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Possible developments in energy conversion using liquid metal magnetohydrodynamics

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Abstract
Liquid metal magneto-hydrodynamic-energy-conversion (LMMHDEC) systems have been a matter of great interest and research & development since 1960. The various states of design and development of such systems go through a step-by-step progress with time. This paper highlights the phenomenon of direct thermal energy conversion systems using liquid metal as an electrodynamics fluid and gas/vapour as a thermodynamic fluid. An analysis of the technological drawbacks responsible for low efficiency of these LMMHDEC systems along with possible R & D solutions have been discussed in this technical research paper. The separation of electrodynamics fluid from thermodynamic fluid at various stages of MHD conversion remained an efficiency challenge of the various types of systems. To meet this challenge, a Dual-cycle MHD system has been designed in this paper. Both the fluids viz. thermodynamic and electrodynamics go through a phase change in this cycle. The thermal efficiency is optimized when one fluid goes into a phase change during a cycle and another fluid does not experience any phase change. The information covered in this paper enables an overview of concepts and the background to choose a cycle for a given temperature range.

Keywords: density difference, energy-conversion, liquid metal, magnetohydrodynamic, pressure-gradient, solar collector

Introduction

When an electrical conductor continuously cut the lines of magnetic induction (Stanford University), the charged particles in the conductor experience a force. This force remains in a direction mutually perpendicular to B (the magnetic flux lines) and to the velocity of the conductor. This electro-motive-force results in a mutually opposing counter movement of positive and negative charged particles and provides basis for the conversion of mechanical energy into electrical energy. The conventional thermal and hydroelectric generators use a solid metal conductor which is caused to rotate between the N and S poles of magnet.

In 1831 Faraday observed small irregular deflections in a galvanometer connected to Thames River water with immersed electrodes at mid span of the Thames Bridge. He interpreted this event that the electrically conducting river water moving through the earth's magnetic field should produce a transverse emf. The phenomenon of the production of emf by conducting fluid flow through magnetic field was defined as magnetohydrodynamic (MHD) power generation.

The green house effect (Kaushik *et al.*), photochemical smog (pan) is a matter of deep concern for the conventional thermal power plant. Fossil fuel energy responsible for ozone layer depletion is used in these power plants. A renewable energy source such as solar heating based LMMHDEC systems can work on low temperature operation without any undesirable emission. Moreover, MHD duct is free from the problems of electrode/duct life, erosion, corrosion, preheating, cooling, condensing, turbine, etc. The problem of nuclear waste management is a cause of great concern for nuclear thermal power plants.

Background

All the conventional thermal and hydro power plants are associated with use of bulk thermomechanical and hydro-mechanical operating systems such as a boiler, condenser, regenerator, feedwater pump, turbine, and generator with a rotary mechanism. This causes various types of efficiency (Lascruces) losses because of thermal leakage, friction, mechanical breakage etc. According to Faraday's Law of Induction, the magnitude of induced current is proportional to the velocity, the magnetic field strength, and the conductivity of the fluid. This conversion system can be used for gas-flow cycles applicable to nuclear generators with higher conversion efficiencies.

The MHD is a direct thermal energy conversion system where no heavy mechanical dynamics are needed. The other major problem is huge space occupation of these conventional power plants with low conversion efficiency. The ground based nuclear power plant using turbo machinery delivery moderate efficiency at the range of 30 - 40%. The space based nuclear generators work on thermo-electric conversion with reduced mass effect but suffer from very low efficiency of 8 -13%.

The Los Alamos National Laboratory, University of Florida, developed a non-moving part conversion system with possible higher efficiency. This system works on recoil enhanced magneto hydrodynamic (REMHD) conversion. In 1970, the Argonne National Laboratory (ANL) (Tillack & Morley, 1998; Patrick *et al.,* 1978; Patrick & Branover, 1985; Fabris *et al*., 1979; Blumenau *et al*., 1986; Morse, 1970) developed a constant velocity DC Faraday generator which uses N_2 with Na and/NaK. Based upon this early work, the Ben-Gurion University initiated work on a variety of power conversion systems that have been analyzed and/or tested contemporarily (Blumenau *et al*., 1986).

The use of liquid metals for MHD conversion enables low temperature application in comparison to an ionized gas MHD generator (Morse, 1970; Hammitt, 1966). High temperature is needed to maintain an ionized gas conducting state. A liquid metal exhibits a high heat transfer and electrical conduction properties. Because of these reasons, any heat source can be used for LMMHDEC applications .e.g. solar, geothermal, nuclear, exhaust gas etc. At the same time, higher electrical conductivity of liquid metal (about 10^6 times that of an ionized gas) enables higher power density with moderate magnet fields. This technical feature benefits in the designing of a small size MHD generator. Liquid metals offer conductivities of the order of 10^6-10^7 $(\Omega m)^{-1}$ at a low temperature where He seeded with 0.45 % Cs at 2000 K yields conductivity of 10 $(\Omega m)^{-1}$. A thermal power plant requires a thermodynamic medium such as gas/steam that can expand and contract on heating and cooling, respectively.

