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# NANOFLUID FLOW AND HEAT TRANSFER THROUGH A POROUS MEDIUM IN A HORIZONTAL CHANNEL WITH AN ELECTRIC AND A MOVING MAGNETIC FIELD

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***Abstract****. This paper discusses fully developed flow and heat transfer of a nanofluid in a horizontal channel through a porous medium, for which the Darcy model is used. The channel walls are horizontal plates at constant but different temperatures. The externally applied magnetic field is homogeneous, perpendicular to the channel walls, and moving at constant velocity in the direction of primary nanofluid flow. The external electric field is homogeneous and perpendicular to the vertical longitudinal plane of the channel. Nanofluid velocity and temperature distributions for different values of the introduced physical parameters were determined and shown graphically. The obtained results were analyzed, emphasizing the possibilities of managing nanofluid flow and heat transfer.*

**Key words**: *nanofluid, heat transfer, moving magnetic field, electric field, porous medium*

## 1. INTRODUCTION

It is well-established that porous media and nanofluids improve heat transfer, which is why their use is recommended wherever heat transfer improvement is a priority, e.g., in numerous industrial applications, transport, electronics, nuclear reactors, biomedicine, and many more. A particularly important fact is that nanofluids are smart fluids and that heat transfer improvement can be managed, specifically, increased or decreased when needed. To ensure the best possible management, magnetic and electric fields are utilized wherever possible. It is consequently believed that nanofluids have a significant advantage over conventional fluids for heat transfer. Therefore, over the last three decades, many researchers have studied nanofluid flow and heat transfer through porous media. To

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understand the dedication of the approach to nanofluid research, it is enough to reference the study by Buongiorno et al. [1]. They investigated only the thermal conductivity of nanofluids using a variety of experimental methods parallelly in 34 scientific research organizations throughout the world, with the entire research having more than 70 co-authors. Some of those studies will be mentioned here, which does not mean that other, omitted studies could not have been mentioned instead.

Khanafer and Vafai [2] offered a critical synthesis of various nanofluid thermophysical properties, motivated by the disagreement between the results for thermal conductivity and viscosity and the experimental results, as reported by multiple researchers. Aaiza et al. [3] studied the unsteady nanofluid magnetohydrodynamic (MHD) flow and mixed convection in a vertical channel through a porous medium. They included four nanoparticle shapes and used water and ethylene glycol as base fluids. Das et al. [4] investigated a fully developed nanofluid mixed convective MHD flow in a vertical channel saturated with a porous medium. They also considered an induced magnetic field and particularly focused on the nanofluids with water as the base fluid and with copper, aluminum oxide, and titanium dioxide nanoparticles. Lima et al. [5] explored the MHD flow and heat transfer of two immiscible fluids in an inclined channel saturated with a porous medium. They considered the following aspects: buoyancy, moving plates, porous layers, inclined magnetic field, Joule and viscous heating, and volumetric heat generation/absorption. Petrović et al. [6] studied the effects of a magnetic field, an electric field, and fluid suction/injection for the purpose of managing flow velocity, tangential stress, and heat transfer in a horizontal channel. Reddy et al. [7] investigated nanofluid flow along an inclined plate immersed in a porous medium with heat radiation and heat generation/absorption. Seth et al. [8] studied the effects of viscous and Joule dissipation and heat generation/absorption on the MHD flow of a Casson fluid over an unsteady horizontal stretching sheet in a non-Darcy porous medium. It was assumed that the fluid slips along the sheet boundary surface. Jangili et al. [9] explored the convective heat transfer and entropy generation of a micropolar fluid in a vertical channel through a non-Darcy porous medium. The channel walls were at constant but different temperatures and the authors also considered radiation heat. Kasaen et al. [10] gave a detailed review of the studies investigating the simultaneous use of nanofluids and porous media to improve heat transfer. Eldabe et al. [11] investigated the peristaltic MHD flow and heat transfer of a non-Newtonian nanofluid in an asymmetrical channel saturated with a porous medium. They considered the Hall effect and viscous and Joule dissipation. Khanafer and Vafai [12] reviewed the application of nanofluids in porous media and recommended future research regarding such application of nanofluids. Khan and Alqahtani [13] studied the nanofluid MHD flow and heat transfer in a vertical channel with permeable walls, saturated with a porous medium. Ethylene glycol and water were used as base fluids. Dogonchi et al. [14] explored the flow and natural convection of a copper-water nanofluid in a channel saturated with a porous medium between a hot rectangular cylinder and a cold circular cylinder under the effect of an external inclined homogeneous magnetic field. They considered different shapes of Cu and CuO nanoparticles, with water as the base fluid. Umavathi and Sheremet [15] investigated the flow and heat transfer of three immiscible fluids in a vertical channel. The middle layer contained a regular fluid flowing in a free medium sandwiched between two layers of nanofluids flowing in a porous medium. The channel walls were at different constant temperatures. Prasad et al. [16] studied the MHD flow and heat transfer of a UCM nanofluid in a permeable channel saturated with a porous medium. They also considered radiation heat and used

