Computational Analysis of Closed Cycle Magneto Hydro Dynamics Power Plant with Liquid Metal as Heat Source

A. Pitchaipillai, G. Kanimozhi Vendhan and V. Jose Ananth Vino

Abstract--- *The increase in high demand of coal with the growing industrial power requirements and necessary to control the emission level in the atmosphere, we need to search for an alternate heat source to drive the modern power plant. Magneto Hydro Dynamic power generation is a non-conventional method in the modern system in which there is no rotating turbine and conventional conductor are used. Argon gas behaves as conductor at its elevated temperature in the ionized plasma condition with the strong influence of magnetic field placed over the CD duct. The positive and negative ions are collected by electrode which are DC in nature, can be converted to AC by an invertor. In the metallurgical industry like Aluminium production, the waste heat recovered from liquid aluminium through a heat exchanger as a heat source to heat the inert gas or argon gas to its plasma range in the MHD. By seeding the plasma gas with alkaline metal like potassium or cessium, the conductivity can be increased. The generated power can be used within the metallurgical industry independently rather than depending on commercial power source, by the characteristics of liquid metal in improved thermal conductivity and flow characteristics.*

Keywords--- *Magneto Hrdro Dynamics, Ionization, Plasma, Magnetic Field, Electric Field, Power Density.*

I. Introduction

The conversion process in MHD was initially described by Michael Faraday in 1893. The first known attempt to develop an MHD generator was made at Westing house research laboratory (USA) around 1938. The first MHD-steam power plant U-25 was put into operation was of 75MW unit in USSR of which 25MW is generated by MHD means in early 1970's.

- The **MHD** (magneto hydrodynamic) **generator** transforms thermal energy or kinetic energy directly into electricity.
- MHD generators are different from traditional electric generators in that they can operate at high temperatures without moving parts. The heating of a gas to plasma or the addition of other easily ionizable substances like the salts of alkali metals accomplishes this increase in conductivity.

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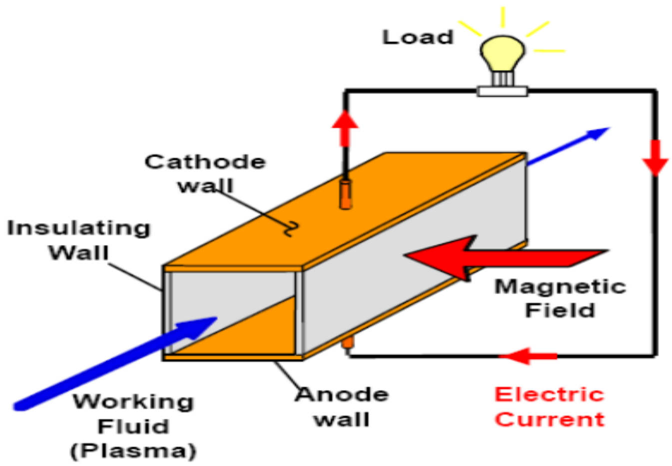

Figure 1: Principle of magneto hydrodynamics

Plasma: The prime system requirement is creating and managing the conducting gas plasma since the system depends on the plasma having a high electrical conductivity. Suitable working fluids are gases derived from combustion, noble gases, and alkali metal vapours.

Power output

The output power is proportional to the cross sectional area and the flow rate of the ionized plasma. The conductive substance is also cooled and slowed in this process. MHD generators typically reduce the temperature of the conductive substance from plasma temperatures to just over 1000°C. An MHD generator produces a direct current output which needs an expensive high power inverter to convert the output into alternating current for connection to the grid.

II. Closed Cycle MHD System

The closed cycle inert gas MHD system was conceived 1965. The main disadvantages of the open cycle system is very high temperature requirement and a very chemically active flow could be removed, by closed cycle MHD system. As the name suggests the working fluid in closed cycle, is circulated in a closed loop. The working fluid is helium or argon with cesium seeding. The complete system has three distinct but interlocking loops. On the left is the external heating loop, coal is gasified and the gas having a high heat value of about 5.30 MJ/kg and temperature of about 525°C is burnt in a combustor to produce heat. In the heat exchanger HX, this heat is transferred to argon the working fluid of MHD cycle. The combustion products after passing through the air preheater (to recover a part of the heat of combustion product) and purifiers (To remove harmful emissions) and discharged to atmosphere.

