Impact of Magnetic Field Strength on Magnetic Fluid Flow through a Channel

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ABSTRACT

In this paper an attempt has been made to study the flow characteristics of a magnetic fluid flowing through a channel under the action of magnetic field keeping the magnet along axial direction and changing its length considering FHD phenomenon with respect to the formation of recirculating bubbles, velocity contour and average stagnation pressure. The continuity and momentum equations have been discretized by a control volume based finite difference method. Power law scheme is used to discretize the convective terms. The discretized equations have been solved iteratively by SIMPLE algorithm, using line-by-line ADI method. The distribution of grid nodes is non-uniform and staggered in both coordinating directions. The shape and size of the bubble and average stagnation pressure have a greater importance in case of various practical applications, such as magnetic hyperthermia, targeted transport of drugs, magnetic wound or cancer tumour treatment, opening the blockage in the artery etc.

1. INTRODUCTION

Numerical study of magnetic fluid flow through a channel has become a very demanding research area for researchers. Over the past few decades, eminent researchers have extensively worked on dynamics of magnetic fluid in the presence of magnetic field. They have made an endeavour to implicate it in the industry, medical technology and bio-engineering. Magnetic fluid or ferrofluid is well known for its wide use in the industry and in the field of medicine, e.g. magnetic drug targeting, ferrofluid sealing, high-gradient magnetic separation, magnetic devices for cell separation, targeted transport of drugs, hyperthermia and reduction of bleeding, cancer treatment, etc. The role of formation of recirculating bubble, velocity contour and average stagnation pressure plays an important role in the stage of above applications.

Literature has been enriched with experimental, numerical and theoretical activities on magnetic fluid flow under the action of magnetic field. From review of literature, it is felt that first work in that field has been carried out by Loukopoulos and E. E. Tzirzilakis [1]. They have numerically presented two dimensional, laminar, incompressible biomagnetic fluid flow in a rectangular channel under the action of a magnetic field. E. E. Tzirzilakis [2] has presented numerical simulation on laminar, incompressible, three dimensional, fully developed viscous flow of a Newtonian biometric fluid in a straight or curved rectangular duct under the action of spatially varying or uniform magnetic field. E. E. Tzirzilakis et al. [3] have presented two dimensional, incompressible Newtonian, electrically conducting turbulent flow between two parallel plates under the action of localized magnetic field. Hayat et al. [4] have studied the effect of magnetic field on a turbulent biomagnetic, electrically conducting fluid flow in a rectangular channel. Ikbal et al. [5] have theoretically investigated the atherosclerotic arteries dealing with mathematical models that represent non-Newtonian flow of blood through a stenosed artery in the presence of a transverse magnetic field of magnetic number ranging from 0 to 4 and Reynolds number from 300 to 1000. E. E. Tzirzilakis [6] has studied the fundamental problem of the biomagnetic fluid flow in a channel with stenosis under the influence of a steady localized magnetic field. Papadopolos et al. [7] have numerically studied the laminar, incompressible, fully developed viscous flow of a biomagnetic fluid in a rectangular duct under the influence of an applied magnetic field of magnetic number range of 3×10^6 to 5×10^6 and Reynolds number range from 200 to 2000.

From the abovementioned review of literature, it has been observed that in all the cases the length of the magnet has not been varied and magnet has been kept along the transverse direction and also they have not studied the flow characteristics with respect to shape and size of the recirculating bubble, velocity contour and average stagnation pressure, so far. Hence in the present work, an attempt has been taken to study the flow characteristics of a biomagnetic fluid flowing through a channel under the action of magnetic field keeping the magnet along axial direction and changing its length considering FHD phenomenon with respect to the formation of recirculating bubbles and velocity contour generated by MATLAB Software, and average stagnation pressure respectively.