In LMMHDEC the thermodynamic fluid i.e. gas/vapour is mixed with electrodynamics fluid i.e. liquid metal. The heat capacity of the liquid phase is greater than the gas phase and MHD fluid together expands and contracts almost isothermally. The results of higher thermal conversion efficiency are reached approximately near the ideal Carnot cycle. A comparison can be analyzed through Figure 1.

Liquid metal magnetohydrodynamic energy conversion (LMMHDEC)

Working principle, advantages and limitations of various systems

The liquid metal magnetohydrodynamic system proposed by Elliott (1962) was based upon the high temperature Rankine cycle. Lithium was used as MHD fluid and Cesium as a vaporizable fluid carrier. This vapour-fluid-carrier (VFC) accelerates the MHD liquid through a magnetic field with a high velocity and converts its kinetic energy into electrical energy. The liquid is separated from the VFC before passing through MHD generator. The moving liquid metal leaves the MHD generator and returns back to a mixer nozzle after passing through a diffuser and heat-source device. The VFC separates from the liquid metal at the separator after passing through a regenerative heat exchanger and condenser unit. It returns back to the mixer nozzle through a pump.

The liquid loop and vapours loop are shown in Figure 2. The achievable efficiency (Petrick & Branover, 1985; Jet Propulsion Laboratory, 1973) ratios between separator cycle and Carnot cycle that have been estimated were in the range of about 0.20 to

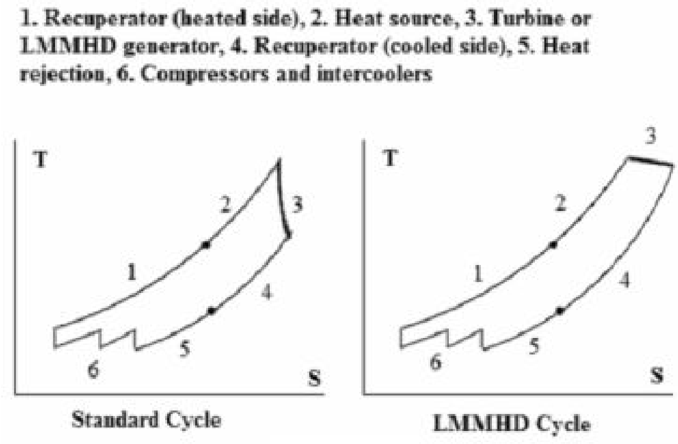
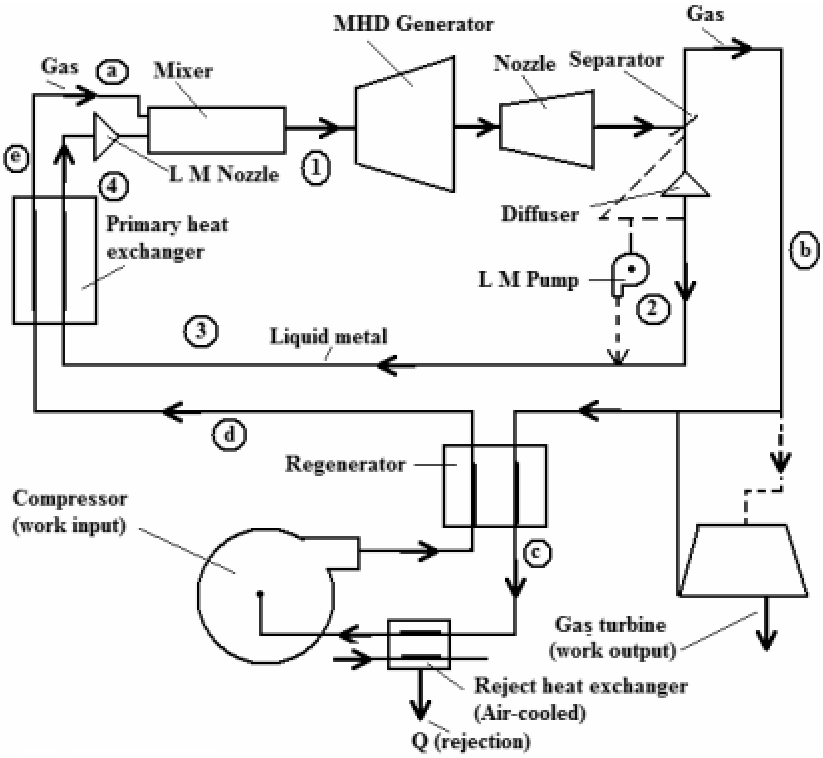


Figure 1: Standard Brayton Cycle compared with MHD Brayton Cycle



1, 2, 3, 4 > Liquid metal loop, and a, b, c, d, e > Gas/ Vapour loop

Figure 2: Schematic of two-phase cycle generator system

0.30. It is difficult to get a complete separation of the two phases, though VFC being small in weight but significant in volume. This disturbs the performance of both the diffuser and generator. The other limiting factor is energy shortage to meet rest of the cycle i.e. energy requirements of vapours loop and MHD-fluid loop during separator to the mixture nozzle processing. Historically, Elliott proposed this cycle with a DC conduction generator.

