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COGENERATION WITH CONCENTRATED SOLAR RADIATION FOR DECENTRALIZED ENERGY SUPPLY IN AGRICULTURE

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Summary:
Solar technologies are very suitable for decentralized energy supply in places where is necessary to ensure thermal and electrical energy in the same time. Concentrated solar radiation systems have small area and they can be highly efficient and cost effective. Coupled with alkali thermoelectric conversion they can find appliance in agriculture and rural areas particularly. This paper deals with hybrid systems for autonomous energy supply. System analysis has been performed taking in account radiative losses and thermal energy losses by thermal radiation, convection and conduction. Commercial applications of these systems are also presented, through evaluation of case studies and possible site for commercial solar energy utilization in agricultural engineering.

Keywords:
solar alkali-metal conversion, concentrated solar radiation, hybrid solar energy system, heat transfer

1. CONCENTRATED SOLAR RADIATION (CSR) EFFICIENCY ASPECTS

Solar technologies are maturing and new opportunities are emerging due to continuing improvements in designs /1/. Concentrated solar radiation technologies, combining less-expensive optical components with small area, highly efficient, and somewhat more expensive devices to achieve low cost, in general, are on the threshold of significant development (/1/, /11/). Thus main components of the system are stretched membrane concentrator cluster and high temperature receiver focally positioned.

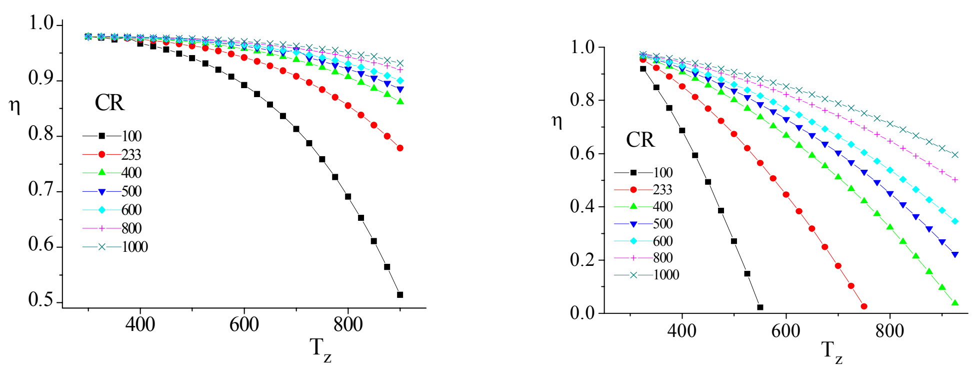
Innovative cavity - heart type receiver presents attractive solution for thermal power and photo thermal applications (/1/, /11/). Concentrated solar radiation transmitted by the receiver's cover and adjacent liquid is absorbed by the absorber which has a black nonselective coating and is with its integrated liquid passages immersed directly inside the circulating stream of liquid. It has been shown that a highly specularly reflective internal skin of receiver walls reduces the complex of radioactive, conductive and convective heat losses and results in a more efficient alternative to highly insulated receiver enclosures /11/. The influence of the solar radiation concentration factor and the temperature on receiver's simultaneous short and long wave radiation and heat transfer is presented here.

The object of our research is efficiency of the CSR-AMTEC system for converting solar energy into electric energy, for the first time presented in (/10/, /11/). Overall thermal conversion efficiency CSR-AMTEC is simply expressed as product of instantaneous receiver thermal efficiency and AMTEC thermal efficiency.

High-temperature part of process is conducted in solar receiver, so the instantaneous receiver thermal efficiency (1) is denoted as ratio of the heat absorbed by the working fluid - sodium and used for its evaporation $\boldsymbol{q_{krf}}$ and total incident concentrated solar energy flux $\boldsymbol{q}$

$$\eta = \frac{q_{krf}}{q} = 1 - \sum_{k=1}^{m} q_g / q \,, \qquad (1)$$

Receiver concentration factor is function of receiver surface CSR and concentrator area.



a b

FIGURE 1. DEPENDENCE ON INSTANTANEOUS THERMAL EFFICIENCY CSR η ON RECEIVER SURFACE TEMPERATURE

On the Fig.1, see diagrams above, we can see the influence of instantaneous thermal efficiency CSR η on receiver surface temperature, ***a*** - thermal efficiency only with radiation losses, ***b*** - thermal efficiency with radiation, convective and conductive losses

$$\eta_u = \eta \cdot \zeta = \left(1 - \frac{q_r + q_z + q_{kon} + q_{pr}}{I_b \cdot \phi \cdot CR \cdot A_p \cdot r}\right) \cdot \frac{\left(T_2 T_1\right)/T_2}{\left(T_2 - T_1\right)/T_2\left[1 + C_p T_1/L\right] + T_1/T_2} \qquad (2)$$

The influence of overall thermal efficiency (2) on the concentration factor, evaporation temperature and condensation temperature, is shown on following diagrams (Fig.2).

