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Heat Transfer in Magnetohydrodynamic Fluid Flows - A Review

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Abstract: The fluid flow parameters associated with increase or decrease in heat transfer is identified from the literature. Control of heat and mass transfer processes by means of external force effects is one of the most important problems in many specialized process and manufacturing applications. The Lorentz force effect inducing the formation of side layer jets in magnetohydrodynamic flows can potentially result in significant variations of the heat transfer properties. Recent developments in computational modeling and experimental methods have given better understanding in several areas which were indistinct in earlier studies. This study is aimed at reviewing the recently reported developments and consolidating the progress in the area of heat transfer in magnetohydrodynamic flows. This includes natural convective fluid flows due to the combined effect of buoyant and magnetic forces as well as magnetic effects on liquids flowing through conduits of different geometry. The different approaches used are briefly discussed.

Keywords: Forced convection, hartmann layer, heat transfer, lorentz force, magnetohydrodynamics, natural convection

INTRODUCTION

Magneto Hydrodynamic (MHD) forces are an inherent part of certain processes equipment like fusion reactors. Effective removal of the volumetrically produced heat is essential and requires enhancement of heat transfer. In other applications, MHD can also be used externally to reduce or enhance the heat transfer. This includes applications like stirring of molten metal, turbulence control in induction furnaces, damping of buoyancy-driven flow during solidification and shaping of ingots during continuous casting processes of molten steel. Earlier studies on effect of MHD on heat transfer showed that enhancement takes place as in Gardner (1968), Gardner *et al*. (1966) and Gardner and Lykoudis (1971). Suppression of heat transfer could also take place depending on the controlling parameters as reported by Miyazaki *et al*. (1983). While it has been already accepted that heat transfer is suppressed by laminarization due to the effect of the magnetic field, it may also be enhanced by a steep velocity gradients near a heated walls, high heat transport in the side layers and large scale velocity fluctuations caused by the M-shaped velocity profile and two-dimensional MHD turbulence. Under this scenario it becomes necessary to elucidate the conditions under which heat transfer is enhanced or suppressed for different types of flow under different conditions. Hence, the primary objective of this study is to identify the conditions for enhancement and suppression of heat transfer in MHD natural and forced convection fluid flow. The main factors affecting the heat transfer include the physical properties of the fluid indicated by its Prandtl number, the intensity and orientation of the magnetic field indicated by the Hartmann number, the flow condition within the fluid characterized by the Raleigh number in the case of natural convection and the Reynolds number in the case of forced convection, wall conductivity of the fluid carrier (enclosure, channel, pipe or duct) which could have different conductivities and other specific operating parameters. The values of the above parameters and the research methods adopted for the analysis differed over wide ranges which motivate a new analysis of results. Moreover, recent developments during the last two decades in the computational modeling capacity have given better insight into previously unknown regimes.

Hence, consolidation of the results has become the priority in this field of science. The secondary objective of this study is to review the latest developments in the area of heat transfer in the presence of magnetic field and to give a summarized picture of the status. The study is organized in two main parts, focusing on natural convection and forced convection processes, successively.

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Table 1: Properties and non-dimensional parameters

Symbol	Description	Formula / Units
B_o	Intensity of the magnetic field	T
H	Height of the flow domain	m
	Characteristic length, m	m
D	Equivalent diameter of flow passage	m
g	Acceleration magnitude due to gravity,	m/s^2
h	Heat transfer coefficient	W/m^2K
k	Fluid conductivity	W/m.K
l	Length of the enclosure	m
v	Fluid velocity	m/s
x(subscript)	Indicates the local value	
ΔT	Wall temperature difference,	^0C
α	Coefficient of thermal expansion	1/K
β	Coefficient of volumetric expansion of the gas	1/K
τ	Ratio of strength of magnetic field to gravitational field	vB_o/g
μ	Dynamic viscosity	Pa.s
ν	Kinematic viscosity	m^2/s
ν_h	Magnetic diffusion	m^2/s
κ	Thermal diffusivity	m^2/s
ρ	Density	Kg/m^3
σ	Electrical conductivity	$1/\Omega.m$
M	Hartmann number	$B_o L\sqrt{\frac{\sigma}{\rho\nu}}$
Re	Reynolds number	$\frac{\rho VD}{\mu}$
Re_m	Magnetic Reynolds number	$\frac{vL}{\nu_h}$
Ra	Raleigh number	$\frac{\alpha g H^3 \Delta T}{\nu\kappa}$
Gr	Grashoff number	$\frac{g\beta\Delta T l^3}{\nu^2}$
Nu	Nusselt number	$\frac{hD}{k}$
Pr	Prandtl number	$\frac{\nu}{\kappa}$
Pr_m	Magnetic Prandtl number	Re_m/Re
Q	Chandershekar number	M^2
Ri	Richardson number	Gr/Re^2
Mn	Magnetic parameter	M/Re
λ	Buoyancy Parameter	Gr_x/Re_x^2
ξ	Magnetic parameter	$\kappa B_0^2 x / \rho U_\alpha$
Pe	Peclet number	$3U_m B/2\alpha$
Ec	Eckert number	$V^2/C_p\Delta T$
Sc	Schmidt number	ν/D

