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# UNIVERSAL EQUATIONS OF UNSTEADY MHD INCOMPRESSIBLE FLUID FLOW WITH VARIABLE ELECTRO-CONDUCTIVITY ON HEATED MOVING PLATE

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**Abstract**. *The laminar, unsteady flow of viscous incompressible fluid caused by moving of semi-infinite flat plate with variable velocity is considered in this paper. The electro-conductivity is assumed as the linear function of velocities ratio. The present external magnetic field is perpendicular to the plate. The fluid properties, except the electro-conductivity, are isotropic and constant. The plate is warmed up (cool down). Dissipation and Joule heat are neglected. For the investigation of described problem the method of "universalisation" is used which has been formulated by L.G.Lojcijanski for boundary layer problems. The universal equations of described problem have been obtained by using this method. The momentum equation of problem is introduced firstly, in order to obtain the universal equations of the described problem. The approximate universal equations of mentioned problem are also given in the paper.*

**Key words**: *MHD incompressible fluid flow, universal equations, general similarity method.*

## INTRODUCTION

One of the first prospectors who considered natural and forced incompressible viscous fluid flow on the solid plates was Ostrach [1]. Later on Grief with associates [2], Gupta with associates [3] and other scientist are researched fluid flow on inert semi-infinite flat plate. With moving of semi-infinite flat plate or solid surface fluid flow is changed and this flow has been the exploration subject of Sakiadis [4]. In our paper [5], we considered MHD fluid flow caused by porous semi-infinite flat plate which moves with constant velocity. In this paper, we will consider unsteady MHD flow of incompressible fluid with variable electro-conductivity caused by moving of semi-infinite flat plate with variable velocity. For contemplation of described problem "universalization" method of laminar

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boundary layer equations has been used, which was formulated by L.G.Loicijanskij [6]. This method has numerous indisputable benefits in comparison with other approximated methods. The universal equations of described problem have been obtained by using this method. The obtained system of universal equations are integrated numerically only once by using a computer. The results of universal equations integration can be on convenient way saved and then used for drawing conclusion about fluid flow and for the calculations of particular problems. In this paper we will be satisfied with the creation of fluid flow universal equations of described problem.

## MATHEMATICAL MODEL

This paper is concerned with the laminar, unsteady flow of viscous, incompressible and electro-conductive fluid caused by variable moving of semi-infinite flat plate along x-axis. The plate moves in its own plane and in the still fluid. The velocity of plate is the function of time t. The present external magnetic field is perpendicular to the plate, and external electric field is neglected. All fluid properties are assumed constant, except the fluid electro-conductivity. The fluid electro-conductivity can be assumed in the following expression:

$$\sigma = \sigma_p \left(1 - \frac{u}{U}\right), \tag{1}$$

where u - means longitudinal velocity of the fluid, U - means plate moving velocity, $\sigma_p$-electro-conductivity at the edge of boundary layer, which is equal to the fluid electro-conductivity at the outer potential flow.

The plate temperature is function of longitudinal coordinate x and time t. Viscous dissipation, Joule's heat, Hole's and polarization effect are neglected. The mathematical model of described problem is expressed by the following equations:

$$\begin{gathered} \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{dU}{dt} + \gamma\frac{\partial^2 u}{\partial y^2} + NU\left(1 - \frac{u}{U}\right)^2 \\ \frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} \\ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \end{gathered} \tag{2}$$

in addition, the boundary and initial conditions:

$$\begin{gathered} u = U(t),\ v = 0,\ T = T_w(x,t)\ \text{ for } y = 0; \\ u \to 0\ ,\ T \to T_\infty\ \text{ for } y \to \infty; \\ u = u_1(x,y),\ T = T_1(x,y)\ \text{ for } t = t_1; \\ u = u_0(t,y),\ T = T_0(t,y)\ \text{ for }\ x = x_0 . \end{gathered} \tag{3}$$