Advantages of LMMHDEC

The working temperature range (Jackson & Pierson, 1962) is not a system constraint – instead it is controlled by the working fluids and material of the nozzle, generator, diffuser etc. Both gas cycle and vapour cycle versions can be developed. The LMMHD separator cycle works at almost constant temperature expansion of the working fluid and thus enables higher thermal efficiency. This co-relates the case of infinite reheating in a conventional Rankine cycle.

The high electrical and thermal conductivity of the liquid metal in comparison t o the plasmas is a factor which improves the efficiency of this cycle. The liquid metal in this LMMHDEC cycle is required to move at high possible velocity. This causes need for high pressure pumping of the liquid metal to achieve such accelerations for MHD conversion. In a conventional Rankine cycle, this accelerated liquid metal may be used to run a turbine based generator. The two-phase LMMHDEC cycle results in considerable losses such as pump power, pressure drop of working fluid at separating, poor mixing of VFC and MHD-fluid at mixer.

The mixer nozzle is an open chamber where VFC and MHD-Fluid get mixed together and proceed with high velocity to the separator where two fluids get separated and MHD-Fluid moves into the MHD generator. This results in mixer losses, pressure drops, slip loss and poor mixing because of partly vaporization of liquid. In slip loss vapour moves faster than liquid and this may occur either at nozzle or generator. Basically the two phases do not get separated completely. Part of the liquid goes with vapour and part of the vapour bubbles remains with MHD-Fluid. This results in heat loss in the re-generative heat exchanger and loss of extra work by pump and diffuser loses because of the presence of vapour in the liquid loop. Poor heat transfer of two phases inhabits desired isothermal expansion of MHD-Fluid. The separation process is particularly difficult, because the desired good mixing with small bubbles in a continuous matrix of liquid is hard to separate.

Multiple cycles and concepts (Petrick & Branover, 1985; Grolmes, 1966) have been proposed by various workers in response to minimize the losses, as mentioned above. They differ in the choices of mixing, acceleration/ or pumping, and separation processes for the two fluids. The single-fluid systems resulted in poor efficiency. The two-phase generator cycle, where the vapour/gas-liquid mixer is the working fluid in the generator, and the OMACON (optimized MHD conversion system) cycle, which uses natural circulation to minimize the losses associated with pumping of liquid metal found to be promising. The two-phase generator cycle, in which vapour/ gas was used as thermodynamic fluid and liquid metal was used as the electrodynamics working fluid has been modified. The modifications took proper care about the various losses in the earlier concepts. The OMACON cycle (optimized MHD conversion system) using natural circulation to reduce liquid metal pumping loss, mixing loss etc. has been found as an improved version of the above.

A two-phase generator cycle

The two-phase generator cycle (see Figure 2), was developed by Petrick and Lee (1964). In this cycle, two fluids i.e. vapour and MHD-Fluid have been allowed to expand through the generator.

The separation of two phases at high velocity is avoided in this design. The liquid can return back to the mixer via any of the two routes:

1. Allowing extra expansion through a two-phase nozzle so the liquid can develop enough kinetic energy after separator and return to the mixer through diffuser.
2. After separator the liquid is driven by an electromagnetic (EM) pump to push it into the mixer through a primary heat exchanger and a LM nozzle. This pump is driven by using some output from the generator.

A two phase fluid flow solar assisted LMMHDEC system (Elliott, 1962; Petric, 1966; Elliott *et al.,* 1966; Elliott, 1966; Petric, 1966; Branover *et al.*, 1966; Geyer & Pierson, 1983; Pierson & Herman, 1983) without any mixer and separator as shown in Figure 3. The two phase fluid flows through a MHD channel in natural circulation cum gravity mode.

The liquid metal is heated via a solar collector up to the desired temperature range. This liquid metal enters the mixer where an organic fluid is injected and soon it starts boiling due to direct heat transfer from latent heat of fusion of liquid metal. The organic gas bubbles experience an isothermal expansion and enable an accelerated flow of a two phase mixer into the MHD channel. A nozzle is also provided through the mixer.