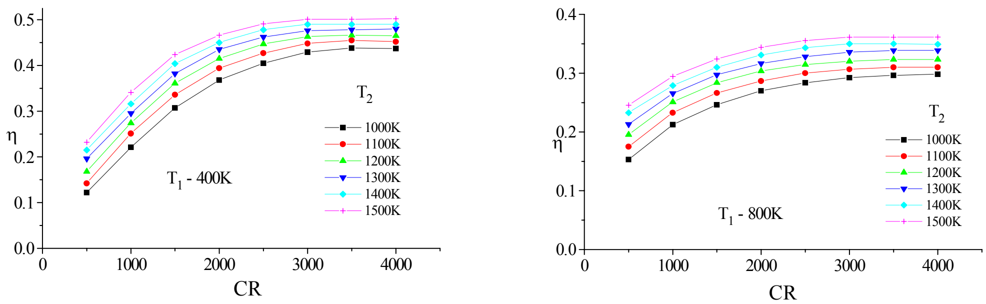


FIGURE 2. INSTANTANEOUS SOLAR/AMTEC THERMODYNAMIC EFFICIENCY DEPENDENCE ON THE CF AND EVAPORATION TEMPERATURE T2

2. THERMODYNAMIC ANALYSIS OF AMTEC HEAT ENGINE

The direct conversion of heat into electricity is an old dream of engineers. A dream which at last may be realized with the development of solid electrolytes of beta-alumina as used for the NaS-battery. The heat engine with such an electrolyte is the Alkali-Metal-Thermo-Electric-Converter called AMTEC, which has no moving parts and promises a high energy conversion rate, low maintenance, high power density and low production costs. The AMTEC is a heat engine which converts heat directly into electricity without any moving parts. The working medium is sodium which is operating in a closed thermal cycle (/5/ - /8/).

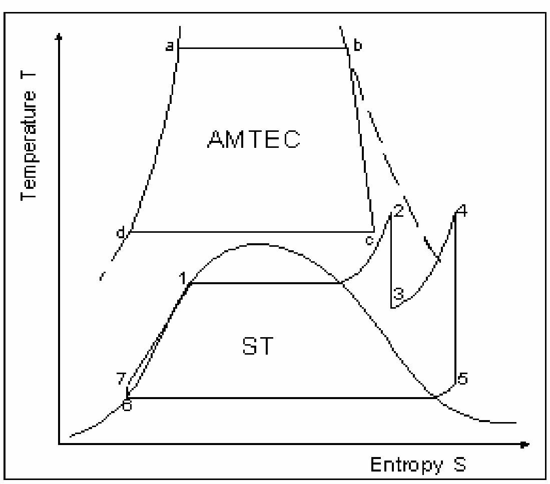


FIGURE 3. THE THERMODYNAMIC CYCLE (T-S DIAGRAM) EQUIVALENT TO THE REVERSIBLE AMTEC PROCESS AND THE BINARY CYCLE CSR-AMTEC/SPC.

The T-S diagram (Fig.3) shows that the process is characterized by isothermal expansion and compression and by isobar heating and cooling. It comes very close to the Carnot cycle and consequently the theoretical process efficiency is not so far from the Carnot efficiency (/1/,/10/).

As for all thermal processes, the efficiency rises with increasing temperature and decreasing temperature. The limits are set by the availability of suitable materials and by economical aspects, which led under the prevailing conditions.

The actual efficiency of the AMTEC cycle is mainly determined by unavoidable heat and electrical losses, which both rise with the temperature over proportionally. Under optimized conditions 43 per cent can be achieved, although the first target is 35 per cent after having realized 20 per cent in laboratory tests /2/.

The actual energy conversion takes place along the isothermal expansion line (points *a* to *b* in T-S diagram) and is realized in an ion conducting solid electrolyte made of beta-alumina. For this purpose the electrolyte is equipped with one electrode on the hp side for the separation and one on the lp side for recombination of the electrons. The usable energy is the electron flow between the two electrodes via an external consumer. The driving force of the process is the energy difference between the hp-and lp-chamber, which is effected by external heat admission to the hp-side and a heat sink on the lp-side. The heat source can either be fossil or nuclear fuel or solar radiation. The heat sink is realized by a water or air cooled condenser. To close the cycle the condensate is returned to the hp-chamber via an electromagnetic pump.

