# Control of heat transfer in engine coolers by Lorentz forces

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**Abstract.** In engine coolers of off-highway vehicles convective heat transfer at the coolant side is a limiting factor of both efficiency and performance density of the cooler. Here, due to design restrictions, backwater areas and stagnation regions appear that are caused by flow deflections and cross-sectional expansions. As appropriate coolants, mixtures of water and glysantine are commonly used. Such coolants are characterized by their electrical conductivity of some S/m. This gives rise to control coolant flow and therefore convective heat transfer by means of Lorentz forces. These body forces are generated within the weakly conducting fluid by the interactions of an electrical current density and a localized magnetic field both of which being externally superimposed. In application this may be achieved by inserting electrodes in the cooler wall and a corresponding arrangement of permanent magnets. In this paper we perform numerical simulations of such magnetohydrodynamic flow in three model geometries that are frequently apparent in engine cooling applications: Carnot-Borda diffusor, 90° bend, and 180° bend. The simulations are carried out using the software package ANSYS Fluent. The present study demonstrates that, depending on the electromagnetic interaction parameter and the specific geometric arrangement of electrodes and magnetic field, Lorentz forces are suitable to break up eddy waters and separation zones and are thus significantly increasing convective heat transfer in these areas. Furthermore, the results show that due to the action of the Lorentz forces the hydraulic pressure losses can be reduced.

**Keywords:** engine coolers, convective heat transfer, Lorentz force

## Introduction

MAHLE Industrial Thermal Systems specializes in efficient and sophisticated thermal management [1]. The portfolio ranges from coolers to entire cooling and air conditioning modules. Areas of application include railway vehicles, busses, agricultural and construction machinery, and special vehicles. Basic requirements in the development of engine coolers are compactness, easy manufacturing, low material costs, and high performance density. These requirements are generally met by coolers designed in package-type blocks, cf. figure 1. Such coolers preferentially operate in the so-called indirect cross-flow mode: air flow (the fluid to be cooled down) and coolant flow are in orthogonal directions and are separated by thin aluminum panels. To increase heat transfer from the air to the coolant, air channels are equipped with corrugated ribs and turbulence enhancing entry sheets both of which made of aluminum [2]. In such complex heat exchange systems limiting factors for both efficiency and performance density include the appearance of stagnant flow, eddy waters, wakes, and separation zones at the coolant side all of which triggered by sudden expansions and/or deflections of the flow [3]. In such zones convective heat transfer is drastically reduced due to a significant drop of wall shear stress [4]. In the present paper we investigate the option of an electromagnetic control [5], [6], [7] of heat transfer in such zones. Control is based on the fact that the coolant is electrically conductive. Hence, in the presence of an electrical current and an applied magnetic field, Lorentz forces can be generated within the coolant. These Lorentz forces may contribute to an increase of heat transfer due to a favorable modification of the flow topology in the critical areas. In the present study electromagnetic control is achieved by superimposing both electrical currents, being inserted via wall electrodes, and localized magnetic fields of constant magnitude and prescribed direction.