The heat addition to the vapour and liquid metal at the regenerator and heat-exchanger is advantageous. Since liquid metal has very good heat transfer properties in comparison to the vapour, better performance is obtained by the heating of liquid metal. It will enable a high constant-temperature-expansion near about the rate of higher Carnot efficiency.

The vapour or gas at the separator end is used to run a turbine based generator. A regenerator pass of vapour improves the efficiency by minimizing heat reject loss. This cycle can be worked by using helium or nitrogen as the non-condensable fluid along with a liquid metal suitable for this operating temperature. Basically this behaves as an Ericsson cycle because of the near constant-temperature-expansion of the gas, and results in efficiency near to an ideal cycle.

The regenerator has a significant impact on efficiency. When water is used with liquid metal (such as tin) the Rankine version of this cycle is obtained. This vapour/steam leaving the generator or the nozzle are in a highly superheated condition, and are used in a turbine.

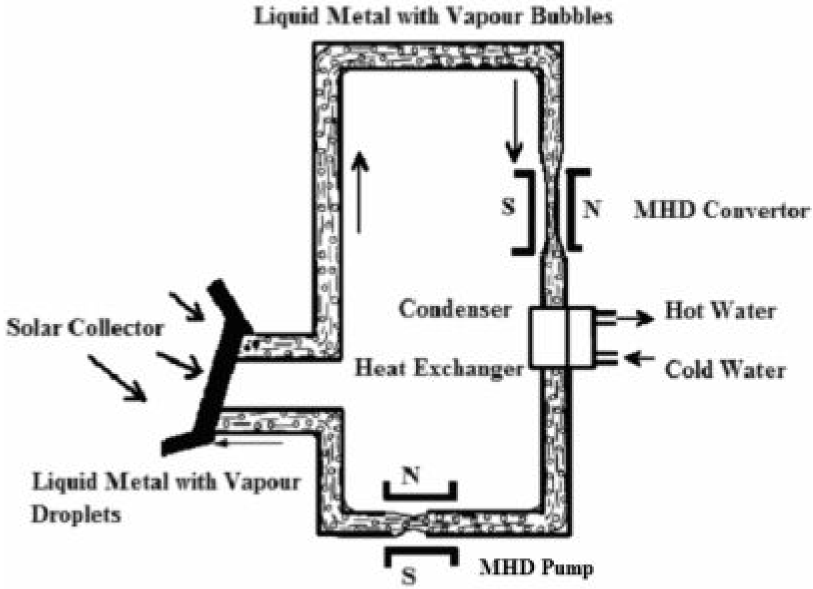


Figure 3: Schematic diagram of solar-energy LMMHDEC system without mixer and separator

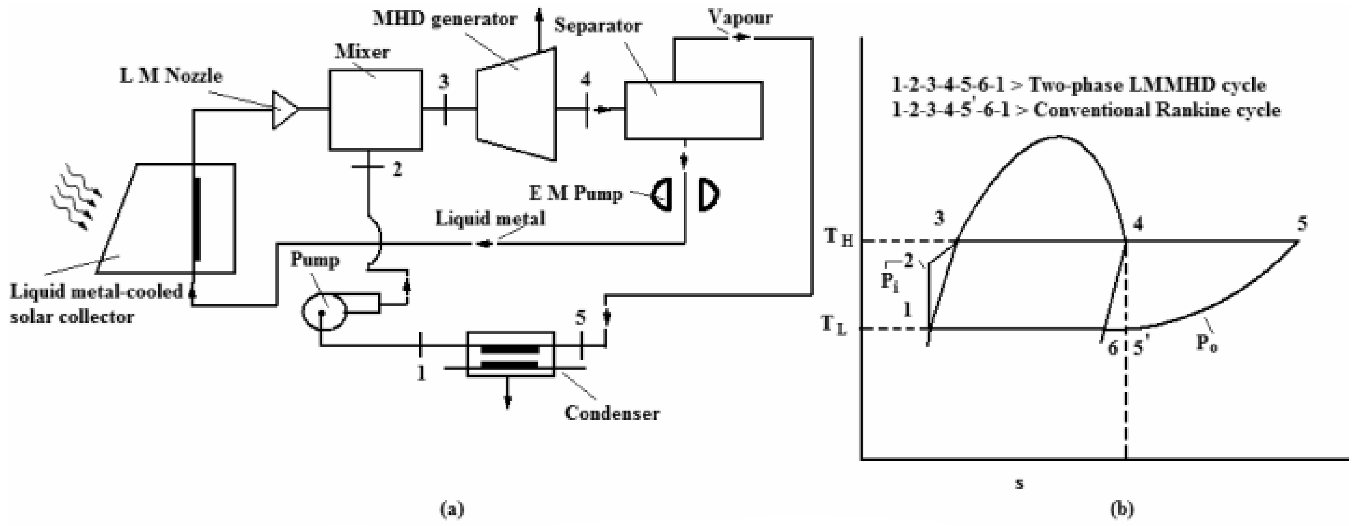


Figure 4 (a & b): Schematic diagram of solar-assisted LMMHD Rankine cycle with liquid metal cooled collector