2. MATHEMATICAL FORMULATION

2.1 Governing equations

The key-line of this work is steady, laminar, incompressible biomagnetic fluid which flows through a channel, under the action of variable axial magnetic field. The origin of the Cartesian coordinate system is located at the leading edge of the lower plate and the flow is subjected to a magnetic source which is placed much closed to the lower plate and below it. The flow at the entrance is assumed to be uniform and fully develop at the exit. A schematic diagram of the computational domain is shown in fig.1. In this study, the dimensional velocity components and the pressure are governed by the mass and momentum conservation equations. Thus the dimensional governing equation along the x, y direction with considering FHD are written as follows,

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad \text{--------------} \quad (1)$$

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\delta p}{\partial x}+\mu_0 M\frac{\partial H}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \qquad \text{------------} \quad (2)$$

$$\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\delta p}{\partial y}+\mu_0 M\frac{\partial H}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \qquad \text{---------} \quad (3)$$

In the above dimensional equations, ρ is the fluid density, μ is the viscosity, H is the magnetic field strength intensity, M is the magnetization and μ_0 is the magnetic permeability under vacuum.
The magnetization linear equation for isothermal cases is given by,

$M=\lambda H$ ----------(4)

Where λ is constant called magnetic susceptibility.

In our study, we have considered the following dimensionless variables,

Length:

$$x^*=\frac{x}{W},\ y^*=\frac{y}{W},\ L^*=\frac{L}{W} \qquad \text{-----------} \quad (5)$$

Velocity:

$$u^* = \frac{u}{U}, v^* = \frac{v}{U} \quad \text{----------------- (6)}$$

Pressure:

$$p^* = \frac{p}{\rho U^2} \quad \text{------------------- (7)}$$

Magnetic field strength:

$$H^* = \frac{H}{H_0} \quad \text{-------------- (8)}$$

Thus with the help of the above non dimensional variables, the governing equation (1) – (3) are transformed to the following equations.

$$\frac{\partial u^*}{\partial x^*} + \frac{\partial v^*}{\partial y^*} = 0 \quad \text{-------------- (9)}$$

$$\left(u^*\frac{\partial u^*}{\partial x^*}+v^*\frac{\partial u^*}{\partial y^*}\right)=-\frac{\partial p^*}{\partial x^*}+M_nH^*\frac{\partial H^*}{\partial x^*}+\frac{1}{\mathrm{Re}}\left[\frac{1}{\partial x^*}\left(\frac{\partial u^*}{\partial x^*}\right)+\frac{1}{\partial y^*}\left(\frac{\partial u^*}{\partial y^*}\right)\right] \quad \text{------------- (10)}$$

$$\left(u^*\frac{\partial v^*}{\partial x^*}+v^*\frac{\partial v^*}{\partial y^*}\right)=-\frac{\partial p^*}{\partial y^*}+M_nH^*\frac{\partial H^*}{\partial y^*}+\frac{1}{\mathrm{Re}}\left[\frac{1}{\partial x^*}\left(\frac{\partial v^*}{\partial x^*}\right)+\frac{1}{\partial y^*}\left(\frac{\partial v^*}{\partial y^*}\right)\right] \quad \text{-------------- (11)}$$

Where M_n is the Magnetic number arising from FHD which is given by,

$$M_n = \mu_0 \lambda H_0^2 / U^2 \rho \quad \text{-------------- (12)}$$

Another non-dimensional parameter which will affect the biomagnetic fluid flow under consideration is Reynolds number, which is given by,

$$\mathrm{Re} = \rho U W / \mu \quad \text{-------------- (13)}$$

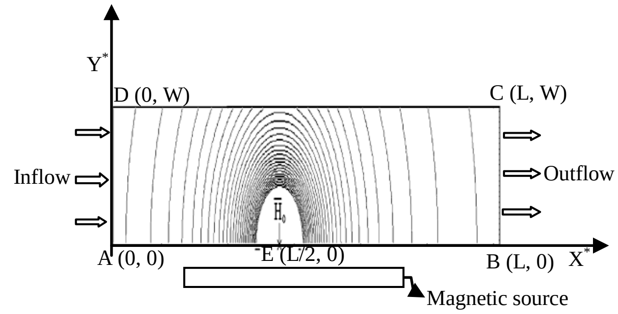

Fig.1. Schematic diagram of the computational domainand contours of the magnetic field strength H.