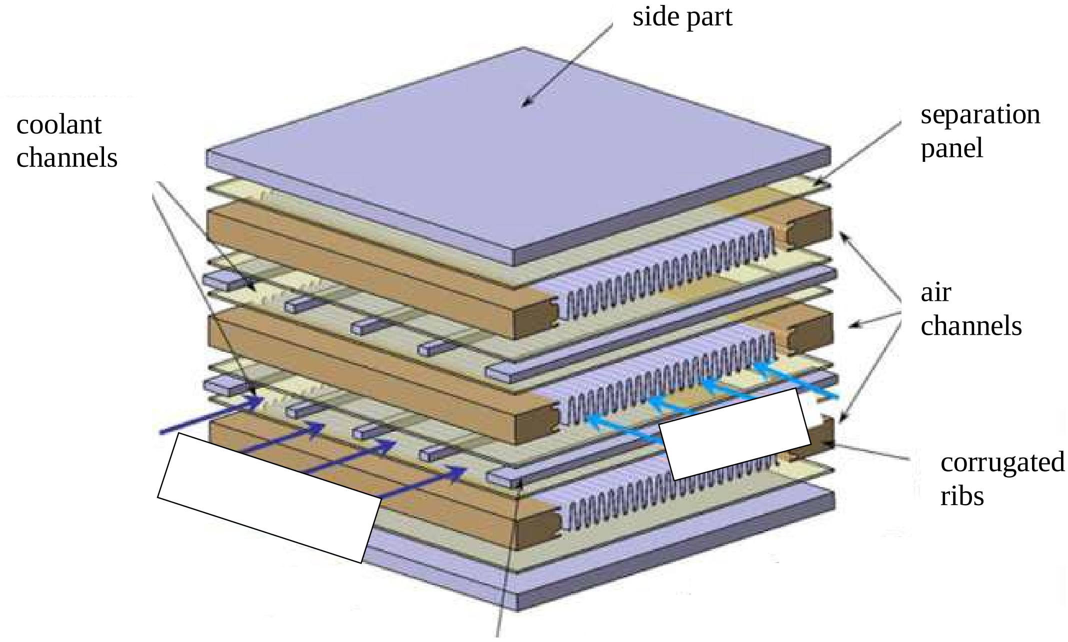



**Figure 1.** Sketch of an indirect package-type cross-flow engine cooler. Air flow and coolant flow are orthogonal and separated by thin panels. To enhance heat transfer air channels are equipped with corrugated ribs. Additionally, turbulence enhancing entry sheets are used.

The present feasibility study aims to demonstrate that convective heat transfer on the coolant side can be increased by electromagnetic means. To this purpose we choose three canonical model geometries within which coolant flow under the influence of Lorentz forces are numerically investigated. These are a Carnot-Borda diffusor and both a 90° and 180° bend all of which characterized by sudden expansions. The paper is organized as follows. In section 2 we describe the governing equations and dimensionless parameters of the problem as well as the used numerical methods. In section 3 we define the model geometries mentioned above and show the main results of the simulations. Finally, section 4 provides a summary and an outlook towards a possible application in engine coolers.

## 2. Governing equations and numerical methods

### *2.1. Governing equations*

Forced flow of the coolant is described by the incompressible Navier Stokes equations. To allow electromagnetic control, we add the Lorentz force density $\mathbf{f_L}$ as a source term on the right hand side of this momentum balance. Moreover, convective heat transfer is governed by the heat transport equation. Under these assumptions the governing equations read as [5], [6], [7]

$$\nabla\cdot\mathbf{u} = 0,\ \partial/\partial t\ \mathbf{u} + (\mathbf{u}\cdot\nabla)\mathbf{u} = -1/\rho\ \nabla p + \nu\nabla^2\mathbf{u} + 1/\rho\ \mathbf{f}_{L,},\ \partial/\partial t\ T + (\mathbf{u}\cdot\nabla)T = \kappa\nabla^2 T. \qquad (1), (2), (3)$$

Here, $\mathbf{u}$, p and T denote the velocity vector, pressure and temperature, respectively. Coolant properties are density $\rho$, dynamic viscosity $\upsilon$, and thermal diffusivity $\kappa$ all of which are taken to be constant. The Lorentz force density is defined as

$$\mathbf{f}_L = \mathbf{j}\times\mathbf{B}, \qquad (4)$$

where $\mathbf{j}$ is the electric current density and $\mathbf{B}$ is the magnetic field. In order to calculate the Lorentz force density, we need some more equations defining the solenoidal vector fields $\mathbf{j}$ and $\mathbf{B}$, see equation (4). In general, these are Ohm's law for a moving conductor and the magnetic induction equation. However, in the present case of superimposed electrical currents and magnetic fields and a weakly conducting coolant, we can neglect the secondary magnetic field induced by the current density itself. Hence, $\mathbf{B}$ is fixed in both magnitude and direction by the applied field defined within regions of electromagnetic control. Secondly, we can neglect any eddy current, induced by the interaction of the flow within a magnetic field. Under this assumption $\mathbf{j}$ is given by the gradient of the electric scalar potential $\phi$, governed itself by Laplacian [8]. Thus we have

$$\nabla^2\phi = 0,\ \mathbf{j} = -\sigma\nabla\phi,\ \mathbf{B} = B_0\cdot\mathbf{e}_B. \qquad (5), (6), (7)$$

