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SOLUTION OF STAGNATION POINT FLOW WITH HEAT TRANSFER ANALYSIS BY OPTIMAL HOMOTOPY ASYMPTOTIC METHOD

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In this paper, we use the optimal homotopy asymptotic method to solve the stagnation point flow and heat transfer. Comparison of results have been made with the numerical solutions obtain in [1]. Further, we investigate by our analysis the velocity field and temperature distributions carefully for various Peclets number. Our results show that this method provides us a suitable way to control the convergence of the series solution using the auxiliary constants which are optimally determined.

Key words: Viscous fluid, Stagnation point flow, Heat transfer, OHAM.

1. INTRODUCTION

In fluid dynamics, more attention has been given to the study of stagnation-point flows because of their importance in many engineering disciplines for example cooling of electronic devices by fans, cooling of nuclear reactors, and many hydrodynamics processes. The analysis of such flows is very important in both theory and practice [2-7].

Non-linear differential equations can be solved analytically by various perturbation techniques. These techniques are very simple in calculating the solutions, but the limitations of these methods are based on the assumption of small parameter and there is no proper way of its selection. The researchers were looking for some new techniques which are independent of the small parameter. An excellent review of such techniques is given by He in [8].

In this paper, a different homotopy approach, namely the optimal homotopy asymptotic method (OHAM) is used to solve the nonlinear title problem. This method combines the He's Homotopy Perturbation Method (HPM) and the method of least squares to optimally identify the unknown constants of the series solutions [9-10]. Marinca et al. [11] proposed this new homotopy technique called the optimal homotopy asymptotic method (OHAM) which also proved to be a reliable approach to strongly nonlinear problems. In a series of papers by Marinca et al. [12-14] and Islam et al. [15-17] have not only applied this method successfully to obtain the solution of some important problems in engineering and fluid mechanics, but also they have shown that this method is a powerful tool than other perturbation tools for non linear problems.

In this work, we first consider governing equations to present stagnation point flow and heat transfer analysis. Then we use Optimal Homotopy Asymptotic Method (OHAM) to obtain approximate solution. Finally we compare our approximate solution with the well known numerical technique and present numerical results which show that the velocity field obtained using OHAM for plane stagnation flow and axisymmetric stagnation flow is approximately same as derived in [1]. Moreover, we also investigate that the results obtained from OHAM is logically good and converge to the exact solution as the constant $c_i's$ increased in the auxiliary function.

2. BASIC GOVERNING EQUATIONS

For an incompressible viscous fluid the equations of conservation of mass, momentum, and energy are given as [1]

$$\nabla \cdot \boldsymbol{V} = 0, \tag{1}$$

$$\rho \boldsymbol{V}^{\bullet} = -\nabla p + \mu \nabla^2 \boldsymbol{V} + \rho \boldsymbol{f}, \tag{2}$$

$$\rho c_p \frac{D\Theta}{dt} = k\nabla^2\Theta + \mathrm{j}, \tag{3}$$

where $\boldsymbol{V}$ is the velocity of the fluid, Θ is the temperature of the fluid, k is the thermal conductivity, j is the dissipation function, $\boldsymbol{f}$ is the body force, c_p is the specific heat of the fluid, ρ is the density of the fluid, μ is the coefficient of viscosity, and $"\bullet"$ denote the total material derivative for velocity and temperature.

2.1. Plane Stagnation Flow

In plane stagnation flow, the stagnation point is a line, i.e., there is no variation in the z direction. The origin is the stagnation point (where $u = \upsilon = 0$ in the frictionless solution), and y is the normal to the plane [1]. The continuity equation (1) reduces to:

$$\frac{\partial u}{\partial x} + \frac{\partial \upsilon}{\partial y} = 0 \tag{4}$$

which can be satisfied by the stream function

$$u = \frac{\partial \psi}{\partial y}, \upsilon = -\frac{\partial \psi}{\partial x}.$$

