Journal of Applied Fluid Mechanics, Vol. 10, No. 5, pp. 1261-1270, 2017.
Available online at www.jafmonline.net, ISSN 1735-3572, EISSN 1735-3645.
DOI: 10.18869/acadpub.jafm.73.242.26935

Curvature Effects on the Electromagnetic Force, Efficiency, and Heat Transfer of a Weak Low Profile Magneto-Hydrodynamic Blanket Propulsion System

M. A. Feizi Chekab and P. Ghadimi †

Department of Marine Technology, Amirkabir University of Technology, Tehran, Iran

†*Corresponding Author Email: pghadimi@aut.ac.ir*

(Received July 16, 2016; accepted April 23, 2017)

ABSTRACT

The present study concerns the numerical assessment of the effects of longitudinal and lateral curvature of a flexible low profile magneto-hydrodynamic blanket on its thrust, performance, and heat transfer. To this end, after validating the solver with the analytical solution of the Hartman problem, negative and positive curvatures are taken into consideration in lateral and longitudinal directions on the blanket and electromagnetic and velocity fields, temperature distributions, force density fields and profiles are extracted and compared to the flat MHD blanket. It is demonstrated that negative curvatures increase the thrust force and temperature of the blanket and the reverse occurs for the positive curvatures. It is also shown that the longitudinal curvature affects the blanket thrust by -2.5% up to 5.2%, its efficiency by nearly 6% and the temperature change from -25 up to 28%. On the other hand, for the lateral curvatures, the overall thrust produced by the blanket is affected by about -6% to +6%, the efficiency is affected by -10% to 25% and temperature change is affected by -2 to 6%.

Keywords: Magneto-hydrodynamics (MHD); MHD propulsive blanket; Heat transfer; Curvature effects; Blanket thrust; Efficiency.

1. INTRODUCTION

After introducing the MHD propulsive blanket as a thin propulsion system which could be attached to the external surface of vessels in water (Feizi *and* Ghadimi 2016), the present study focuses on the performance issues which arise in response to the curvature of the propulsive blanket. In order to attach the MHD propulsive blanket to a submerged body of any kind, having a curved surface is almost inevitable and it is necessary for the blanket to be flexible. Therefore, assessing the effects of the convex and concave curvatures on the blanket is very important and imperative.

Marine magneto hydrodynamic propulsion systems were first introduced by Rice (1961), Friauf (1961) and Way (1967) in their patents related to MHD propulsion systems for the surface and underwater vessels in early 60s and perhaps one of the most famous implementation of the MHD propulsion system is the Yamato vessel commissioned in early 90s (Motora *et al.* 1991).

Different aspects of the MHD propulsion systems have been studied through analytical, experimental, and numerical methods, afterwards. For instance, the effects of different electric and magnetic field strength and patterns were numerically investigated by Han *et al.* (2002) and also experimentally by Lin *et al.* (1992). The effects of magneto-hydrodynamic channel shapes were analytically and experimentally assessed by Gilbert *et al.* (1995) and numerically analyzed by Doss *et al* (1990). Abdollahzadeh (2014) also studied the stability issues of the magneto-hydrodynamic propulsion systems.

An important issue in the numerical analysis of MHD flows is the coupled numerical analysis of momentum and mass transfer, electromagnetic and heat transfer, which is used in the present study to investigate the targeted problem. Many studies have been published from 1960s to the present on this topic, namely Poots *et al.* (1961) who solved two dimensional MHD problems taking into account the heat transfer of the fluid along with the electromagnetic equations. Also, Alpher (1961) studied the magnetohydrodynamic flow between two plates considering heat transfer. The numerical coupling of these equations are still of high interest. Kiasatfar *et al.* (2014) and Hassan *et al.* (2016) are good examples, who studied the MHD pumps and MHD flow in the micro channels, respectively.

Because of the heating problems of the MHD systems, the use of super conduction was experimentally studied by Meng *et al.* (1991), Yan *et al.* (2002) and Hales *et al.* (2006) among many other researchers. Also, another issue which has been of interest in this field is the water conductivity enhancement which has been experimentally studied by Lin *et al.* (1990, 1991) to improve the electro-magnetic thrust production and efficiency of the system. Meanwhile, some researchers have attempted the use of MHD in flow control (Brown *et al.* 1994) and drag reduction (Shatrov *et al.* 2007).

As pointed out earlier, the present study focuses on the numerical assessment of the effects of longitudinal and lateral curvature on the thrust production, the efficiency and heat transfer of the MHD propulsive blanket which has been previously introduced by the present authors (Feizi and Ghadimi 2016). The Ansys-CFX numerical software has been used in the current study in order to validate the analysis. Accordingly, the Hartman problem has been modeled and compared to the analytical solutions (DePuy 2010).

The governing equations, validation, and discussion of results are presented in the following sections.