Here $\sigma$ is the electrical conductivity of the coolant, and $B_0$ and $\mathbf{e}_B$ are the flux density and the unit vector of the applied field, respectively. In our simulations we shall apply a constant current density at the wall electrodes and electrically insulating walls elsewhere. As hydrodynamic boundary conditions we fix the mass flux at the inlet and the pressure at the outlet. Moreover, we apply no-slip conditions at rigid walls. The thermal boundary conditions are a fixed inlet temperature and isothermal walls.

*2.2. Dimensionless parameters*

The present problem is governed by two dimensionless groups, the Reynolds number Re and the electromagnetic interaction parameter N. These groups are defined according to the relations

$$Re = UL_1/\nu,\ N = j_0 B_0 L_2/(\rho U^2). \qquad (8), (9)$$

Here U is fluid inlet velocity based on mass flux and $L_1$ and $L_2$ are characteristic length scales for fluid dynamics (hydraulic diameter) and electromagnetics (dimension of electrode). Throughout this study we shall use Re = 3.000 which is a typical value in application. The interaction parameter represents the ratio of electromagnetic forces to inertia. We expect that for $N \ll 1$ Lorentz forces will have little effect on the flow since inertia dominates. In turn, for $N \gg 1$ there will be strong modifications of the flow structure due to the presence of Lorentz forces. In application, N may be varied by changing the values of both $j_0$ and $B_0$. Important output quantities are the mean Nusselt number Nu and the pressure coefficient $c_p$. These parameters are defined as

$$Nu = \alpha L_1/\lambda,\ c_p = \Delta p/(\tfrac{1}{2}\rho U^2). \qquad (10), (11)$$

Here $\alpha$ denotes the convective heat transfer coefficient, $\lambda$ is heat conductivity of the coolant and $\Delta p$ is pressure drop across the geometry. The Nusselt number can be interpreted as the ratio of convective to conductive heat transfer. The parameter $c_p$ relates the pressure drop to the dynamic pressure of the flow. The present study aims to find the relations Nu = Nu (N) and $c_p = c_p(N)$.

### *2.3. Numerical approach*

The equations above are numerically solved in three dimensions by using the commercial program ANSYS Fluent 16.2 and its MHD (magnetohydrodynamic) module [9]. This module allows defining volumes within which a constant magnetic field is present. In this study the imposed magnetic fields point either in the x- or y-direction, cf. figure 2. Moreover, the module allows defining wall areas at which electrical currents are injected. In the present study the injected currents point in the z-direction, cf. figure 2. According to equation (4) the main component of the Lorentz forces are then acting either in the y- or x-direction. The MHD module solves for the electrical potential and calculates the Lorentz force density, cf. equation (4). The data are then read into the CFD solver ANSYS Fluent, cf. equation (2). In the present study we fix the Reynolds number at Re = 3.000. Some pre-studies [10] show that in the present geometries the transition Reynolds number is about 1.000. Hence, we are in the regime of turbulent flow. We use the standard k-ω SST turbulence model. Moreover, the pre-studies show that equidistant meshing with a grid size of $\Delta = 0.3$ mm is appropriate. Coolant properties are fixed at $\sigma = 0.4$ S/m, $\rho = 1028$ kg/m³, $\upsilon = 8.8$ e-7 m²/s, $\kappa = 1.2$ e-7 m²/s, and $\lambda = 0.435$ W/(m·K). Temperatures were fixed at 30°C and 200°C at inlet and isothermal walls, respectively. Validation of the numerical scheme was performed for the case when Lorentz forces are absent. We found almost perfect agreement of our calculated results for $c_p$ with respective data in literature [11], [12].