In the equations (2) and the boundary and initial conditions (3) the parameter labelling used is common for the theory of MHD boundary layer: x,y - longitudinal and transversal coordinate respectively; t-time; v -transversal velocity component, $\nu$ - coefficient of the kinematics viscosity of fluid. $N = \sigma_p B^2/\rho$ where B - magnetic field induction, $\rho$ - density of fluid, $\sigma_0$ - fluid electro-conductivity in infinity, $\alpha = K/(\rho C_p)$ - temperature conduction coefficient, K - heat conduction coefficient, $C_p$ - specific heat at constant pressure, T - fluid temperature , $T_w$ - plate temperature, $T_\infty$ - fluid temperature in infinity; $u_1(x,y)$ and $T_1(x,y)$ - disposition of longitudinal velocity and fluid temperature in time moment $t = t_1$ respectively; $u_0(t,y)$ and $T_0(t,y)$ disposition of longitudinal velocity and fluid temperature for $x = x_0$, $t_1$-intial time moment for which the velocity and temperature distribution $u_1(x,y)$ and $T_1(x,y)$ are given.

For further consideration, we introduced flow function with relations:

$$\frac{\partial\Psi}{\partial x} = -v \ , \ \frac{\partial\Psi}{\partial y} = u \ , \tag{4}$$

which transform the system of equations (2) into the equations:

$$\frac{\partial^2\Psi}{\partial t\partial y} + \frac{\partial\Psi}{\partial y}\frac{\partial^2\Psi}{\partial x\partial y} - \frac{\partial\Psi}{\partial x}\frac{\partial^2\Psi}{\partial y^2} = \frac{dU}{\partial t} + \gamma\frac{\partial^3\Psi}{\partial y^3} + NU\left(1 - \frac{1}{U}\frac{\partial\Psi}{\partial y}\right)^2 ;$$

$$\frac{\partial T}{\partial t} + \frac{\partial\Psi}{\partial y}\frac{\partial T}{\partial x} - \frac{\partial\Psi}{\partial x}\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} ; \tag{5}$$

and the boundary and initial conditions (3) into conditions:

$$\frac{\partial\Psi}{\partial y} = U(t) \ , \Psi = 0, T = T_w(x,t) \quad \text{for} \quad y = 0 \ ;$$

$$\frac{\partial\Psi}{\partial y} \to 0, T \to T_\infty \quad \text{for} \quad y \to \infty \ ;$$

$$\frac{\partial\Psi}{\partial y} = u_1(x,y), \ T = T_1(x,y) \ \text{ for } \ t = t_1 \ ;$$

$$\frac{\partial\Psi}{\partial y} = u_0(t,y), \ T = T_0(t,y) \ \text{ for } \ x = x_0 \ . \tag{6}$$

For every particular problem i.e. for given values of U, N, $T_w$ and $T_\infty$; $u_1(x,y)$; $u_0(t,y)$ and $T_0(t,y)$ the system of equations (5) can be solved with corresponding boundary and initial conditions (6).

## UNIVERSAL EQUATIONS

V.J.Skadov [7], L.G. Loicijanskij [6] and V.N. Saljnikov [8] have constituted the general similarity method in the boundary layer theory in different forms. This method brings to the corresponding so-called universal equation and because of that very often in literature, this method is called "universalization" method. Essential of mentioned method is in adequate choice of transformations (new variables) and then similarity parameters with what the system transforms on universal equations and universal boundary conditions. Obtained universal equations and corresponding boundary conditions can be numerically integrated only once for given geometry flow, do not depend on particular problem, and results can be stored on convenient way, used for drawing the general conclusion about fluid flow and used for calculation of particular flow on given flow geometry. This method gives good results not only for simple boundary layer problems also for very complicated. Considering what we already told in this paper, we make attempt to evolve the general similarity method in Lojcijanski version on the described problem.