Natural convection: Natural convection flow in cubic enclosures related to the fusion reactor is important for breeder reactors. Interest in natural convection stems, in part, from the large pressure drop encountered in forced convection. MHD forces in fusion blankets are typically 4 to 5 orders of magnitude higher than inertial and viscous forces and hence they change the dynamics of the fluid flow. Table 1 gives the nomenclature and the non dimensional terms used in these studies. A consolidated list of studies in this area and the values of non-dimensional parameters used are given in Table 2.

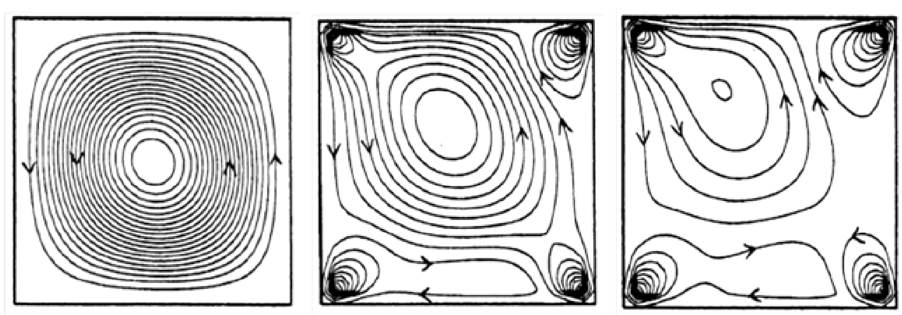
Cubic enclosures: Breeder reactors are mostly conceptualized in the form of cubic enclosures. Joule heating in electric glass melting or slag re-melting in metallurgical industry is also analyzed in the form of cubic enclosures with combined buoyant and Lorentz forces. Studies were mostly done for two dimensional models with variation in heating modes for fluids with different Pr, Ra, wall conductance ratios and angle of incidence of the magnetic field. The magnetic field effects are characterized using magnetic Ra, Q or M.

Liquid metals: Tagawa and Ozoe (1997) reported an increase in heat transfer by 5-7% in the region of Pr = 0.025 and Ra = 10^5-10^6 for M in the range of 100 to 200. Decrease in the heat transfer occurred at M above 200. Yamaguchi *et al*. (1999) made experimental and numerical studies for natural convection in a square cavity which is heated at the bottom. They showed the increase in heat transfer rate with the vertically imposed magnetic field above a certain critical Ra. Fig. 1 shows the section of a cubical enclosure with MHD convection with internal heat generation and isothermal walls and gives the isotherms with and without the effect of magnetic field. Aurnou and Olson (2001) experimented with Rayleigh–Bénard convection of liquid gallium in large aspect ratio cavities (1:8 and 1:6) subjected to transverse magnetic field and reported the convection effects under different conditions. Burr and Müller (2002) performed experimental and analytical studies of a similar problem for a large aspect ratio rectangular box with the horizontally oriented uniform magnetic field. They observed the magnetic braking effect and a consequent shift in the onset of convection to a higher value of M.