The loop in the centre is the MHD loop. The hot argon gas is seeded with cesium and passed through MHD generator. The dc power output of MHD generator is converted to A.C. by the inverter and is then feed into the grid. The loop shown on the right hand side in fig is the steam loop for further recovering the heat of the working fluid and converting this heat into electrical energy.

The fluid passes through the heat exchanges, where it imparts its heat to water which gets converted to steam. This steam is used partly for during a turbine which runs the compressor partly for turbine driver an alternator. The output of the alternator is also to the grid. The working fluid goes back to the heat exchanges HX) after passing through compressor and intercooler. A closed system can provide more useful power conversion at lower temperatures (around 1900 K as compared to 2500o\ K for open cycle system).

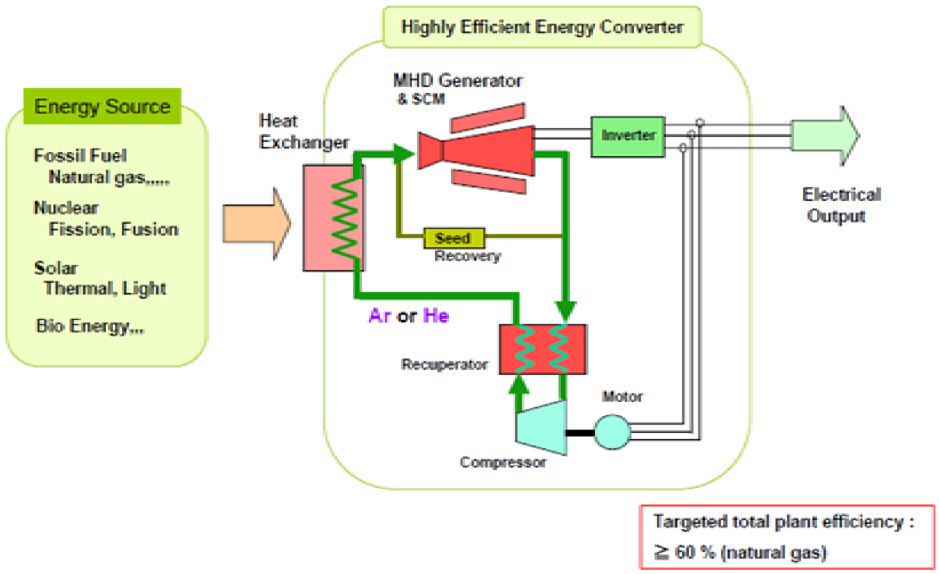

Figure 2: Layout of closed cycle MHD power plant

III. Literature Review

1. Alexander N. Karpushov, René Chavan.The TCV tokamak contributes to the physics understanding of fusion plasmas, broadening the parameter range of reactor relevant regimes, by investigations based on an extensive use of the existing main experimental tools: flexible shaping and high power real time-controllable electron cyclotron heating (ECH) and current drive (ECCD) systems. A proposed implementation of direct ion heating on the TCV by the installation of a 20–35 keV neutral beam injection (NBI) with a total power of 1–3MW would permit an extension of the accessible range of ion to electron temperatures (Ti/Te ~0.1–0.8) to well beyond unity, depending on the NBI/ECH mix and the plasma density. A NBI system would provide TCV with a tool for plasma study at reactor relevant Ti/Te ratios ~1 and in investigating fast ion and MHD physics together with the effects of plasma rotation and high plasma ˇ scenarios. The feasibility studies for a NBI heating on TCV presented in this paper were undertaken to construct a specification for the neutral beam injectors together with an experimental geometry for possible operational scenarios.

2. Naoyuki Kayukawa The efficiencies of six MHD topping combined power generation systems and one gas turbine topping combined system driven by deferent combinations of fuel and oxidant supply schematics were compared and classified on the bases of overall chemical reaction models for the combustion and gasification processes. The primary fuel was carbon that modeled a coal. The fuel types considered were coal and coal-

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synthesized gases which were provided by either conventional top gasification or by the tail gasification process. The oxidant was either pure oxygen, oxygen enriched air or air. In the MHD topping cases, the oxidant was preheated to each appropriate temperature. The enthalpy extraction of the corresponding power generation units in the topping and bottoming systems and the temperatures at the inlets of regenerators as well as at the stacks were assumed to be identical in all cases, except the inlet temperatures at the recuperative air heaters and the steam generators. We showed that the tail gasification system with an MHD topping and a combined gas turbine and steam turbine bottoming exhibited the highest plant efficiency insofar as it was based on the state-of-the-art technology of the power generation units and the heat exchanger.