A schematic of a Rankine cycle base LMMHDEC (Piersen, 1980; Amend *et al.,* 1974) system is shown in Figure 4 (a & b). The liquid metal loop follows the path sequence as Mixer – MHD generator – Separator – EM pump – Liquid metal cooled solar collector – LM nozzle – Mixer. The organic vapour loop follows a path sequence as Mixer – MHD generator – Separator – Condenser – Pump – Mixer. The T-s diagram for organic vapour, which goes under isothermal expansion at constant high temperature T_H and isothermal contraction at constant low temperature T_L is shown in (b). The inlet pressure P_i and outlet pressure P_o of the channel is constant. The liquid metal does not experience any phase change throughout its processing in the cycle.

This Rankine cycle based solar-assisted LMMHDEC (Branover *et al.,* 1980; Geyer & Pierson, 1982; Pierson & Herman, 1983; Branover *et al.,* 1981) is best suited for a low heat-source (370 K - 850 K temperature range). The theoretical efficiency of a given temperature can be fairly reached above than those of conventional steam cycles for the same temperature, because of no mechanical work. Application or choice of heat-exchanger depends on the working temperature range.

The thermodynamic fluid in the mixer gets boiling due to direct heat transfer from the hot liquid metal. NaK is observed to be a right choice for low temperature electrodynamic fluid. This possesses excellent heat-transfer and electrical conductivity. The sensitive heat down to condensation of the vapour is used for regeneration. The LMMHD system can be operated in the temperature range as low as between 350 to 700 K, using flat plate solar collectors (Pierson *et al.,* 1980).

The Carnot efficiency for source and sink temperature of 353 and 298 K is 0.156 and a solar collector of 0.6 efficiency results in LMMHD efficiency of 0.043. Considerable improvements of up to 25% are possible while using liquid metal in the collectors with a direct contact boiler. This is because of the higher top temperature of the thermodynamic fluid.

The efficiency of the Brayton version is more attractive for temperatures above ~810 K. The sodium cooled solar collectors have good properties and is preferred for such applications. At 1089 K the efficiency is calculated at ~0.5 for both the pure LMMHD (without gas or steam turbine) and the LMMHD-gas turbine cycles with helium and lithium as the fluids. The mixing of liquid metal vapour with the gas/steam at separator end, results in high heat rejection loss. This lowers efficiency at high temperatures. Sodium is used at a low temperature application and lithium is preferred above ~867 K to minimize vapour inclusion loss.

An open-cycle LMMHD generator

The Open-Cycle LMMHD (Pierson *et al.,* 1985) is a novel concept which uses combustion gas as the thermodynamic fluid and liquid copper as electrodynamics fluid. The coal powder is burned under compressed air and the combustion gas is mixed with liquid copper. The copper will remove all the sulphur and nitrogen oxides from the combustion gas. This fluid mixer travels through the MHD generator to produce electricity. After the generator, this mixer is subjected to a rotating separator where combustion gas is separated from liquid copper. The sensible heat of this clean gas is utilized in a conventional steam plant before discharge into the atmosphere. The removal of sulphur enables production of good quality copper as a by-product of the cycle. Also, the same existing boiler with minor modifications can be used in this cycle. The development of LMMHDEC plant components is easy

