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A magneto-hydrodynamic analysis of liquid metal flows in the conducting and insulating wall ducts using a finite element tool

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A magneto-hydrodynamic analysis of liquid metal flows in the conducting and insulating wall ducts using a finite element tool

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ABSTRACT

In various fusion reactors, a liquid conducting metal has been considered an ideal breeder and a coolant. The magneto-hydrodynamic (MHD) analysis of liquid metal flow in a typical square duct plays a major role in designing reactor components. Conducting fluid flow induces an eddy current in a magnetic field, which, produces electromagnetic force leading to high MHD pressure drop. The electrical conductivity of the walls substantially affects the number of liquid metal flows and forces produced due to eddy current, producing severe pressure drop in it. To reduce the effect of eddy current and MHD pressure drop, the time-varying electromagnetic FE analysis has been carried out for electromagnetic forces and computational fluid dynamic analysis in the coupled field environment with conducting wall ducts and with insulated walls. FEA results are compared with analytically calculated parameters and validated.

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KEYWORDS
Magneto-hydrodynamics; finite element analysis; finite element method; liquid metal; pressure drop; uniform magnetic field

1. Introduction

The fusion reactor is a toroidal-shaped device, in which a plasma ring is confined by twisting the magnetic fields using vacuum vessels (Song et al. 2014a). A plasma is made up of charged particles and confinement of plasma within the walls of the vacuum vessel is achieved using a large magnetic field (Walker et al. 2020). Poloidal and toroidal coils are used to confine the plasma as it follows the magnetic flux lines. Immediately behind the first wall of the fusion reactor, blanket modules are provided through which coolant is passed (Nygren 1981), (Pironti and Walker 2005), (Sykes et al. 2014). Blanket modules have used square straight channels to flow electrically conducting fluid in it. The MHD pressure drop is a severe problem in the fusion reactor and the problems arising from the MHD effects can be interesting for the researchers. Therefore, the study of the MHD analysis in the coupled field environment is very interesting among researchers. In this paper, an extensive analysis has been carried out to reduce the MHD effect in the square channels used for the fusion reactor. A finite element analysis of MHD rotational flow of non-fluid was investigated by (Ali et al. 2020). In (Umavathi et al. 2005), the turbulent two-fluid flow and heat transfer in a horizontal channel were examined. The computational methods have been studied by increasing the field intensity with a significant influence on the fluid flow (Adesanya et al. 2015).

As shown in Figure 1, the liquid metal flows through a square channel across the magnetic field B, the current J gets induced in the liquid metal and the field produced due to this current alters the magnetic field (Selimefendigil, Öztop, and Chamkha 2020), (Hussein et al. 2016) and (Khodak 2016). At the same instant, currents J flowing in the liquid metal interact with the magnetic field B and produce mechanical force, known as Lorentz force $J \times B$ which alters the liquid metal flow. Maxwell's equations through the Lorentz force, $J \times B$, and Ohm's law in the coupled field environment are given by

$$J = \sigma(E + u \times B) \tag{1}$$

where J is the electric current density which can be expressed through the magnetic field B. E and B are electric field and magnetic field, respectively, and σ is the electric conductivity of the fluid.

The Lorentz force is such that it will oppose the liquid metal flow in square channels (A. J. Chamkha 1995), leading to a significant drop in pressure, turbulence, changes in cooling properties, etc. (Bhuyan and Goswami 2008). If the coolant-carrying square channel walls are conducting, then the conducting walls provide a return path to the eddy currents produced in the liquid metal, as shown in Figure 2(A,B). Hence, due to the low resistance path of the walls, the large amount of eddy current flows resulted in significant pressure drops in the square channel (Song et al. 2014b).