3. **Binhang Yan, Yi Cheng** Using thermal plasma for coal pyrolysis to acetylene provides a direct route to make chemicals from coal resources, where the temperature field in the reactor plays a dominant role in the performance of coal devolatilization. A comprehensive computational fluid dynamics with discrete phase model (CFD-DPM) has been established to describe the rapid coal pyrolysis process in a reactor under ultra-high temperatures, chemical transformations of the coal structure. This model was proved to be qualified for describing the complex gas–particle reaction behavior with milliseconds residence time by the operation experience of a 5-MW plasma reactor. Then the simulations revealed the fact that the particle heating and devolatilization are strongly affected by the grade of the temperature and the residence time of coal particles in the high temperature zone(s). Highly concentrated energy input in the reactor may not intensify the reactor performance. As a potential solution, multi-stage heating design would provide more flexibilities to effectively adjust the devolatilization performances under the same energy input.

IV. SUMMARY

From the above literature I have learned more such as there is no one try to do liquid metal as fuel for bring the inert gas to plasma. were they used coal , nuclear reactor ,natural gas as fuel. The magnetic field strength was classical one and avoids superconducting magnets. Using moderate temperature electrodes not used high temperature electrodes. coal as using a fuel but it not reused ,it need separate component for avoid pollution. The seed such as increasing ionization process and not implement best electrical conductivity salt.

V. PROJECT DESCRIPTION

Objective

- Theoretical investigation of closed cycle magneto hydro dynamics power plant with using liquid metal aluminium as fuel.
- Analyzing plasma property and its parameter with changing the heat
- Estimating the comparison between coal and liquid metals for efficiency.
- Calculate the various heat transfer dimensionless parameters such as prandtl number ,Reynolds number , nusselt number.
- Study about the best superconducting magnet and high temperature electrodes for my project.
- Analyzing flow for liquid metals to gas heat transfer.

Problem identification

- Coal is not reused after burn.
- Co, co_x emission is more.
- Nuclear heat source is not safe.
- Solar radiating heating is not much possible.
- Not proper Cooling system for MHD plant.
- Electrode corrosion occurs during high temperature heating.

Methodology

- Study the existing system.
- Literature review.
- Problem identification.
- Proposing the topic.
- Study the convective heat transfer for liquid metals.
- Study the argon ionization.
- Calculating plasma ionization parameters.
- Calculating the heat transfer coefficient between argon gas and liquid metals.
- Choosing best materials, superconducting magnets and high temperature electrodes.

Formula used

1. The static pressure of gas in the MHD generator

$$P_1 = \frac{p_0}{\left(1 + \frac{\gamma - 1}{2} M_1^2\right)^{\frac{\gamma}{\gamma - 1}}}$$