The operating cycle of the AMTEC is presented on Fig.4. A closed vessel is divided into two regions by a separator of base and a pump. Liquid sodium fills upper region, which is maintained at a vapor temperature T_2 in the range 900 to 1300K by an external heat source. Vapor pressure of sodium is about 0.6 bar. The lower region, containing mostly sodium vapor and small amount of liquid sodium, is in contact with heat sink at T_1 in the range 400 to 800K.

A porous electrode covers the low-pressure side of the base separator. At the beginning of the AMTEC cycle, sodium at temperature T_1 from the condenser enters the hot zone and absorbs externally supplied thermal energy until it reach T_2. Electrical power outputs of 500W/m^2 appear achievable. If an electromagnetic pump pr wick is used, the only moving part is circulating sodium (/5/-/8/, /10/).

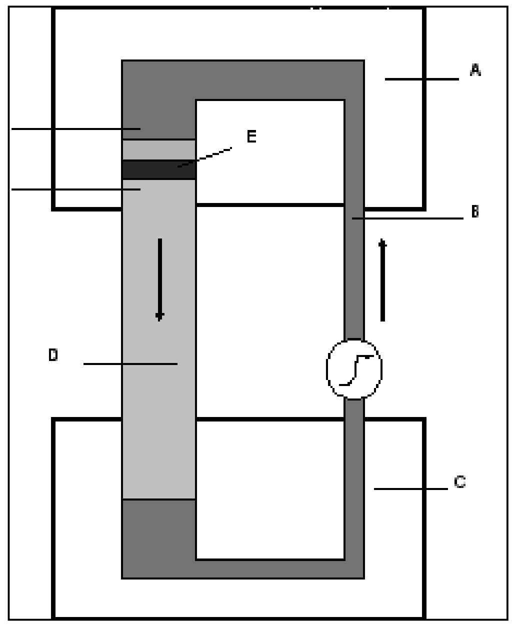


FIGURE 4. OPERATING CYCLE OF THE AMTEC
A – Heat source of the temperature T2
B – Liquid Sodium, **C** – Heat sink of the temperature T1, **D** – Sodium vapor, **E** – Solid electrolyte

3. ALKALI METAL THERMOELECTRIC CONVERSION - SIMPLE AND BINARY CYCLES

The Alkali Metal Thermo - Electric Conversion (AMTEC) a very prospective solution for a high performance power generation became recently a subject of our interest. The key element of an AMTEC is the β alumina solid electrolyte (BASE) which conducts positive sodium ions much better than sodium atoms or electrons. A sodium pressure difference across a thin BASE sheet drives sodium ions from the high pressure side to the low pressure side, and electrons collection on the high pressure side results in

an electrical potential. The thermodynamic cycle equivalent to an AMTEC device is shown on Fig.3.
The results of performed analysis of the instantaneous thermal efficiency of the thermodynamic model of the combined system CSR - AMTEC (coupled concentrated solar radiation subsystem CSR and AMTEC) are very positive and optimistic. Further thermodynamically has been studied binary cycle - combination of AMTEC and steam power cycle. Obtained combination of relevant scheme components of CSR - AMTEC given on Fig.5. are significantly higher than the corresponding values of any conventional power plant in existence today /10/.

