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Investigation of handmade ferrofluids' motion in a ventilated cavity using computational fluid dynamics

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ABSTRACT

In this research, some more applicable ferrofluids are produced and their mechanical specifications are measured, experimentally. Also, their treatments in the ventilated cavity geometry are assessed numerically. The magnetite nanoparticles are produced by a chemical combination of Fe^{2+} and Fe^{3+} with NH_3. In order to solve the nanoparticles in the new mediums, a proper coating is added to them. Then they are solved in kerosene, brake oil, hydraulic oil and motor oil with different particle fractures. A pressure-based procedure to solve Navier-stokes equations with finite volume formulation is developed to simulate a magnetic fluid in ventilated cavity geometry. One of the usages of this geometry is found in magnetic separation. The ventilated cavity geometry includes a square medium with one velocity inlet and one velocity outlet. In addition, a magnetic field due to a DC current carrying wire is employed on the geometry. The magnetic field intensities, its positions and ferrofluids' mediums are changed. Then, the flow characteristics for each case are obtained to find the optimum situation for magnetic separation. Finally, the optimum situations for magnetic separation and for local cooling are obtained and the best ferrofluid is suggested for each application.

Keywords: *Ferro fluid; CFD; Ventilated cavity; Magnetic separation; MHD.*

INTRODUCTION

Ferrofluid or magnetic fluid is an over growing topic for mechanical engineers in the current decade. A ferrofluid is a type of fluid which absorbs to a magnetic field source. Generally, magnetic fluids are divided into two groups: hydrophobic and hydrophilic. The hydrophobicity of ferrofluids is usually due to the surfactant which is used to stabilize the magnetic nano particles in the liquid carrier. In the case that the surfactant is polar it would be solved in polar solvents like water but if the surfactant is nonpolar, it would solve in nonpolar surfactants like oil thus the ferrofluid becomes hydrophobic. Magnetic fluids' industrial background comes back to 1940.

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In that time magnetic fluids – with particle size of a few microns – were used in magnetic clutches. In 1960 ferrofluids with nano sized particles were produced on behalf of NASA. The aim was to produce a magnetic nano particle which can be solved in space craft fuel so the movement of the fuel could be controlled in the space (A gravity free place).

Thereafter, ferrofluids were used as a non-porous seal. Also with the aid of these fluids, high quality load speakers were produced. This technology annually is being applied in more than 100 million load speakers. In medicine, magnetic fluids are used as contrast agents for Magnetic Resonance Imaging and can be used for cancer detection. They are in this case composed of iron oxide nanoparticles and called SPION, for "Super paramagnetic Iron Oxide Nanoparticles". There is also much experimentation with the use of ferrofluids in an experimental cancer treatment called magnetic hyperthermia. It is based on the fact that if this kind of fluid is placed in an alternating magnetic field it releases heat [1].

A lot of researches in this field have been done in the last decade. Some tried different methods for solving the flow parameters like two phase solutions or lattice Boltzmann methods [2, 3]. Some other papers refer to different geometries like cavity, Journal bearing or micro channels [3-8] and some of them used different magnetic field sources like permanent magnet or a magnetic dipole [9, 10]. In 2005, Rhodes et al in an experimental work placed a droplet of ferrofluid in a Hele - Shaw cell then the droplet was exposed to different magnetic fields. Due to the different magnetic field types and strengths, different shapes of magnetic droplet were obtained [10]. In the case of simple geometries, In 2003 Chang et al. presented a paper on the stability of ferrofluid flow between two concentric cylinders. In his work the mentioned fluid was exposed to a magnetic field and so the specifications of flow were estimated [11]. In March of 2006, Jue presented an investigation of ferrofluid flow in cavity geometry. In his work convective forces and the force due to a magnetic field source were combined [12]. Rinaldi et al studied magnetic fluid flow between two concentric cylinders to investigate the magneto viscosity of ferrofluids [13]. He could reach to zero magneto viscosities for certain magnetic fields. Singh and Bajaj also used this geometry to estimate ferrofluid stability [14].