$\mathrm{P_1} =$ static pressure

$\mathrm{p_0} =$ total pressure

$\gamma =$ ratio of heat capcities $\left(\frac{c_p}{c_v}\right)$

$\mathrm{M_1} =$ mach number

2. The static temperature of gas in the MHD generator

$$T_1 = T_O \left(\frac{P_1}{P_0}\right)^{\gamma - 1/\gamma}$$

$\mathrm{T_1} =$ static gas temperature

$\mathrm{T_0} =$ total gas temperature

$\mathrm{P_1} =$ static pressure

$\mathrm{p_0} =$ total pressure

3. Neutral particle density calculation

$$\boldsymbol{n_n = \frac{p_1}{kT_1}}$$

n_n = neutical particle density

p_1 = static gas pressure

T_1 = static gas temperature

k = boltzmans constant

K= $1.3806488 \times 10^{-23} m^2 kg\, s^{-2} k^{-1}$

Electron temperature 2500 k from chart

T_e = electron temperature

4. Electron density calculation

$$\frac{n_e^2}{n_e - n_n} = \frac{(2\pi m_e k T_e)^{3/2}}{h^3} e^{-e_0/kT_e}$$

n_e = electron density

n_n = neutral particle density

m_e = mass of electron

h = planks constant

T_e = electron temperature

K= Boltzmann constant

e_0 = first ionization potential

e_0 = 15.75 eV for argon gas

K= $1.3806488 \times 10^{-23} m^2 kg\, s^{-2} k^{-1}$

h = $6.62606957 \times 10^{-34} m^2 kg\, s^{-1}$

5. Debye shielding length ($\boldsymbol{\lambda_D}$)

$$\lambda_D = \sqrt{\frac{\epsilon_0 k_b T_e}{n_e q_e^2}}$$

$\varepsilon_0 = 8.854\ X\ 10^{-12}\ \frac{faraday}{meter}$

K= Boltzmann constant

q_e = charge of electron

6. Debye shielding length parameter

$$\cap = \frac{3}{2zz_1 e^3}\left(\frac{k^3 T_e^3}{\pi n_e}\right)^{\frac{1}{2}}$$

$\cap =$ debye shielding length to average impact parameter

$zz_1 =$ number of electronic charges associated with ion and electron

$T_e =$ electron temperature

K= Boltzmann constant

$n_e =$ electron density

K= 1.3806488 × $10^{-23} m^2 kg\, s^{-2} k^{-1}$

$n_e = 7.08499 \text{ X } 10^{12}\ m^{-3}$

$zz_1 = 1$

$T_e = 2500$ k

Solving with known values

$\cap = 1.238 \text{ X } 10^4 (T_e^{3/2} / n_e^{1/2})$

7. Conductivity due to ions

$$\sigma_i = \frac{1.51\ X\ 10^{-2} T_e^{3/2}}{ln \cap}$$

$\sigma_i =$ Conductivity due to ions

8. Conductivity due to neutrals $(\boldsymbol{\sigma_n})$

$$\sigma_n = \left(\frac{e^2}{m_e \left(\frac{8k}{\pi m_e}\right)^{\frac{1}{2}}}\right)\left(\frac{n_e}{T_e^{\frac{1}{2}}(n_n - n_e)Q_{en}}\right)$$

m_e =9.10938291 ×10^{-31} kilograms

$Q_{en} =$ seed and electron neutral elastic collision at cross section

For potassium seed Q_{en} =3.6 ×$10^{-17}\ m^2$

$e = 1.6021\ X\ 10^{-19}$ coulombs

Compile the above equation with known value

$\sigma_n = \frac{4.525\ X\ 10^{-8} n_e}{\sqrt{T_e}\,(n_n - n_e)Q_{en}}$

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9. Plasma conductivity ($\boldsymbol{\sigma_p}$)

$$\sigma_p = \frac{\sigma_i \sigma_n}{\sigma_i + \sigma_n}$$

$\sigma_p = plasma\ electrical\ conductivity$

$\sigma_i = conducitivity\ due\ to\ ions$

$\sigma_n = conductivity\ due\ to\ neutral\ particle$

10. Magnetic field calculation

$$\omega\tau = \left(\frac{\frac{T_e}{T_1} - 1}{\frac{\gamma}{3} M_1^2} \right)^{1/2}$$

$\omega\tau = cyclotron\ frequency$

$\omega\tau(\ dimension\ less)$

$$B(1-k) = \frac{n_e ec\ \omega\tau}{\sigma_p}$$

11. Gas velocity calculation

$$u = \sqrt{\frac{\gamma R T_1}{m_n}}$$

Argon property:

R= 8.134

$\gamma = 1.66$

$m_n = 0.039$ kg/mol

12. Plasma pressure

P = n T k

13. Power output

$$p = \frac{1}{4} \sigma u^2 B^2$$

14. Conversion efficiency

$\eta_c = \frac{v_{max}}{u.B}$

η_c = conversion efficiency

u = gas velocity

v_{max} = maximum potential difference

B = magnetic field

$$v_{max} = u\,B\delta - I_{max}\left(\frac{\delta}{\sigma A}\right)$$

$$I_{max} = \frac{(u\,B\,A\sigma)}{2}$$

15. Heat transfer calculation

Mass flow rate for burn 100 kg of argon

Heat lost by liquid aluminum = Heat gained by argon

$$\dot{m}_{al}\,c_{p(al)}(T_2 - T_1) = \dot{m}_{ar}\,c_{p(ar)}(t_2 - t_1)$$

m_{al} = mass flow rate of aluminium

$c_{p(al)}$ = heat value of aluminium

T_2 = outlet temperature

T_1 = inlet temperature

16. Area for argon chamber

$m_{ar} = \rho_{ar} A_{ar}\ v_{ar}$

m_{ar} = mass flow rate of argon gas

A_{ar} = area of argon gas chamber

ρ_{ar} = density of argon gas

v_{ar} = velocity of argon gas

17. Area for aluminum chamber

$m_{al} = \rho_{al} A_{al}\ v_{al}$

m_{al} = mass of aluminium

ρ_{al} = density of aluminium

A_{al} = area of aluminium chamber

v_{al} = velocity of liquid aluminium

18. Prandtl number

$$P_r = \frac{c_p \mu}{k}$$

P_r = prandtl number

c_p = heating value

μ = dynamic viscosity

19. Reynolds number

$$R_e = \frac{ud\rho}{\mu}$$

R_e = reynolds number

u = velocity of liquid metal flow

d = diameter of liquid aluminium chamber

ρ = densityofliquid aluminium

μ = dynamic viscosity

20. Nusselt number calculation

$$Nu_X = 5 + 0.025\,(Re_x P_r)^{0.8}$$

Nu_X = nusselt number

Re_x = reynolds number

P_r = prandtl number

21. Heat transfer coefficient

$$Nu_x = \frac{hd}{k}$$

Nu_x = nusselt number

h = convective heta transfer coefficient

k = thermal conductivity of material

22. Heat transfer

$$Q = h\,A\,\Delta T$$

Q = heat transfer

A = area

h = convective heat transfer

ΔT = temperature difference

VI. CONCLUSION

The liquid metal aluminium has carried here as secondary heat source and bring it for heat transfer between the MHD working fluid argon with the mass flow rate of 36 kg/s at temperature of 1850 k for heating the 100 kg/s of argon at 400 k after the heat transfer between argon and liquid aluminium.The argon get raise temperature of 1200k and so far the given it as input in MHD duct at applying constant magnetic field of 3.2 tesla it generate the power generation of 12.88 MW of electrical current. It need a less mass flow rate of heat source at the range of 36 kg/s instead of using the 180 kg/s of burning coal for heating the working gas. liquid aluminium has employed in recycling process also when it bring for condensation process.

VII. RESULT AND DISCUSSION

Introduction

This chapter has describing the analysis included the heat transfer and MHD analysis such as current density, velocity, electric potential determination at constant magnetic field of 3.2 tesla in C-D duct.

VIII. COMPUTATIONAL INVESTIGATION

Heat transfer between argon and liquid metal aluminium

The heat transfer between MHD working fluid argon gas and liquid metal aluminium has been conducted. aluminium has good thermal conductivity even in liquid phase also thermal conductivity of liquid aluminium at 1500-1800k is 45 w/mk.

Property of aluminium in liquid phase (1500-1800k)

Property	**Value**
Thermal conductivity	65 w/mk
Volume expansion	6 %
Density	2368 kg/ m^3
Viscosity	1.05 x 10^{-3} pa-s
Boiling point	2792 k
Heat capacity	1177 j /kg.k
Heat of vaporization	10897 kj/kg k

Aluminium in liquid phase is act as hot fluid and working gas argon as cold fluid

Cold fluid (argon) property at 300k

Property	**Value**
Thermal conductivity	17.72×10^{-3} W/m K
Density	1.78.10 $^{-6}$ Kg/m ^{3}
Heat capacity	20.78 J / Kg k
Heat of vaporization	6.53 J/Kg k

Heat transfer between aluminium in liquid phase and argon gas in regenerative heat exchanger. **Specification of hot fluid pipe (molybdenum)**

Property	**Value**
Thermal conductivity	120 w/mk
Density	9000kg/ m^3
Boiling point	2792 k
Heat capacity	420j /kg.k

IX. BOUNDARY CONDITION

Cold Fluid

1) Inlet argon temperature = 350k

2) Mass flow rate of argon = 100 kg/s

3) Velocity of cold fluid = 80m/s

Hot fluid

1) Inlet liquid aluminum temperature = 1500°C – 1800°C

2) Mass flow rate of liquid aluminum = 36 kg/s.

3) Velocity of hot fluid =68.6 m/s.

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