2.2 Boundary conditions

Three types of boundary conditions have been considered to the present problem. They are as follows,

1. At the walls: No slip condition is used, i.e. $u^* = 0, v^* = 0$.
2. At the inlet: Uniform flow condition is specified and the transverse velocity is set to zero, i.e., $u^* = 1, v^* = 0$.
3. At the exit: Fully developed condition is assumed and hence gradients is set to zero, i.e., $\partial u^* / \partial x^* = 0, \partial v^* / \partial x^* = 0$.

3. NUMERICAL SIMULATION

The non-dimensional partial differential continuity and momentum equations (9)-(11) have been solved according to the SIMPLE method in the finite volume formalism by use of a non-uniform and staggered grid in both coordinating directions allowing higher grid node concentrations in the region close to the walls and close to the higher rate of change of magnetic field. The convection and diffusion terms have been discretized with the help of Power law scheme [8]. The discretized equations have been solved iteratively by using line-by-line ADI (Alternating directional implicit) method. For all calculations, the length of the channel is considered to be 220. During computation, the numerical mesh is considered to be comprising of 160 × 60 grid nodes in x and y direction respectively.

4. RESULT AND DISCUSSION

During our study, a series of numerical simulation is performed and the parameters those affect the flow characteristics, are identified as,

i) Reynolds number, Re = 100.

ii) Magnetic number arising from fero hydrodynamics (FHD), $2\times10^4 \leq M_n \leq 5\times10^4$.

iii) Uniform velocity at inlet and fully develop at exit.

iv) The length of the magnet ranging from 4 non-dimensional units to 22 non-dimensional units and magnet is placed at the middle of computational domain keeping equal unit of non-dimensional length in each side of the middle point of the channel.

4.1 Variation of streamline and Velocity contours

In all the cases, we have shown the variation of streamline contours and velocity contours of the flow subjected to axial magnetic field. Fig.2 and Fig.3 show the streamline and velocity contour of the channel flow without considering magnetic number for a typical value of Re of 100. Here all the streamlines are straight, parallel and perpendicular to the cross section of the channel as there is no external force acting on the fluid particle during its motion along the streamline. The velocity profile is uniform at the inlet of the channel and fully develop after covering a short distance and also remain fully develop up to the exit of the channel. Fig.4.1. and Fig.4.2.show the effect of length of magnet on streamline and velocity contour for a typical value of Re of 100 and Magnetic number of 2×10^4. Fig.5.1 and Fig.5.2 show the effect of magnetic number on streamline and velocity contour for a typical value of Re of 100 and magnet of 20 unit of non-dimensional length. In all the cases, separation phenomenon occurs just before the entrance of the magnetic field and reattaches just after the magnetic field. It is also observed that the size of the recirculation zone increases along the axial direction and decreases along transverse direction with the increase in the length of the Magnet and Magnetic number as the imaginary external magnetic lines of force increases with increasing length of the magnet and magnetic number. This magnetic force, along the axial direction, acts on the magnetic fluid particle which is flowing through the channel. From fig. 4.1, 4.2, 5.1 and 5.2, it has been also observed that the complete recirculating zone has formed at that zone where the velocity profile developed a small velocity loop, which may be a positive loop or a negative loop i.e. the complete recirculating zone has formed at that zone where the velocity suddenly changes from negative to positive and again from positive to negative and vice versa. Moreover, with the increase in recirculating zone, it can be expected that the rate of heat transfer as well as temperature of the working fluid will increase mainly due to conversion of kinetic energy of the working fluid in to heat energy. Due to the increasing recirculating zone, retention of blood or magnetic fluid at a particular area will increase as a result of which, toxide medicine, if injected at that location, will get time to be sedimented on the required area, without affecting the important part of the body like heart, kidney, liver, lung etc. Recirculating bubble may create turbulence in the fluid flow which is used for proper mixing in combustor, carburetor etc.