In the absence of body force, momentum equation (2) takes the form [1]:

$$u\frac{\partial u}{\partial x} + \upsilon\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right], \tag{5}$$

$$u\frac{\partial \upsilon}{\partial x} + \upsilon\frac{\partial \upsilon}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu\left[\frac{\partial^2 \upsilon}{\partial x^2} + \frac{\partial^2 \upsilon}{\partial y^2}\right] \quad u = \upsilon = 0, \text{ at } y = 0. \tag{6}$$

Neglecting the dissipation function φ, the energy equation (3) becomes [1]:

$$\rho c_p\left(u\frac{\partial T}{\partial x} + \upsilon\frac{\partial T}{\partial y}\right) = k\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right] \quad T = T_w \text{ at } y = 0, \ T = T_\infty \text{ at } y \to \infty. \tag{7}$$

Introducing the non-dimensional parameters

$$\eta = y\sqrt{\frac{A}{\nu}}, \ \Psi = xF(\eta)\sqrt{A\nu}, \ u = AxF'(\eta), \ \upsilon = -F(\eta)\sqrt{A\nu}, \ \Theta(\eta) = \frac{T - T_w}{T_\infty - T_w},$$

where T_w and T_∞ are the temperatures of the fluid at the wall and at $y \to \infty$.

$$F''' + FF'' + 1 - F'^2 = 0 \quad ; \quad F(0) = 0, F'(0) = 0, F'(\infty) = 1, \tag{8}$$

$$\frac{d^2\Theta}{d\eta^2} + \Pr F(\eta)\frac{d\Theta}{d\eta} = 0 \quad ; \quad \Theta(0) = 0, \Theta(\infty) = 1, \tag{9}$$

where the Prandtl number $\Pr = \mu c_p / k$ is assumed to be constant.

2.2. Axisymmetric Stagnation Flow

In axisymmetric stagnation flow, the stagnation point is a point, and we interpret x as the cylindrical radius coordinate r, and y is the axial coordinate. The continuity eq. (1) reduces to

$$\frac{1}{x}\frac{\partial(xu)}{\partial x} + \frac{\partial \upsilon}{\partial y} = 0, \tag{10}$$

which can be satisfied by the stream function, $u = -\frac{1}{x}\frac{\partial \psi}{\partial y}, \upsilon = \frac{1}{x}\frac{\partial \psi}{\partial x}$.

In the absence of body force, momentum equation (2) takes the form [1]:

$$u\frac{\partial u}{\partial x} + \upsilon\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left[\frac{1}{x}\frac{\partial}{\partial x}\left(x\frac{\partial u}{\partial x}\right) - \frac{u}{x^2} + \frac{\partial^2 u}{\partial y^2}\right] \tag{11}$$

$$u\frac{\partial \upsilon}{\partial x} + \upsilon\frac{\partial \upsilon}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu\left[\frac{1}{x}\frac{\partial}{\partial x}\left(x\frac{\partial \upsilon}{\partial x}\right) + \frac{\partial^2 u}{\partial y^2}\right] \quad ; \quad u = \upsilon = 0, \text{ at } y = 0. \tag{12}$$

Neglecting the dissipation function j, the energy equation (3) becomes [1]:

$$\rho c_p\left(u\frac{\partial T}{\partial x} + \upsilon\frac{\partial T}{\partial y}\right) = k\left[\frac{1}{x}\frac{\partial}{\partial x}\left(x\frac{\partial T}{\partial x}\right) + \frac{\partial^2 T}{\partial y^2}\right] \quad ; \quad T = T_w \text{ at } y = 0, \ T = T_\infty \text{ at } y \to \infty. \tag{13}$$

The equations of momentum and energy (11-12) and (13) take the following form with the corresponding boundary conditions by introducing the mentioned dimensionless variables [1]

$$\eta = y\sqrt{\frac{A}{\text{v}}},\ \Psi = -x^2 G(\eta)\sqrt{A\text{v}},\ u = AxG'(\eta),\ \upsilon = -2G(\eta)\sqrt{A\text{v}},\ \ \theta(\eta) = \frac{T - T_w}{T_\infty - T_w},$$

$$G''' + 2GG'' + 1 - G'^2 = 0 \quad ; \quad G(0) = 0, G'(0) = 0, G'(\infty) = 1, \tag{14}$$

$$\frac{d^2\theta}{d\eta^2} + 2\Pr G(\eta)\frac{d\theta}{d\eta} = 0 \quad ; \quad \theta(0) = 0, \theta(\infty) = 1, \tag{15}$$

where $\Pr = \mu c_p / k$ is the Prandtl number during the calculation it is kept constant.