Buongiorno's model. Manjeet and Sharma [17] explored the MHD flow and heat convection of two immiscible fluids in a horizontal channel with $H_2O$-Ag nanofluid in the bottom layer and gasoline in the top layer. Nikodijević et al. [18] investigated the unsteady MHD flow and heat transfer in a horizontal channel saturated with a porous medium. The externally applied magnetic field was homogeneous and inclined in relation to the channel, and the channel walls were at different constant temperatures. Umavathi and Chamkha [19] studied the double-diffusive free and forced convective flow of a nanofluid in a vertical channel, for the purpose of which they developed a new mathematical model. Raji [20] explored the EMHD flow and heat transfer of two immiscible fluids through a horizontal channel in a rotating framework with the Hall effect. Umavathi and Oztop [21] presented a numerical simulation for the analysis of electric and magnetic field influence on nanofluid flow and heat transfer in a vertical channel. The temperatures of the left and right channel were different but constant. Das et al. [22] proposed a mathematical model for investigating the effect of Hall currents on an unsteady MHD flow of an ionized EG-Ag nanofluid through a vertical permeable channel exposed to a strong transversal magnetic field, Darcy resistance, and heat radiation. At the moment, it can be strongly argued that, from an engineering and industrial perspective, nanofluid transport in magnetic media has emerged as a new field of research. The present authors reviewed numerous relevant studies globally available in the literature and found no study specifically focusing on the effects of a moving magnetic field on nanofluid flow and heat transfer, even though it is well-known that magnetic field movement influences both Lorentz force and Joule dissipation. This is what motivated the present study. In our opinion, the study can be applied in engineering and industrial practice, but especially in biomedicine, as it will contribute to increased safety of patients during precise medical imaging.

## 2. PROBLEM FORMULATION

The research is presented using the problem of a fully developed MHD flow of a nanofluid in a horizontal channel. The channel walls consist of two parallel infinite impermeable plates at distance h from one another and at different constant temperatures – $T_{w1}$ for the top plate and $T_{w2}$ for the bottom plate. The channel is saturated with a porous medium with porosity $K_0$. The external magnetic field with induction B is homogeneous and perpendicular to the channel walls, moving at velocity $u_0$ in the direction of primary flow. The external electric field with strength E is homogeneous and perpendicular to the longitudinal vertical plane of the channel. The physical configuration of the problem and the selected coordinate system are shown in Fig.1.

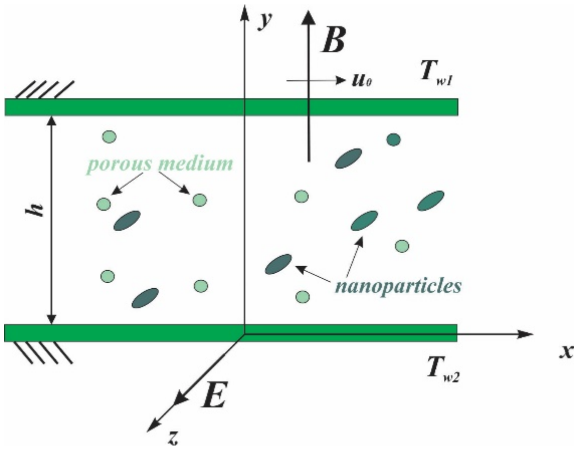


**Fig. 1** Physical configuration

Assuming that the physical properties of the nanofluid are constant, then equations:

$$\frac{\partial p}{\partial x}+\mu_{nf}\frac{d^2u}{dy^2}-\frac{\mu_{nf}}{K_0}B\sigma_{nf}[E+(u-u_0)B]=0, \tag{1}$$

$$k_{nf}\frac{d^2T}{dy^2}-\mu_{nf}\left(\frac{du}{dy}\right)^2+\frac{\mu_{nf}}{K_0}u^2+\sigma_{nf}[E+(u-u_0)B]^2=0 \tag{2}$$

and boundary conditions:

$$u(0)=0, u(h)=0,\ T(0)=T_{w2},\ T(h)=T_{w1} \tag{3}$$

constitute the mathematical model of the analyzed problem. Equations (1) and (2) and boundary conditions (3) utilize the following letters: x, y, z – Cartesian coordinates; p, u, T – pressure, velocity, and temperature of the nanofluid, respectively; and knf, μnf, σnf – thermal conductivity, dynamic viscosity, and electrical conductivity of the nanofluid, respectively. It is apparent from equations (1) and (2) that the magnetic field movement affects Lorentz force and Joule heating.

The following classical expressions are used for the nanofluid physical properties:

$$\mu_{nf}=\frac{\mu_f}{m}, \rho_{nf}=(1-\phi)\rho_f+\phi\rho_s, m=(1-\phi)^{2.5},$$

$$X_{nf}=X_f\varphi(X), \varphi(X)=\frac{2X_f+X_s-2\Phi(X_f-X_s)}{2X_f+X_s+\Phi(X_f-X_s)}, \tag{4}$$

where ϕ is the volume fraction of the nanoparticles and the subscripts *f*, *s*, and *nf* denote the base fluid, the nanoparticles, and the nanofluid, respectively. The two expressions (4) need to be altered with X=k to determine thermal conductivity and with X=σ to determine electrical conductivity.

## 3. SOLUTION

To determine the analytical solution of equations (1) and (2) with boundary conditions (3), they first need to be transformed into their dimensionless forms. For this purpose, the following dimensionless quantities are introduced:

$$y^* = \frac{y}{h},\ u^* = \frac{u}{U},\ \Theta = \frac{T - T_{w2}}{T_{w1} - T_{w2}},\ U = \frac{h^2 P}{\mu_f},\ P = -\frac{\partial p}{\partial x} = const. \tag{5}$$

With the introduced dimensionless quantities (5), equations (1) and (2) are transformed into the following dimensionless equations:

$$\frac{d^2 u}{dy^2} - \omega^2 u = A, \tag{6}$$

$$\frac{d^2 \Theta}{dy^2} + Br\left[b\left(\frac{du}{dy}\right)^2 + b\Lambda u^2 + cHa^2(K + u - d)^2\right] = 0, \tag{7}$$

respectively, while boundary conditions (3) are transformed into the following dimensionless conditions:

$$u(0) = 0, u(1) = 0,\ \Theta(0) = 0,\ \Theta(1) = 1. \tag{8}$$

For brevity, equations (6) and (7) contain the following lettering:

$$\Lambda = \frac{h^2}{K_0},\ K = \frac{E}{BU},\ d = \frac{u_0}{U},\ Ha = Bh\sqrt{\frac{\sigma_f}{\mu_f}},\quad Br = \frac{\mu_f}{\sigma_f}\frac{U^2}{T_{w1} - T_{w2}},$$

$$a = \varphi(\sigma)m, \omega^2 = \Lambda + aHa^2,\ A = aHa^2(k - d) - m,\ b = \frac{1}{m\varphi(k)},\ c = ab, \tag{9}$$

where Λ – porosity factor, K – external power factor, d – dimensionless velocity, Ha – Hartmann number, and Br – Brinkman number. For brevity, the asterisk marks (*) for dimensionless longitudinal velocity and dimensionless transversal coordinate have been omitted, but it is implied that these quantities are dimensionless hereinafter.