For that purpose in sense of following general similarity method-"universalization" method [6],[7],[8] we introduced new variables in next form:

$$\Phi(x,t,\eta)=\frac{\Psi}{U\delta^{**}},\ \eta=\frac{y}{\delta^{**}},\ \Theta(x,t,\eta)=\frac{T-T_\infty}{T_w-T_\infty} \tag{7}$$

where $\delta^{**}$ - thickness of momentum loss, defined with expression:

$$\delta^{**}=\int_0^\infty \frac{u}{U}\left(1-\frac{u}{U}\right)dy\,. \tag{8}$$

By using the new variables (7), we transform the system of equations (5) into the equations:

$$\frac{\partial^3\Phi}{\partial\eta^3}+\left(\frac{1}{2}F\Phi+\frac{1}{2}\eta p\right)\frac{\partial^2\Phi}{\partial\eta^2}+g_{1,0}\left(1-\frac{\partial\Phi}{\partial\eta}\right)^2+f_1\left(1-\frac{\partial\Phi}{\partial\eta}\right)=z\frac{\partial^2\Phi}{\partial t\partial\eta}+UzX(\eta;x)$$

$$\frac{1}{P_r}\frac{\partial^2\Theta}{\partial\eta^2}+\frac{1}{2}(F\Phi+\eta p)\frac{\partial\Theta}{\partial\eta}-l_{1,0}\Theta\frac{\partial\Phi}{\partial\eta}-l_{0,1}\Theta=z\frac{\partial\Theta}{\partial t}+UzY(\eta zx) \tag{9}$$

where, for the sake of shorter expression, the notations are introduced:

$$z=\frac{\delta^{**2}}{\gamma},\ F=U\frac{\partial z}{\partial x},\ f_1=\frac{z}{U}\frac{dU}{dt},\ g_{1,0}=Nz,\ \Pr=\frac{\gamma}{\alpha}\text{-Prandtl number,}$$

$$l_{1,0}=\frac{Uz}{T_w-T_\infty}\frac{\partial T_w}{\partial x},\ l_{0,1}=\frac{z}{T_w-T_\infty}\frac{\partial T_w}{\partial t},\ p=\frac{\partial z}{\partial t},$$

$$X(x_1;x_2)=\frac{\partial\Phi}{\partial x_1}\frac{\partial^2\Phi}{\partial\eta\partial x_2}-\frac{\partial\Phi}{\partial x_2}\frac{\partial^2\Phi}{\partial x_1\partial\eta}\ ;\ Y(x_1;x_2)=\frac{\partial\Phi}{\partial x_1}\frac{\partial\Theta}{\partial x_2}-\frac{\partial\Phi}{\partial x_2}\frac{\partial\Theta}{\partial x_1}\,. \tag{10}$$

Obtained system of equations (9) are integrated with respect to the next boundary conditions

$$\frac{\partial\Phi}{\partial\eta}=1,\ \Phi=0,\Theta=1\ \text{ for }\ \eta=0\,;$$

$$\frac{\partial\Phi}{\partial\eta}\to 1,\ \Theta\to 0\ \text{ for }\ \eta\to\infty\,, \tag{11}$$

which is derivated from conditions (6).

By further following the -"universalization" method we introduced in consideration three sets of parameters:

$$f_k = \frac{1}{U}\frac{d^k U}{dt^k} z^k \quad (k = 1,2,...);\; g_{k,n} = U^{k-1} z^{k+n} \frac{\partial^{k-1+n} N}{\partial x^{k-1} \partial t^n},$$

$$l_{k,n} = \frac{U^k}{q}\frac{\partial^{k+n} q}{\partial x^k \partial t^n} z^{k+n}, \; (k,n = 0,1,2,...;\; k \vee n \neq 0), \text{ where } q = T_w - T_\infty, \tag{12}$$

and constant parameter:

$$p = \frac{\partial z}{\partial t} = \text{const}, \tag{13}$$

which replace longitudinal coordinate x and time t. The introduced sets of parameters reflect the characteristics of plate velocity alteration, characteristic of variables alternation N and q and, a part from that, in the integral form (by means of $z$ and $\partial z / \partial t$) pre-history of flow. The assumption that parameter p=const is correct, for some determined flat plate velocity the method is correct and for the other velocities the method is approximate. Introduced sets of parameters enable transformations of equations system (9) unto universal form in sense that neither equations nor boundary conditions depend of external values i.e. from values that characterized particular problems.

