

An Analysis of Alkali Metal Thermal Electric Converter

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ABSTRACT

AMTEC (Alkali Metal Thermal Electric Converter) is a device of the type Concentration-Differential cells. It uses properties of an electrolyte called β alumina also called β alumina solid electrolyte or BASE. In BASE, if the concentration of sodium ions in anode is greater than that of cathode, Ions will diffuse and accumulate between Cathode and anode. This accumulate of ions create an electric field that drives an upward drift of ions. In equilibrium, the downward flux equals upward flux.

Introduction

A HEAT source raises the temperature and pressure of the sodium vapour while a heat sink, causes the condensation of the metal into a liquid, which is circulated back to the heat source by pump. Sodium in the heat-sink can be in either the liquid or the vapour state. P_A is the vapour pressure of sodium at the temperature T_A and P_{res} is the vapour pressure of the liquid sodium in the heat sink at temperature T_{res} .

The efficiency of an AMTEC is $\eta = \frac{\text{Electric Power Delivered to the Load}}{\text{Total Heat Input Power}}$

In the case When there is no problem is no parasitic losses ($Q_{loss} = 0$), AMTEC would operate at its maximum efficiency also called electrode efficiency is

$$\eta_{\text{electrode}} = \frac{1}{1 + [311.4 \times 10^{-16}(T_A - T_{res}) + 0.924]/V}$$

The efficiency for given values of T_A and T_{res} depends on the operating point.

What is AMTEC and on which Principle it work's ?.

AMTEC stands for Alkali Metal Thermal Electric Converter and is an example of a class of devices known as Concentration- Differential Cells. Its operation is conceptually simple. It takes advantage of the special properties of β alumina, which is an excellent conductor of alkali metal ions but a bad conductor of electrons. In other words, it is an electrolyte. A slab of this material constitutes β alumina solid electrolyte or BASE, a some what unfortunate acronym because it may suggest the "base" electrode of some semiconductor devices.

If the concentration of sodium ions on the upper part of the slab (anode) is larger than that at the lower (cathode), sodium ions will diffuse downward through the slab, accumulating in the lower interface between it and porous electrode that serves as cathode. Such an accumulation of ions will create an electric field that drives an upward drift of ions. In equilibrium; the downward diffusion flux equals the upward drift flux

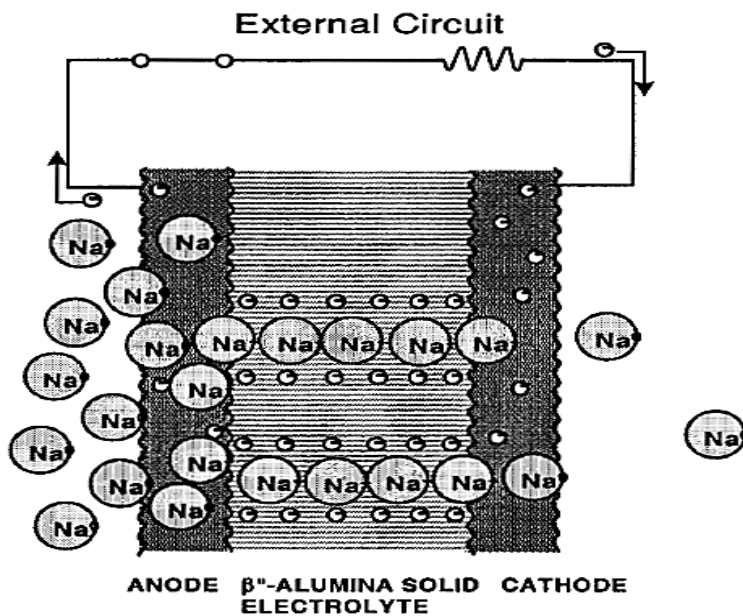


Figure 1. AMTEC internal ionic circulation

What is the voltage developed by a concentration cell? Let N be the concentration of the migrating ion (Na^+ , in the cell described above) and X be the distance into the BASE slab, counting from the top toward the bottom. The flux ϕ_D , owing to the diffusion of ions is

$$\phi_D = -D \frac{dN}{dx}$$

Where D is the diffusion constant. The ion migration causes their concentration at the bottom of the slab to differ from that at the top. An electric field appears driving a return flux, ϕ_E ,

$$\phi_E = N_\mu E,$$

Where μ is the mobility of the ions and $E = -dv/dx$ is the electric field. In equilibrium, the two fluxes are of the same magnitude.

$$D \frac{dN}{dx} = \mu N \frac{dV}{dx}$$

$$\frac{DdN}{\mu N} = dV$$

Integrating from anode to cathode,

$$\frac{D}{\mu} (\ln N_A - \ln N_C) = V,$$

Where N_A is the ion concentration at the anode (top) and N_C is that at the cathode (bottom). V is the potential across the cell.

According to Einstein's relation, $D/\mu = kT/q$. Thus,

$$V = \frac{kT}{q} \ln \frac{P_A}{P_C}$$

because $p = NkT$.