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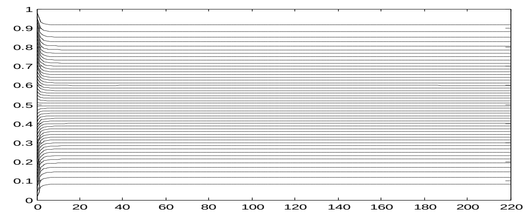

Fig.2. Streamline contour without Considering Magnetic number at Re of 100

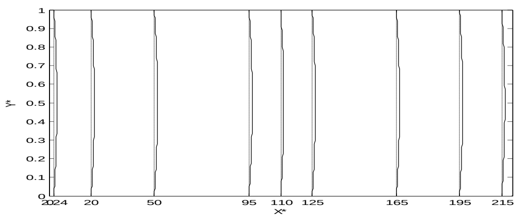

Fig.3. Velocity profile without Considering Magnetic number at Re of 100

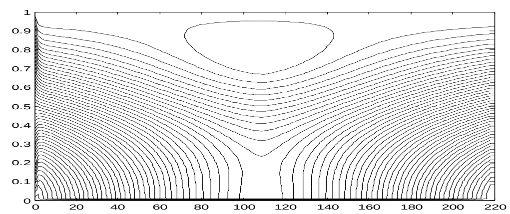

Fig.4.1.1. Mn-20000, Re-100, Magnet Length-4unit

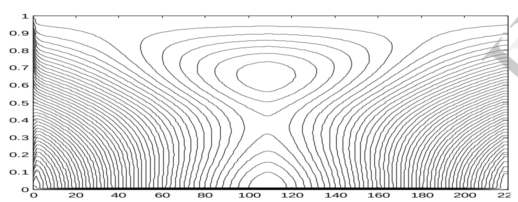

Fig.4.1.2. Mn-20000, Re-100, Magnet Length-6unit

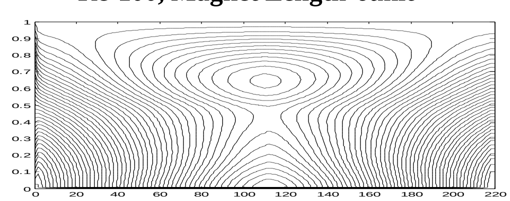

Fig.4.1.3. Mn-20000, Re-100, Magnet Length-16unit

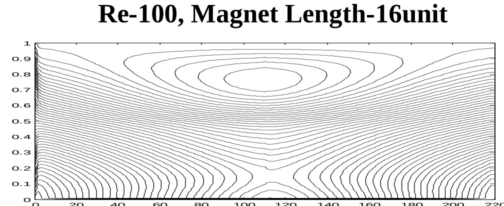

Fig.4.1.4. Mn-20000, Re-100, Magnet Length-20unit

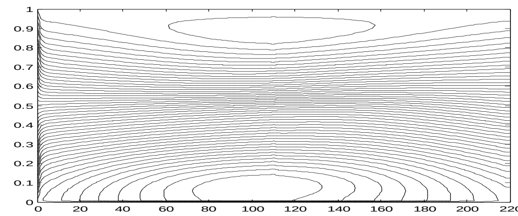

Fig.4.1.5. Mn-20000, Re-100, Magnet Length-22unit

Fig.4.1. Effect of Length of Magnet on streamline contour for fixed Magnetic Number and Reynold Number