Solutions to equations (6) and (7) are relatively easy to determine, as given in the following expressions:

$$u(y) = C_1 exp(\omega y) + C_2 exp(-\omega y) + D, \tag{10}$$

$$\Theta(y) = Br[R_4 exp(2\omega y) + R_5 exp(-2\omega y) + R_7 exp(\omega y) + R_8 exp(-\omega y) + R_2 y^2 + C_3 y + C_4] \tag{11}$$

respectively, where $C_1$, $C_2$, $C_3$, and $C_4$ are the integration constants. Once again, for brevity, expressions (10) and (11) contain the following lettering:

$$D = -\frac{A}{\omega^2}, R_1 = b\Lambda + cHa^2,$$

$$R_2 = \frac{1}{2}[R_1(D^2 + 2C_1C_2) - 2b\omega^2 C_1 C_2 + 2(K - d)cDHa^2(K - d)^2],$$

$$R_3 = \frac{1}{4\omega^2}(b\omega^2 + R_1), R_4 = R_3 C_1^2, R_5 = R_3 C_2^2, R_6 = \frac{2}{\omega^2}[DR_1 + (K - d)cHa^2],$$

$$R_7 = R_6 C_1,\ R_8 = R_6 C_2. \tag{12}$$

Using dimensionless boundary conditions (8), it is simple to determine the integration constants, which have the following values:

$$C_1 = -\frac{DR_{11}}{R_9}, C_2 = -\frac{DR_{10}}{R_9},$$

$$C_3 = R_4[1 - exp(2\omega)] + R_5[1 - exp(-2\omega)] + R_7R_{10} + R_8R_{11} - R_2 - \frac{1}{Br},$$

$$C_4 = -(R_4 + R_5 + R_6 + R_7 + R_8),\ R_9 = exp(\omega) - exp(-\omega),$$

$$R_{10} = 1 - exp(\omega), R_{11} = 1 - exp(-\omega). \quad (13)$$

## 4. RESULTS AND ANALYSIS

The obtained analytical expressions (10) and (11) for nanofluid velocity and temperature distributions in the channel depend on the introduced physical parameters. To explore the influence of specific parameters on the two distributions, this section presents the results for the case of a water-copper nanofluid. The values of water and copper physical properties are given in Table 1.

**Table 1** Values of physical properties

| Physical properties | ρ (kg/m3) | k (W/(Km)) | σ (S/m) | μ (Pas) |
|---|---|---|---|---|
| Water | 997.1 | 0.613 | 5.5·10-6 | 0.001 |
| Copper | 8933 | 401 | 59.6·106 | - |

For a simpler and clearer analysis of the influence of specific physical parameters, the results are also shown graphically in the figures below. Figures 2 and 3 show velocity and temperature distributions when the channel operates in pump mode (K=-1), and for different Hartmann numbers, respectively. According to Figure 2, higher Hartmann numbers, i.e., stronger external magnetic field, correspond to higher nanofluid velocities in the channel. The increase in velocity is due to the increased Lorentz force intensity. Figure 3 shows that higher Hartmann numbers correspond to lower nanofluid temperatures in the channel. Therefore, the selection of magnetic field strength can influence nanofluid velocity and temperature, which means that the two quantities can be managed.