Above equation gives the value of the open-circuit voltage of the AMTEC. In the case of an ideal (reversible) AMTEC, the load voltage, V_L , is the same as

V_{oc} because the internal resistance of the device is zero. Then, when μ kilomoles of sodium ions (which are singly ionized and thus carry a positive charge equal, in magnitude, to that of an electron) pass through the BASE, the electric energy delivered to the load is

$$W_e = \mu N_{oq} V_L = \mu N_{oq} \frac{kT}{q} \ln \frac{P_A}{P_C} = \mu RT \ln \frac{P_A}{P_C},$$

Which is the energy delivered by the isothermal expansion of μ kilo moles of gas from P_A to P_C .

Configuration of an AMTEC

An AMTEC can be built in the manner shown in . A heat source raises the temperature and, consequently, the pressure of the sodium vapor in contact with the anode of the cell, while a heat sink causes the condensation of the metal into a liquid, which is circulated back to the heat source by means of a pump. Wires are attached to the electrodes in contact with the BASE.

The sodium pressure at the anode, P_A , is the vapor pressure of sodium at the temperature, T_A , while P_{res} is the vapor pressure of the liquid sodium in the heat-sink chamber reservoir at temperature T_{res} .

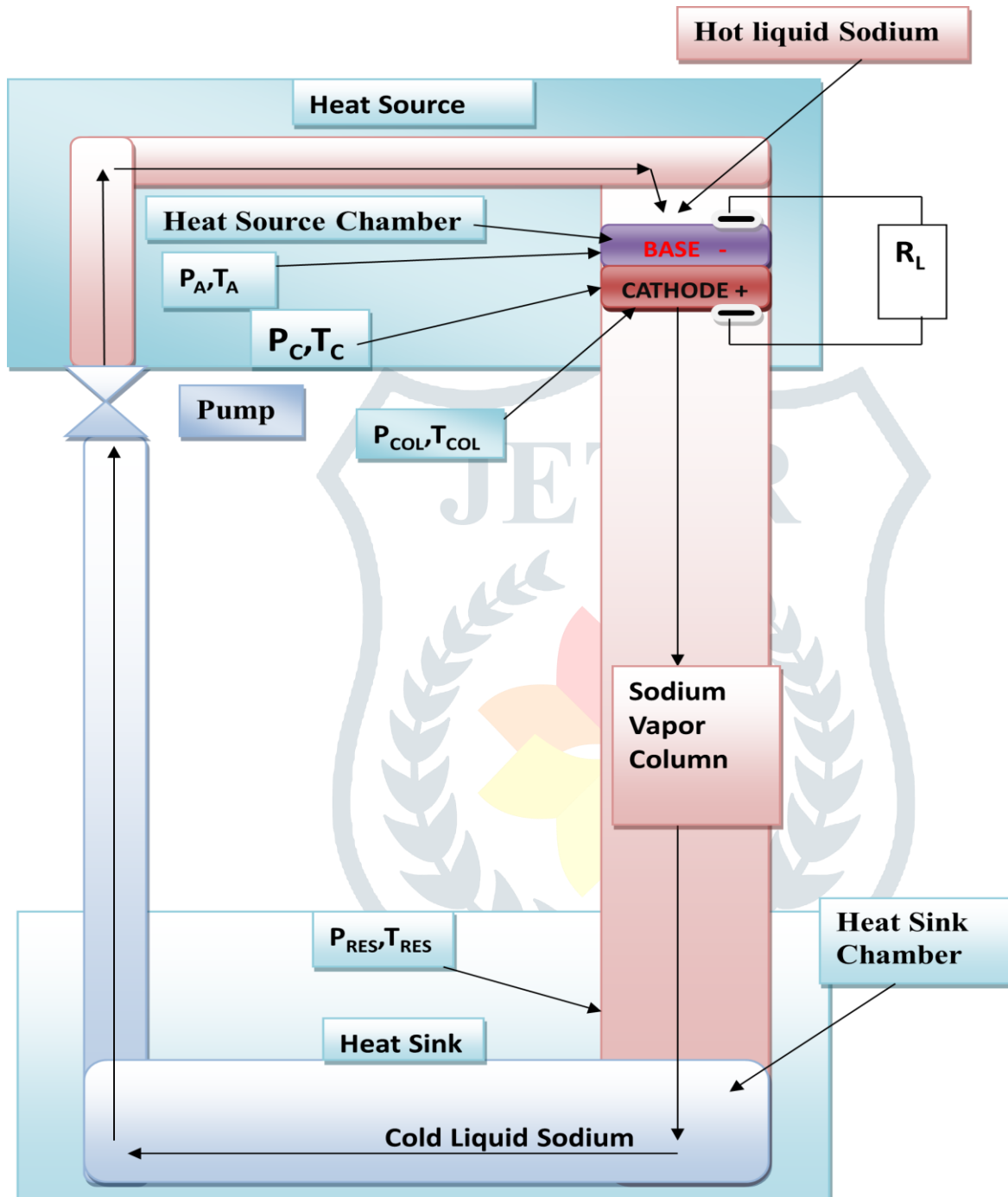


Figure 2. AMTEC Configuration

The sodium in the heat-sink chamber can be in either the liquid or the vapor state. In our examples we will consider the liquid case, the case of the liquid-fed AMTEC.