Although fine works have been done on this kind of fluid, there are still some points which need to be discussed. Most of working ferrofluids are based on kerosene or water. These mediums can reduce their applicability in a lot of industrial purposes. Also a vast number of papers are investigating ferrofluids' behavior in situations which low density fluids cannot tolerate e.g. magnetic seals. So in this work we tried to produce some more applicable ferrofluids and then their mechanical specifications were measured, experimentally. Afterward, the ventilated cavity geometry was solved via CFD methods using these new ferrofluids' specifications.

Governing Equations

In order to determine ferrofluids' behavior in the presence of a magnetic field, the continuity and enhanced Navier-Stokes equations are used:

$$\nabla . V = 0 \tag{1}$$

$$\rho \frac{dV}{dt} = -\nabla P + \rho g + \mu \nabla^2 V + \mu_0 M . \nabla H \tag{2}$$

In the above equations: μ, μ_0, M and H are referred to fluid viscosity, air permeability, magnetization of ferrofluid and the magnetic field intensity respectively. Actually the only term which is added to the familiar Navier-Stokes equations is the last term of equation 2($\mu_0 M . \nabla H$). As we know the conservation of mass equation does not change, because the final result of the steady state flow should satisfy the mass conservation condition. But the conservation of momentum equation should vary due to the magnetic momentum. The non dimensional forms of these equations in the Cartesian coordinate system can be written as [15 and 16]:

$$\frac{\partial u^*}{\partial x^*} + \frac{\partial v^*}{\partial y^*} = 0 \tag{3}$$

$$\frac{\partial}{\partial x^*}\left(u^{*2}-\frac{1}{\mathrm{Re}}\frac{\partial u^*}{\partial x^*}\right)+\frac{\partial}{\partial y^*}\left(u^*v^*-\frac{1}{\mathrm{Re}}\frac{\partial u^*}{\partial y^*}\right)$$
$$=-\frac{\partial p^*}{\partial x^*}+\beta h_m^*\frac{\partial h_m^*}{\partial x^*} \qquad (4)$$
$$\frac{\partial}{\partial x^*}\left(u^*v^*-\frac{1}{\mathrm{Re}}\frac{\partial v^*}{\partial x^*}\right)+\frac{\partial}{\partial y^*}\left(v^{*2}-\frac{1}{\mathrm{Re}}\frac{\partial v^*}{\partial y^*}\right)$$
$$=-\frac{\partial p^*}{\partial v^*}+\beta h_m^*\frac{\partial h_m^*}{\partial v^*} \qquad (5)$$

The dimensionless variables are defined as:

$$x^*=\frac{x}{l},\qquad y^*=\frac{y}{l},\qquad u^*=\frac{u}{U_{in}},$$
$$v^*=\frac{v}{U_{in}},\qquad p^*=\frac{p}{\rho U_{in}^2},\qquad \mathrm{Re}=\frac{\rho U_{in} l}{\mu},$$
$$\mathrm{h}_{\mathrm{m}}^*=\frac{h_m}{h_{mo}},\qquad \beta=\frac{\mu_0\chi_m(h_{mo})^2}{\rho U_{in}^2}$$

Here, l refers to the length of cavity; U_{in} is the inlet velocity, h_{mo} is the characteristic value of magnetic field intensity and ρ,μ,μ_0 are referred to the density, viscosity and the gap magnetic permeability, respectively. In rest of this text, the superscript of * is deleted for simplicity, while all the used parameters are dimensionless.

In order to solve this set of equations, next step is to calculate h_m. In this paper, a wire was used as a magnetic field source. It's known that the magnetic field intensity is a function of the magnetic field strength and the distance between the particles and the magnetic source. In this case, the magnetic field strength is proportional with the current of the wire. The field lines would be concentric circles with the wire at their center. So the magnetic field intensity for any point on the geometry is calculated by this equation:

$$h_m(x,y)=\frac{I}{2\pi\sqrt{x^2+y^2}} \qquad (6)$$

Since the value of h_m is neither a function of the fluid velocity nor time, it will remain constant during the solving processes.

EXPERIMENTAL

The magnetite nanoparticles were produced by a chemical combination of Fe^{2+} and Fe^{3+} with NH_3, the black deposit of Fe_3O_4 nanoparticles will be produced. In order to solve the nanoparticles in the new mediums, a proper coating should be added to them. In this case the oleic acid was the hydrophobic surfactant; which was added to the particles while their mixture with water was heated. Then they were solved in kerosene, brake oil, hydraulic oil and the motor oil with different particle fractures (Figure 1).