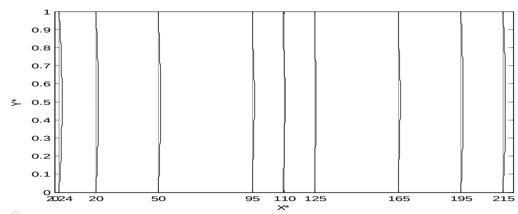

Fig.4.2.1. Mn-20000, Re-100, Magnet Length-4unit

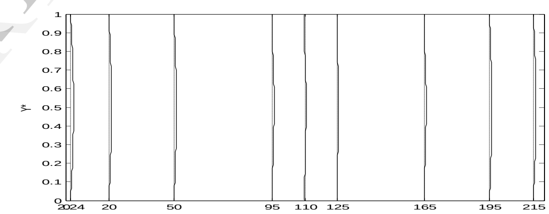

Fig.4.2.2. Mn-20000, Re-100, Magnet Length-6unit

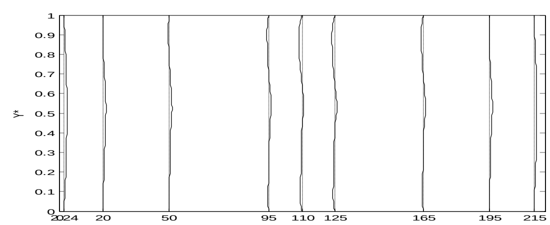

Fig.4.2.3. Mn-20000, Re-100, Magnet Length-16unit

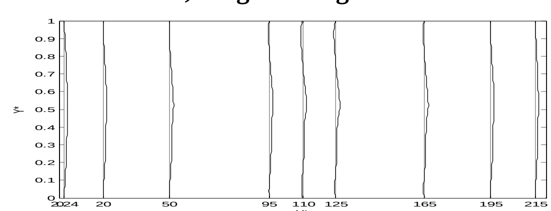

Fig.4.2.4. Mn-20000, Re-100, Magnet Length-20unit

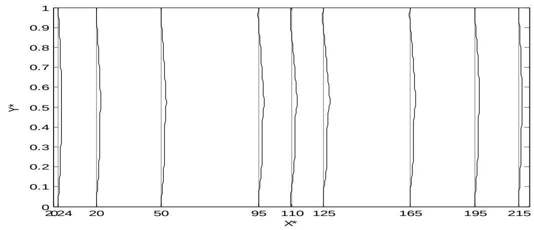

Fig.4.2.5. Mn-20000, Re-100, Magnet Length-22unit

Fig.4.2. Effect of Length of Magnet on Velocity Contour for Fixed Magnetic and Reynold Number