2. GOVERNING EQUATION

The present numerical analysis involves the mass, momentum, and energy equations along with the electromagnetic and heat transfer equations. The conservation of mass, momentum, and energy equations are considered as follows (ANSYS Inc., 2013):

$$\frac{\partial \rho}{\partial t}+\nabla(\rho U)=0 \tag{1}$$

$$\frac{\partial \rho U}{\partial t}+\nabla\cdot(\rho U\otimes U)=-\nabla p+\nabla\cdot\tau+F_{emag} \tag{2}$$

$$\frac{\partial(\rho h_{tot})}{\partial t}-\frac{\partial p}{\partial t}+\nabla\cdot(\rho U h_{tot})=\nabla\cdot(\lambda\nabla T)+\nabla\cdot(U\cdot\tau)+S_E \tag{3}$$

where ρ is the fluid density, U is the velocity vector, τ is the viscous stress, T represents the temperature, λ is the thermal conductivity and $\nabla.(U.\tau)$ is the viscous work term. Also, the term S_E represents the energy source due to resistive heating of the fluid given by *(J.E)* where J is the current density and E is the electric field.

In the above equations, F_{emag} is the electromagnetic momentum source term calculated using Maxwell equations as follows:

$$h\nabla\times E=-\frac{\partial B}{\partial t} \tag{4}$$

$$\nabla\times H=J+\frac{\partial D}{\partial t} \tag{5}$$

$$\nabla\cdot B=0 \tag{6}$$

$$\nabla\cdot D=\rho_e \tag{7}$$

In the above equations, B is the magnetic induction, D is the electric displacement, E is the electric field, H is the magnetic field, J is the current density, and ρ_e is the electric charge density. Also the conservation of electric charge is extracted as follows:

$$\nabla\cdot J=\frac{\partial \rho_e}{\partial t} \tag{8}$$

Also, constitutive relationships are applied to close the system of equations (Thess *et al.* 2007). Using these equations, F_{emag} is calculated by

$$F_{emag}=J\times B \tag{9}$$

where $J=\sigma(E+U\times B)$ and σ is the electrical conductivity. Also, h_{tot} is the total enthalpy related to the static enthalpy *h (T, p)* defined by

$$h_{tot}=h+\frac{1}{2}U^2 \tag{10}$$

In the present study, the heat transfer in the electrodes are analyzed using the conjugate heat transfer governed by the equation

$$\frac{\partial(\rho h)}{\partial t}=\nabla\cdot(\lambda\nabla T) \tag{11}$$

where h, ρ, and λ are the enthalpy, density, and thermal conductivity, respectively.

In the present study, the flow has been assumed laminar and incompressible, which implies a constant density for the water. Also, the density of the fluid does not vary with temperature. Gravitational forces are neglected to bypass the effects of the direction off the blanket in the results.

The reciprocal effects of electric currents and magnetic induction in the fluid are taken into account. However, it has been assumed that the external magnets which provide the primary magnetic field are not affected by the electromagnetic state of the fluid. Also, it has been assumed that the electric and thermal conductivity of the fluid and the solids are constant and not affected by the temperature. Finally, the resistive heating is assumed to be the only heat source of the problem and no volumetric heat source has been added to the analysis.

As pointed out earlier, the numerical analysis has been performed using the Ansys-CFX commercial software. The mentioned software is using the Finite element based Finite volume method to solve the mentioned equations (equations 1 through 11).

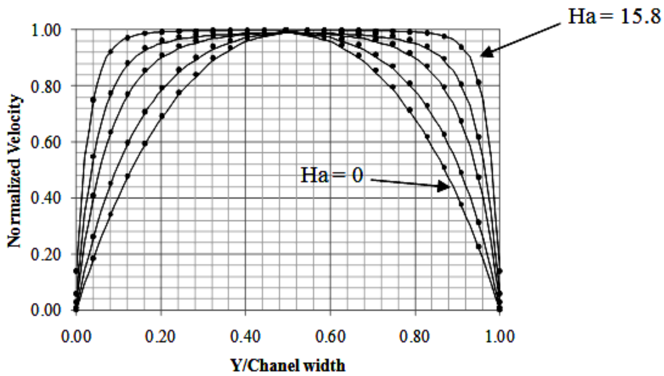

Fig. 1. Normalized velocity Vs Normalized vertical position at different Hartman numbers for Numerical (-) and analytical (●) solutions.

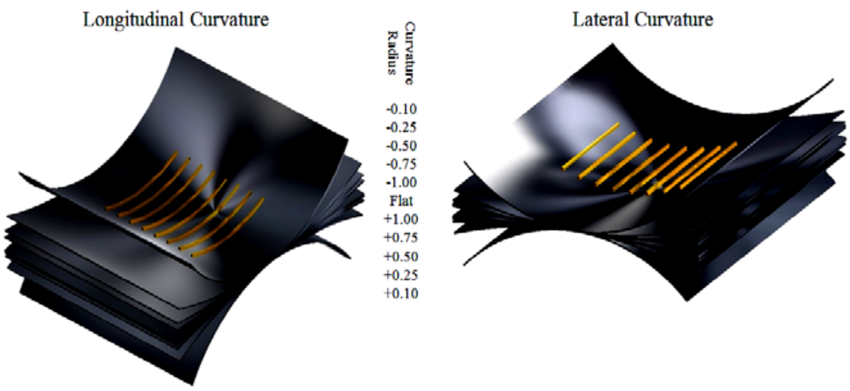

Fig. 2. Lateral and Longitudinal Curvatures and the curvature radii taken into account.