The conductivity of the walls of the square channel greatly affects the flow of liquid coolant by providing a low resistance path to eddy currents. This can be overcome by providing insulation coating on the inner side of the conducting walls and various pieces of literature have been reviewed for the solutions. Examining the combined effects of heat radiation and magnetic field on molybdenum nanofluid in a channel with varying walls is discussed in (Raza, Mebarek-Oudina, and Chamkha 2019). The impacts of the Hartmann magnetic number, particle loading, viscosity ratio and temperature inverse Stokes number on the solutions are proven through an extensive parametric investigation (Chamkha 2000). On a semi-infinite permeable moving plate with a constant heat source, diffusion-thermo,

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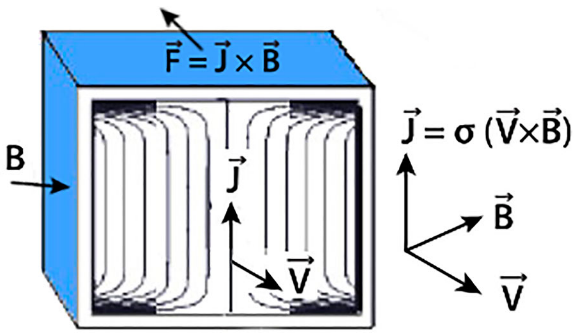

Figure 1. The basic concept of MHD.

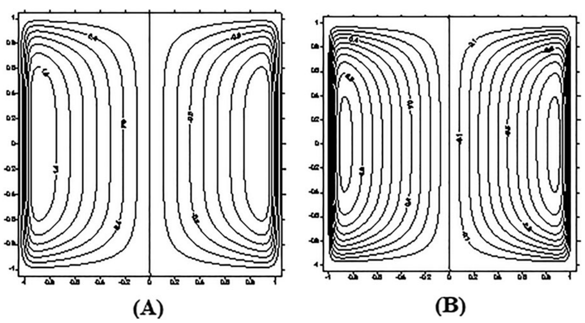

Figure 2. (A) Conducting wall and (B) An Insulating wall.

radiation-absorption, Hall effects and ion slip on the MHD-free convective rotating flow of nano-fluids are explored (Veera Krishna and Chamkha 2019) and with a transverse magnetic field and convective boundary conditions in (Krishna and Chamkha 2022). Using the optimal homotopy analysis method, numerical research on the nanofluid flow between two inclined stretchable walls has been conducted (Biswal et al. 2022). In (Seth, Sarkar, and Makinde 2016), the electrically conducted fluid using a rotating channel with arbitrary conducting walls has been studied for analysis. The thermal effect of third-grade electrically conducted has been studied (Rundora and Makinde 2016). The insulation would not allow the current to flow through the channel walls and the current would be required to flow through Hartmann layers (Jiajia et al. 2016), which have high resistance, thereby significantly reducing current and pressure drops.

The pressure drops due to the liquid metal flowing perpendicular to the magnetic field (Jeyanthi and Ganesh 2020), the drop in the pressure inside the channel is obtained by solving Maxwell's equations and Navier-Stokes equations for fluid motion (Severe et al. 2005), (Bangun and Utsunomiya 2008) and (Zhang, Pan, and Xu 2014). In the case of a conducting wall, $\frac{1}{H} \leq C \leq 1$, could be written in the form of an equation,

$$\Delta P = vL\sigma B^2 C \tag{2}$$

where

$$C = \frac{\sigma_W . t_W}{\sigma a} \tag{3}$$

$$\Delta P = vL\sigma B^2 \frac{\sigma_W . t_W}{\sigma a} \tag{4}$$

where $\Delta \boldsymbol{P}$ is the pressure drop, $\boldsymbol{v}$ is the velocity of liquid metal, $\boldsymbol{L}$ is the channel length, $\boldsymbol{\sigma}$ is the liquid metal conductivity, $\boldsymbol{B}$ is the magnetic flux density, σ_W is the electrical conductivity of channel walls and $\boldsymbol{t_w}$ is the wall thickness, $\boldsymbol{a}$ is the half-width of the channel in the direction of a magnetic field, $\boldsymbol{H}$ is the Hartmann Number $= Ba\left(\frac{\sigma}{\mu}\right)^2$, C is the wall conductivity ratio. The skin friction coefficient is expressed by