Fig. 1. Ferrofluid based on hydraulic oil

The effect of both density and kinematic viscosity of these four ferrofluids are measured. In order to measure the kinematic viscosity of each ferrofluid a Cannon-Fenske Transparent Viscometer (CFR) was used. This viscometer has a glass tube and an oil bath (Figure 2). When this tube is filled with ferrofluid, the exit time can be measured. There is a table enclosed to this device which is calibrated for temperature and from it, the kinematic viscosity versus time can be obtained.

Fig. 2. Cannon-Fenske viscometer and the oil bath

The measured kinematic viscosities for the ferrofluids are presented on Table 1. As can be seen, the motor oil and kerosene have the maximum and minimum kinematic viscosities respectively. These viscosities will be used in the CFD code as an identifier for the medium changes.

Table 1. kinematic viscosity for handmade ferrofluids

Medium fluid	*kinematic viscosity*
kerosene	*11.493 mm²/sec*
Hydraulic oil	*84.544 mm²/sec*
Brake oil	*62.615 mm²/sec*
motor oil	*256.274 mm²/sec*

RESULTS AND DISCUSSION

It is worth mentioning that all the parameters in this study are Dimensionless. As shown in Figure 3, the geometry which is solved is a 3*3 cavity with 1 entrance and 1 exit. The entrance and the exit width are 1 and 0.6, respectively. The velocity at the entrance is assumed to be 1(dimensionless) and the no slip condition is applied to all walls. A 100*100 mesh was generated and the Control Volume method was applied to solve the enhanced Navier Stokes equations on the geometry. The mesh independence test is shown in Figure 4. As can be seen the results for two meshes 100*100 and 120*120 are almost the same. So for the rest of this paper 100*100 mesh is chosen.

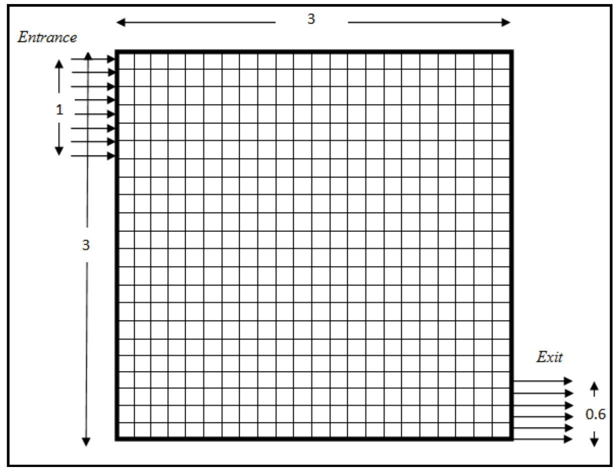

Fig. 3. The Geometry of the solution with 1 entrance and 1 exit.

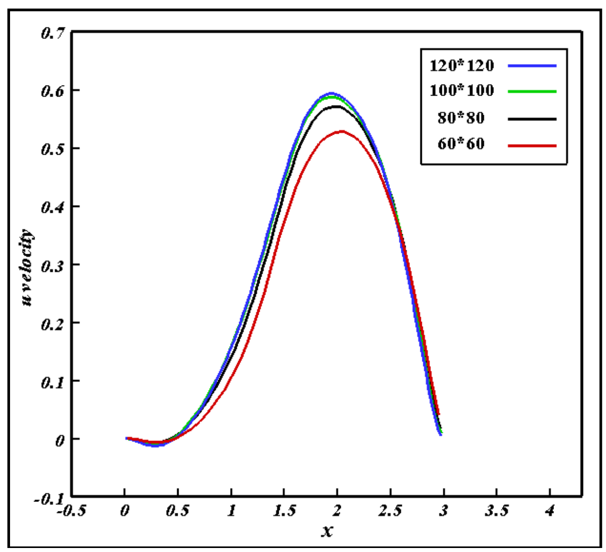

Fig. 4. Mesh independence results

Also to verify the numerical simulation, the results of *v* velocity in the horizontal middle section of a lid-driven cavity are compared with Ghia et al [17] and Wahba [18]. These comparisons verify the present numerical simulation (Figure 5).