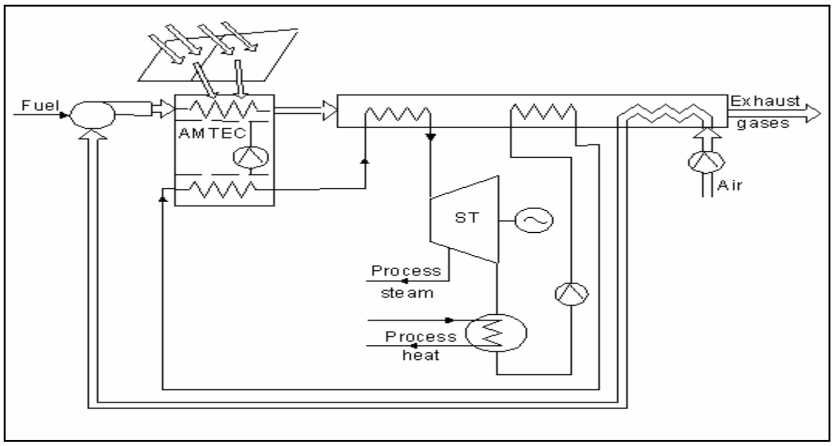


FIGURE 5. COMBINATION OF AMTEC AND STEAM (ST) POWER CYCLE

4. HYBRID AND COGENERATION SYSTEMS ENERGY DEMANDS

For spreading the use of solar energy it is mandatory to be fully dispatch able and the best way to do this nowadays is by hybridization with natural gas or oil. In particular both near- and mid-term applications are foreseen for different hybrid solar systems (/1/, /10/). Hybrid systems, especially those based on concentrated solar radiation conversion technologies are much more competitive and better suited for many diverse applications and emerging international markets than mono-type technologies.

In addition to the possible impact on decentralized energy production development, combined hybrid solar CSR - AMTEC systems applications include as very prospective generally autonomous systems (for example electricity for the self powered convective solar dryers – Fig.6). (/1/, /10/).

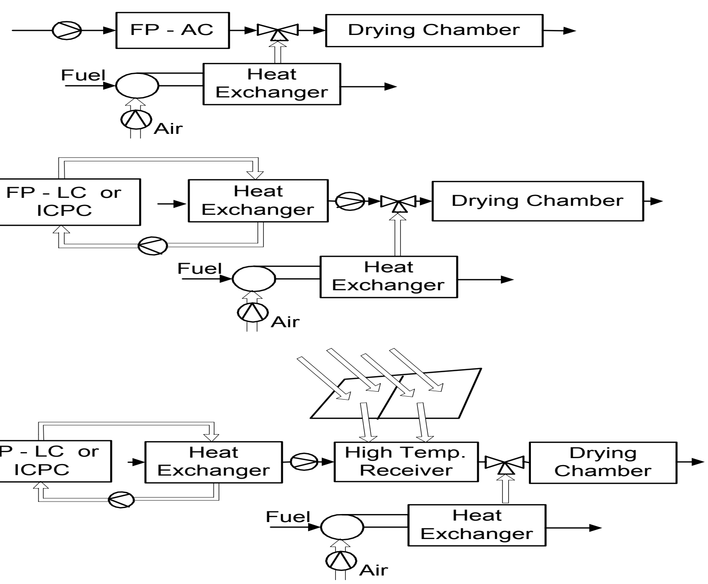


FIGURE 5. SCHEMES OF CONVECTIVE SOLAR DRYERS WHICH BECOME SELF POWERED AND CONTROLLED - BY THE ADDITION OF CSR - AMTEC UNITS /11/.

General philosophy of solar subsystem design that will be to design and optimize facility for average solar radiation conditions and specific energy demand, but taking in account real dynamic behavior of local terrestrial solar irradiance and users energy demands. Proceeding technical evaluation of the designed hybrid solar thermal systems will give special attention to the specific criteria which are commonly used in evaluation and assessment of the energy sources regarding local resources, technological development, energy efficiency, environmental impact and economics (/1/, /10/).

The main tasks are to focus on dispatch able hybrid systems encompassing concentrated SOLAR radiation, combined with some of classical, fossil fuel based energies, optimized for certain locations and applications (modular units under and around 1 MW capacity (Tab.1) /11/). Concentrator technologies combine less-expensive optical components with small area, highly efficient, and somewhat more expensive devices to achieve low cost.

TABLE 1

CONSUMER TYPE	ENERGY SUPPLY INSTALED CAPACITY		THERMAL
	Electrical kW	Thermal kW	Electrical
Aromatic oils extraction	6.69	49	7.32
Dairy (500-2500 l/8h)	8.5 - 57.9	38.9 - 150	4.58 - 2.59
Animal food production (3 t/h)	82.1	30.6	0.37
Distillation plant (30-120 m^3/h) wine, 10% Vol.	24.52 - 67.3	198 - 860	8.07 - 12.77
Pharmaceutical industry plant	3455	6880	1.99