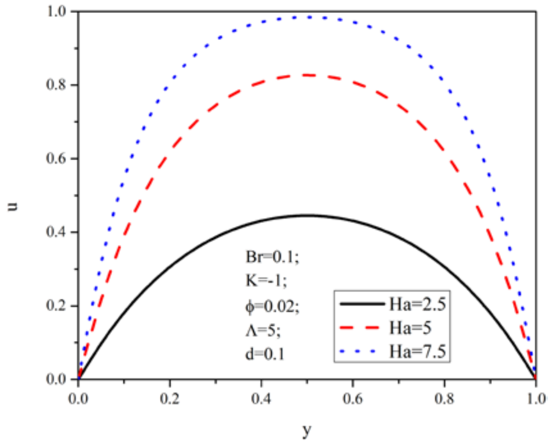


**Fig. 2** Velocity distributions for different Ha values

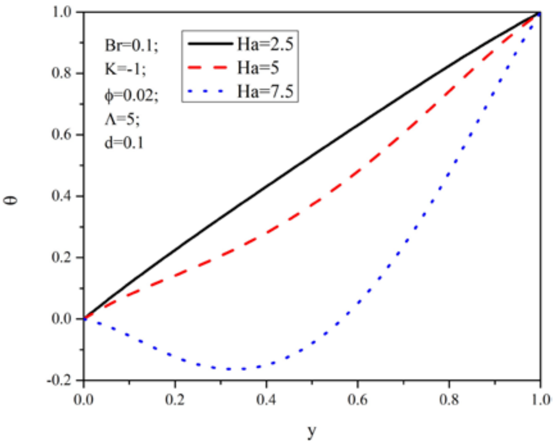


**Fig. 3** Temperature distributions for different Ha values

Figs. 4 and 5 show velocity and temperature distributions for different porosity factors, respectively. Fig. 4 shows that higher porosity factors, i.e., lower permeability of a porous medium, correspond to lower nanofluid velocities in the channel. This is due to the higher intensity of the porous medium resistance force. However, Fig. 5 shows that higher porosity factors correspond to higher nanofluid temperatures. The temperature increase is due to the energy increase to overcome the fluid flow resistance force in the porous medium. The energy is transformed into thermal energy.

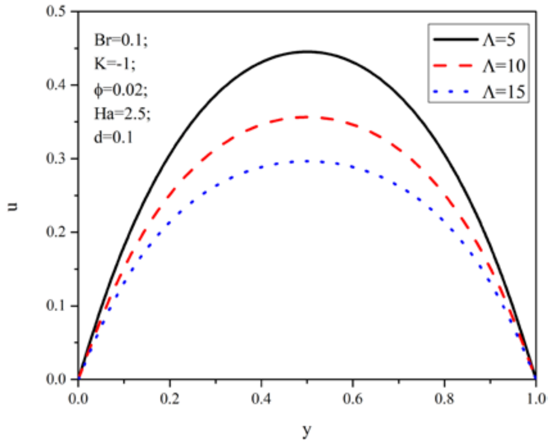


**Fig. 4** Velocity distributions for different Λ values

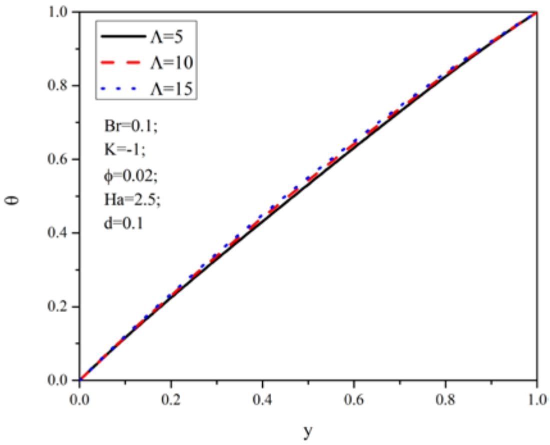


**Fig. 5** Temperature distributions for different Λ values

Thus, when designers need to consider the external magnetic field, its velocity, the external magnetic field, etc., they may change nanofluid velocity and temperature by selecting a specific permeability of the channel medium.

Figs. 6 and 7 show velocity and temperature distributions for different external magnetic field velocities, respectively. Higher velocities of the external magnetic field correspond to higher nanofluid velocities and temperatures. Higher magnetic field velocity increases the intensity of the Lorentz force, which is the active force here and causes the increase in nanofluid velocity, and at the same time increases Joule heating, in turn leading to a higher nanofluid temperature. It follows that changing the velocity of the external magnetic field can change nanofluid velocity and temperature, i.e., the two quantities can be managed.