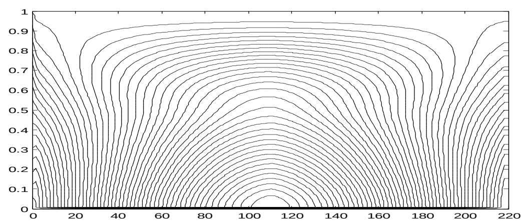

Fig.5.1.1. Considering Magnetic Number Mn- 2×10^4

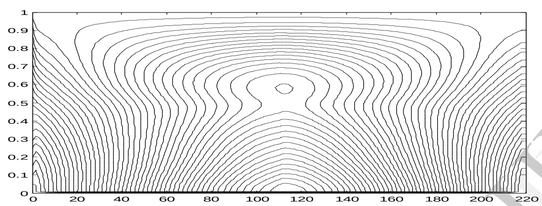

Fig.5.1.2. Considering Magnetic Number Mn-3×10^4

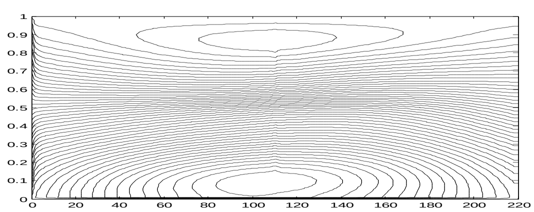

Fig.5.1.3. Considering Magnetic Number Mn-4×10^4

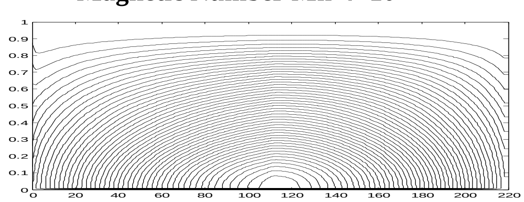

Fig.5.1.4. Considering Magnetic Number Mn-5×10^4

Fig.5.1. Effect of Magnetic number on the streamline contour for a fixed Reynold number

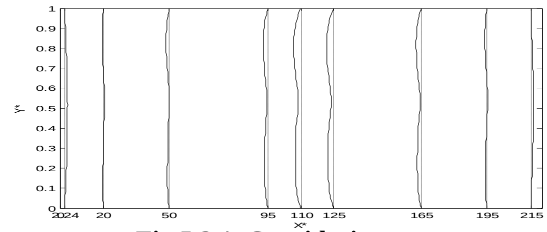

Fig.5.2.1. Considering Magnetic Number Mn-2×10

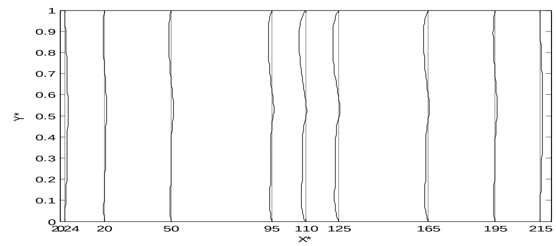

Fig.5.2.2. Considering Magnetic Number Mn-3×10^4

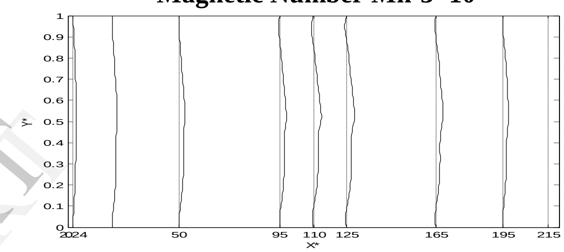

Fig.5.2.3. Considering Magnetic Number Mn-4×10^4

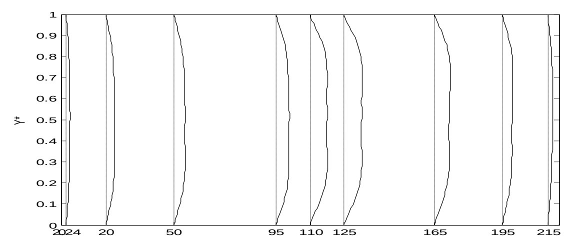

Fig.5.2.4. Considering Magnetic Number Mn-5×10^4

Fig.5.2. Effect of Magnetic number on Velocity profile at Re of 100 and magnet length 20 unit

4.2 Variation of average stagnation pressure along the length of the channel

Fig. 6.1 show the variation average stagnation pressure without considering magnetic number. From the Figure it is cleared that average stagnation pressure gradually decrease along the length of the channel due to friction. Fig.6.2 show the effect of length of magnet on average stagnation pressure for a typical value of Re of 100 and Magnetic number of 2×10^4. Fig.6.3 show the effect of magnetic number on average stagnation pressure for a typical value of Re of 100 and magnet of 20 unit of non-dimensional length. From the Fig.6.2 and 6.3 it is clear that average stagnation pressure increases with increase in magnetic number as well as with the increase in length of the magnet due to formation of recirculating bubble from just after the inlet to just before the outlet of the channel. But there is a sharp rise of average stagnation pressure at the magnetic zone. It has also been observed that as we increase the magnetic number and length of the magnet, its impact has been started earlier on the magnetic fluid flow. The generation of high pressure at that magnetic zone may compress the stenosis, formed inside the artery which will lead to opening of the blockage in the artery.