Piazza and Ciofalo (2002a) studied the free convection with differentially heated perfectly conducting walls and reported about the suppressed convective motions for increasing M. The average Nu decreased from 1.403 to 1.007 when M increased from 100 to 1000. Further, increasing wall conductance resulted in increasing Lorentz force and decreased convective heat transfer. Piazza and Ciofalo (2002b) investigated the effects of M, wall conductance ratio and Ra in buoyancy-driven MHD flow in a liquid-metal filled cubic enclosure with internal heat generation using 3-D numerical simulation. The Nu decreased with increase in M, increase in the wall conductivity and decrease in Ra. At M

Table 2: MHD study parameters for natural convection

Sl.No	Reference	Fluid / Pr	Flow Parameter	Magnetic parameter
1	Ahmet (2011)	Pr = 0.7	Ri = 0, 1, 5, 10	Mn = 0, 0.5, 1, 2
2	Anuar *et al*. (2010)	Pr = 0.7,1	λ= -4 to 3	M = 0, 1, 2
3	Aurnou and Olson (2001)	Pr = 0.023	Ra- 3.0 x 10^3 to1.6 x 10^4	Q < 2.6 x 10^3
4	Burr and Müller (2002)	Pr = 0.02	Ra = 10^3 to 8 x 10^4	0<M<200
5	Ganesan and Palani (2004)	Pr = 0.7 and 7	Gr=10^6	M = 1, 2, 3, 4
6	Giuseppe and Michele (2006)	Electrically conducting fluid	Gr = 10^{10}	M = 0.1 to 10000
7	Hirdesh and Mirza (2008)	Pr = 0.01	Ra = 10^7 Q = 5.0625 x 10^4 to 1.21* 10^6	Pr_m = 4 x 10^{-4}
8	Jalil and Al-Taey (2007)	Pr = 0.01085	Ra = 10^{10}	M = 0-44970
9	Kakarantzas *et al*. (2007)	Pr = 0.0321	Ra = 10^3 to 10^5	M = 100
10	Kakarantzas *et al*. (2009)	Liquid metal	Ra = 10^2 to 10^6	M = 0 to 50
11	Kenjeres *et al*. (2010)	Pr = 0.006, 0,0.025,0.054	Ra = 10^7 to 10^9	M = 0 to 300
12	Kenjeres *et al*. (2010)	7% Na_2SO_4 solution/water	Re = 500 -8250	M = 8
13	Krakov *et al*. (2005)	Magnetic fluid	Gr = 0	Gr_m^2 = 5000
14	Lo (2010)	Pr = 0.01 to 10	Gr = 10^4and10^5	M = 0 to 100
15	Mayasuki *et al*. (2004)	Pr = 0.71	Ra = 10^5-10^6	Y = 0-10, B= 5-10 Tesla
16	Parvin and Nasrin (2011)	Pr = 0.7	Ra = 10^3-10^6	M = 0-70
17	Piazza and Ciofalo (2002a)	Pr = 0.0321 (Li-Pb)	Ra = 10^5	M = 100, 200, 100 k = 0 to infinity
18	Pirmohammadi and Majid (2009)	Pr = 0.02	Ra = 10^5,10^6	M^3 = 0-100
19	Piazza and Ciofalo (2002b)	Pr = 0.0321 (Li-Pb)	Ra = 10^5-10^7	M = 100-1000 K = 0 to infinity
20	Riki *et al*. (2003)	Pr = 0.71	Ra = 10^5	γ = 1-100
21	Sarris *et al*. (2005)	Pr = 0.015	Ra_E = 10^5,10^6	S = Ra^4_I /Ra_E = 0 to 100 M^3 = 0-100
22	Sankar *et al*. (2006)	Pr = 0.054	Ra = 10^3 to 10^6	M = 0-100
23	Shigemitsu *et al*. (2003)	Pr = 0.71	Ra-10^4,10^5,10^6,10^7	γ = 0, 0.1, 1, 10
24	Sugilal *et al*. (2005)	Pr = 10-1000	Ra-2.5 x 10^5	M = 4 x 10^7
25	Tagawa and Ozoe (1997)	Pr = 0.025	Ra = 10^5-10^6	M = 100 to 200
26	Tagawa *et al*. (2002)	Pr = 0.71	Ra = 10^5	γ = 0, 1, 10
27	Tomasz *et al*. (2005)	Pr = 584	Ra = 0.99 x 10^5 to 1.49 x 10^5	B = 0 to 5T
28	Uda *et al*. (2000)	Lithium Pr = 0.05	Gr = 6.5 x $10^7$to 1.5 x 10^9	M = 0–1.3 x 10^4
29	Wang *et al*. (2010)	LiPb	ΔT = (650 -300)	M = 20-200
30	Wen *et al*. (2002)	water-based Fe_3O_4 magnetic	Ra = 4.1, 39.1	Ra_m^5 = 0, 670
31	Yamaguchi *et al*. (1999)	Mn-Zn ferrite in alkylnaphthalene base fluid.	Ra = 0-10000, Ra_m= 3.973 x 10^6 to 9.932 x 10^6	M = 40-100
32	Xiaohui and Mo (2011)	Pr = 1.0.1, 0.01	Ra = 10^4, 10^5	M = 1.414 x 10^3