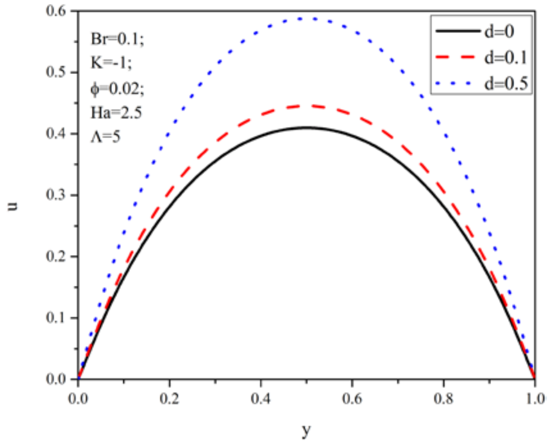


**Fig. 6** Velocity distributions for different d values

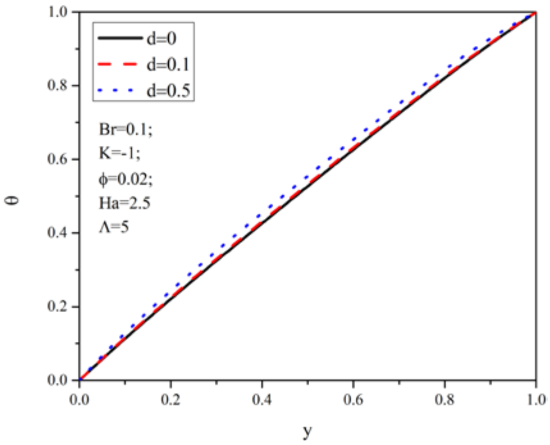


**Fig. 7** Temperature distributions for different d values

Figs. 8 and 9 show velocity and temperature distributions for different nanoparticle volume fractions, respectively. It is apparent that the increase in volume fraction increases the nanofluid density and the intensity of the flow resistance force. Consequently, nanofluid velocity decreases and the increased energy to overcome the flow resistance force is transformed into thermal energy, causing an increase in nanofluid temperature. Again, nanofluid velocity and temperature can be managed by changing the volume fraction of the nanoparticles. Of course, the stability of this suspension must be considered.

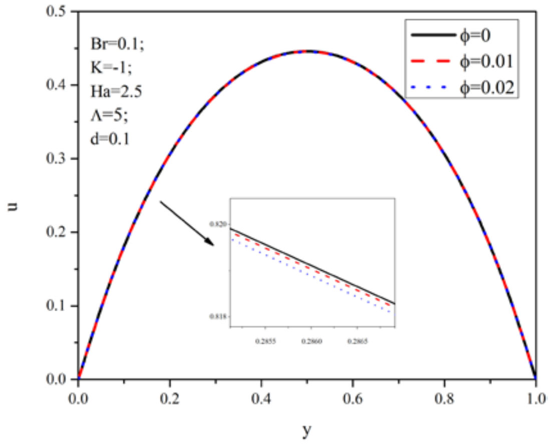


**Fig. 8** Velocity distributions for different ϕ values

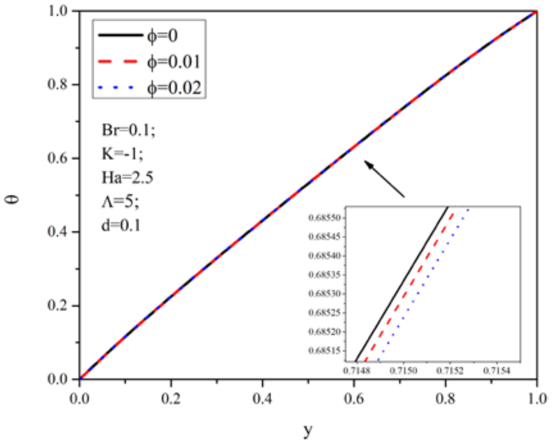


**Fig. 9** Temperature distributions for different ϕ values

Fig. 10 shows temperature distributions for three Brinkman numbers. Higher Brinkman numbers, i.e., lower temperature differences between channel walls, correspond to higher nanofluid temperatures. This is to be expected, as the Brinkman number was the multiplier in the obtained temperature expression. The Brinkman number does not affect velocity distribution, because it does not appear in impulse equations either explicitly or implicitly.