In this method, the domain is first discretized using an appropriate mesh. Subsequently, the mesh is used to form finite volumes used to conserve relevant quantities such as mass and momentum.

To this end, the equations are integrated over each control volume, and the volume integrals are then converted to surface integrals over each face of the finite volume. The obtained integrals are then discretized and solved in a system of equations.Afterward, the obtained solutions are evaluated inside each finite volume using shape functions to improve the resolution of the solution.

Since the main focus of the present paper is the study of the MHD blanket using this software, one may refer to the Ansys-CFX theory guide (2013) for more details on the numerical discretization of the equations.

3. Validation

In order to validate the MHD solution of the solver, the Hartman problem (DePuy 2010; Thess *et al.* 2007) is investigated for different Hartman numbers including Ha = 0, 3.2, 6.3, 9.5, and 15.8, and the obtained results are compared against available analytical solutions. In Fig. 1, the normalized velocity profile obtained for different considered cases and their analytical solutions are displayed.

The root mean square of errors of the numerical solution compared to analytical solutions displayed in Fig. 1 is 0.16% for all the considered cases which is reasonable for engineering purposes. More details on the validation process were presented in the previous works by the present authors (Feizi and Ghadimi 2016).

4. Results And Discussion

As mentioned in the introduction, different parametric analyses on the flat MHD propulsive blanket were presented in a previous work by the present author (Feizi and Ghadimi 2016). However, in the current study, the effects of the blanket curvature on its functionality compared to the flat blanket are investigated. The main functional parameters of interest of the MHD blanket include the generated force, efficiency, and heat exchange with its environment which manifests as temperature raise of the surrounding fluid. As illustrated in Fig. 2, in this study, longitudinal and lateral curvatures are taken into consideration.

As evident in Fig.1, ten different curvatures are applied both in longitudinal and lateral directions to conduct the targeted parametric analyses. The setup of the considered problem is illustrated in Fig. 3.

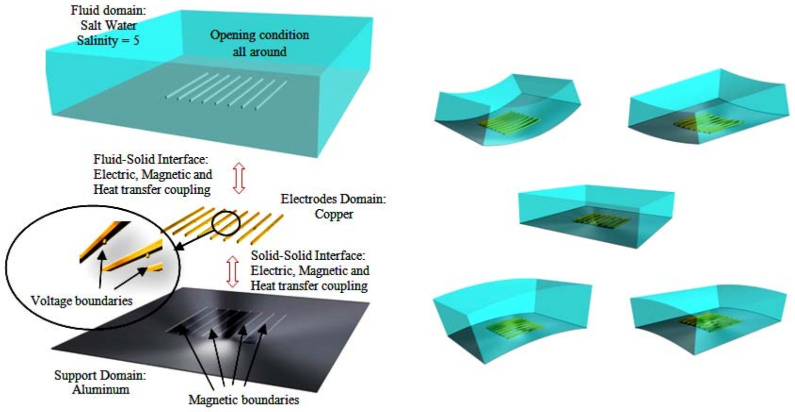

Fig 3. Problem setup and prescribed boundary conditions.

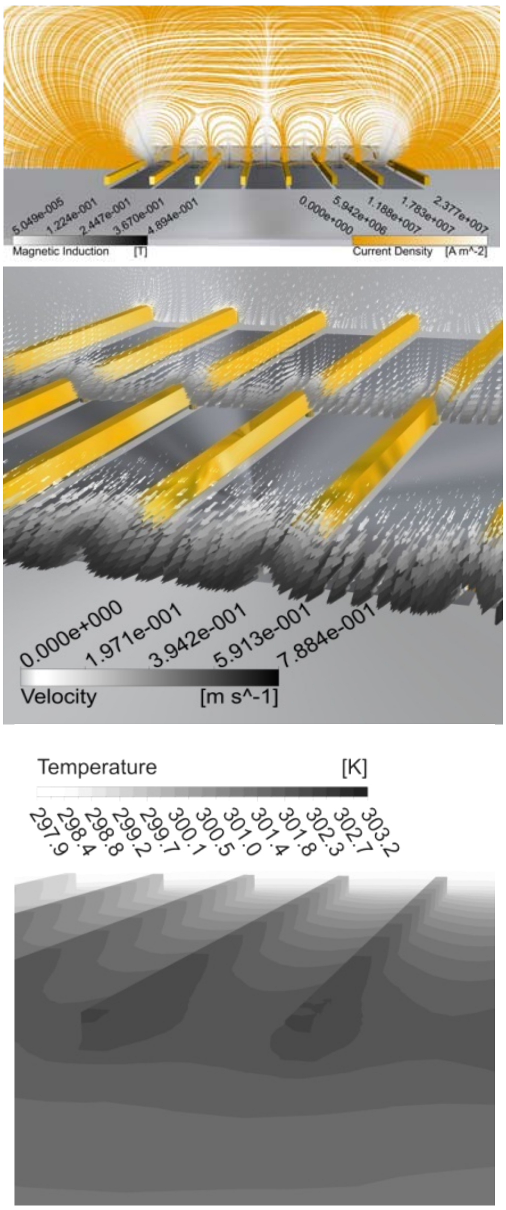

Fig. 4. Magnetic and Electric Fields (Top), Velocity Vector Field (left) and Temperature Contour for the flat blanket (Right).