Vapour Pressure

The values of the sodium vapor pressure in the hot and in the cold ends of the device play a decisive role in determining its performance.

The vapor pressure of sodium and of potassium is listed in Table below and the sodium pressure is plotted versus temperature graph in these elements have melting and boiling points of, respectively, 370.9 K and 1156 K for sodium and 336.8K and 1047 K for potassium. Potassium has much less favorable characteristics than sodium. Consequently, we will concentrate on sodium.

The vapor pressure of sodium can be estimated with an accuracy adequate for modeling AMTEC performance by using the following formula:

$$\ln p = -62.95 + 0.2279T - 2.9014 \times 10^{-4}T^2 + 1.7563 \times 10^{-7}T^3 - 4.0624 \times 10^{-11}T^4$$

The formula yields acceptable values of p for $400 \leq T \leq 1400$

Showing below the table and graph for Pressure Vs Temperature.

S.NO	TEMPERATURE (K)	SODIUM (Pa)	POTASSIUM (Pa)
1	400	0.0004	-
2	500	0.158	5
3	600	8	126
4	700	119	1236
5	800	1006	6964
6	900	5332	26834
7	1000	19800	78482
8	1100	60492	189462
9	1200	150370	-
10	1300	3363101	-
11	1400	626220	-

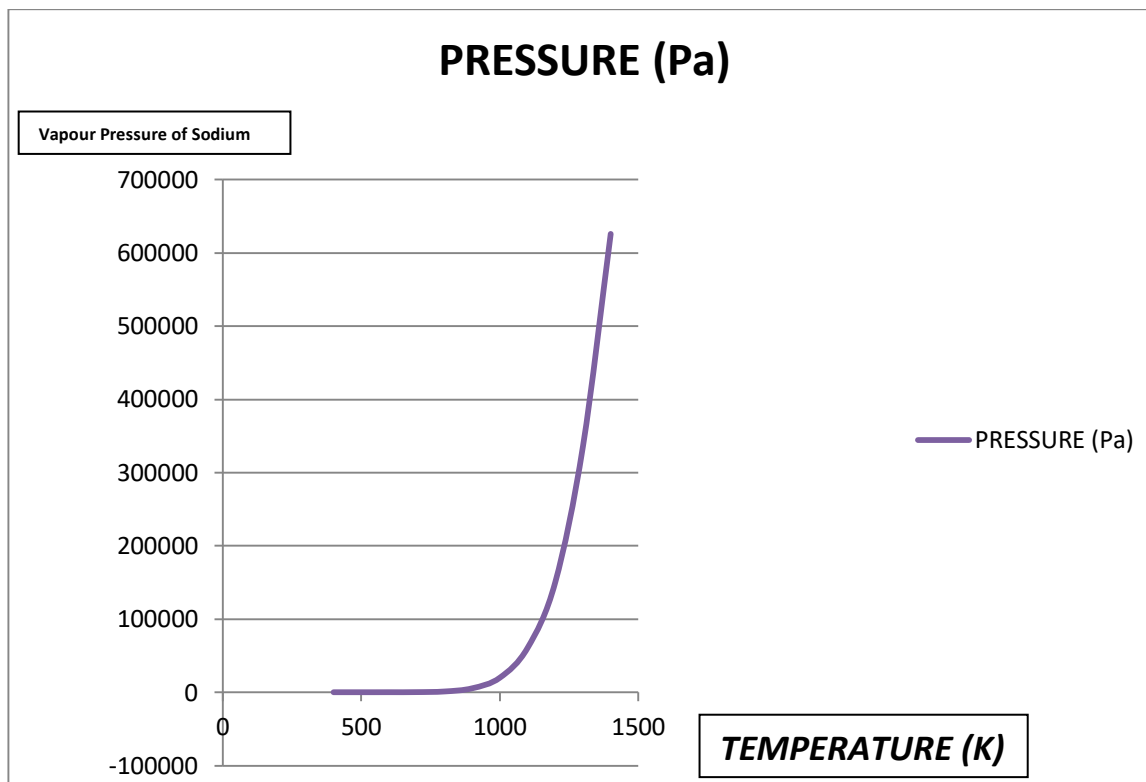


Figure 3. Pressure analysis of AMTEC

Mean Free Path of Sodium Ions

The mean free path, l , of a gas molecule can be estimated from

$$l = \frac{4}{4nA}$$

where n is the gas concentration and A is the cross-sectional area of the molecule, which, for sodium can be taken as $110 \times 10^{-21} \text{ m}^2$. Thus,

$$l = \frac{2.28 \times 10^{18}}{n}$$

From the perfect-gas law, $p = nkT$, or $n = \frac{p}{kT}$: hence,

$$l = 2.28 \times 10^{18} k \frac{T}{p} = 31 \times 10^{-6} \frac{T}{p}$$

If the gas is at its saturation pressure, then for each value of T , the value of pressure can be determined from above table and a plot of l as a function of T can be constructed as shown in graph below.