In intention to induce universal equations, we introduced new independent variables $\eta, f_k, g_{k,n}, l_{k,n}$ in equations (9). Now using the differentiation operators

$$\frac{\partial}{\partial x} = \sum_{k=1}^{\infty} \frac{\partial f_k}{\partial x}\frac{\partial}{\partial f_k} + \sum_{\substack{k,n=0\\ k\vee n\neq 0}}^{\infty} \left( \frac{\partial g_{k,n}}{\partial x}\frac{\partial}{\partial g_{k,n}} + \frac{\partial l_{k,n}}{\partial x}\frac{\partial}{\partial l_{k,n}} \right)$$

$$\frac{\partial}{\partial t} = \sum_{k=1}^{\infty} \frac{\partial f_k}{\partial t}\frac{\partial}{\partial f_k} + \sum_{\substack{k,n=0\\ k\vee n\neq 0}}^{\infty} \left( \frac{\partial g_{k,n}}{\partial t}\frac{\partial}{\partial g_{k,n}} + \frac{\partial l_{k,n}}{\partial t}\frac{\partial}{\partial l_{k,n}} \right) \tag{14}$$

and with accomplishment of intended operations in system of equations (9), we came to next equation system:

$$\Im_1 = \sum_{\substack{k,n=0\\ k\vee n\neq 0}}^{\infty} [K_{k,n} X(\eta(g_{k,n}) + M_{k,n} X(\eta(l_{k,n})] +$$

$$+ \sum_{\substack{k,n=0\\ k\vee n\neq 0}}^{\infty} \left[ L_{k,n} \frac{\partial^2 \Phi}{\partial \eta \partial g_{k,n}} + N_{k,n} \frac{\partial^2 \Phi}{\partial \eta \partial l_{k,n}} \right] + \sum_{k=1}^{\infty} \left[ Q_k X(\eta(f_k) + E_k \frac{\partial^2 \Phi}{\partial \eta \partial f_k} \right]$$

$$\Im_2 = \sum_{\substack{k,n=0\\ k\vee n\neq 0}}^{\infty} [K_{k,n} Y(\eta(g_{k,n}) + M_{k,n} Y(\eta(l_{k,n})] +$$

$$+ \sum_{\substack{k,n=0\\ k\vee n\neq 0}}^{\infty} \left[ L_{k,n} \frac{\partial \Theta}{\partial g_{k,n}} + N_{k,n} \frac{\partial \Theta}{\partial l_{k,n}} \right] + \sum_{k=1}^{\infty} \left[ Q_k Y(\eta(f_k) + E_k \frac{\partial \Theta}{\partial f_k} \right] \tag{15}$$

where the following markings have been used for shorter statement: $\Im_1, \Im_2$-left side of first and left side of second equations of system (9) respectively,

$$Uz\frac{\partial f_k}{\partial x} = kFf_k = Q_k \ ; \ z\frac{\partial f_k}{\partial t} = f_k(kp - f_1) + f_{k+1} = E_k \ ;$$

$$Uz\frac{\partial g_{k,n}}{dx} = (k+n)g_{k,n}F + g_{k+1,n} = K_{k,n} \ ;$$

$$z\frac{\partial g_{k,n}}{\partial t} = [(k-1)f_1 + (k+n)p]g_{k,n} + g_{k,n+1} = L_{k,n}$$

$$Uz\frac{\partial l_{k,n}}{\partial x} = [-l_{1,0} + (k+n)F]l_{k,n} + l_{k+1,n} = M_{k,n} \ ;$$

$$z\frac{\partial l_{k,n}}{\partial t} = [kf_1 - l_{0,1} + (k+n)p]l_{k,n} + l_{k,n+1} = N_{k,n} \ . \qquad (16)$$

Boundary conditions, which are appropriate to equations (15), have the form:

$$\frac{\partial \Phi}{\partial \eta} = 1, \ \Phi = 0, \Theta = 1 \ \text{ for } \ \eta = 0 \ ;$$

$$\frac{\partial \Phi}{\partial \eta} \to 1, \ \Theta \to 0 \ \text{ for } \ \eta \to \infty \ ;$$

$$\Phi = \Phi_0, \Theta = \Theta_0 \quad \text{for} \quad f_k = 0 \ (k = 1,2,...), g_{k,n} = 0, \ l_{k,n} = 0$$

$$(k, n = 0,1,2,...; k \vee n \neq 0), \ p = 0 \qquad (17)$$

where $\Phi_0$ and $\Theta_0$ are solutions of following system of equations:

$$\frac{\partial^3 \Phi}{\partial \eta^3} + \frac{1}{2}F\Phi\frac{\partial^2 \Phi}{\partial \eta^2} = 0 \ ,$$

$$\frac{1}{\Pr}\frac{\partial^2 \Theta}{\partial \eta^2} + \frac{1}{2}F\Phi\frac{\partial \Theta}{\partial \eta} = 0 \ . \qquad (18)$$