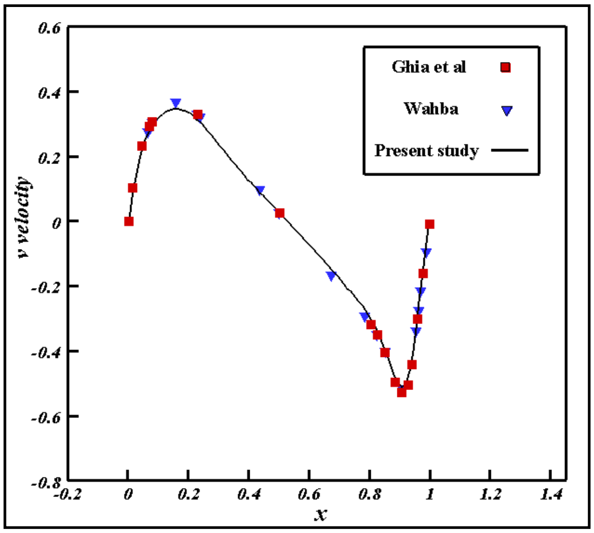

Fig. 5. Comparison of the present results with [17, 18]

The admixture of fluid is a significant factor in many industrial applications e.g. magnetic separation. In this study, the mention parameter for different Re Numbers is assessed.

First of all, the magnetic field position is considered to be fixed on the bottom left corner of the cavity and the ferrofluid is based on Kerosene. The results for the magnetic field intensities H_m = 0, 0.67, 0.8 and 1 are presented in Figure 6 a-d.

As it can be seen, in the case of no magnetic field there are two main vortexes on the whole region. As the magnetic field intensity starts to grow, a third vortex begins to grow as well. This can provide a very fine local mixing environment with respect to the entrance and exit.

On the second attempt, the ferrofluid mediums were changed. The most famous mediums for ferrofluids are water and kerosene. But as mentioned before, due to their low density and viscosity and also the corrosion effects of water, they cannot provide wide range of mechanical applications. So the new handmade ferrofluids were tested under the same conditions. In this case, the magnetic field source is fixed on the right bottom corner with an intensity of 0.67 for all cases and the results are demonstrated for different mediums (Figure 7).

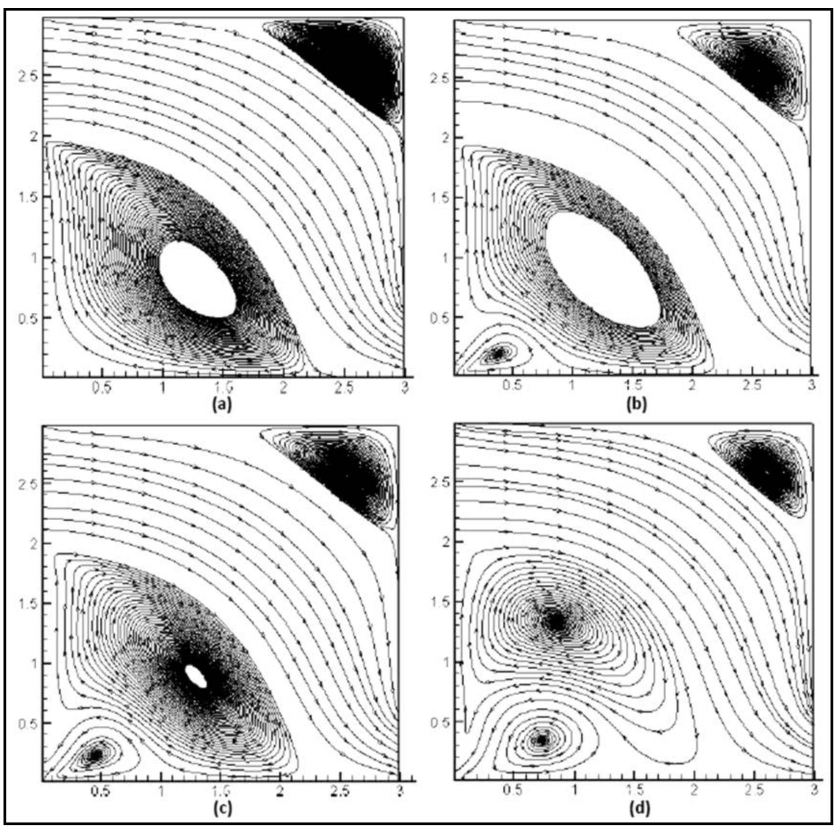

Fig. 6. The stream lines of the flow for a certain ferrofluid (Kerosene-based) for different magnetic field intensities. H_m for a = 0, b = 0.67, c = 0.8 and d = 1.