As observed in Fig.3, three different numerical domains are modeled. The fluid domain contains water with an electric conductivity of 5 *S/m*. Opening boundary condition is applied on all free sides of this domain. Electromagnetic, heat transfer, and momentum equations are taken into account inside the domain, along with the magneto-hydrodynamic momentum term subject to equation (5). The dimensions of the domain are 200mm by 100mm by 50mm.The electrodes domain is a solid domain containing 8 copper electrodes. The electrodes are 72 *mm* long, 2mm high, and 1mm wide, enhanced with a voltage boundary of 0.75*mm* radius and 1mm height placed at 11mm distance from each other. Each adjacent pair of electrodes provides a 24 V electric potential. The support domain is a solid domain made of aluminum on which the electrodes and water domain are placed.

The support domain is 1*mm* thick and contains 7 magnetic boundaries (10*mm* by 72*mm*), each providing a 0.25*T* magnetic field on the surface of the support domain. Electro-magnetic and heat transfer equations are taken into account in solid domains. Also, as presented in Fig. 3, the interfaces between the domains ensure the continuum of electro-magnetic and heat transfer. It should be pointed out that only the space above the middle pair of electrodes is used to extract the final results of the present study to ensure the elimination of boundary effects.

After the setup of the problem, the flat (Curvature Radius = Infinity) MHD propulsive blanket is first analyzed to provide the base for comparing the curved blankets.

The velocity and electromagnetic force vector fields along with the temperature contour on the blanket and electrodes are illustrated in Fig.4.

As observed in Fig.4, the electric and magnetic fields are present a good orthogonality, especially between the middle pair of the electrodes. The temperature of the blanket reaches 303.2 K on the extreme tip of the electrodes which represents a maximum temperature rise of 5.05 K in the water. The fluid velocity reaches a maximum of 0.788 m/s in vicinity of the blanket at the end of the electrodes. The thrust produced by $1\,m^2$ of the blanket reaches 12.95 N with an efficiency of 0.00245%.

To avoid any repetitious comments, for more comprehensive explanations on the performance of flat MHD propulsive blankets, interested readers are referred to the authors' previous work on the subject (Feizi and Ghadimi 2016).

Figure 5 illustrates the magnetic and electric fields of the extreme curvatures. To avoid unnecessary elongation of the manuscript, illustrations of the intermediate curvatures are not presented.

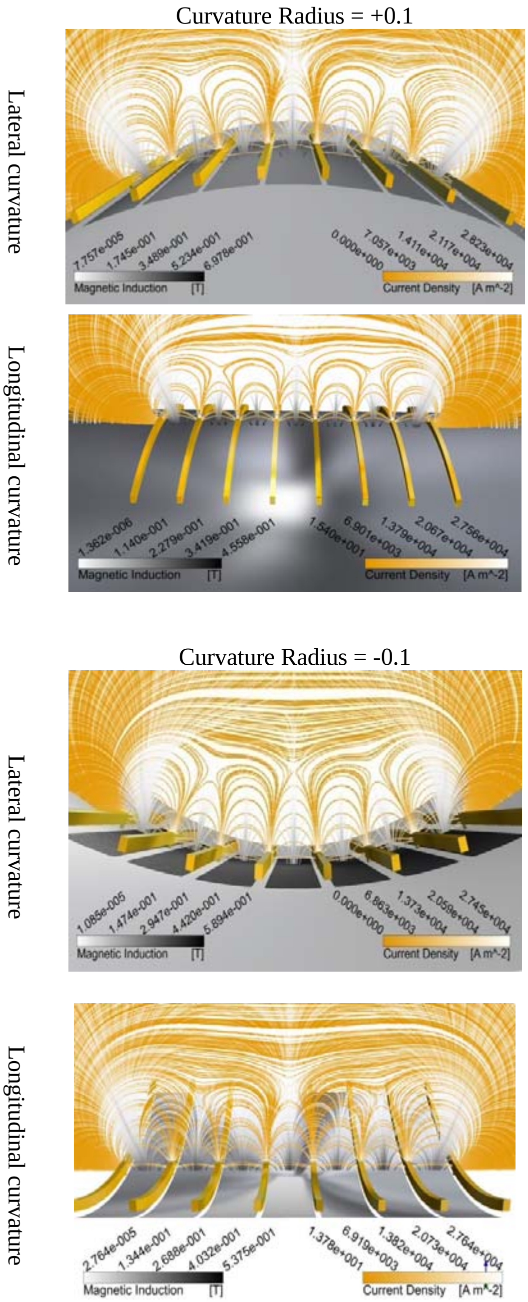

Fig. 5. Magnetic and Electric fields for the extreme curvatures.