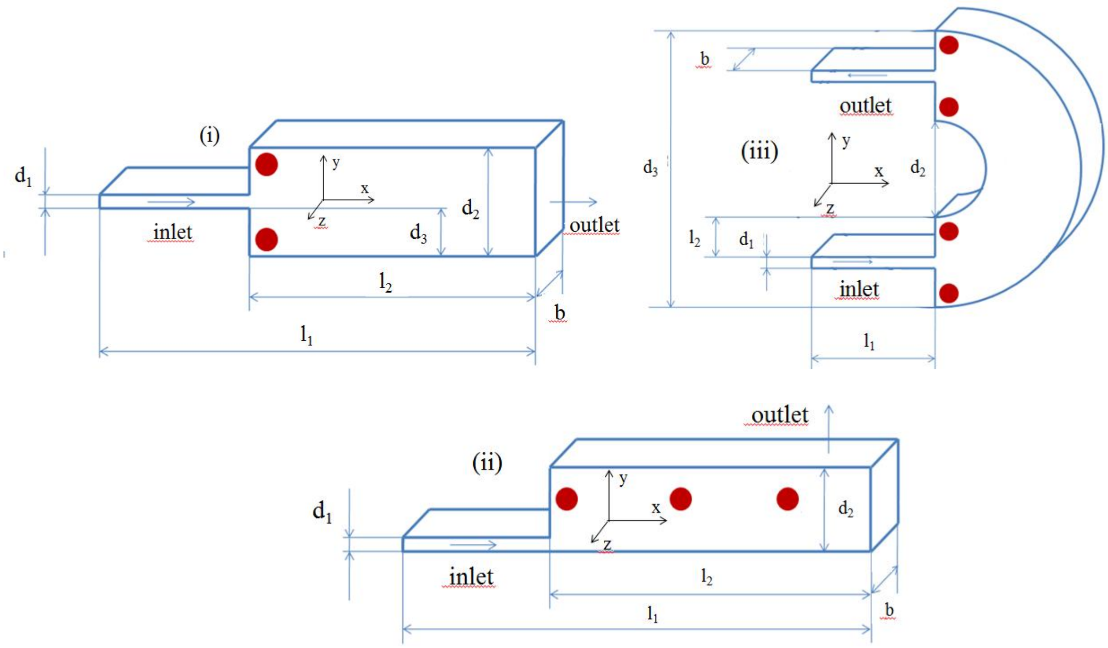



**Figure 2.** Model geometries: (i) Borda-Carnot diffusor; $d_1 = 2.6$ mm, $d_2 = 17.6$ mm, $d_3 = 7.5$ mm, $l_1 = 193$ mm, $l_2 = 113$ mm, b = 10 mm; (ii) 90° bend; $d_1 = 2.6$ mm, $d_2 = 17.6$ mm, $l_1 = 193$ mm, $l_2 = 113$ mm, b = 10 mm; (iii) 180° bend; $d_1 = 2.6$ mm, $d_2 = 20$ mm, $d_3 = 55.2$ mm, $l_1 = 80$ mm, b = 10 mm. Red dots indicate zones of stagnant flow. Wall electrodes are inserted at which an electrical current density in the z-direction is applied. Directions of the applied magnetic fields are either in the x- and/or y-direction generating Lorentz forces pointing in the y- and/or x-direction, respectively.