(a) (b) (c)

Fig. 1: MHD effect on natural convection in a cubical enclosure showing the initiation and growth of the vortex with increase in the strength of the magnetic field, (a) Without magnetic field, (b) For a magnetic Raleigh number 3.973x10^6, (c) For a magnetic Raleigh number 9.932 x 10^6

of 100 and wall conductance ratio of 10^{-2}, the increase in Ra from 10^5 to 10^7 resulted in the doubling of Nu. Figure 1 gives the section of a cubical enclosure with MHD natural convection with internal heat generation and isothermal walls and gives the isotherms with and without the effect of magnetic field. This study reveals the possibility of increasing the heat transfer under laminar flow conditions. Sarris *et al*. (2005) studied natural convection in a square cavity with simultaneous walls and internal heating.

The ratio of Ra values (which is the internal over external Ra) was varied and the effect of changing M was studied. Heat transfer decreased for low values of this ratio and was enhanced with increase in this ratio. However, no significant influence of magnetic field on heat transfer was observed for the low values of M used in the study. These findings support earlier results from numerical simulations. Jalil and Al-Taey (2007) studied the heat transfer in turbulent natural convection in square enclosures for molten sodium using k-ϵ model and reported a decrease in Nu with increase in Hirdesh and Mirza (2008) studied the MHD effect on low Pr fluids in a cubical cavity with aspect ratio of 8:1. Application of a transverse magnetic field did not suppress convection but actually augments it for higher values of Q which represents the ratio of the Lorentz force to the fluid viscosity. Pirmohammadi and Majid (2009) studied natural-convection flow in the presence of a magnetic field in a tilted enclosure heated from below and cooled from top and Pirmohammadi *et al*. (2009) studied enclosures heated from right and cooled from left with partition on the horizontal walls. The dependence of Nu on the inclination angle for relatively small values of M was studied. In general, convection was found to be reduced at low Ra and showed an increasing trend towards an inclination angle of 45º for higher Ra. Wang *et al*. (2010) studied the natural convection heat transfer of the liquid LiPb and reported increased convection at M up to 200. The behavior of the high velocity jets along the electrically conducting walls that contributed to increased heat transfer was studied.

Air: Tagawa *et al*. (2002) studied the effect of the orientation of the magnetic field on the convective forces on air in cubical enclosures. When the direction of the magnetic field was not orthogonal to the hot or cold wall, an increase of Nu was observed compared to the no magnetic field case. MHD forces can be used for the acceleration of air for different applications. Riki *et al*. (2003) reported on the enhancement of heat transfer due to magnetic field in an inclined cubical enclosure with magnetic coils placed in the plane of the top wall. Ra was 10^5 and the magnetic parameter varied from 1to100. Shigemitsu *et al*. (2003) conducted computational studies for combined magnetizing and gravitational force fields with simultaneous heating and cooling of opposite vertical walls. The range of Ra was from 10^4 to 10^7 and the magnetic parameter was from 0 to 100. Convection rolls due to the attraction of cold air by magnetic field was observed.

This was confirmed by flow visualization experiments and numerical analysis conducted by Mayasuki *et al*. (2004). They reported the increase in Nu from 4.476 to 5.160 when the magnetic parameter was increased from 0 to 10. Parvin and Nasrin (2011) studied the free convection in a square enclosure with a cylindrical obstacle in the center. The average Nu at the surface of the obstacle was increased y increasing the Ra and the diameter but decreased with an increase of M.

