1400 °C to room temperature at a heating and cooling rate of 0.8 Ks^{-1}. Corrosion and lifetime tests are presently carried out in a combustion atmosphere.

The current–voltage characteristics of a Molw/o $Al2O_3$ emitter and a Mo collector were measured. Conditions were varied over a significant range, both with and without Cs. The work functions of both Mo and Molw/0 Al_2O_3 were assessed. Using a Molw/o Al_2O_3 emitter, the power density obtained was lower than obtained with a Mo emitter, see fig. 1.

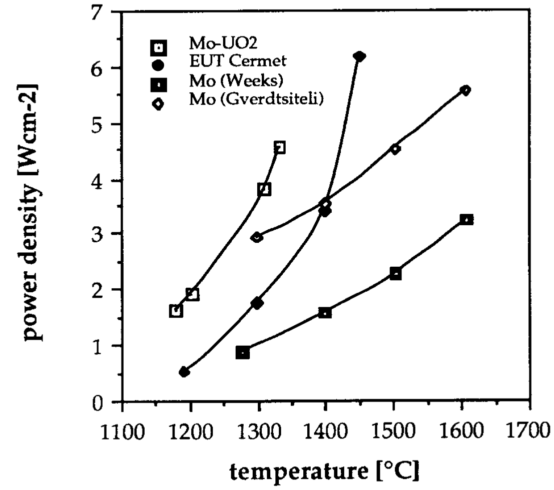

Figure 1 power density of a diode with several emitter materials and a molybdenum collector: a molybdenum-uranium oxide emitter, the EUT Cermet emitter, Mo emitter of Weeks et al. and Mo emitter of Gverdtsiteli et al.

The minimum workfunction of a Mo-15w/o Al_2O_3 Cermet as determined by electron emission microscopy was 1.2 eV. The measurements were carried out in a metal confinement *research diode* as well as in a glass confinement *low pressure Cs diode*. In the low pressure Cs diode a minimum work function of 1.5 eV for a Mo0.5w/o Al_2O_3 was found. When treated in a hydrogen plasma a minimum work function of 1.3 eV for a cesiated Mo electrode was found in the low pressure Cs diode. In a research diode the bare work function of Mo-1w/o Al_2O_3 was 4.9 eV as compared to 4.4 eV for a pure Mo collector (measured in the retarding range).

The heat pipe collector is made of stainless steel (SS 321). In one of the test TEC's the collector side of the heat pipe is coated with plasma sprayed Ni, though it is not expected that the work functions of stainless steel and Ni differ markedly.

Vacon 12S matches the coefficient of expansion of the hot shell best and is used for the bellows connecting hot shell and ceramic seal. The ceramic seal consists of Al_2O_3 and Vacon 70.

4. Water cooled TEC

A water cooled TEC was developed by the Physical Chemistry Department of the EUT in order to accurately measure the performance and to demonstrate the thermionic energy conversion. A line drawing, fig. 2, shows the layout and dimensions.

The ceramic hot shell is bell shaped so as to fit in the furnace wall, the active emitter area being larger than the projected area. The geometry of the collector head causes the difference in ΔT from water to collector surface to be as small as possible.

The interelectrode spacing adjustment fixture allows both radial and axial precise movement of the collector with respect to the hot shell. Electrical insulation between collector and emitter is provided by an Al_2O_3 ring between the flexible bellows and by sapphire spheres between emitter fastening ring and adjustment fixture.

The brazed water cooling system is pressureless. Consequently the maximum water temperature is about 100 °C. Higher water temperatures are possible by using other connection techniques, but cost and stability of the heat transfer process make it unlikely to reach the desired temperature of 600 °C (equal to the collector temperature T_{coll}).