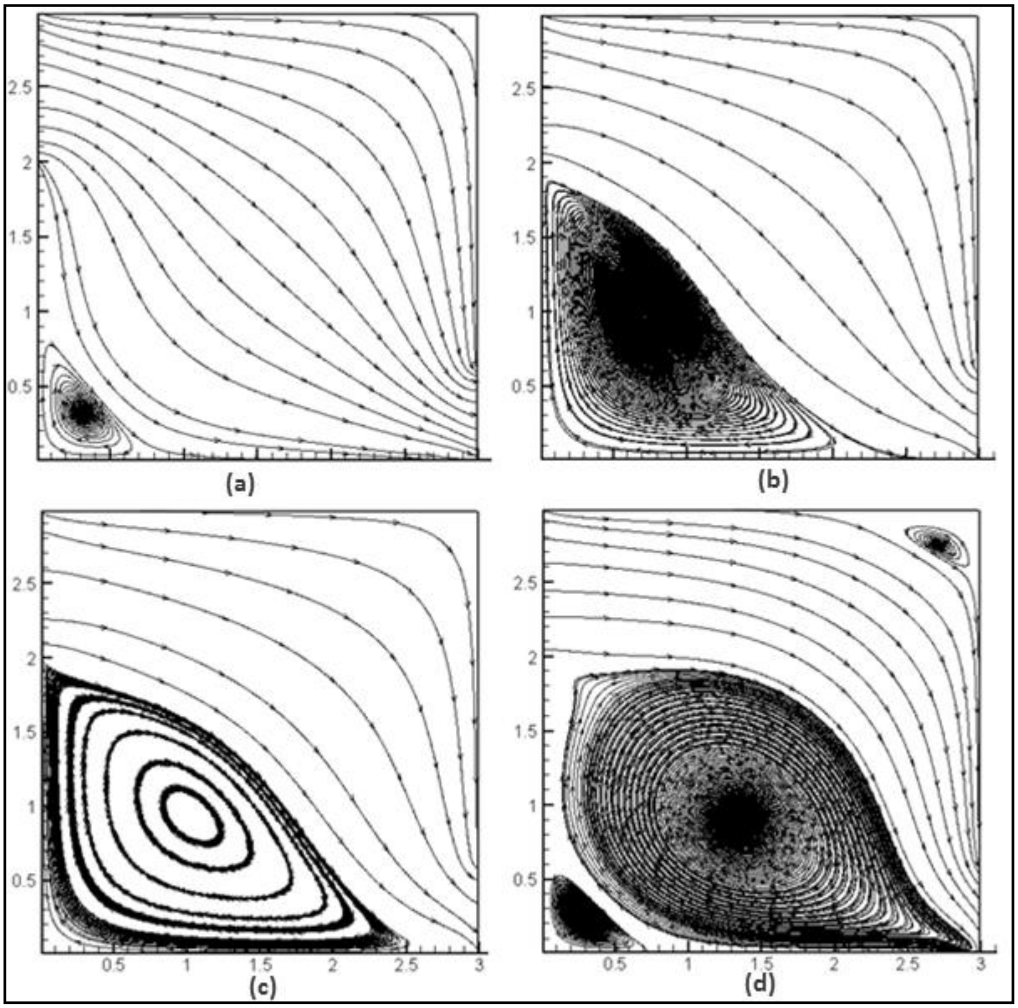

Fig. 7. The stream lines of the flow for the handmade ferrofluids based on: a. Motor oil, b. Hydraulic oil, c. Brake oil and d. Kerosene.