Other types of fluids: Kenjeres and Hanjalić (2004) conducted numerical studies for natural convection in cubical enclosures for a range of Ra and M under turbulent conditions for electrically conducting fluids at different Pr. Sugilal *et al*. (2005) studied the behavior of different fluids with high Pr in a rectangular cavity with an aspect ratio of 2. They showed that the heat transfer is governed by the self induced electromagnetic effect when $M^2Pr/Ra > 100$. Pr had a remarkable influence on heat transfer for electromagnetically driven flows and negligible effect for thermally driven flows. Krakov *et al*. (2005) experimentally showed the transition to different convective movements with changing magnetic field intensity as well as the changes in the temperatures within a rectangular enclosure. Tomasz *et al*. (2005) experimentally investigated the effect of a strong magnetic field on the average heat transfer rate and flow profiles of joint gravitational and thermo-magnetic convection of a paramagnetic fluid in a cubic enclosure heated from below and cooled from above using an aqueous solution of glycerol and reported an increase in Nu with the magnetic field. Similar experimental study was made for vertical walls by Tomasz *et al*. (2009) and inferred that the magnetic field enhances the heat transfer. Experiments were compared with three dimensional numerical computations. Kenjeres *et al*. (2010) made a combined numerical Large Eddy Simulation as well as experimental Particle Image Velocimetry study of the behavior of an electrolyte solution in a rectangular cavity under magnetic field and established the effect of magnetic field in controlling the heat and mass transfer.

Kahveci and Oztuna (2008) investigated the MHD flow and heat transfer in a tilted enclosur with a centered partition and found that for high Ra, the average Nu shows an increasing trend as the inclination angle increases and a peak value is detected. Pr was seen to have only a marginal effect on the heat transfer.

Lo (2010) employed the differential quadrature method to investigate the effect of a transverse magnetic field on buoyancy driven flow in a rectangular enclosure for a range of Gr, Pr and M. Similar methods were adopted in other studies targeting at pressure drop reduction by means of thermal insulation. Heat transfer was lesser at higher magnetic intensity. Two-dimensional unsteady thermal convection was simulated numerically by Xiaohui and Mo (2011) at different Pr. They identified that the transient heat transfer rates varied with Pr. Abishek and Subrahmanya (2011) studied natural convection in tilted square enclosures and proposed correlations for heat transfer.

Flow in other geometries: Uda *et al*. (2002) studied natural convection liquid metal flow between a tube and a heater pin that was placed on its axis and obtained increasing Nu at certain magnetic field intensities. Nu is emphasized to have a large peak at

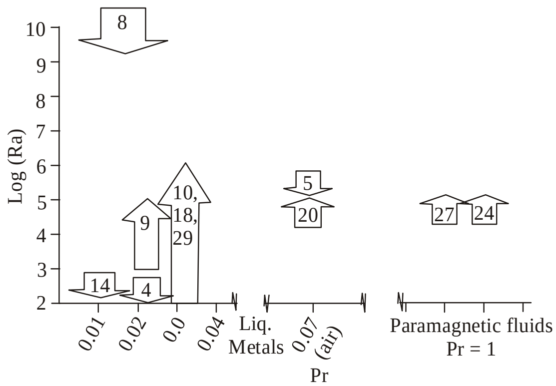


Fig. 2: Data representing the increase or decrease in the heat transfer for different Pr and log of Ra. The direction of the arrow shows the trend of the heat transfer and the numbers inside gives the serial number of the relevant paper as given in Table 2

magnetic field intensity of 0.05 Tesla. For the region greater than 0.05 Tesla, the heat transfer decreased monotonically. Wen *et al*. (2002) experimentally studied the effect of magnetic field in a Hele-Shaw cell with an aspect ratio of 1. Shadowgraph was used to study heat transfer in a bottom heated shell with insulated side walls. They confirmed the increase in heat transfer at the super critical states of the Ra. Incompressible viscous fluid flow past semi-infinite vertical or inclined plates was investigated by Ganesan and Palani (2004) for variable surface heat and mass flux under transient condition. Average Nu decreased with increased magnetic field.