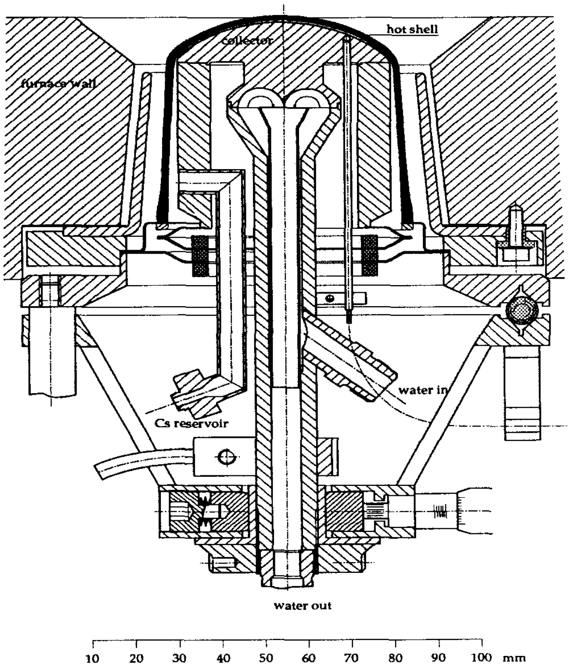

Figure 2 water cooled test thermionic energy converter of the EUT

5. Air cooled TEC

Air cooling as compared to water cooling has the advantage that heat from the collector cooling can be directly resupplied to the high temperature burner, saving the remaining exergy content. The exergy loss, E_{loss}, defined as:

$$E_{loss} = T_{amb}\left(\frac{T_{coll} - T_{cool}}{T_{coll} * T_{cool}}\right)Q_{cool}$$

amounts to 700 W if the collector cooling medium is cooled (Q_{cool} = 1055 W) to ambient temperature. In a pressureless water cooled TEC with a coolant temperature, T_{cool}, of 100 °C the exergy loss is 475 W, whereas in an air cooled TEC, heating the cooling air to 500 °C, the exergy loss is 45 W. In an air cooled TEC the 430 W difference with a water cooled TEC can (ideally) be converted to power in e.g. a steam turbine.

Air cooling as compared to water cooling also has a major disadvantage: a much lower specific heat and consequently a lower heat exchanging capacity, leading to larger cooling area, larger flowrate and potential higher power requirement. Geometries to fit the necessary heat exchanging area inside the bell shaped collector are rather complex and require a high pressure difference for the cooling air flow and will result in a non uniform temperature field in the collector. A heat pipe collector eliminates this disadvantage as this isothermal passive element can amplify the heat exchanging area at a more convenient location outside the TEC.

The layout of the air cooled TEC is shown in the exploded view, fig. 3.

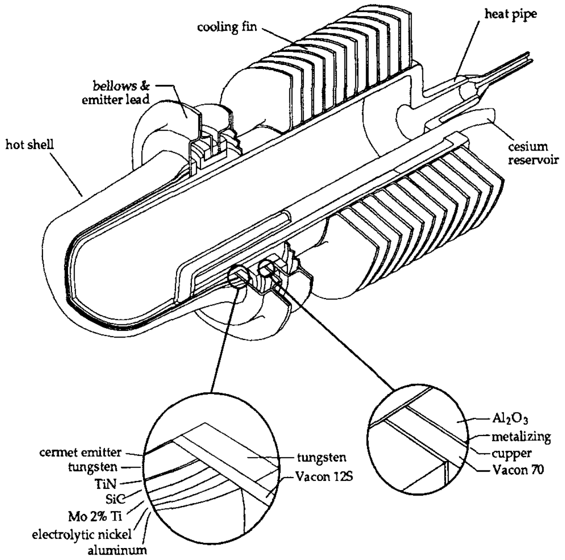

Figure 3 exploded view of the air cooled TEC

The air cooled TEC features a compact design: the connection between the interelectrode space and the cesium reservoir consists of a tube inside the heat pipe, leaving the bellows intact. The bellows connected to the heat pipe are flexible to allow for axial adjustment of the interelectrode spacing. The metal–ceramic joints of the ceramic seal are shielded from the hot heat pipe and cooled by air. This is necessary since the joining technique used allows an operating temperature of only 450 °C.

With a simplified model of the energy management of the TEC a heat balance has been calculated, anticipating the intended parameter estimation. The results are summarized in fig. 4.