At sufficiently low temperatures, the mean free path becomes surprisingly large because the vapor pressure is so low and may very well exceed the dimensions of the sodium vapor column in the device. Under these circumstances, the Knudsen conditions prevail.

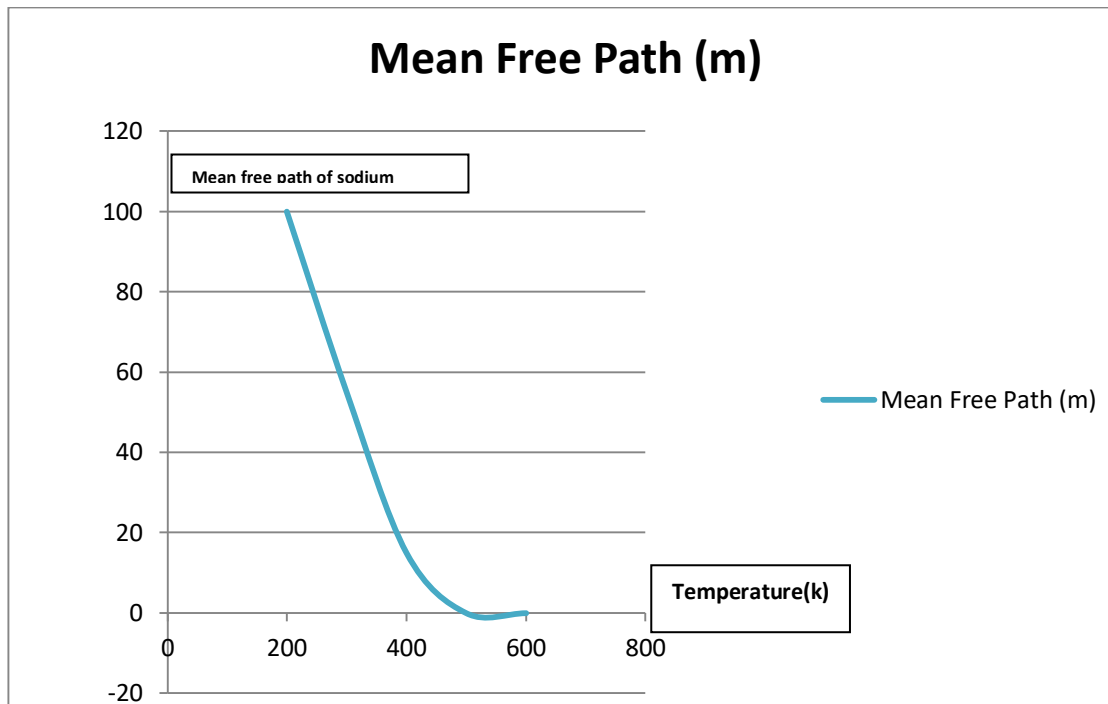


Figure 4. Mean Free Path Analysis

V-I Characteristics of an AMTEC

Under open-circuit conditions, there is no net flow of sodium ions through the BASE and through the cathode slab of the device. However if there is an external current through a load connected to the terminals of the AMTEC, then ions must flow through the base and recombine with electrons in the cathode. A net flux, ϕ , of sodium atoms is established in the vapor column between the cathode the cathode and the cold liquid sodium. To drive this flux, a vapor pressure differential Δp , must appear between the top of the BASE and the bottom of the cathode slab. the relationship between the flux and the pressure differential is

$$\phi = \frac{\Delta p}{\sqrt{2\pi mkT_A}}$$

where m is the mass of a sodium ion (22.99 daltons or 38.18×10^{-27} kg). This equation, known as the **Langmuir Assumption**. We are assuming that $T_A = T_C$

the current density is $J = q\phi$

$$\Delta p = \frac{\sqrt{2\pi mkT_A}}{q} J = xJ,$$

$$x = \frac{\sqrt{2\pi mkT_A}}{q}$$

$$V = \frac{kT_A}{q} \ln \frac{PA}{PRe_s \sqrt{\frac{T_A}{TRe_s} + xJ}} = \frac{kT_A}{q} [\ln p_a - \ln(PRe_s \sqrt{\frac{TA}{TRe_s} + xJ})]$$

$$J_V = \frac{PRe_s}{x} \sqrt{\frac{TA}{TRe_s}},$$

$$V_{oc} = V_p - \frac{kTA}{q} \ln(J_V) \quad \text{When } J=0, V=V_{oc}$$

In the preceding derivation, we assumed that there is no resistance to the flow of ions in the BASE. This ideal situation is not achievable, and a voltage drop, $J\mathfrak{R}$, appears across that component. $\mathfrak{R} = AR$ is the specific resistivity of the cell. Here A is the cross-sectional area of the BASE, and R is its resistance. The load voltage becomes.

$$V = V_p - \frac{kT_A}{q} \ln(J\phi + J) - J\mathfrak{R}$$

The values are plotted using above equation. Both the load current density and the load power density are quite high a Characteristic of AMTECs