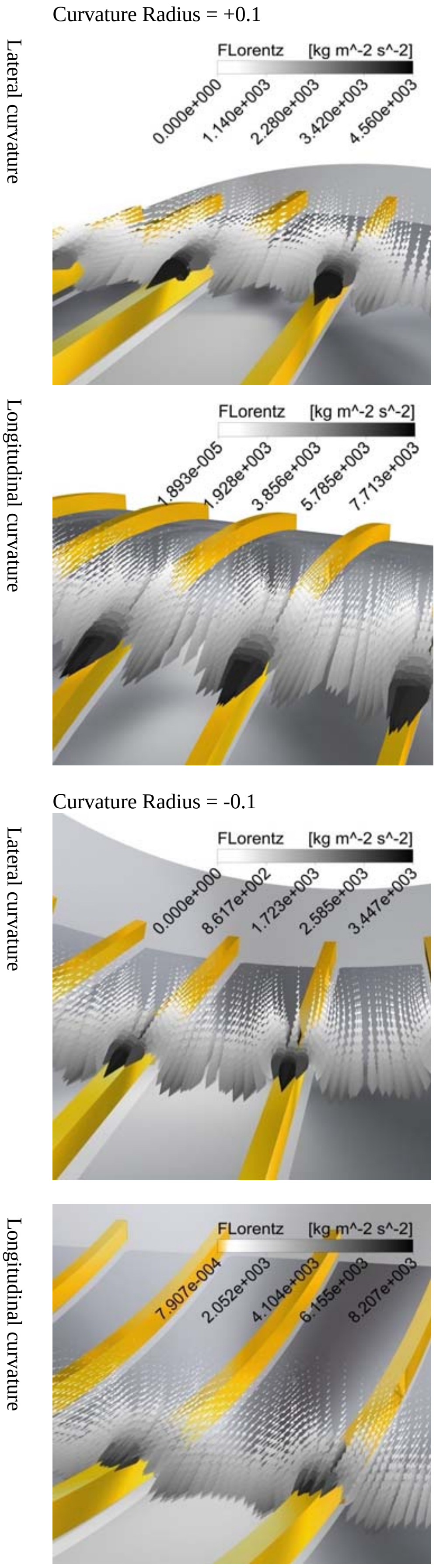

Fig. 6. Electromagnetic force density vector field for the extreme curvatures.

It is clearly observed in Fig.5 that the curvature of the blanket affects the magnetic and electric fields. However, more interesting observation is that the orthogonality of the two fields is highly maintained, due to the fact that the curvature has the same effects on both fields in the lateral direction for all curvatures. The orthogonality is important due to the fact that the electromagnetic force is maximized with the orthogonality of the magnetic and electric fields. The electromagnetic force density due to the interaction of the two fields is displayed in Fig.6.

As evident in Fig.6, the overall distribution of force density does not seem to change with the curvature. To better observe the effects of curvature on the force density distribution, vertical profile of the force density in the mid line of the blanket is illustrated in Fig.7 for all the curvatures.

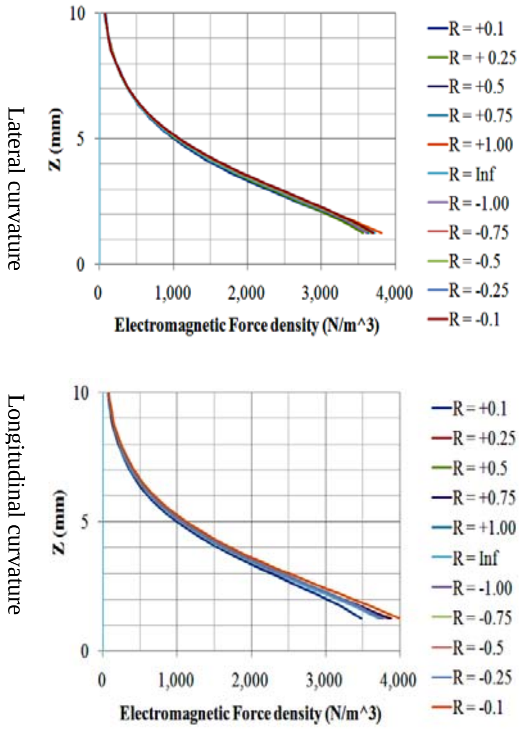

Fig. 7. Vertical profile of the electromagnetic force density in the middle of the blanket.

It is clearly observed in Fig.7 that main trend of the force density profile is not affected by the curvature. However, the force density is changed by a maximum of ± 250 N/m^3 in the adjacency of the blanket. The force density increases for the negative curvatures. This may be attributed to the condensation of the electromagnetic forces in a smaller space above the blanket. It is also observed that positive curvature decreases the force density due to the expansion of the space above each pair of the electrodes.

As a result of the force density, a velocity profile is induced to the fluid. The velocity vector field on the blanket is presented in Fig.8.