Here, Figure 7(a-d) is in the case of Motor oil-based ferrofluid. As can be seen in this case the main vortex is so smaller than all other mediums so that the fluid flow can be assumed laminar in most regions of the geometry. This, in return, will provide higher pressure field on the system. On the other hand the biggest vortex is for the case of kerosene-based ferrofluid (Figure 7d). Although it provides better mixing than the others, but regarding to its poor mechanical properties and its flammability, the Hydraulic oil and Brake oil may be considered for different purposes as well. Finally, four different locations for the magnetic field source were chosen for particular magnetic field intensity and Re. Figure 8 presents the stream lines of each case throughout the cavity. These locations are at a) the left-bottom corner, b) the right-upper corner, c) the right-bottom corner and d) the left-upper corner of the cavity.

Figure 8 basically, shows that any changes in the place of the magnetic field source will have a direct effect on the ferrofluid flow. In the cases of Fig.8-a and Fig.8-c, it can be seen that the lower vortex is extended and it has almost filled the whole region. With a more precise look at these cases, we will recognize that the flow in the case a passes on the vortex but in the case c it is driven under the vortex due to the magnetic field. Also as mentioned before, the Fig.8-b and Fig.8-d positions are considered for local mixings. In these cases, case 8-b because of its extra vortex can be assumed to work more efficiently. Also the velocity profiles for each case are presented on Figure 9.

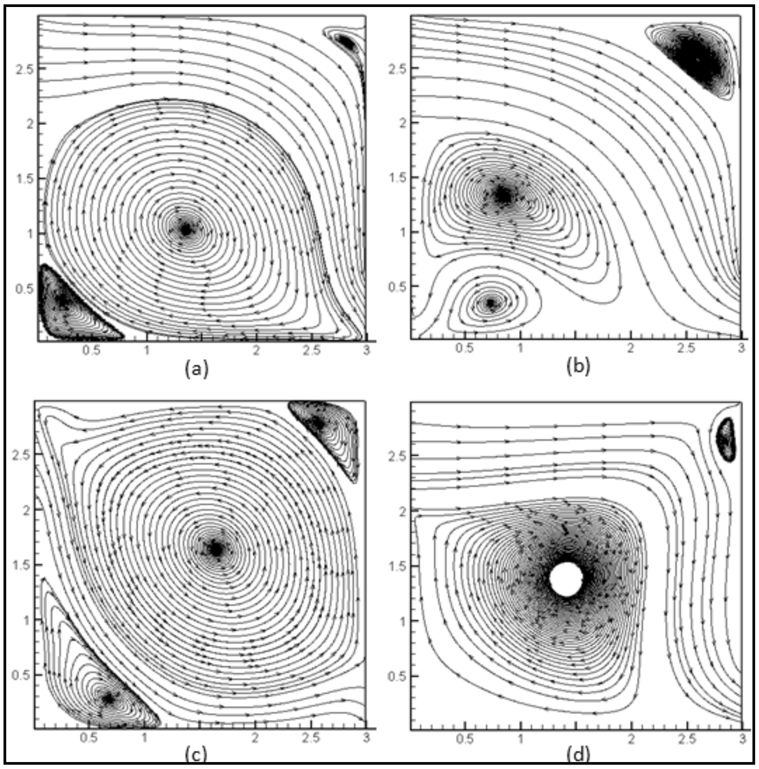

Fig. 8. Stream lines changes due to the location change of the magnetic source for a certain ferrofluid (Kerosene-based) where the magnetic field sources are located on a. the right-bottom corner, b. the left-bottom corner, c. the left-upper corner and d. on the right-upper corner of the cavity.