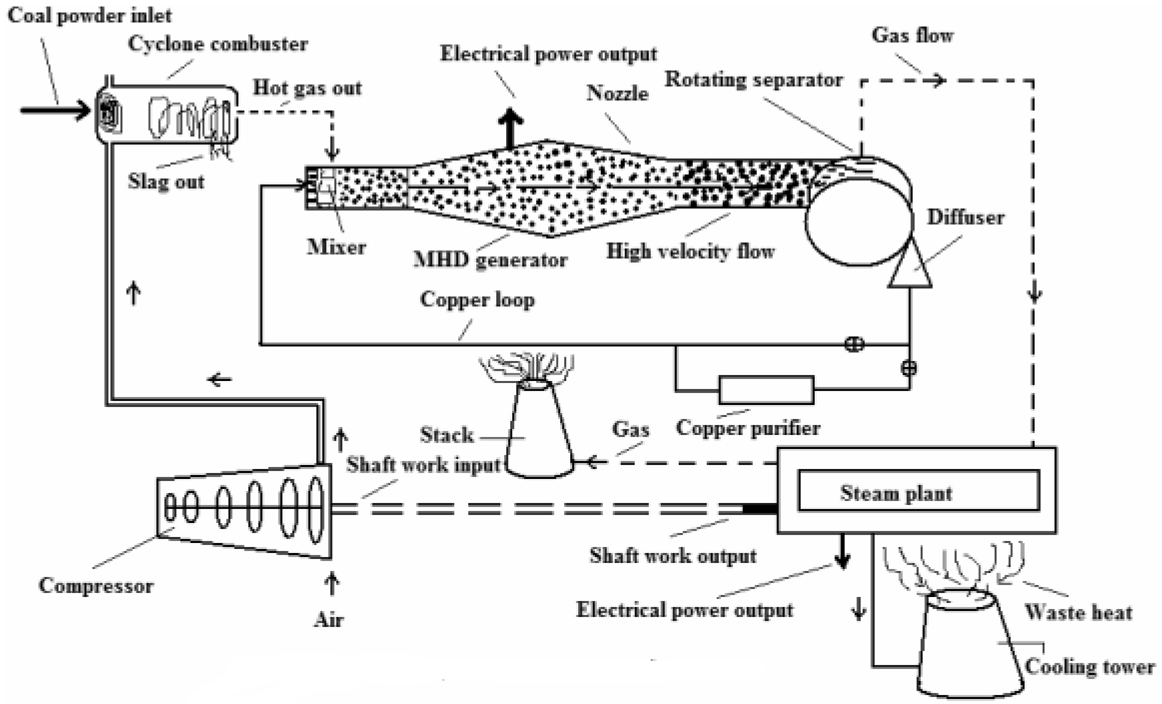


Figure 5: A schematic diagram of an open cycle LMMHDEC system

because of the small and simple nature of fabrication and assembly. A schematic diagram is shown in Figure 5.

The oil-fired plant works at an efficiency of 0.289. The LMMHDEC system at stoichiometric ratios of 0.8 before the copper mixer and 1.05 in the boiler at the temperature of 1501 K, generates 119 MW with an efficiency of 0.341. The efficiency is proportional to the stoichiometric ratio and copper temperature. It is clear from all the above cycles, the LMMHD conversion seems most economical and easy running relative to the other existing coal/nuclear options of power generation.

The OMACON Cycle

The OMACON system was developed by Patrick and Branover (1985; 1988) as shown in Figure 6. The system allows natural circulation of fluids without any need for a pumping operation. A simple OMACON system consists of two pipes viz. a riser upward-flowing and a downward-flowing. These pipes are connected at the bottom by a crossover pipe.

The top is connected by a gas/vapour-liquid sep-

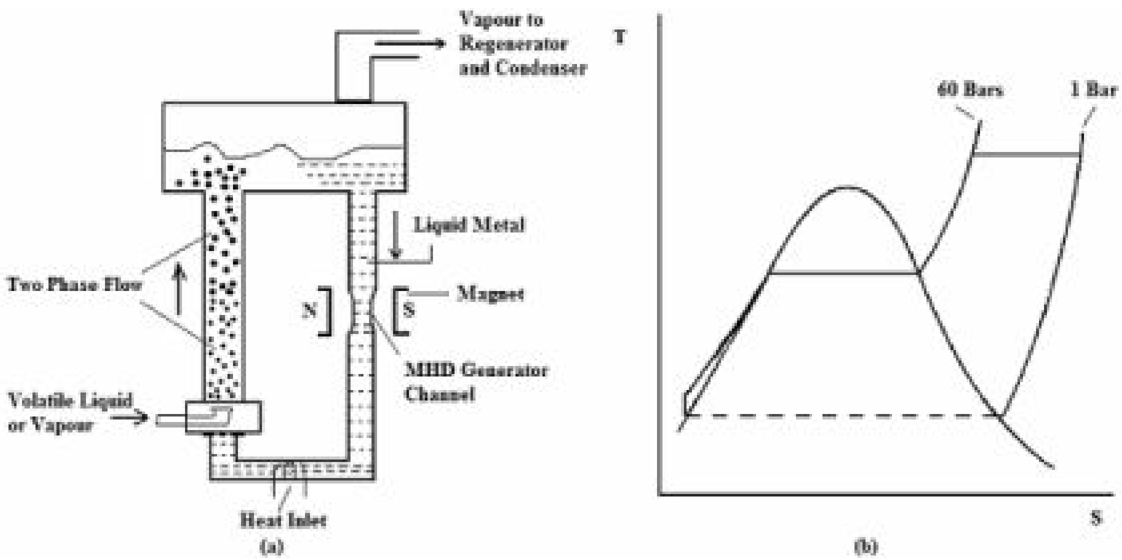


Figure 6 (a) Schematic diagram of OMACON system; (b) T-s diagram of an OMACON Rankine cycle

arator. This vapour from the separator is subjected to the Regenerator and Condenser. Loss due to the two-phase nozzle, separator, diffuser and pumping is absent in this system. Also a single phase MHD generator can be used for low-flux-density magnets. This system can be designed for low frictional losses. The system can be operated as a Rankine or Brayton cycle at various temperature ranges suitable for a particular fluid. Physical size (Branover *et al*., 1988; Petrick *et al*., 1988) requirements to meet practical pressure differences between two-phase-flow and liquid metal MHD channel flow is the biggest limitation of the OMACON concept. The presence of huge liquid metal inventory and its processing is another cause of concern. The use of heavy liquid and design for multiple stage processing is one of the solutions that came into light. A hybrid concept that combines features of the OMACON system with the LMMHDEC system which uses the nozzle, separator and diffuser can be a solution for the above limitations of metal inventory and pressure differences.