$$C_f = {}^{t_s}\!/_{0.5\rho v^2} \tag{5}$$

where $\boldsymbol{C_f}$ is the skin friction coefficient, $\boldsymbol{\rho}$ is the density of the fluid**,** $\boldsymbol{v}$ is the free stream speed and $\boldsymbol{t_s}$ is a skin shear stress on a surface. The governing nonlinear partial differential equations are numerically computed using finite element methods (Anwar 2020) and mixed convection, MHD and a new mass flux theory are also investigated (Irfan et al. 2020).

This paper describes the Magneto-hydrodynamic (MHD) analysis on the blanket module used for fusion grade tokamaks, where square channels are used to flow the liquid conducting material. In both industry and academia, the finite element method (FEM) has become the most widely utilised method for solving electromagnetic and computational fluid problems. The finite element analysis software enables engineers to create computer models of structures, products and components, transfer CAD models and analyse them in a multiphysics environment. The electromagnetic transient finite element analysis (Patel and Vora 2017), (Patel and Vora 2020) and (Habib 2021) has been carried out and the same elements are used for fluid analysis in the coupled filed environment. For the contact elements, a cylindrical gap treatment mesh has been applied for the convergence. The analysis uses a coupled field environment in which the sliding mode contact elements and steady elements have reported an error and solved using proper element characteristics. The fluid elements are used to model fluid and/or non-fluid regions in transient or steady-state fluid/thermal systems. For the eddy current computation, the VOLT degree of freedom is considered for all non-source regions with a specified non-zero resistivity. This allows eddy current computation. At two different types of interfaces, boundary conditions are added to the MHD equations. The first is a contact discontinuity, which is the interface between two multiple outlets, and the second is a shock front that the fluid must pass. Using Stoke's theorem, the boundary condition on the electric field is obtained by integrating Maxwell's equation $\nabla \times E = -\frac{\partial B}{\partial t}$ over the area limited by the circuit.

The uniform magnetic field has been applied and the finite element analysis of induced eddy current has been carried out using a coupled field environment due to the interaction of the applied magnetic field to the moving conducting liquid and its effect on liquid metal flows. Section 2 presents an analysis of a square channel conducting wall duct without an insulator and section 3 presents the analysis of a square channel conducting walls with an insulator and a conclusion has been given in section 4.

2. Square channel conducting wall analysis

The cross-sectional area of the square channel conducting wall ducts without insulating walls and the uniform magnetic field applied perpendicular to the flow of liquid in the channel are depicted in Figure 3 and Figure 4, respectively.

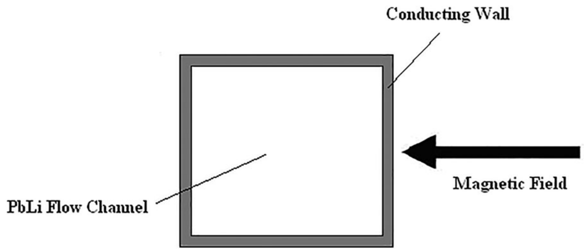

Figure 3. The cross-sectional area of a square channel without an insulating wall.

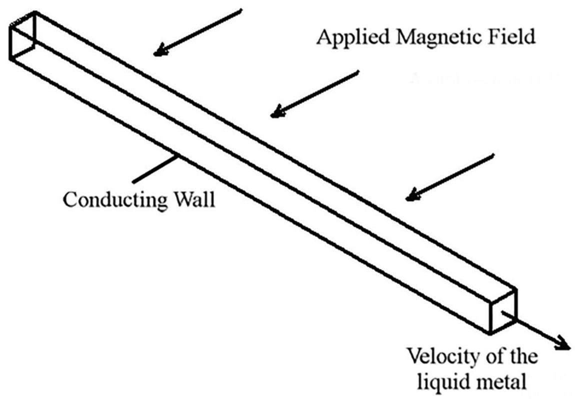

Figure 4. An Isometric view of the conducting wall without an insulating wall.