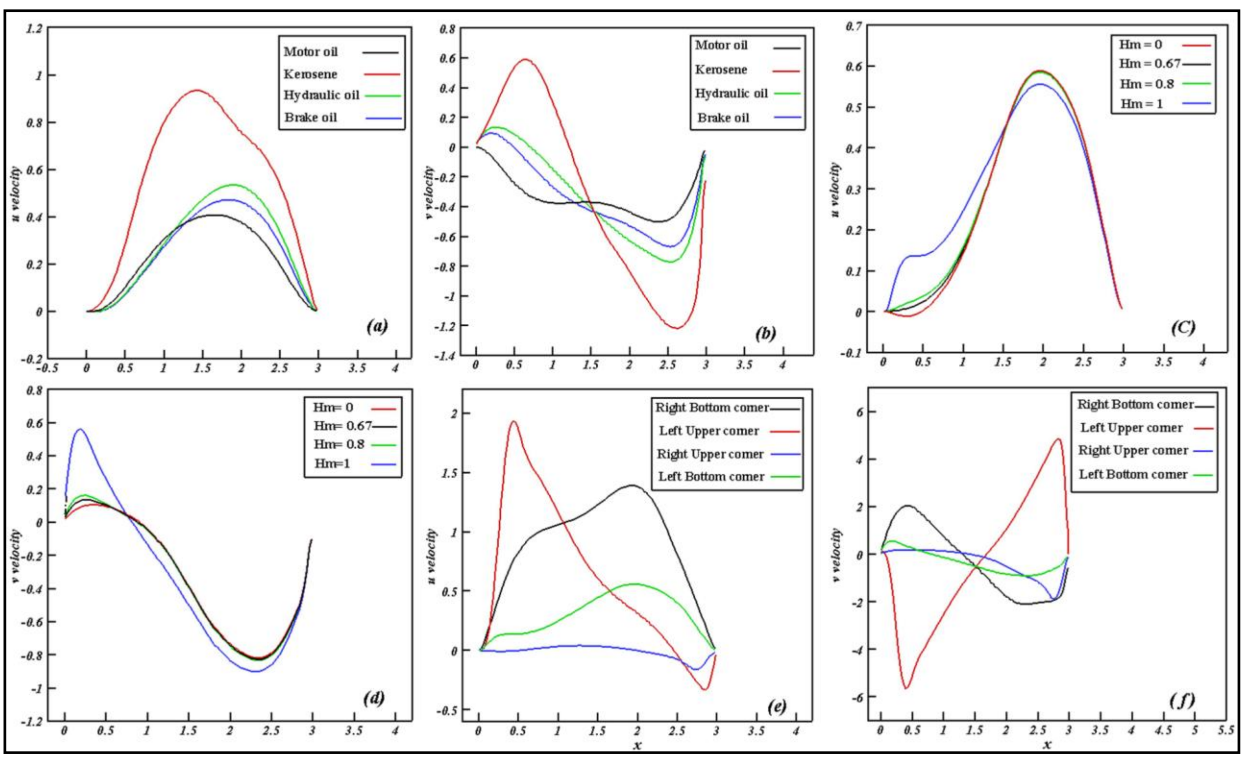

Fig. 9. *u* and *v* velocity profiles for each case. *(a, b)*: For Four different based handmade ferrofluids, *(c, d)*: For different Magnetic field intensities for kerosene based ferrofluid and *(e , f)*: For different position of magnetic field source for kerosene based ferrofluid with a fixed intensity.

In Figure 9, the *u* and *v* components of the velocity are plotted for *a,b* different mediums, *c,d* different magnetic field intensities and *e,f* for different magnetic field source positions. As can be seen on Figure 9a and 9b the maximum changes in the velocity profiles is for the kerosene and the minimum is for the motor oil. In Figure 9c and 9d the changes of the velocity profiles due to the increase of the magnetic field intensity are presented. Figures 9e and 9f show the most influenced cases due to repositioning are the left – upper and right – bottom corner positions. In mentioned positions, the lower vortex extends and occupies almost the whole cavity. This can also be seen on the velocity profiles, where the *v* velocity amplitudes are almost four times higher than the right-upper and left-bottom cases.

CONCLUSIONS

The enhanced Navier – Stokes equations of magnetic fluids are solved in the ventilated cavity geometry. The results for ferrofluids flow are obtained for different handmade ferrofluids, magnetic field source positions and intensities. These results showed that for the case of kerosene-based ferrofluids, the best circulation behavior is observed and the motor oil-based ferrofluids could tolerate the highest pressure gradient. So the usage of these new ferrofluids can be defined per their physical specifications for different environmental situations. Also the position of left – upper and right – bottom corners showed the maximum influences of the magnetic field on the flow. In the case of the right – upper corner position, influence of the field is the least. In the case of a left – bottom corner position, 2 main vortices will appear which makes this position the best for local circulation.

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