Development of a confined metal-foil seeded duel-cycle LMMHDEC system

The proposed LMMHDEC system (see Figure 7) does not require a mixer, separator, compressor and diffuser. Basically a solar heating source, a confined thermodynamic fluid (gas or liquid metal), an electrodynamics fluid (liquid metal), and a condenser are the chief requirements of this system. The thermodynamic fluid is confined/or filled in a Metal-foil-container (Mfc). This Mfc is of flexible/squeezing type, which can expand and contract with temperature conditions of the thermodynamic fluid. The other important feature of this Mfc is its ability to sink (partially or fully) into the electrodynamics fluid during its either expanding and/ contracting state or both. However, it will also work when Mfc is floating at a heat-addition state and sinking in its heat-rejection state (condensing).

Working principle and basic requirements

This proposed LMMHDEC system works on the principle of a Differential-Pressure-Gradient (DPG). A DPG in the system occurs because of the Mfc expansion at the heat-addition and its contraction at the heat-rejection. A racecourse condition in electrodynamics fluid is established because of simultaneous continuous expansion and contraction of Mfc at two locations in the system i.e. heat-addition and heat-rejection zones. This enables a high velocity flow of electrodynamics fluid across the MHD channel.

Basically this is a perfectly closed thermodynamic system where electrodynamics fluid does not experience any phase change. The thermodynamic fluid in Mfc may go into a phase change if it is a low-melting-high-density (LMHD) metal and it will not experience any phase change if it is a gas e.g. Helium, Argon etc. The key requirement of Mfc is its tendency to sink into the electrodynamics fluid. This can be achieved if Mfc is designed to follow the principle of buoyancy to get a fully submerged body condition during the cycle. The selection of the density of both i.e. foil material and thermodynamic fluid material in the foil along with the volume of expansion and contraction of Mfc is the basic design parameter to meet a submerged body condition for Mfc. These parameters must be such that the Mfc should sink into the electrodynamics fluid after heat-rejection.

Junction valve V is allowed to open in only one direction i.e. downward. As the amount of both condensed electrodynamics fluid and Mfc is reached to a threshold condition then a sufficient gravitation force is developed to open this valve downwards. This will lead to the continuous supply of electrodynamics fluid along with Mfc to the heat-

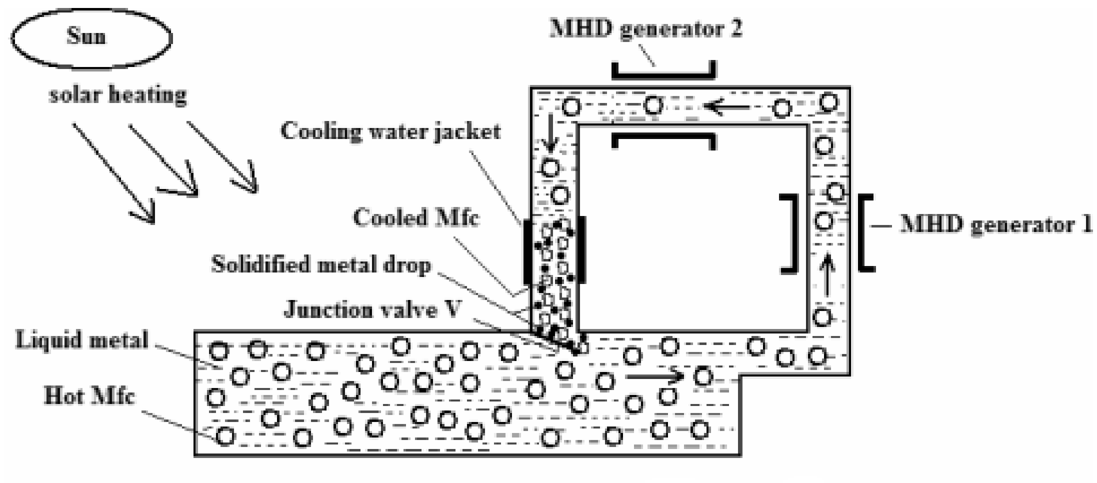


Figure 7: Schematic diagram of a dual cycle LMMHDEC system

addition zone and complete the perfectly closed thermodynamic cycle of this system. Here it is assumed that the junction valve V is the integral part of the system. The thermodynamic fluid (Mfc) and electrodynamics fluid do not cross the thermodynamics boundary of the system. Basically this is a perfectly closed isothermal thermodynamic system which exchanges heat with surroundings at a constant temperature (heat-addition and heat-rejection take place at constant temperature). The thermal efficiency of the system is optimized when a melting point temperature range between the electrodynamics fluid and thermodynamic fluid is least. It enables minimum entropy loss during condensing in the cooling jacket.