In liquid metal channel ducts where a liquid is coming in direct contact with the conducting wall, the currents induced in the liquid metal due to velocity effects get a return path through the conducting walls. Therefore, very large current flow through the conducting walls and liquid metal results in a very large amount of pressure drop.

In this case of a channel with conducting walls, an ‘M- shaped’ velocity profile is obtained. High velocity is observed close to the walls and near the centre of the channel, there is a steep drop in the fluid pressure. This ‘M-shaped’ velocity profile occurs due to high flow-opposing vertical Lorentz force in the bulk, while a negligible force appears near the parallel walls. The flow structure strongly depends on channel dimensions a and b (Zhang, Pan, and Xu 2014). The parameter considered for the analysis (Hong-yan, Yi-can, and Xiao-xong 2002) is shown in Table 1.

Figure 5 shows the meshed model created in a finite element (FE) environment using the FEA tool. The direction of the liquid metal flow and the direction of the external uniform magnetic field created by the Helmholtz coil perpendicular to the flow are shown in Figure 6.

Table 1. Parameters for the MHD analysis.

Particular	Values
Magnetic flux density (B)	5.3 T
Liquid metal resistivity	1.1765e-6 ohm-m
Liquid metal conductivity	8.5e5 ohm-m^{-1}
Liquid metal dynamic viscosity	0.00187 Pa-s
Liquid metal density	9530 kg/m^3
Duct wall electrical conductivity	1.43e6 ohm-m^{-1}
Duct wall electrical resistivity	7e-7 ohm-m
Channel half width	0.1m
Channel half height	0.1m
Channel characteristic length	4m
Channel wall thickness	0.01m
The velocity of liquid metal	0.1 m/s
Insulating coating thickness	1e-3m

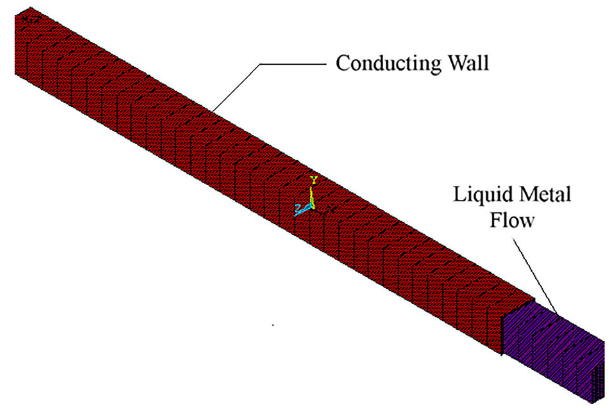

Figure 5. The FEA meshed model showing a conducting wall and a liquid metal flow.

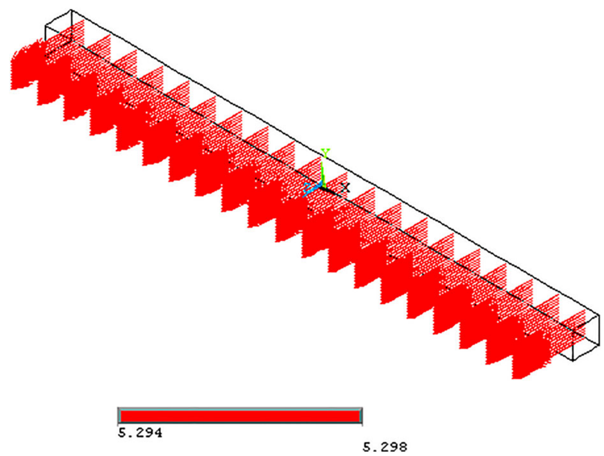

Figure 6. External applied magnetic field perpendicular to the flow of liquid metal.