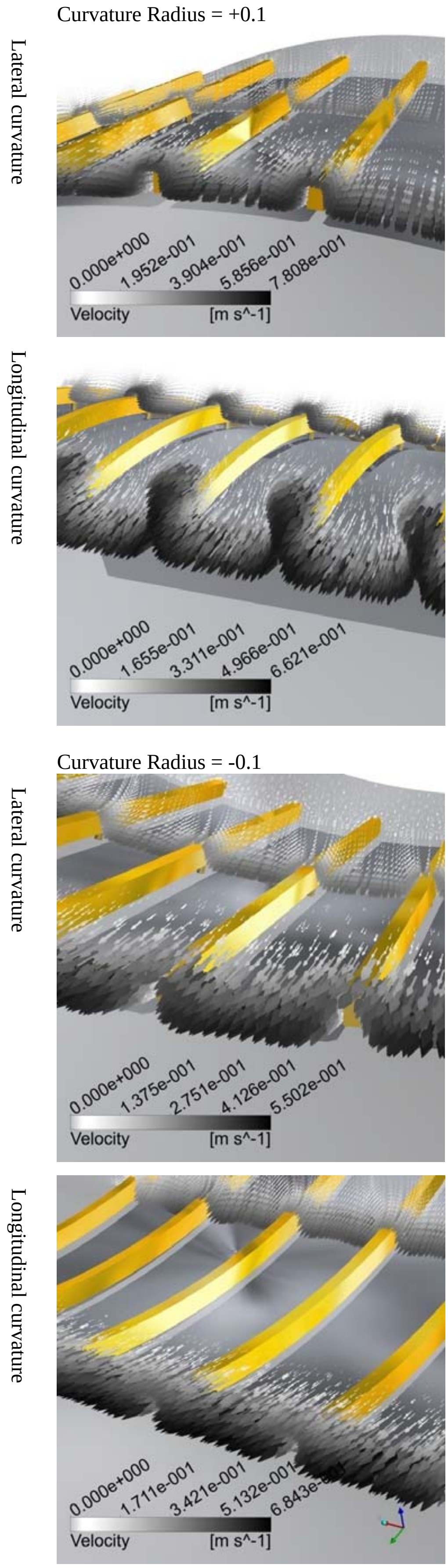

Fig. 8. Velocity vector fields for the extreme curvatures.

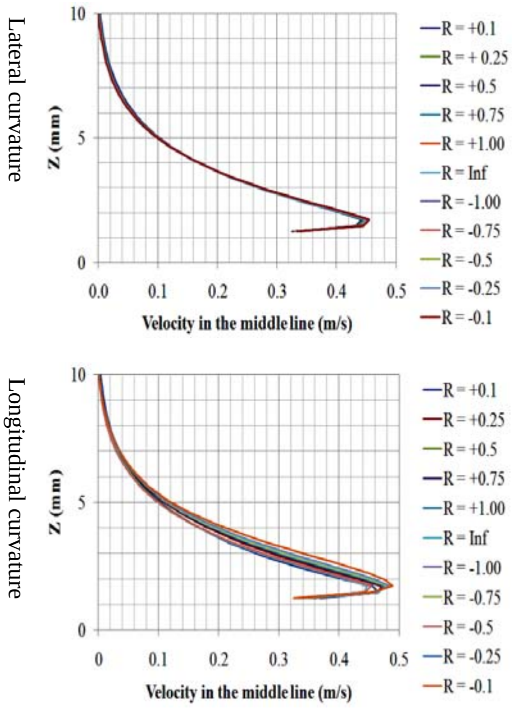

Fig. 9. Velocity profile in the middle of the blanket.

As observed in Fig.8, the velocity field is affected by the curvature, mainly at the exit of the blanket. In general, the velocity increases for the concave blankets. Fig. 9 presents a better view of the effects.

As evident in Fig.9, the effect is very small on the lateral curvatures, where the main effect is observed in the proximity of the blanket ($z < 2mm$). These effects are maximized for the longitudinal curvatures. This is due to the separation of the flow from the convex curvatures and compression of the flow in concave curvatures which results in a velocity effects in higher distances from the blanket ($z < 6mm$).

Another important parameter is the temperature increase on the electrodes, the blanket, and the surrounding fluid. Fig. 10 shows the temperature contour for the extreme curvatures.

As observed in Fig.10, the temperature changes are more distributed in the longitudinal curvatures. However, to have a better view of the temperature changes, the temperature profile is plotted in Fig. 11.

As shown in Fig.11, temperature profile is not significantly affected by the lateral curvatures. Also, concave curvatures have higher temperature profiles in the longitudinal curvatures. Recalling the flow velocity profile changes (Fig.9), the cause of this temperature change is the fact that the flow velocity field spreads the temperature changes more in the domain which results in a more distributed temperature contour and profile.