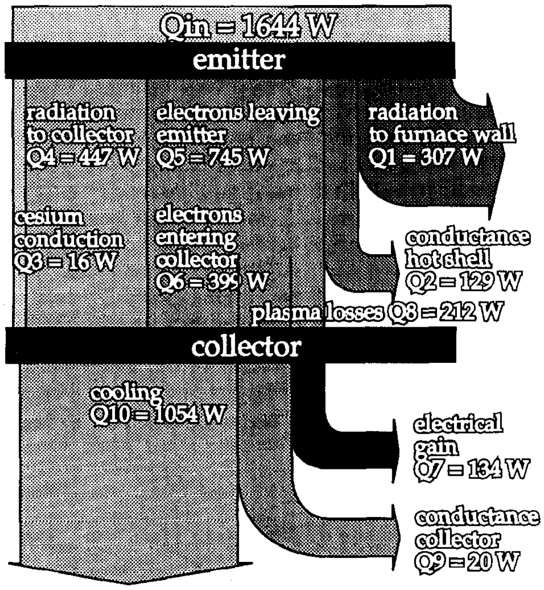

Figure 4 energy flows in the air cooled TEC

6. Heat pipe collector

The heat pipe collector is designed to operate at a temperature of 600 °C. Several working media can be used at this temperature, notably Hg, Cs, K and Na. The heat pipe is required to transport a 400 kWm^{-2} regardless of its inclination. The candidate working media have been evaluated with a program, written by van der Weide [12], with respect to the power limitations as a function of temperature. Sodium was selected because of its high evaporation enthalpy and surface tension. The power limits of a Na heat pipe are the sonic limit at temperatures below 500 °C and the capillary limit at higher temperatures. Viscous and entrainment limits are not applicable. Fig. 5 gives the calculated results of a heat pipe with the evaporator on top.

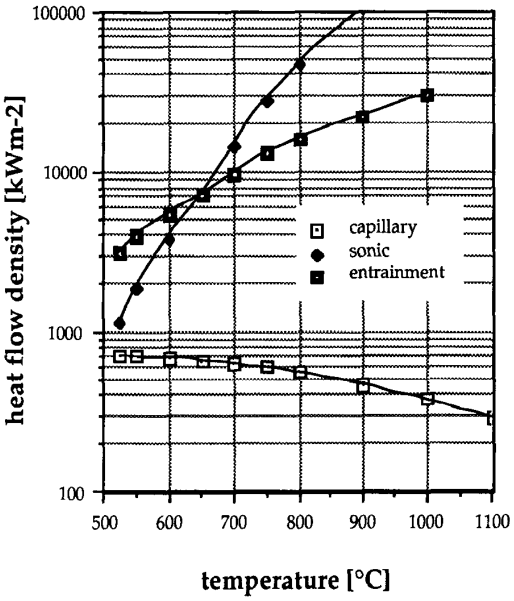

Figure 5 specific heat flow limits of the Na heat pipe

When the condenser is on top, the power limit is about 3.5 times higher. The thermal resistance of the heat pipe is 6 10^{-5} $KW^{-1}m^2$ at 600 °C resulting in a ΔT of 13 K over the heat pipe at normal operation conditions.

A heat pipe with roughly the dimensions of the one shown in fig. 3 has been designed and manufactured It was subsequently tested in an electrical furnace over a range of working fluid temperatures (500–750 °C) and heat flows (0–380 kWm^{-2}). The evaporator was directly irradiated by the furnace at temperatures up to 1450 °C. The condenser was cooled by forced convection with ambient air. The measured energy balance was consistent up to a temperature of 650 °C (within 7%). In this temperature range the calculated temperature difference over the heat pipe matches the measured one within several percent. Above 650 °C the measurements tend to be unreliable because of parasitic heat losses.

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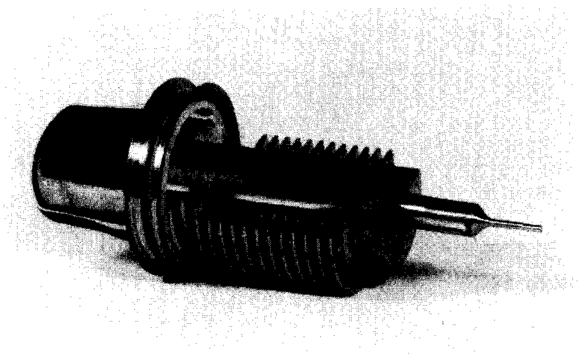

Figure 6 demostration model of the air cooled TEC, showing the interior of the sodium heat pipe