Due to the interaction of the applied external magnetic field and moving conducting material, the eddy current is induced in it and is shown in Figure 7. This eddy current again creates the magnetic field, as shown in Figure 8.

The calculated electromagnetic forces for the 4-metre-long conducting channel are 64269 N and the MHD pressure drop is 1.6 MPa for Hartmann Number 11300. In Table 2, the various parameters are calculated and compared with the results obtained by the FE analysis.

Due to the eddy current in the conducting material, there is a pressure drop. Figure 9 shows the velocity of liquid metal and Figure 10 shows the M-shaped velocity profile perpendicular to the applied magnetic field. Figure 11 shows the pressure drop plot for square channel conducting wall ducts. The shape of this velocity profile is due to the electromagnetic forces produced by the interaction of the applied magnetic field and liquid metal velocity, both are perpendicular to each other. The development of the jet is caused by a strong flow-opposing vertical Lorentz force in the bulk although there is no force near the parallel walls. The calculated and the FEA results are compared and tabulated.

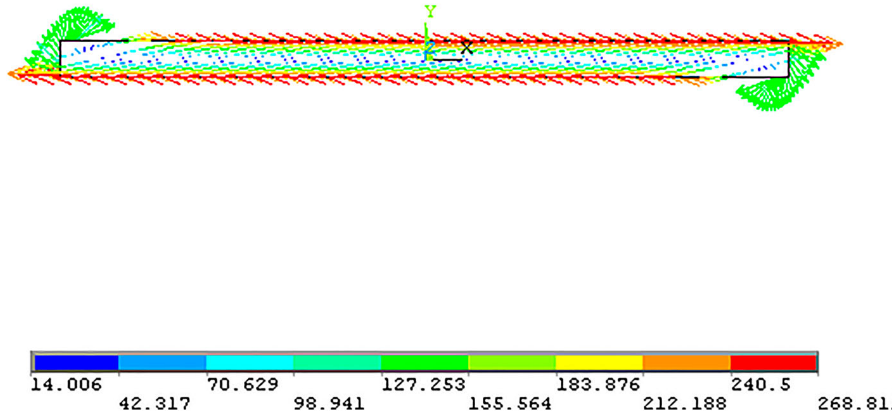

Figure 7. The induced current due to the interaction of the applied magnetic field and the moving conducting liquid.

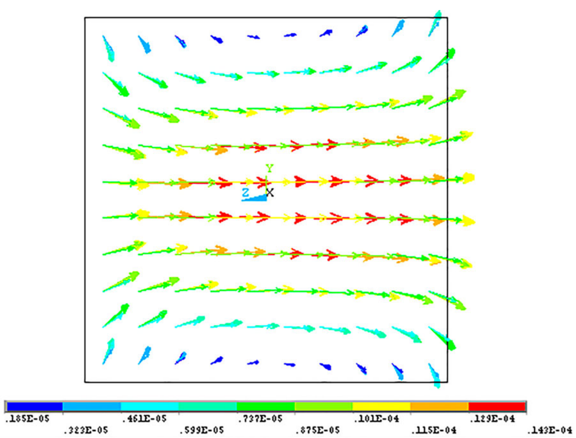

Figure 8. Magnetic field due to the induced eddy current.

Table 2. Comparison of results for square channel conducting walls.

	Calculated Parameters	FE analysis Results
Hartmann Number	11300	–
Magnetic Reynolds Number	0.427	–
Lorentz Forces	64269 N	59542 N
MHD Pressure drop	1.6 MPa	1.49 MPa

3. Square channel insulated wall analysis

A feasible insulator coating material for square channel wall duct must meet some minimum requirements, i.e. stable at high temperatures up to 600°C, having chemical compatibility with lithium and the structural materials, capable of self-healing to repair any cracks or faults and sufficiently high electrical resistivity. Self-healing capability is an indispensable property as cracks provide a passage for the flow of electric current by conducting channels and defy the very purpose of insulating the duct channels.