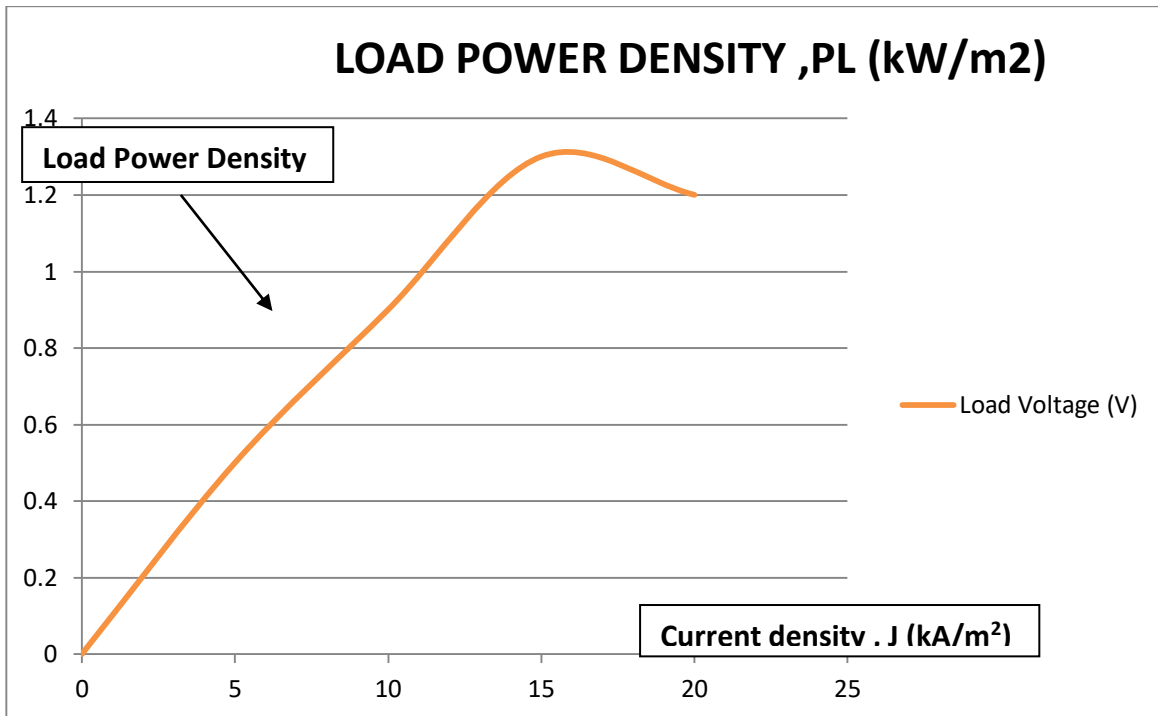


Figure 5. Load Power Density analysis of AMTEC

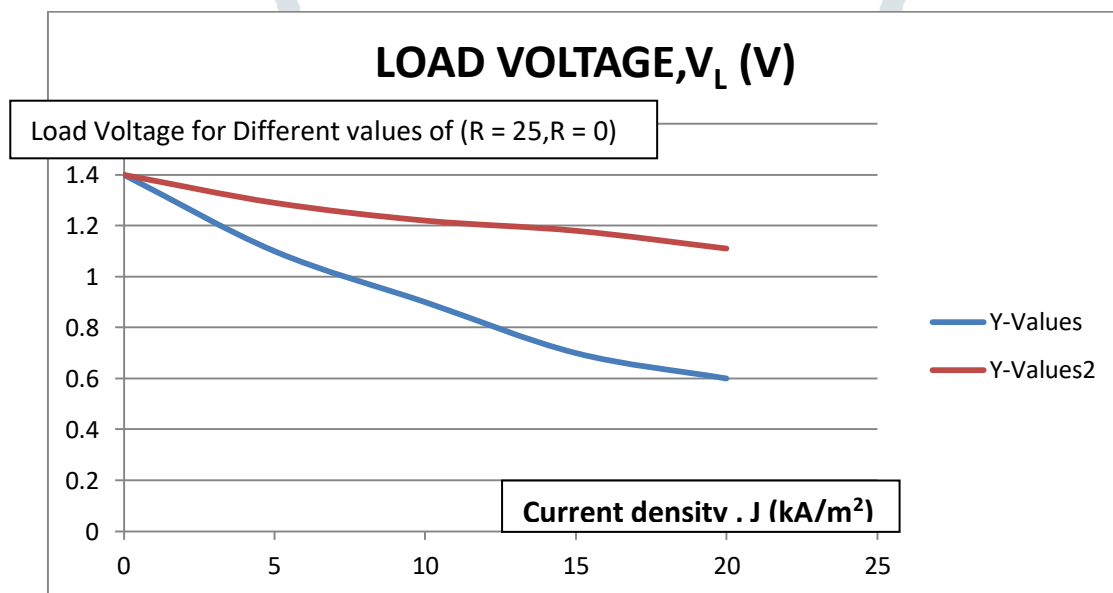


Figure 6. Load Voltage, analysis of AMTEC

Efficiency

The efficiency of an AMTEC is (Cole 1983)

$$\eta = \frac{\text{Electric power delivered to the load}}{\text{Total heat input power}}$$

The AMTEC uses up heat by the following four processes:

1. The liquid sodium has to have its temperature raised from T_{Res} to T_A . This amounts to a heat power of

$$Q_1 = c(T_A - T_{Res})\phi = c(T_A - T_{Res}) \frac{J}{qN_o}$$

$$= 311.4 \times 10^{-6} (T_A - T_{Res}) J,$$

Where $c = 30 \text{ kg K}^{-1} \text{ kmole}^{-1}$ is the specific heat of sodium and ϕ is the sodium flux, which is, of course, proportional to the current density through the AMTEC.