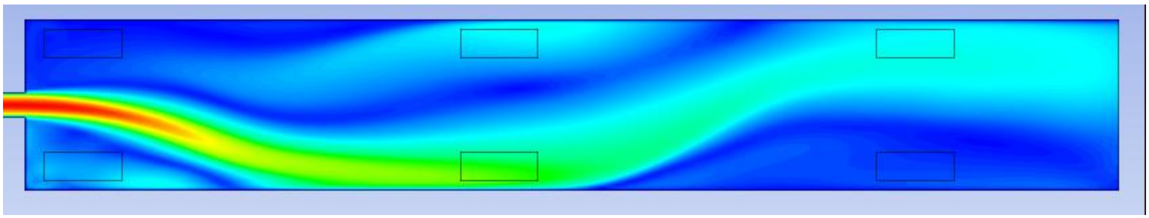
## 3. Results

### *3.1. Model Geometries*

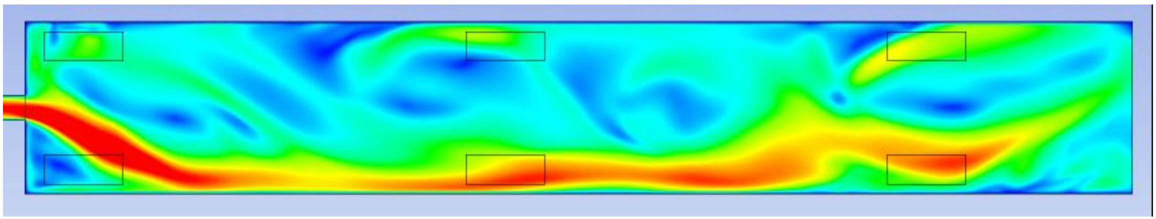
We select three canonical model geometries to investigate the effect of Lorentz forces on heat transfer: Borda-Carnot diffusor, cf. figure 2 (i), 90° bend, cf. figure 2 (ii), and 180° bend, cf. figure 2 (iii). Areas within which stagnant flow with reduced convective heat transfer is expected are indicated by red dots. In these areas we insert pairs of electrodes at the front and back side walls on which an electric current density of magnitude $j_0$ is applied in the z-direction. The specific arrangements of the applied magnetic field are chosen in such a way that the resulting Lorentz forces are pointing either in the x-direction and/or the y-direction.

### *3.2. MHD flow in a Carnot-Borda diffusor*

We start with the electromagnetic control of flow in a Carnot-Borda diffusor. Figure 3 shows a color plot of the magnitudes of velocity in the x-y mid plane. Colors are corresponding to 0 (deep blue) until 1.27 m/s (deep red). Figure 3 (i) refers to the case N = 0, i.e. when Lorentz forces are absent. Here, we observe that due to the Coanda effect [13], the jet entering the diffusor is deflected to the bottom wall. The jet separates from the wall at some position downstream. At the outlet the velocities are considerably reduced. As is obvious from figure 3 (i), there are extended regions of stagnant flow at inlet and outlet within which convective heat transfer from the walls is diminished.



(i)



(ii)

**Figure 3.** Color plot of the magnitudes of velocity in the x-y plane of symmetry in a Borda-Carnot diffusor at Re = 3.000 and (i) N = 0 and (ii) N = 3. The magnitudes range from 0 (deep blue) to 1.27 m/s (deep red). Mean flow is in the positive x-direction. Rectangles indicate the wall electrodes driving an electrical current in the negative (bottom electrodes) and in the positive (top electrodes) z-direction. The applied localized magnetic fields act in the positive y-direction. The generated Lorentz forces are pointing in the positive (bottom) and negative (top) x-direction, respectively.

In contrast, figure 3 (ii) refers to the case N = 3, i.e. when electromagnetic control is active. Here, rectangles represent the electrodes that are inserted in the walls. In detail, 6 pairs of electrodes are arranged in such a way that the three pairs at the bottom and the top generate an electrical current in the negative and positive z-direction, i.e. into and out of the plane, respectively. Furthermore, within the electrode regions we apply localized magnetic fields pointing into the positive y-direction. This arrangement result in Lorentz forces acting in the negative and positive x-direction at top and bottom, respectively. As a result a large-scale forced circulation is generated. As is obvious from figure 3 (ii) the wall jet is accelerated and its separation from the bottom wall is prevented. Moreover, due to the electromagnetically forced circulation almost all regions of stagnant flow disappear. We conclude that this special arrangement of applied electrical current and magnetic field contributes to an increase of convective heat transfer. However, due to the formation of an extended zone of recirculation, we may expect a slight increase of pressure drop, cf. subsection 3.5.