Figure 12 shows the square channel conducting wall ducts with insulation used inside the conducting wall ducts. When the conducting walls are insulated with a coating of insulating material, the induced current in the liquid metal has no path available through conducting channel walls and is forced to flow through the Hartmann layers only. The Hartmann layers have very large electrical resistance compared to that of the conducting wall and, therefore, the electrical currents and the pressure drop reduce significantly. There is a significant improvement in the velocity profile which is more or less flat in the liquid metal bulk.

In this analysis, the insulating layer over the conducting walls is considered to be made up of Al_2O_3, this reduces pressure drop in the channel and acts as a thermal insulator to separate conducting material P_bL_i having a higher temperature from the steel

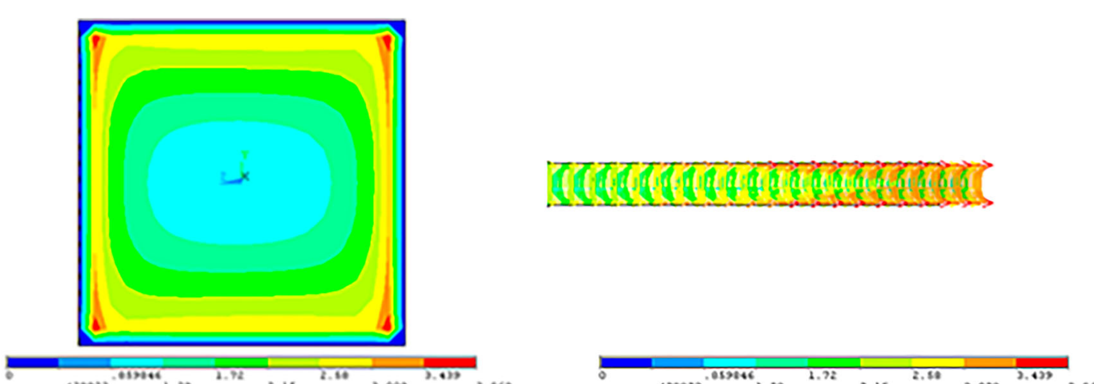

Figure 9. Velocity and plot without insulating walls.

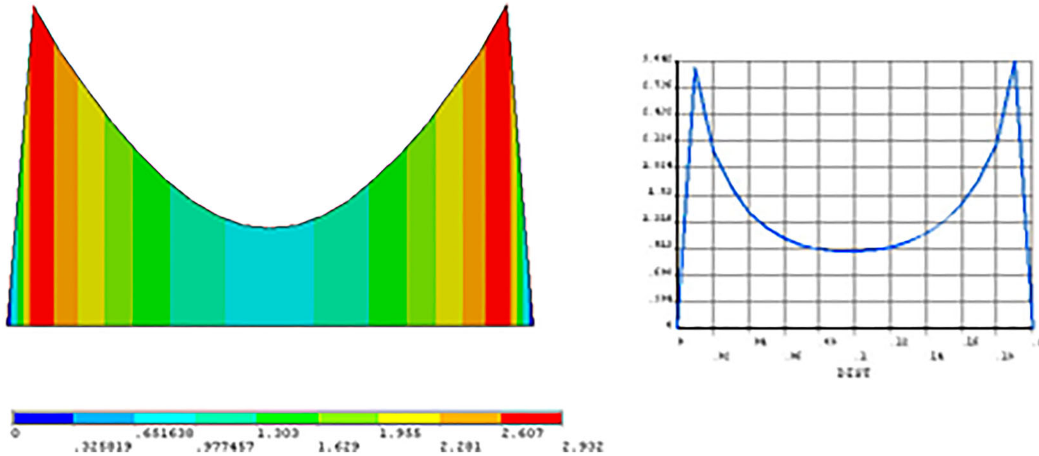

Figure 10. M-shaped velocity profile without insulating walls.