2. The heat power needed to vaporize the liquid sodium. This amounts to a heat power of

$$Q_2 = \Delta h_{vap} \phi = Q_2 = \Delta h_{vap} \frac{J}{qN_o} = 0.924 J,$$

where $\Delta h_{vap} = 89 \text{ MJ K}^{-1} \text{ kmole}^{-1}$ is the heat of vaporization of sodium.

3. The heat power needed to drive the output electric power.

$$Q_3 = VJ$$

4. The sum of all parasitic heat losses, $Q_4 = Q_{loss}$. The main contributors to these parasitic losses are heat conduction through the output leads and heat radiation from the cathode.

Equation of efficiency

$$\eta = \frac{JV}{J[V + c \frac{(T_A - T_{Res})}{qN_o} + \frac{\Delta h_{vap}}{qN_o}] + Q_{loss}}$$

$$\frac{JV}{J[V + 311.4 \times 10^{-6} (T_A - T_{Res}) + 0.924] + Q_{loss}}$$

In the hypothetical case in which there are no parasitic losses ($Q_{loss} = 0$), the AMTEC would operate at its maximum efficiency, which Cole (1983) calls the **electrode efficiency**. It is

$$\eta_{electrode} = \frac{1}{1 + [311.4 \times 10^{-6} (T_A - T_{Res}) + 0.924] / V}$$

The efficiency for given values of T_A and T_{Res} depends, of course, on the operating point. Graph shown below how the electrode efficiency of a sodium AMTEC operating between 1175 and 423 K varies with the load current, and, consequently, output power. Although the

electrode efficiency exceeds 60% at low-power outputs, at the maximum power of 6.64 kW/m² ($I_L=11.5 \text{ kA/m}^2$), the efficiency is down to 33.3%.

Parasitic losses considerably radiation losses from the cathode (neglecting heat conduction losses through the output leads.) If both the cathode and the surface of the liquid sodium pool were to act as black body radiators, the surface of the liquid sodium pool were to act as black body radiators, the radiation loss from the cathode would be

$$P_r = \mathcal{G}(T_A^4 - T_{Res}^4) \approx \mathcal{G}T_A^4$$

$$= 5.67 \times 10^{-8} \times 1175^4 = 108,000 \text{ W/m}^2$$

With such large radiation losses, the efficiency of the AMTEC in our example would barely exceed 5% at maximum power. Fortunately, the surface of the liquid sodium in the heat-sink chamber is far from a black body (which would absorb 100% of the radiation falling on it). In fact, the liquid sodium will do almost the opposite: it reflects more than 98% of the infrared radiation it receives. If the reflected radiation is reabsorbed by the cathode (even if the latter were a black body radiator), the net losses would be 50 times smaller than that calculated above. This would result in an efficiency of 30% for the AMTEC in the example. For such a reduction of radiation losses to take place, it is necessary to have the radiation from the liquid sodium focused back onto the cathode. This may not be easy to arrange.

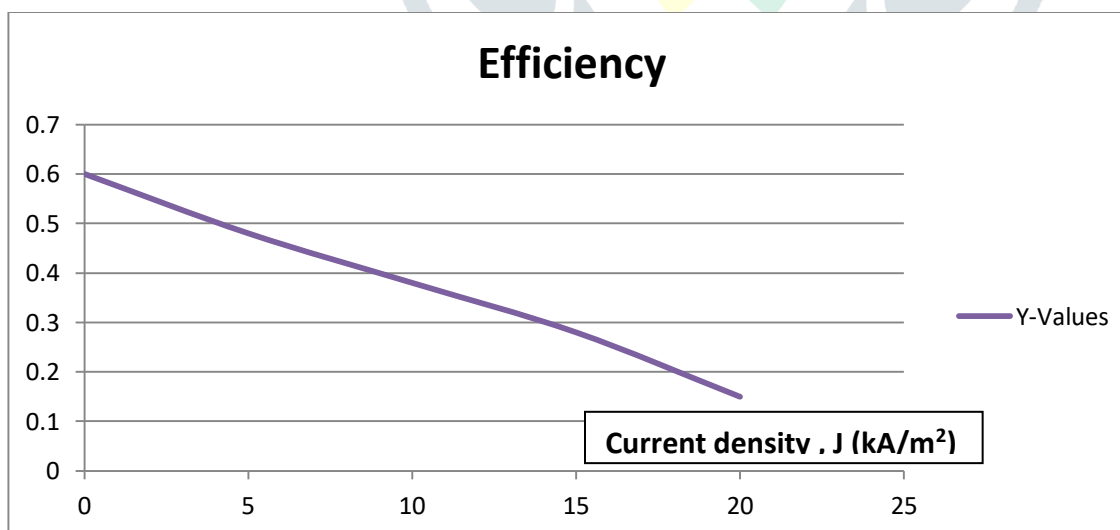


Figure 7. Efficiency plot

Conduction losses are far from negligible. The output leads connect a very hot BASE to the cool world outside. These leads must have high electric conductance, which implies high heat conductance. Low –conductance leads reduce heat conduction losses is to operate a

number of AMTEC cells in way to reduce conduction losses is to operate a number of AMTEC cells in series so that for all but the first and the last cell, there is no temperature differential across the leads.