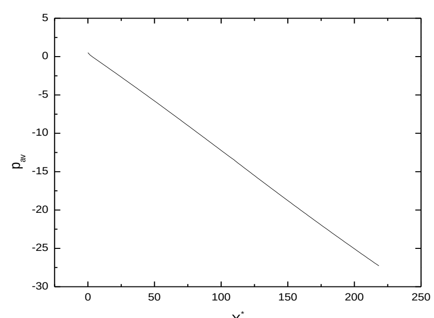

Fig.6.1. Average stagnation pressure without considering Magnetic Number and considering Re-100

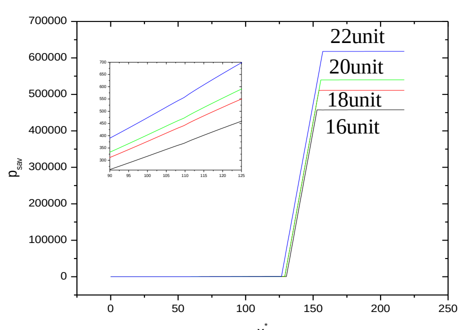

Fig.6.2. considering Re-100 and Mn-20000

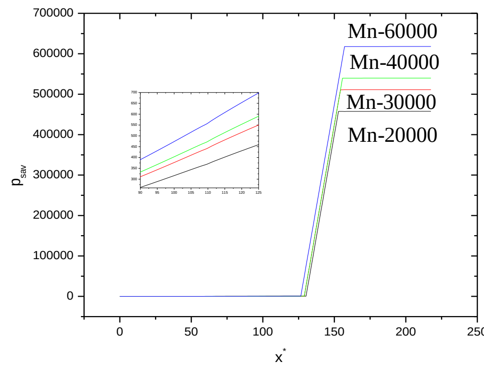

Fig.6.3. considering Re-100 and Magnet length 20 unit

Fig.6. Effect of Length of Magnet and Magnetic number on average stagnation pressure

5. CONCLUSION

The shape and size of the bubble and average stagnation pressure having greater importance in case of various practical applications, such as magnetic hyperthermia and reduction of bleeding, the development of magnetic devices for cell separation, targeted transport of drugs using magnetic particles as drug carriers, magnetic wound or cancer tumour treatment etc, as magnet can control the magnetic particle. It is expected that the rate of heat transfer as well as temperature of the flowing fluid will increase as the recirculating zone increases. It occurs mainly due to conversion of kinetic energy of the flowing fluid in to heat energy. Due to the increasing recirculating zone, retention of blood or magnetic fluid at a particular area will increase as a result of which, toxide medicine, if injected at that location, will get time to be sedimented on the required area, without affecting the important part of the body like heart, kidney, liver, lung etc. Recirculating bubble may create turbulence in the fluid flow which is used for proper mixing in combustor, carburetor etc. The generation of high pressure at that magnetic zone may compress the stenosis, formed inside the artery which will lead to opening of the blockage in the artery.

NOMENCLATURE

H Magnetic field intensity, $Amp.m^{-1}$
H_0 Magnetic field intensity, $Amp.m^{-1}$ at the middle of the channel
L Length of the channel, m
M Magnetization, Amp. m^{-1}
M_n Magnetic Number arising from FHD
P Static pressure, Nm^{-2}
Re Reynolds Number
u Velocity in x-direction, ms^{-1}
U Average velocity, ms^{-1}
v Velocity in y-direction, ms^{-1}
W Height of the channel, m
x, y Cartesian co-ordinates
ρ Density, kg m^{-3}
μ Dynamic viscosity, kg $m^{-1}s^{-1}$
μ_0 Magnetic permeability of vacuum, Tesla. m. $Amp.^{-1}$
λ Magnetic susceptibility

Superscripts

* Dimensionless terms

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