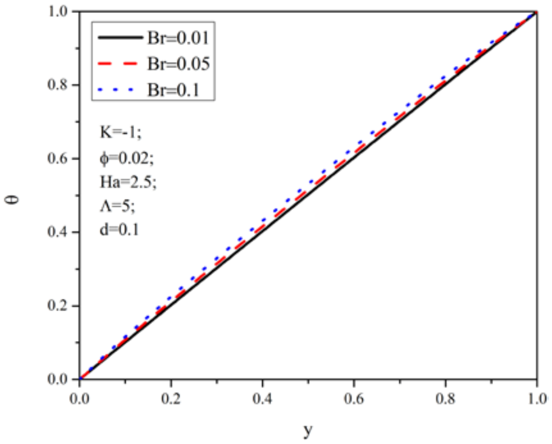


**Fig. 10** Temperature distributions for different Br values

Figs. 11 and 12 show velocity and temperature distributions for different external power factors, respectively. The lowest velocity and temperature occur when K=0. When K=-1, nanofluid velocity is the highest, while the temperature increases. When K=1, the velocity is lower than the velocity in the previous case and follows the opposite direction, whereas the temperatures differ only slightly.

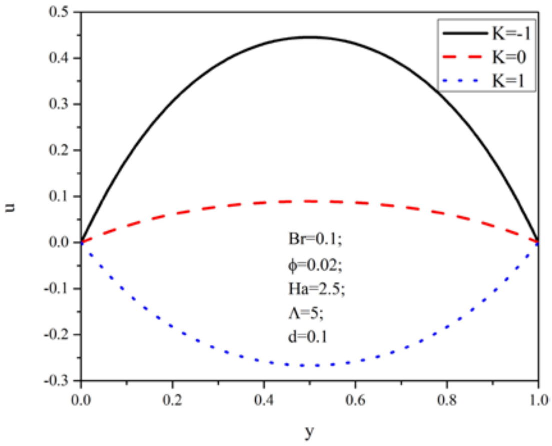


**Fig. 11** Velocity distributions for different K values

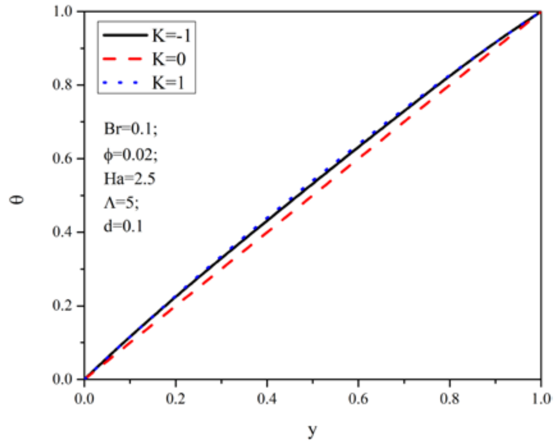


**Fig. 12** Temperature distributions for different K values

Changes of the power factor influence nanofluid velocity and temperature. When the sign and the value of the power factor change, i.e., when the external electric field direction changes, the direction of nanofluid velocity in the channel can also be changed.

## 5. CONCLUSION

This paper discussed nanofluid flow and heat transfer in a horizontal channel saturated with a porous medium and influenced by external electric and magnetic fields. For the analyzed problem, analytical expressions were determined for velocity and temperature distributions and presented graphically for multiple values of the introduced physical parameters. Results were presented for a water-copper nanofluid when the channel operates in pump mode. The results indicate that the Hartmann number increases the nanofluid's flow velocity in the channel but lowers its temperature. The porosity factor decreases nanofluid velocity but increases nanofluid temperature. Nanoparticle volume fraction decreases the velocity but increases nanofluid temperature. The Brinkman number increases nanofluid temperature but has no effect on velocity. External magnetic field velocity increases both the velocity and the temperature of the nanofluid. Finally, the power factor also increases both velocity and temperature, but it can alter the nanofluid velocity direction as well.

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