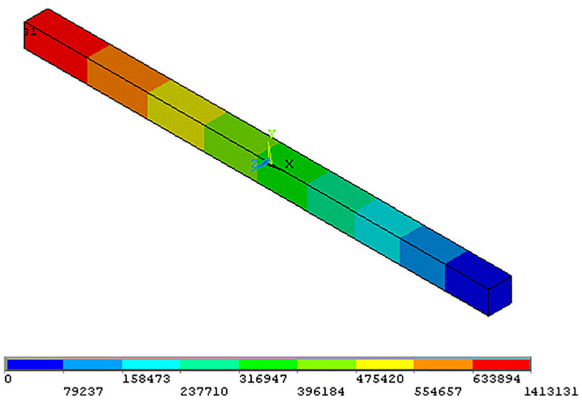

Figure 11. Pressure drop plot with conducting walls.

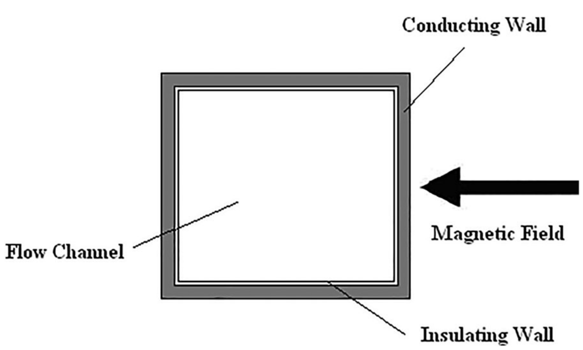

Figure 12. The cross-sectional area of the square channel conducting wall with insulation.

wall structure. For insulated or non-conducting walls, where wall conductivity ratio $C = 0$, equation 2 would be

$$\Delta P = vL\sigma B^2/H \quad (6)$$

$$\Delta P = vBL(\sigma\mu)^{1/2}/a \quad (7)$$

The above equation is used to calculate the pressure drop when the walls are insulated with the insulating materials. Table 3 shows the result obtained from the FEA tool and is validated through the calculated parameters. With conducting walls, the pressure drop is around 1.6 MPa and with insulated walls it is reduced to 0.019 KPa. Figure 13 shows the velocity plot with insulating walls of a square channel duct.

Table 3. MHD Pressure drop for a square channel with insulating wall duct.

	With conducting walls		With insulating walls
Particular	Calculated values	FEA results	FEA results
Lorentz forces	64269 N	59542 N	7.6e-4N
MHD pressure drop	1.6 MPa	1.49 MPa	0.019 KPa

Figure 14 shows the velocity profile for the insulating walls of the square channel conducting wall. Velocity patterns caused by electromagnetic forces produced due to the movement of liquid metal flowing in the duct are flattened with the help of insulating material used inside the duct.

Figure 15 shows the pressure drop plot with an insulating wall.

4. Conclusion

The square channel conducting wall with and without insulating covering has been investigated using a finite element simulation for the MHD study in a coupled field environment. The MHD pressure drop of liquid metal in the straight long channel has been calculated and analysed. The liquid metal has a direct contact with the metallic wall, most of the current pass through the metallic wall and hence more MHD pressure drop in the first case. Analytically calculated results of Lorenz's force and MHD pressure drop are validated through FE analysis for the square channel without an insulator and the MHD pressure drop is in good agreement within 7 per cent variation. After insulating the channel ducts, the MHD pressure drop has reduced to ninety-nine per cent to 0.019 KPa as compared with 1.6 MPa for the first case. This analysis will help the researcher's community to use adequate insulating material for square ducts, for the typical blanket modules used in a fusion reactor. Furthermore, the