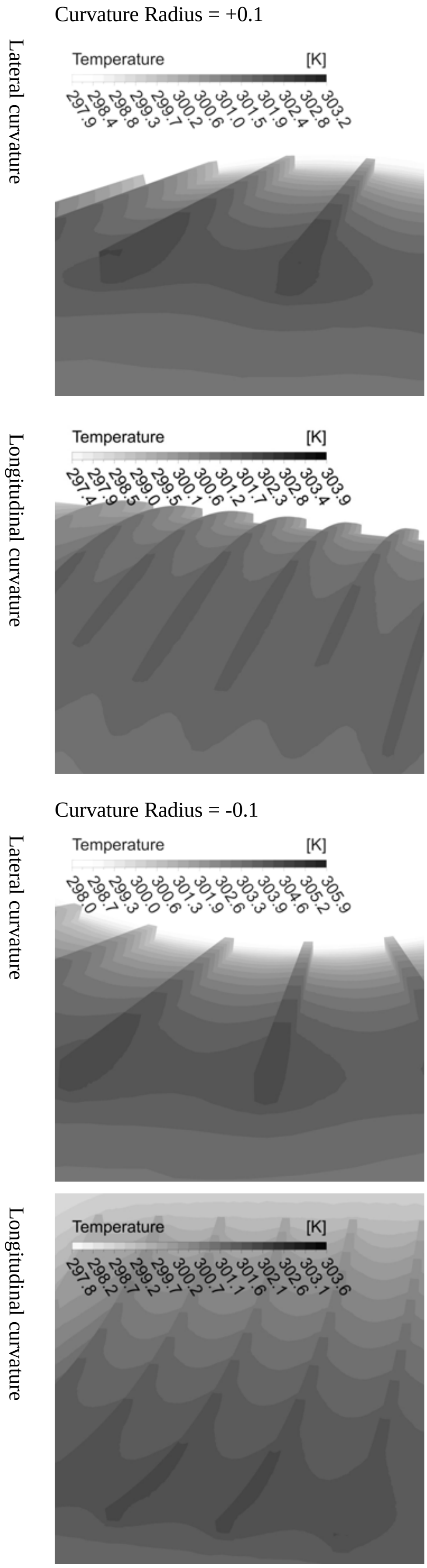

Fig. 10. Temperature contours for the extreme curvatures.

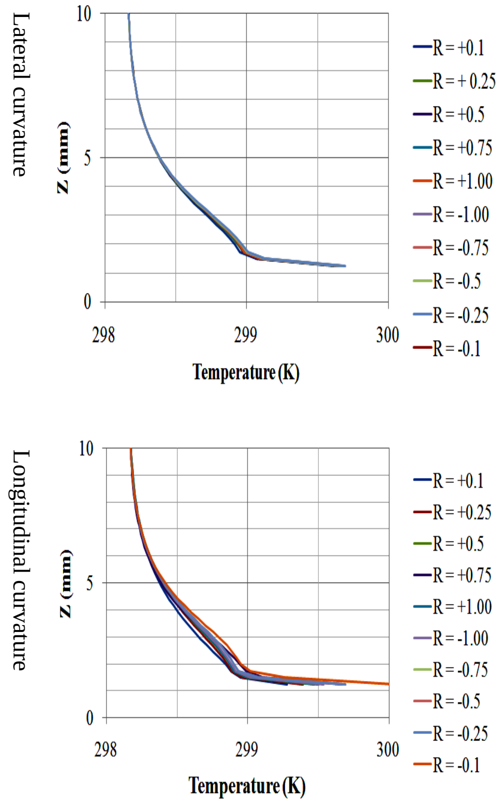

Fig. 11. Temperature profile in the middle of the blanket.

For a quantitative summarization of the curvature effects on the blanket produced force, the total force produced by 1 m^2 of the blankets with different curvatures is displayed in Fig.12.

As observed in Fig.12, the total force produced by 1m^2 of the flat blanket is 12.9*N*. The lateral curvature affects the produced force by ±6% and the longitudinal curvature changes the generated force from -2.5% up to 5.2%. It is also shown that convex curvature decreases the produced force of the blanket, and the concave blankets increase the thrust. Another main concern of the current study is the efficiency of the blanket which is displayed in Fig.13.

As illustrated in Fig.13, the efficiency of the flat blanket is 0.0025%. Efficiency variations do not seem to have a clear trend versus the curvature. This may be due to the simultaneous correlation of the effects of different aspects of the blanket. However, it is observed that longitudinal curvature does not significantly affect the efficiency of the blanket, but there is a decreasing trend in the efficiency going from convex to concave curvatures for the lateral cases. Although, the efficiency changes do not seem significant, the percentages of these changes are as high as -10% to 25% for the lateral curvatures and up to 6% for the longitudinal curvatures.

Same assessment is presented for the temperature changes of the blanket in Fig.14. It is shown that temperature is increased by 1.5K for the flat blanket. It is also demonstrated that this temperature change is increased for the concave curvatures and decreases for the convex ones, and the Lateral curvature has a very small effect of -2 to 6% compared to the effects of the longitudinal curvatures which affect the temperature rise by -25 to 28%.

As explained earlier, the MHD propulsion system has been presented and studied by different researchers for more than a half century. However, no study has been presented on the effect of the curvature of the MHD propulsive blankets on its performance. The main contribution of the present results is a vision of the effects of the curvature of the MHD propulsive blanket on its different aspects, namely thrust, efficiency and boundary layer velocity and temperature profiles.