5. APPLICATIONS AND SOLUTIONS FOR FURTHER DEVELOPMENT

The AMTEC can be used in a variety of unit sizes for decentralized power generation in stationary and mobile units, solar power stations, for small and medium sized cogeneration plants, or as a topping cycle for coal-fired power stations. In the field of remote power generation, the AMTEC competes with the diesel engine. While production costs and fuel consumption are similar for both systems, the AMTEC is practically maintenance free (no mechanical wear and stress), operates without noise and vibrations, handles all kinds of fuels (also solid ones), does not need catalysts for removal and can start without auxiliary power. Furthermore it has good partial load efficiency. There is also a big potential for mobile applications, especially for noiseless and clean battery charging of electrically driven buses and trucks. Due to its capability to handle radiation heat of high temperature at good efficiencies, the AMTEC is a very suitable heat engine in a solar thermal plant which offers attractive generating costs. In areas with high insulation (annual radioactive energy input: >1800 kWh/[m^2]a), where remote solar plants of small unit size (10 to 50 kW) are required, such an AMTEC solar plant could produce solar power at $0.19/kWh which is much less than with any photo-voltaic plant /3/.

Reliability, efficiency, portability and quiet operation are qualities that make AMTEC a very attractive technology for spacecraft power, auxiliary and remote power, portable power, and self-powered appliances, to name but a few potential applications. Based solely on an electro-chemical process and a closed cell design, AMTEC has no moving parts and therefore no noise or vibration, and it provide high reliability and virtually maintenance-free operation. The cells are also very small and light relative to their power output. For example, a cell that produces 4 to 6 watts of power is currently 100 mm long by 40 mm across and weighs about 0.2 kg. The cells are also modular, allowing for more powerful systems to be made simply by connecting smaller cells together.

Since the AMTEC can take solar heat as well as other heat sources, hybrid operation is also possible, which makes the electricity supply independent from the sun. Due to its small investment costs, low maintenance requirements as well as silent and vibration free operation, the AMTEC could also be used in cogeneration plants from 20 kW to 10 MW. With its capability to handle the fuel energy at a high temperature level, it can also be used as a topping cycle in steam power stations comparable to fuel cells or gas turbines in combined cycles. Whereas gas turbines and fuel cells, however, can only handle well cleaned gas, the AMTEC can also accept solid fuel. Its use is expected to lead to an average improvement in the cycle efficiency of over 10 per cent. The combination of improved efficiency, low specific costs, small space requirements (5 [m^3]/MW) and noise and vibration free operation is expected to make AMTEC economically attractive for both installation in new coal fired power stations and the up rating of old power plants.

Other important fields of development are the improvement of the efficiency by lowering the losses on the electrical (Ip-electrode, current collector), the thermal- (insulation, radiation shields) and flow side. Development targets are furthermore the sodium transport (electromagnetic pump) and the electrical connections of the individual cells (series connection). At the heart of the new power cells lies a ceramic material, beta double prime-alumina solid electrolyte (BASE), which has some unique properties. The most notable is its excellent conduction of sodium ions, but poor conduction of electrons. The BASE ceramic is in the form of individual tubes inside the AMTEC cell. Electrodes and current collectors are placed on the inside and outside surfaces of the BASE tubes. Liquid sodium, the working fluid in the cell, is heated from one end of the tube and turns into sodium vapor. An electrode and current collector on the inside surface of the tube collect electrons from the sodium ions, which then easily pass through the tube wall. Sodium ions reaching the outer surfaces of the tubes pick up electrons, once again becoming sodium atoms, and then they evaporate. A cooled surface in the cell condenses the evaporated sodium back into a liquid. It is then returned to the hot end of the cell by a fine-pore wick, and the process starts all over again /3/.

A previously critical item, the ceramic electrolyte, has lost some of the uncertainties of the past. Due to extensive research work and experience in the NaS-battery, the electrical and mechanical properties of the beta-alumina tubes have been improved and are calculable nowadays to a great extent. Long term tests proved their stability an Na-atmosphere at 1000 [degrees]C. The heating of the sodium inside the BASE tube creates a greater pressure inside than outside the tube. This pressure differential defines a potential energy. The sodium can expand to change the potential to kinetic energy only by moving through the BASE material when the sodium is in the ion form. Sodium atoms are stripped of an electron, becoming positively charged sodium ions. They then travel through the tubes, converting the pressure differential into work. On the other hand, the flow of electrons produces electrical power. When a load is placed on the system, it draws current produced by stripped sodium electrons that flow from the inner electrode, through the load, to the outer electrode. The electrons are finally reunited with the sodium ions on the outer surface of the BASE tubes. The sodium atoms are then condensed into liquid form, wicked back to the hot end of the cell where they evaporate, and the sodium begins to flow through the cell all over again /4/.

The AMTEC is an engine which has great potential. Although a great deal of development work is still necessary, a huge market is expected to appear as soon as the first prices worthy modules have proven their reliability over a certain period of time.

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