Natural convection of a low Pr electrically conducting fluid under the influence of either axial or radial magnetic field in a vertical cylindrical annulus has been numerically studied by Sankar *et al*. (2006). They observed the axial magnetic field was effective in suppressing heat transfer in shallow cavities and radial magnetic field for tall cavities. The parallel, fully developed flow of an electrically conducting fluid between plane parallel walls under the simultaneous influence of a driving pressure head, buoyancy and MHD forces was studied by Giuseppe and Michele (2006). Kakarantzas *et al*. (2007) reported results of direct numerical simulations to study the natural convection heat transfer between concentric cylinders at different Rayleigh and M. The flow occurs due to temperature gradient between the inner and the outer walls. Both laminar and turbulent flows are observed depending on the magnitude of the Ra and M. The results show the three dimensional nature of turbulence and the tendency of the magnetic field to form narrow Hartmann layers, three dimensional jets and wakes at specific azimuthal angles. Kakarantzas *et al*. (2009) conducted numerical studies on natural convection in cylinders with sinusoidal heated top wall. Their results showed that the increase of Ra promotes heat transfer by convection while the increase of M favors heat conduction. The vertical magnetic field reduces the Nu more than the horizontal. Anuar *et al*. (2010) studied the steady MHD mixed convection flow adjacent to a bounding surface immersed in an incompressible viscous fluid. The governing system of partial differential equations was first transformed into a system of ordinary differential equations, before being solved numerically by a finite-difference scheme. Ahmet (2011) made numerical study of mixed convection flow about a vertical cylinder with wall conduction and reported increase in the heat transfer parameter for increasing M, Pr and Sc.

Figure 2 represents the increase or decrease in the heat transfer for the different values of controlling parameters for each of the above cases.

Forced convection: A comprehensive study of the heat transfer characteristics of free and forced convective MHD flows at fusion-relevant conditions was conducted by Burleon *et al*. (2001). The geometries considered were full and annular rectangular and circular cross sections, triangular cross sections and closed and open channels. Both conducting and non-conducting walls were considered.

Duct flows are characterized by the formation of Hartmann layers which are normal to the field and the thickness of which are proportional to the reciprocal

Table 3: Study parameters for forced convection

S.No.	Reference	Fluid/Pr	Flow parameter	Magnetic parameter
1	Hulin and Bo (2010)	Pr = 0.05	Re = 3000	M = 30-70
2	Joao *et al*. (2007)	Pr = 1	Ec = 0.0508	M = 0, 1, 2
3	Nakaharai *et al*. (2007)	KOH (30%) solution	Pr = 6.2, 9.8 Re = 5000, 20000	Turbulent pipe flow M = 0, 5, 10, 15
4	Naotaka and Takahashi (2002)	Lithium Pr = 0.05	Re = 2500-20000	M = 1900 M/Re>1/225
5	Takahashi *et al*. (1998)	Lithium Pr = 0.05	Re = 2.43 x 10^3-2.23 x 10^4	M = 0- 1.93 x 10^3
6	Uda *et al*. (2002)	Li, Pr = 0.05	Re = 4 x 10^3-1.4 x 10^5	B = 0.2 T
7	Yamamoto *et al*. (2008)	Pr = 5.7	Re = 150	M = 0 to 16
8	Yih (1999)	Pr = 0.733,1	E_c = 0, 1	ξ = 0, 0.5, 1, 1.5, 2
9	Yokomine *et al*. (2007)	FliBe Simulant Pr = 5	Re = 7400-20000	M^2/Re = 0 to 0.1 M = 0, 10, 20
10	Zniber *et al*. (2005)	Conducting fluids	Pe = 50, 1.5	M = 0, 6, 50, 100.

of M. These play an important role in heat transfer. The side layers parallel to the field scale to the inverse square root of M and are much thicker than the Hartmann layers. Table 3 lists study parameters used in some of the studies in this area.

Rectangular duct and pipe flows: Earlier studies were restricted to small M. A liquid metal forced-convection fully developed laminar flow inside a square duct, whose surfaces are electrically insulated and subjected to a constant temperature in a transverse magnetic field is solved numerically by Mohamed *et al*. (2006) using the spectral method. Accurate calculation of the skin friction and Nu were made using this method. Also the effect of magnetic field was found to be lower in square ducts compared to circular pipe flows. Similar studies were conducted by Yokomine *et al*. (2007) who reported a significant reduction in the pressure drop. Nakaharai *et al*. (2007) experimentally investigated the influence of a transverse magnetic field on the local and average heat transfer of an electrically conducting high Pr fluid (30% KOH solution) with turbulent fluid flow. Nu decreases with increase in the magnetic parameter. However, decrease in Nu was lesser for higher values of Re. Figure 3 gives the temperature profile in a pipe due to different magnetic field at a particular value of Reynolds number and Prandtl number. Ellahi and Arshad (2010) developed an analytical solution for MHD flow of non-Newtonian fluids in pipes. They obtained the expressions for the velocity and temperature using the homotopy analysis method.