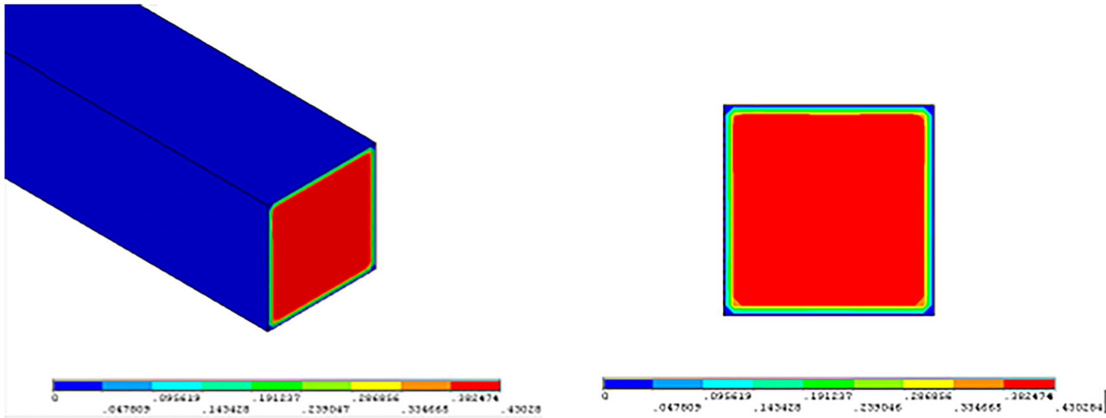

Figure 13. Velocity plot with insulating walls.

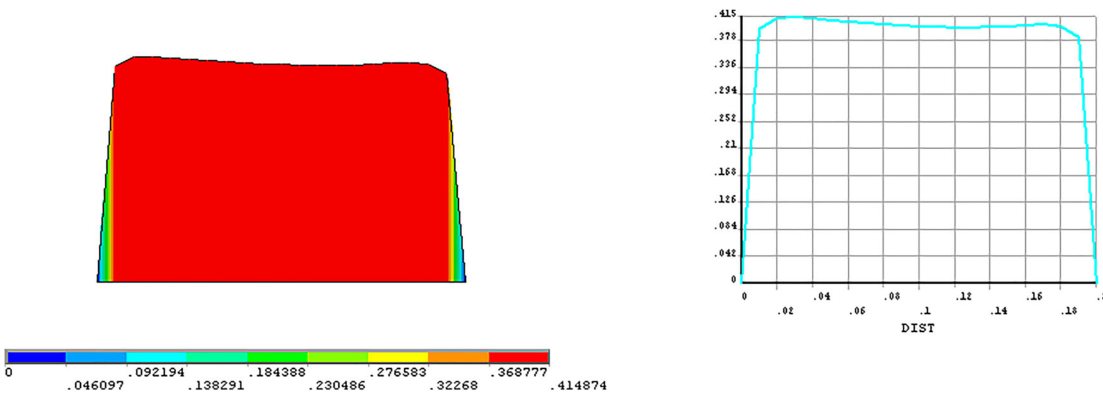

Figure 14. Velocity profile due to the insulating wall duct.

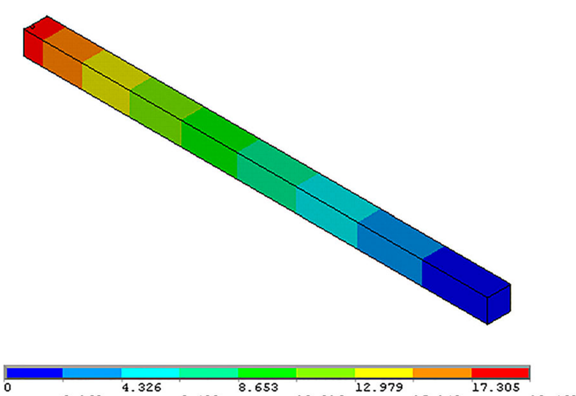

Figure 15. MHD pressure drop plot with insulating walls.

methodology can be applied to carry out an MHD analysis of different shaped ducts in which the liquid metal flows with and without insulators and comparisons of their results.

Future scope

The authors have compared the various results of the square duct without an insulator for magneto-hydro dynamic analysis and could be analyzed with the different insulating materials inside the square ducts. This analysis is useful for various industrial applications.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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