In order to make the system of equations (15) universal, it is necessary to deprive parameter F from it. Adequate problem in boundary layer theory has been prevailed by using the momentum equation, so we will try to do so here. Following the Karman ideas, the first equation of system (2) can be written in form:

$$\frac{\partial}{\partial t}(u - U) + \frac{\partial}{\partial x}(u^2) + \frac{\partial}{\partial y}(uv) - NU\left(1 - \frac{u}{U}\right)^2 = \nu\frac{\partial^2 u}{\partial y^2} \qquad (19)$$

and third equation of the same system after multiplication with U in form:

$$\frac{\partial}{\partial x}(uU) + \frac{\partial}{\partial y}(vU) = 0 \ . \qquad (20)$$

If we subtract equation (20) from equation (19) and integrate in that way obtained equation, transversal to the flow in boundary's from 0 to $\infty$, with respect to boundary conditions (3) we derivate next equation:

$$\frac{\partial}{\partial t}\left[U\int_0^\infty\left(1-\frac{u}{U}\right)dy\right]+\frac{\partial}{\partial x}\left[U^2\int_0^\infty\frac{u}{U}\left(1-\frac{u}{U}\right)dy\right]+NU\int_0^\infty\left(1-\frac{u}{U}\right)^2dy=-\gamma\left(\frac{\partial u}{\partial y}\right)_\infty \tag{21}$$

By assuming the existing of integrals:

$$\delta^*=\int_0^\infty\left(1-\frac{u}{U}\right)dy\,,\ \delta_1=\int_0^\infty\left(1-\frac{u}{U}\right)^2dy \tag{22}$$

last equation became:

$$\frac{\partial}{\partial t}(U\delta^*)+\frac{\partial}{\partial x}(U^2\delta^{**})+NU\delta_1=-\gamma\left(\frac{\partial u}{\partial y}\right)_\infty \tag{23}$$

and represent the momentum equation of the observed problem.

If we write the derivations on the left side of equation (23) in expanded form and replace variables (7) and parameters (12) like new independent variables, we obtain the equation that can be solved according to parameter F:

$$F=-2\left[\zeta+H\left(f_1+\frac{1}{2}p\right)-H_1g_{1,0}+\sum_{k=1}^{n}E_k\frac{\partial H}{\partial f_k}+\sum_{\substack{k,n=0\\k\vee n\neq 0}}^{\infty}\left(L_{k,n}\frac{\partial H}{\partial g_{k,n}}+N_{k,n}\frac{\partial H}{\partial l_{k,n}}\right)\right] \tag{24}$$

where, for the sake of brevity, the notation is introduced:

$$\zeta=\left(\frac{\partial^2\Phi}{\partial\eta^2}\right)_\infty;$$

$$H=\frac{\delta^*}{\delta^{**}}=\int_0^\infty\left(1-\frac{\partial\Phi}{\partial\eta}\right)d\eta;$$

$$H_1=\frac{\delta_1}{\delta^{**}}=\int_0^\infty\left(1-\frac{\partial\Phi}{\partial\eta}\right)^2d\eta. \tag{25}$$

Values, $\zeta$, H and $H_1$ depend only from parameters (12) and that mean also for value F which is expressed with equation (24), so it can be stated now that the system of equations (15) is the universal equations system of observed problem. System of equations (15) and corresponding boundary conditions (17) has the same form for every analytic function of values N, $T_w$, U. At this way the system of differential equations (2), which contain in itself and in boundary conditions (3) features of particular problems, is transformed to the system of universal differential equations (15) which is the same for every particular problem. Equations system (15) with boundary conditions (17) can be integrated by using computer, and during that process only "snipping" of equations has been considered. Obtained results can be on convenient way saved and then used for general conclusion conveyance about fluid flow and for calculations of particular problems.