### *3.3. MHD flow in a 90° bend*

Next we investigate electromagnetic control of flow in the 90° bend. Figure 4 shows again a color plot of the magnitudes of the velocity in the x-y mid plane. Colors are corresponding to 0 (deep blue) until

1.26 m/s (deep red). Figure 4 (i) again refers to the case N = 0. Here, we observe that the jet entering the bend remains at the bottom wall and widens up. At the right end the jet is bent into the upward direction. Again, this hydrodynamic flow pattern gives rise to extended regions of stagnant flow with reduced convective heat transfer at the top part and the lower right corner of the bend. Figure 4 (ii) shows the velocity field modified by the action of Lorentz forces for the case N = 3. In order to break up the eddy waters observed in figure 4 (i), a total of 4 pairs of wall electrodes and corresponding localized magnetic fields are implemented. At all electrodes an electrical current density pointing out of the plane, i. e. in the positive z-direction is injected. In the region of the electrodes at the inlet and the right end of the bend, the direction of the magnetic field is in the positive x-direction. Hence, the generated Lorentz forces act in the positive y-direction, i.e. in the direction of the outlet flow. On the other hand, in the regions of the two pairs of electrodes arranged in the middle of the bend, the corresponding magnetic fields are pointing in the negative y-direction. This arrangement results in Lorentz forces acting in the positive x-direction. As a result of this specific set-up of electromagnetic control, the inlet jet is deflected towards the bulk region. As a consequence, stagnant flow at the inlet area is broken up. Moreover, in the the center part of the bend, coolant is pushed to the right end. Here, the Lorentz forces support the bending of the fluid into the positive y-direction of the outlet flow. Again, the area of stagnant flow at the right end is broken up. As before, we conclude that the imposed electromagnetic control shall lead to an increase of convective heat transfer. Moreover, in contrast of the previous case of a diffusor, we may expect that due to the fact that the generated Lorentz forces support the bending of the flow, the pressure drop shall significantly decrease, cf. subsection 3.5.

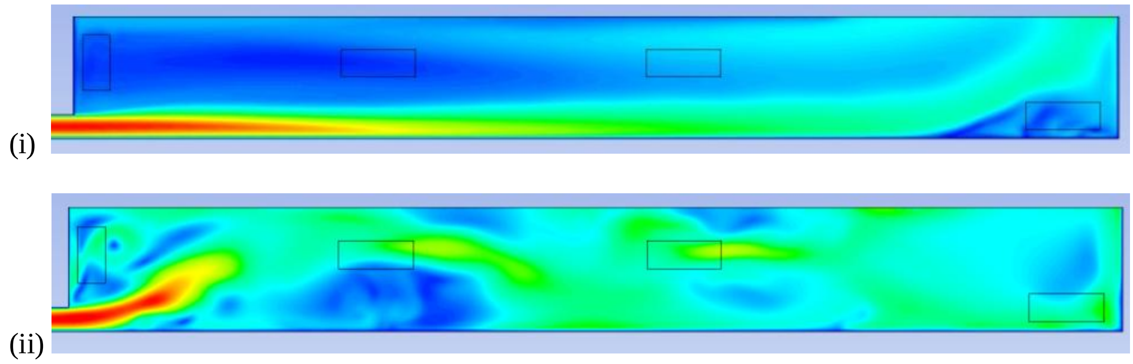



**Figure 4.** Color plot of the magnitudes of velocity in the x-y plane of symmetry in a 90° bend at Re = 3.000 and (i) N = 0 and (ii) N = 3. The magnitudes range from 0 (deep blue) to 1.26 m/s (deep red). Inlet flow at the left is in the positive x-direction, outlet flow is at the top in the y-direction. Rectangles indicate the wall electrodes driving an electrical current in the positive z-direction out the plane. The applied localized magnetic fields act either in the positive x-direction (left and right electrode) or in the positive y-direction (middle electrodes), respectively. The generated Lorentz forces are pointing in the positive y-direction (left and right electrode) and in the positive x-direction (middle electrodes), respectively.