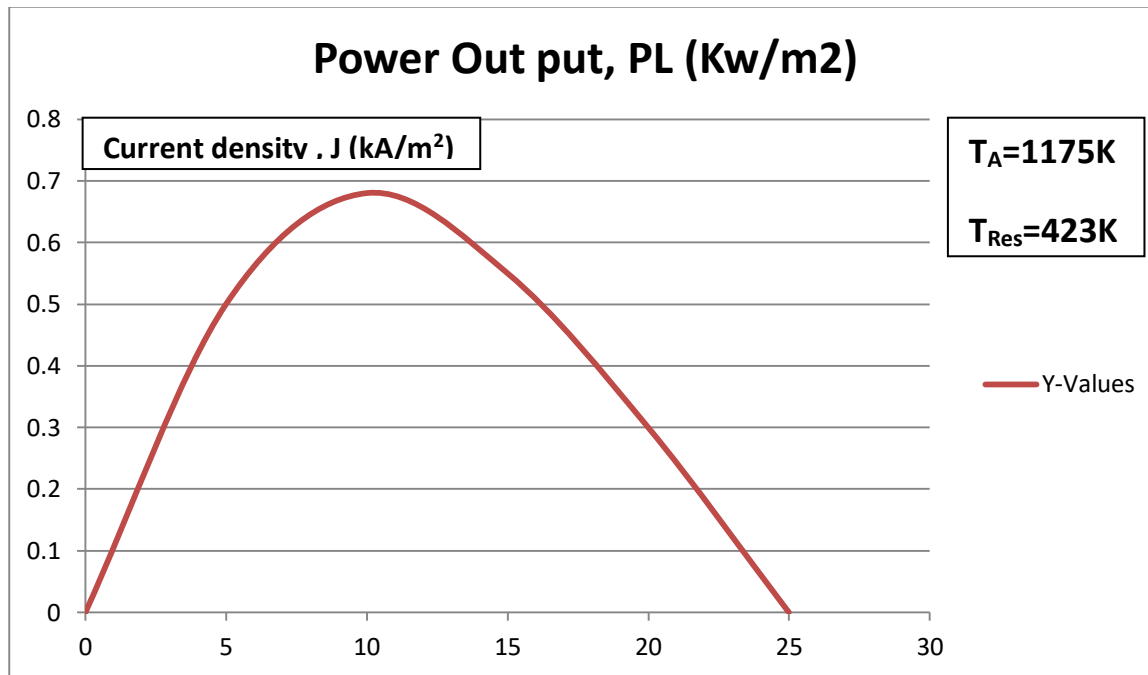


Figure 8. Power output, PL

Thermodynamics of an AMTEC

We will examine the thermodynamics of a liquid-fed sodium AMTEC cell by following the states of the working fluid through a complete cycle. Please refer to p-V and to the T-S diagrams. The fluid sodium will be in one of the several regions of the cell described in

1. Heat-sink chamber
2. Pump
3. Heat-source chamber
4. Base
5. Cathode
6. Sodium Column

In this example, the device uses 0.001 kmole ($\mu = 0.001\text{kmole}$) of sodium (about 0.032 kg) and operates between the 1200 K and 600 K. we will start at state 1 when the sodium vapor is in the heat-sink chamber and is in contact with the heat sink. Its temperature is 600K, and its vapor pressure is 7 Pa. the vapor occupies a volume,

$$V = \frac{\mu RT}{p} = \frac{1 \times 10^{-3} \times 8314 \times 600}{7} = 713 \text{ m}^3$$

State 1 (sodium vapor, in the heat-sink chamber).

$$V = 713 \text{ m}^3,$$

$$T = 600 \text{ K},$$

$$P = 7 \text{ Pa},$$

$$S = 150 \text{ aeu (arbitrary entropy units)}.$$

In step 1 → 2, the sodium vapor condenses isothermally and isobarically. When fully condensed, the 0.001 kilomole of liquid occupies $23.3 \times 10^{-6} \text{ m}^3$ (assuming a liquid sodium density of 970 kg/m^3).

State 2 (liquid sodium, in the heat-sink chamber).

$$V = 23.3 \times 10^{-6} \text{ m}^3,$$

$$T = 600 \text{ K},$$

$$P = 7 \text{ Pa},$$

$$S = 32 \text{ aeu}.$$

In step 2 → 3, a pump pressurizes the liquid sodium to a pressure equal to the vapor pressure at 1200 K. In this example, it will be 150,400 Pa. the pressurization is carried out at constant temperature, so points 2 and 3 cannot be distinguished in the temperature/entropy plot but are quite apart in the pressure/volume plot.