5. CONCLUSIONS

The MHD propulsive blanket is originally designed to be attached to the external body of the submerged objects and because of the arbitrary shape of different bodies in water, the blanket should inevitably be curved to fit the body. Accordingly, in order to assess the effects of the curvature on the performance of the blanket, the effects of convex and concave curvature of a magneto hydrodynamic propulsive blanket on its thrust force, heat transfer, efficiency and electromagnetic fields are numerically analyzed in the present paper.

To this end, the blanket is curved in two longitudinal and lateral directions and 10 positive and negative curvatures in each direction have been taken into consideration. After validating the numerical model with analytical solutions of the Hartman problem, the results of all considered cases are presented in the form of magnetic and electric fields streamlines, electromagnetic force and velocity vector fields and vertical profiles, temperature distribution contours and profiles, and finally the maximum effects of the curvature are extracted and analyzed.

It is demonstrated that the electromagnetic force density, velocity, and temperature profiles in the middle of the blanket are more affected by the longitudinal curvature and the lateral curvature has very small effects on these profiles. However, it is shown that in all targeted cases, the concave curvatures increase the force density and the temperature change and convex curvatures decrease these parameters. It is also demonstrated that in lateral curvatures, the overall thrust produced by the blanket is affected by -6% to +6%, the efficiency is affected by -10% to 25%, and temperature change is affected by -2 to 6%. On the other hand, it is indicated that longitudinal curvature affects the blanket thrust by -2.5% up to 5.2%, its efficiency by nearly 6%, and the temperature change from -25 up to 28%.

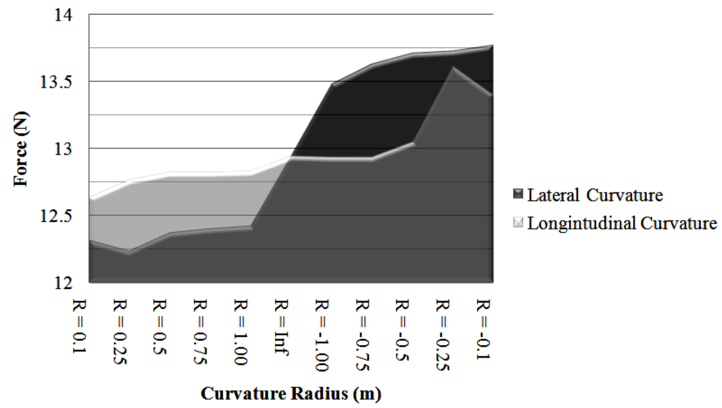

Fig 12. Total force per square meter of the MHD propulsive blanket versus the curvature.

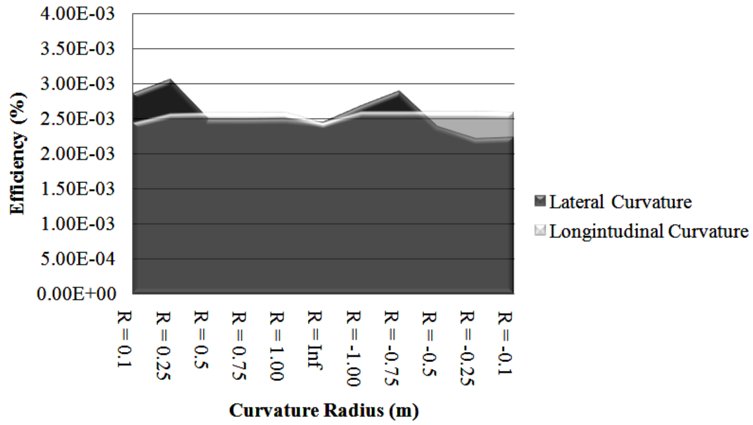

Fig. 13. Efficiency of the MHD propulsive blanket versus the curvature.

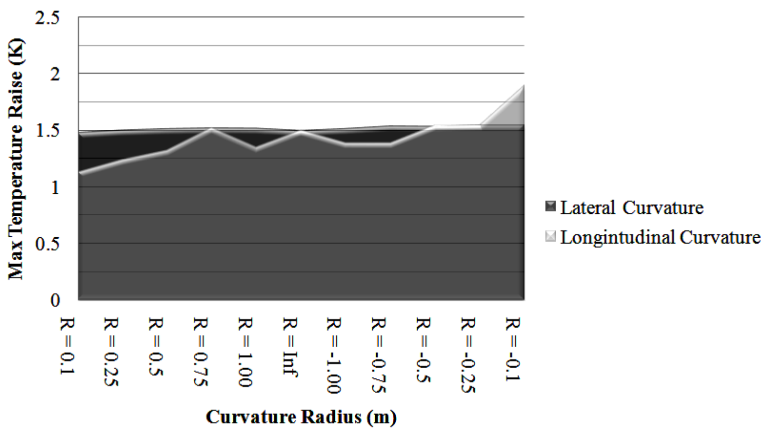

Fig 14. Maximum temperature change of the MHD propulsive blanket versus the curvature.

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