*3.4. MHD flow in a 180° bend*

Finally we investigate electromagnetic control of flow in the 180° bend. Figure 5 shows as before the color plot of the magnitudes of the velocity in the x-y mid plane. Colors are corresponding to 0 (deep blue) until 1.63 m/s (deep red). The case when Lorentz forces are absent, i.e. N = 0, is illustrated in figure 5 (i). Here, we observe that the inlet jet hits the right wall and keeps attached to the curved contour in the downstream direction. At the end of the bend the coolant is deflected towards the direction of the outlet flow, i.e. the negative x-direction. This flow structure again results in the formation of extended regions of stagnant flow within the bend. As obvious from figure 5 (i), especially the areas above and below the inlet duct and the entire left part of the bend are considered to be regions of reduced convective heat transfer. In order to break up these regions, we implement a total of 5 pairs of wall electrodes and corresponding magnetic fields in such a way that all generated Lorentz forces are pointing in the negative y-direction. According to equation (4) this is achieved by inserting an electrical current density into the negative z-direction (into the plane) and fixing the magnetic fields in the positive x-direction of the inlet flow. As a result of this arrangement, similar to the case of the diffusor, a large-scale circulation in the bulk of the bend is established. Coolant flowing up the outer wall recirculates downwards along the inner wall of the bend. This flow pattern is shown in figure 5 (ii) for an interaction parameter of N = 3. Also in this case we may conclude that this specific set-up of electromagnetic control results in an increase of convective heat transfer. However, similar to the case of the diffusor, due to the circulation this benefit will be accompanied by some increase of pressure drop, cf. subsections 3.2 and 3.5.

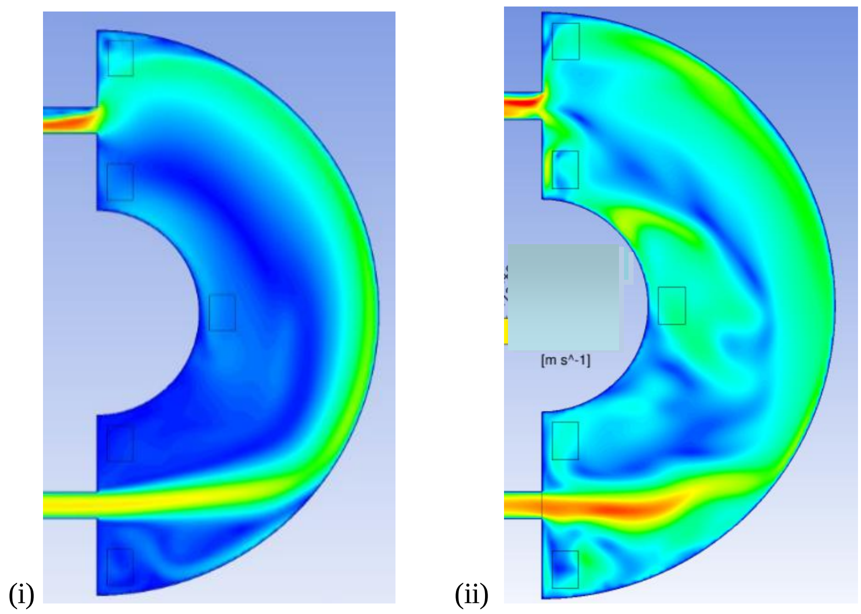



**Figure 5.** Color plot of the magnitudes of velocity in the x-y plane of symmetry in the 180° bend at Re = 3.000 and (i) N = 0 and (ii) N = 3. The magnitudes range from 0 (deep blue) to 1.63 m/s (deep red). Rectangles indicate the wall electrodes driving an electrical current in the negative z-direction into the plane. The applied localized magnetic fields act in the positive x-direction of inlet flow. The generated Lorentz forces are pointing in the negative y-direction.