Thermodynamically there are two independent cycles which occur simultaneously in a single system. The isothermal expansion and isothermal contraction of Mfc fluid takes place at a constant temperature and renders an ideal efficiency to the cycle at the rate of ideal Carnot cycle. The electrodynamics fluid also expands and contracts isothermally. As a matter of fact, this is the most desirable feature of this MHD system where both the cycles occur in a perfectly closed thermodynamic boundary. The overall efficiency of this system is dictated by the efficiency of the solar heating device, MHD channel, condenser and mechanical operation of junction valve v.

Velocity analysis

A relation between velocity of electrodynamic fluid and shrink volume of Mfc can be established. Let 'a' is the cross sectional area of the MHD duct, which is uniform throughout the flow of electrodynamic fluid and Mfc. V1 is the volume of Mfc before shrink. V2 is the volume of Mfc after shrink. The volumetric space V created by one Mfc after shrink can be found as:

$$V = V1 - V2$$

Let N numbers of Mfc get shrink per second, than total volumetric space Vt created per second is given as:

$$Vt = N\,(V1\text{-}V2)$$

This space volume will be occupied by the electrodynamic fluid. Let 'u' is the velocity of the electrodynamic fluid by which it occupies the space volume Vt while passing through duct area 'a'. Then 'u' is given as:

$$u = Vt / a$$

$$u = N\,(V1\text{-}V2) / a$$

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Concluding remarks and discussions

Basically, the overall cycle efficiency of the conventional (plasma MHD and liquid-metal gas/vapour mixer types) design of LMMHDEC is a function of all the respective efficiencies of individual component subsystems viz. solar collectors, mixer, nozzle, MHD channel, separator, diffuser, condenser, pumps and heat exchangers. As the number of components in the system increases more, the chances of efficiency breakage in the power generation plant are determined. Use of liquid metals for MHD conversion enables low temperature application in comparison to ionized gas MHD generator.

In previously discussed LMMHDEC systems, thermodynamic fluid i.e. gas/vapour is mixed with electrodynamics fluid i.e. liquid metal. The heat capacity of the liquid phase is greater than the gas phase and MHD fluid together expands and contracts almost isothermally. The results of higher thermal conversion efficiency are reached approximately near the ideal Carnot cycle.

In the proposed Dual-cycle LMMHDEC the gas/vapour phase has been replaced by a liquid metal in the Mfc, resulting near ideal Carnot cycle efficiency. The function of the mixer is to mix the thermodynamic fluid with the electrodynamics fluid (liquid metal) in an efficient way. The heat and pressure losses occurring in the mixer is a serious concern to obtain effective overall cycle efficiency. Complete separation of the two phase's viz. vapour and MHD-fluid is difficult to achieve and the energy shortage to meet rest of the cycle i.e. energy requirements of vapours loop and MHD-fluid loop during separator to mixer nozzle processing is another drawback with the Elliott's dc conduction generator.

The various types of losses associated with the mixer, separator, nozzle, etc. have been discussed in this paper. Wetting layer, slip ratio and void fraction problems arise due to the mixing of two-phase fluids. In the slip loss vapour moves faster than liquid and this may occur either at the nozzle or generator. This contributes to the non-uniformities in the electrical output efficiency in all the organic vapour mixed liquid metal MHD systems described above.

In the proposed Dual-cycle system there is no need for a mixer, separator, nozzle, vapour loop and MHD-fluid loop. The efficiency of the cycle depends on the efficiency of the MHD channel, solar collector, and condenser. In this Dual-cycle system flow of cooled (shrinked) Mfc and solidified electrodynamics liquid metal across the valve V do occur under gravity. Thermal energy and gravitational energy is the only driving force which leads the cycle. This dual cycle LMMHDEC system is very simple and highly efficient than other systems discussed in this paper. This solar assisted liquid metal MHD system is very attractive regarding efficiency and initial/running costs point of view, and is also competent with both photovoltaic and conventional thermodynamic conversion systems. Solar heating can be replaced by lower grade thermal energy sources viz. lien coal, bag-gasses, cow-dung, etc. Simplicity of design and control, isothermal expansion, direct contact heat transfer, higher cycle efficiency, simple and robust components are some of the excellent features of this Dual-cycle system.

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