## APPROXIMATED UNIVERSAL EQUATIONS

Actual solving of equations (15) requires limitation of independent variables number. This leads us to indispensable application of "snipping" method, which consists of neglecting of all parameters starting with some index. That brings us to approximated universal equations of described problem. If we retain influence of parameters $f_1$; $g_{1,0}$; $l_{1,0}$ and neglect influence of the rest of parameters and their derivatives, we obtain the system of universal equations in four-parameter approximation

$$\begin{aligned}\Im_1 &= g_{1,0}FX(\eta;g_{1,0}) + f_1FX(\eta;f_1) + l_{1,0}(F - l_{1,0})X(\eta;l_{1,0}) + g_{1,0}p\frac{\partial^2\Phi}{\partial\eta\partial g_{1,0}} + \\ &\quad +(f_1+p)l_{1,0}\frac{\partial^2\Phi}{\partial\eta\partial l_{1,0}} + f_1(p-f_1)\frac{\partial^2\Phi}{\partial\eta\partial f_1} \\ \Im_2 &= g_{1,0}FY(\eta;g_{1,0}) + f_1FY(\eta;f_1) + l_{1,0}(F - l_{1,0})Y(\eta;l_{1,0}) + g_{1,0}p\frac{\partial\Theta}{\partial g_{1,0}} + \\ &\quad +(f_1+p)l_{1,0}\frac{\partial\Theta}{\partial l_{1,0}} + f_1(p-f_1)\frac{\partial\Theta}{\partial f_1}.\end{aligned} \tag{26}$$

Corresponding boundary conditions for equations (26) have the following form:

$$\begin{gathered}\frac{\partial\Phi}{\partial\eta} = 1,\ \Phi = 0, \Theta = 1 \ \text{ for } \eta = 0; \\ \frac{\partial\Phi}{\partial\eta} \to 1,\ \Theta \to 0 \ \text{ for } \eta \to \infty; \\ \Phi = \Phi_0, \Theta = \Theta_0 \\ \text{for } f_1 = 0,\ g_{1,0} = 0,\ l_{1,0} = 0,\ p = 0,\end{gathered} \tag{27}$$

where $\Phi_0$ and $\Theta_0$ represent solution of system of equations (18).

On the same way, we can acquire other approximated equations of described problem.

SUMMARY

This paper is concerned with unsteady MHD flow of incompressible fluid caused by moving of semi-infinite flat plate with variable velocity. The fluid electro-conductivity is variable. The semi-infinite flat plate moves in its own plane in and in "undisturbed" fluid. Variable plate temperature is function of longitudinal coordinate and time. Universal equations of the observed problem are obtained by using the general similarity method. The momentum equation and approximated universal equations are also derived in this paper.


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# UNIVERZALNE JEDNAČINE NESTACIONARNOG MHD STRUJANJA NESTIŠLJIVOG FLUIDA PROMENLJIVE ELEKTROPROVODNOSTI NA ZAGREJANOJ PLOČI


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*U radu se razmatra laminarno, nestacionarno strujanje, viskoznog, nestišljivog fluida izazvanog kretanjem ravne ploče, promenljivom brzinom. Pretpostavlja se da je elektroprovodnost fluida linearna funkcija odnosa brzina. Prisutno je spoljašnje magnetno polje koje je upravno na ploču. Sve karakteristike fluida, osim elektroprovodnosti su izotropne i konstantne. Ploča je zagrejana (hlađena). Disipacija i Džulova toplota se zanemaruju. Za razmatranje opisanog problema primenjuje se metoda "univerzalizacije" jednačina laminarnog graničnog sloja koju je formulisao L.G. Lojcijanski. Univerzalne jednačine ovog problema su dobijene korišćenjem opisane metode. Pri dobijanju jednačina najpre se uvodi impulsna jednačina opisanog problema. Pridbližne univerzalne jednačine, za dato strujanje takođe su date u ovom radu..*