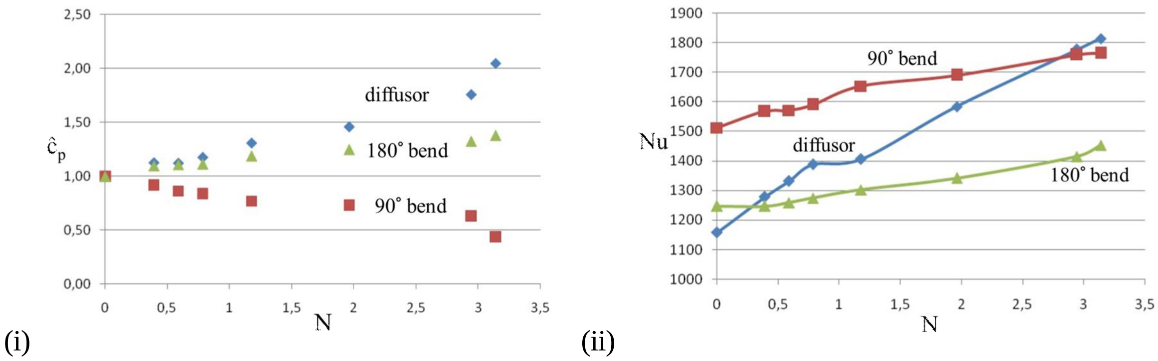



**Figure 6.** Reduced pressure coefficient (i) $\hat{c}_p = c_p/c_{p0}$) and (ii) Nusselt number as a function of the interaction parameter N for all three model geometries.

### *3.5. Pressure drop and heat transfer*

The main results of our simulations are summarized in figure 6. Here, figure 6 (i) shows the reduced pressure coefficient $\hat{c}_p = c_p/c_{p0}$ as a function of the interaction parameter N, where $c_{p0}$ denotes the pressure coefficient for the case N = 0. For the 90° bend we find a remarkable decrease in pressure drop when the electromagnetic control is present. As discussed before, in this case the generated Lorentz forces support the bending of the coolant flow. Contrary, for the diffusor and the 180° bend we find an increase in pressure drop. In order dissolve areas of stagnant flow the coolant has to recirculate. Hence, the Lorentz forces act as an additional electromagnetic brake. Figure 6 (ii) shows the corresponding Nusselt number as a function of N. Here, for all geometries we find a significant increase of convective heat transfer when electromagnetic flow control is active. For instance, for N = 3.2 the increases in Nu are about 60% for the diffusor and about 20 % for the 90° and 180° bend.

## 4. Conclusions and outlook

We have studied electromagnetic control of coolant flow and convective heat transfer in three canonical model geometries: a diffusor, a 90° bend and a 180° bend. Under the action of superimposed electrical currents and magnetic fields, in the electrically weakly conducting coolant Lorentz forces are generated that tend to dissolve areas of stagnant flow with reduced heat transfer. As a result we find an increase in the Nusselt number when the electromagnetic control is active. Moreover, when the Lorentz forces do not create recirculating flow enhanced heat transfer is accompanied by a reduction in pressure loss. To evaluate the efficiency of the electromagnetic control we define the ratio of the increase in heat transfer and the electric power consumption of the electrodes [10]. A rough estimate shows that in the case of the diffusor this ratio is greater than unity when the electrical conductivity may be greater than 70 S/m. Thus, to transfer these findings into application it is necessary to increase significantly the electrical conductivity of the coolant, either by additives or by development of new mixtures. By that the magnitude of the injected current density and therefore costs for control can be drastically reduced. Other benefits of an increased conductivity are that the heating up of the coolant via Joule losses and possible generation of hydrogen via electrolysis can be avoided [10].

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