Channel flows: Takahashi *et al*. (1998) conducted experimental studies on the pressure drop and heat transfer characteristics for lithium single-phase flow in horizontal conducting rectangular channels under a horizontal transverse magnetic field. Naotaka and Takahashi (2000) numerically investigated the heat transfer characteristics of lithium flow in a conducting rectangular channel in the presence of a transverse magnetic field. They reported increase in Nu with M which is attributed to the cooling effect of the side layer jet. Graetz problem deals with combined forced convection and conduction in channels or ducts. The effect of axial conduction becomes significant at low values of Pe. Thermally developing laminar Hartmann flow through a parallel-plate channel, including both viscous dissipation, Joule heating and axial heat conduction with a step change in wall temperatures, has been studied analytically by Lahjomri *et al*. (2002) and they showed that the Nu increased in the developed flow region for insulating walls. For conducting walls, the Nu decreases with M in the entrance region and the trend is opposite in the developed region where the Nu is less sensitive to the M. Nu was found to be larger for non-conducting walls than for conducting walls for constant and large values of M. Surface heat transfer degradation due to turbulence redistribution in open channel flow was studied using the k-epsilon model by Sergey *et al*. (2002) by considering different orientation of the magnetic field and the damping effects of the magnetic field were demonstrated. Zniber *et al*. (2005) studied thermally developing MHD flow in a duct subjected to a magnetic field with sinusoidal wall heat flux by considering the axial conduction term in the energy equation. Increased Nu is observed at low values of Pe at certain heat flux frequencies. Hulin and Bo (2010) numerically proved that the non-uniform electrical conductivity distribution of a channel wall with protrusions can create alternate Lorentz forces along span-wise direction, which can effectively produce flow disturbance, promote mixture, reduce the thickness of boundary layer and enhance heat transfer in MHD flow. Yamamoto *et al*. (2008) conducted a study on the MHD pressure loss and heat-transfer characteristics of the low-magnetic Re and higher Pr fluid such as the FLiBe (molten salt) by means of direct numerical simulation and showed the reduction of heat transfer with increase in the magnetic field under certain conditions.

Flow through other geometries: Flows over flat plate were analyzed for different types of liquids have been reported. Yih (1999) has analyzed the flow adjacent to a non-isothermal wedge and obtained local Nu. Increase in the heat transfer with increase in magnetic parameter as well as with the Pr is reported for constant Ec. However, at particular values of magnetic parameter and Pr, the heat transfer decreased with increase in the Ec. This was confirmed later by many researchers. Uda *et al*. (2000) experimented on the MHD effect on heat transfer in liquid lithium annular flow with an emphasis on heat transfer enhancement and local turbulence. The heat transfer was observed to increase over a particular region and the peak value was 5-10% higher than that for zero magnetic fields. This was explained as a result of local turbulence enhancement in the vicinity of the heating wall. Experimental studies on heat transfer in liquid Lithium flow was conducted to compare with earlier studies by Naoki *et al*. (2011). Shin-Ya *et al*. (2006) conducted numerical simulations for Flibe flow with cylindrical obstructions for heat transfer enhancement. The effect of flow stirring produced by the obstructions on the heat transfer and pressure drop was studied. Joao *et al*. (2007) developed a hybrid solution through the Generalized Integral transform Technique for the MHD flow and heat transfer of a Newtonian fluid in parallel-plates channel for temperature dependent viscosity and obtained the results for different Yamamoto and Kunugi (2011) simulated channel flow for high Re and Pr values with high performance computing and reported turbulence restriction in the channel center.