State 3 (liquid sodium moving through the pump).

$$V = 23.3 \times 10^{-6} \text{ m}^3,$$

$$T = 600 \text{ K},$$

$$P = 150,400 \text{ Pa},$$

$$S = 32 \text{ aeu}.$$

In Step 3 → 4, the liquid sodium is now in the heat- source chamber and temperature rises to 1200 K. the process is isobaric and essentially isometric because of the small expansion of the liquid sodium. For this reason, points 3 and 4 cannot be distinguished in the

pressure/volume plot, but owing to the large increase in temperature and a modest increase in entropy, they are widely apart in the temperature/entropy plot.

State 4 (liquid sodium, in the heat-source chamber).

$$V=23.3 \times 10^{-6} \text{ m}^3,$$

$$T=1200 \text{ K},$$

$$P=150,400 \text{ Pa},$$

$$S=60 \text{ aeu}.$$

In Step 4 \rightarrow 5, the liquid sodium vaporizes isothermally and isobarically.

State 5 (sodium, vapour, in the heat-source chamber).

$$V=0.0663 \text{ m}^3,$$

$$T=1200 \text{ K},$$

$$P=150,400 \text{ Pa},$$

$$S=80 \text{ aeu}.$$

In step 5 \rightarrow 6, the sodium vapor expands isothermally until the pressure is slightly above that of the initial State 1. Say, $p = 10 \text{ Pa}$.

State 6

$$V=997.7 \text{ m}^3,$$

$$T=1200 \text{ K},$$

$$P=10 \text{ Pa},$$

$$S=157 \text{ aeu}.$$

Finally, in Step 6 \rightarrow 1, the sodium vapor cools to 600 K and is returned to the initial State 1.

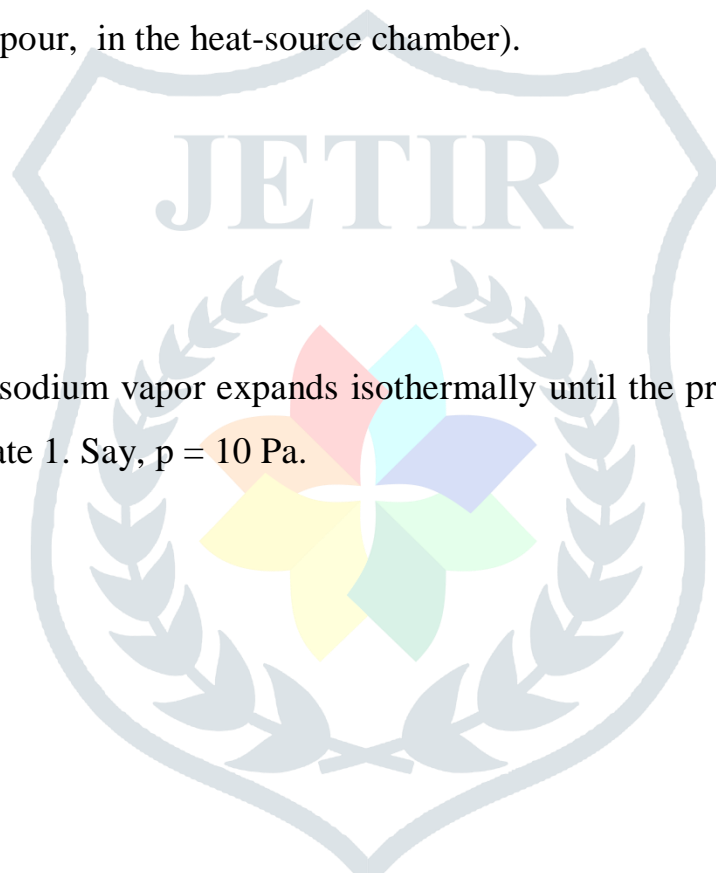
State "1" (sodium, vapor, in the heat-sink chamber).

$$V=713 \text{ m}^3,$$

$$T=600 \text{ K},$$

$$P=7 \text{ Pa},$$

$$S=150 \text{ aeu}.$$



Conclusion

AMTEC (Alkali Metal Thermal Electric Converter) is a device of the type Concentration-Differential cells. It uses properties of an electrolyte called β alumina, also called β -alumina solid electrolyte or BASE. In BASE if the concentration of sodium ions will diffuse between cathode & anode. This accumulation of ions creates an electric field that drives an upward flux equal's upward flux.

A heat source raises the temperature and pressure of the sodium vapour while a heat sink causes the condensation of the metal into a liquid, which is circulated back to the heat source by means of the pump. Wires are attached to the electrodes in contact with the BASE.

P_A is the vapour-pressure of sodium at the temperature T_A while P_{pres} is the vapour-pressure of the liquid sodium in the heat-sink chamber at temperature T_{res} . The values of the sodium vapour pressure in the hot & in the cold ends of the device play a decisive role in determining its performance.

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