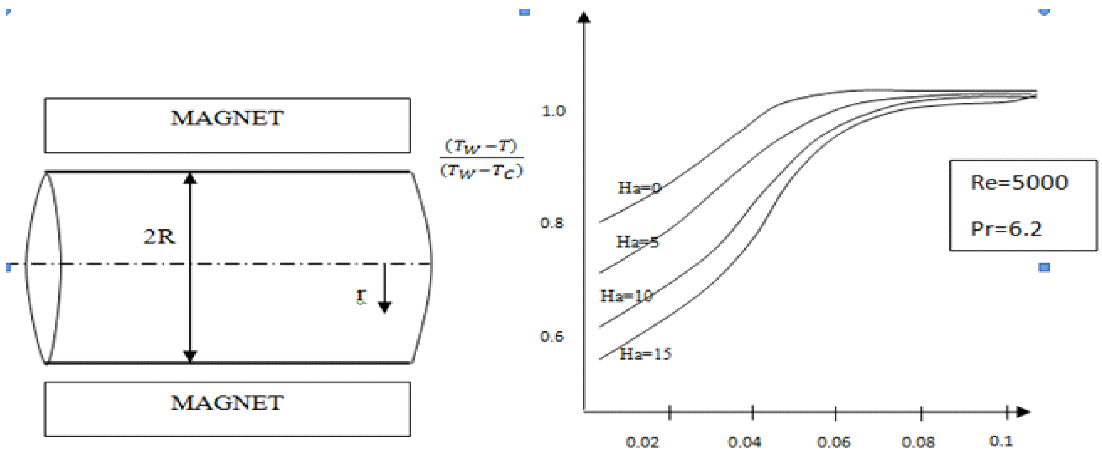


Fig. 3: Temperature profile in a pipe due to different magnetic parameters (R- Pipe diameter, r- radial distance from the center, T_W- Pipe wall temperature, T_C- Pipe center temperature, M- Hartmann number)

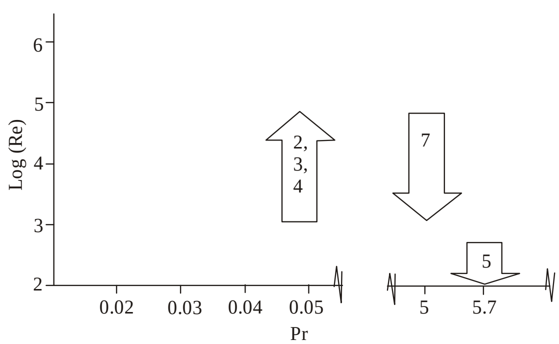


Fig. 4: Effect of Re on the heat transfer for different values of Pr as obtained from the literature. The direction of the arrow shows the trend of the heat transfer and the numbers inside gives the serial number of the relevant paper as given in Table 3

Rao and Hari (2011) later conducted numerical studies for higher magnetic fields showe that the Nusselt number near the perpendicular walls decreases with increase in magnetic field and increases near the parallel walls at low Re. Insulated ducts showed decrease in the heat transfer.

Figure 4 represents the increase or decrease in the heat transfer for the different values of the operating parameters for the above cases.

CONCLUSION

Studies on natural convection inside cubical enclosures included cubes with laterally heated or cooled sides, internal heating and Raleigh Bernard convection. It was observed that effect of Lorentz force on heat transfer differed on a case by case basis. For enclosures with liquid metal with laterally heated sides, mostly suppression of heat transfer due to reduced convective motion was reported except for a particular set of conditions in which enhancement of the Nu is observed. In the case of liquid metals and paramagnetic fluids (high Pr fluids) this occurred for the Ra of 10^5 and for M ranging from 100-200. Similar studies with air as the working fluid revealed both positive and negative impact on the heat transfer depending on the orientation of the field. More studies for higher magnetic intensities were not available for air. Increasing the wall conductance suppressed the convective motion in all the fluids. Most of the studies in natural convection were numerical in nature and experimental studies were limited to liquid metals.

In the case of forced convection flow, it was observed that viscous dissipation and joule heating had a significant effect on the heat transfer depending on the electrical conductivity of the wall. It was found that when the wall was non-conductive, Nu did not decrease monotonously with increase in magnetic field and in fact increased with M in the thermally developed region. The trend was opposite for conducting walls. Studies on flow in annular geometry revealed that the pressure drop in an annular film MHD flow was of the same order of magnitude as that of a single-phase MHD pipe flow under similar liquid metal flow conditions. Annular flow exhibited a more asymmetric heat transfer behavior at higher magnetic field intensities. Studies on fluids with varying Pr revealed that heat transfer performance degradation of high Pr fluid was more sensitive to the Pr than that by low Pr fluid.

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