3. SOLUTION APPROACH

We construct a Homotopy for equation (8), where

$$L = \frac{d^3}{d\eta^3},\ N = \left(F\frac{d^2 F}{d\eta^2} - \left(\frac{dF}{d\eta}\right)^2\right), \text{ and } g(\eta) = 1. \tag{16}$$

We obtain problems of different orders after equating the like terms of p:

Zeroth-order problem:

$$F_0'''(\eta) = -1, \quad ; \quad F_0(0) = 0,\ F_0'(0) = 0,\ F_0'(\infty) = 1, \tag{17}$$

with the solution

$$F_0(\eta) = \frac{1}{12}(11\eta^2 - 2\eta^3). \tag{18}$$

First-order problem:

$$F_1'''(\eta, c_1) = 1 + c_1 - c_1 F_0'^2 + c_1 F_0 F_0'' + F_0''' + c_1 F_0''' \quad ; \quad F_1(0) = 0,\ F_1'(0) = 0,\ F_1'(\infty) = 0, \tag{19}$$

having the solution with the specified boundary conditions:

$$F_1(\eta, c_1) = \frac{\left(5{,}9913\eta^2 c_1 - 1{,}694\eta^5 c_1 + 308\eta^6 c_1 - 24\eta^7 c_1\right)}{60{,}480}. \tag{20}$$

Second-order problem:

$$\begin{gathered} F_2'''(\eta, c_1, c_2) = c_2 - c_2 F_0'^2 - 2c_1 F_0' F_1' + c_2 F_0 F_0'' + c_1 F_1 F_0'' + c_1 F_1'' F_0 + c_2 F_0''' + F_1''' + c_1 F_1''', \\ F_2(0) = 0,\ F_2'(0) = 0,\ F_2'(\infty) = 0, \end{gathered} \tag{21}$$

give the solution of the problem with the corresponding boundary conditions are:

$$F_2(\eta, c_1, c_2) = \frac{1}{1{,}437{,}004{,}800} \begin{pmatrix} 14{,}236\eta^2 c_1 - 40{,}2494\eta^5 c_1 + 73{,}181\eta^6 c_1 - 57{,}024\eta^7 c_1 + \\ +58{,}0898\eta^2 c_1^2 - 12{,}724\eta^5 c_1^2 + 15{,}227\eta^6 c_1^2 - 5{,}703\eta^7 c_1^2 - \\ -21{,}962\eta^8 c_1^2 + 53{,}240\eta^9 c_1^2 - 11{,}616\eta^{10} c_1^2 + 576\eta^{11} c_1^2 + \\ +14{,}236\eta^2 c_2 - 40{,}2494\eta^5 c_2 + 73{,}181\eta^6 c_2 - 57{,}024\eta^7 c_2 \end{pmatrix}. \tag{22}$$

The second order approximation of equation (8) becomes:

$$\begin{aligned} \tilde{F}(\eta, c_1, c_2) = {} & \frac{1}{12}(11\eta^2 - 2\eta^3) + \frac{5{,}9913\eta^2 c_1 - 1{,}694\eta^5 c_1 + 308\eta^6 c_1 - 24\eta^7 c_1}{60{,}480} + \\ & \frac{1}{1{,}437{,}004{,}800} \begin{pmatrix} 14{,}236\eta^2 c_1 - 40{,}2494\eta^5 c_1 + 73{,}181\eta^6 c_1 - 57{,}024\eta^7 c_1 + \\ +58{,}0898\eta^2 c_1^2 - 12{,}724\eta^5 c_1^2 + 15{,}227\eta^6 c_1^2 - 5{,}703\eta^7 c_1^2 - \\ -21{,}962\eta^8 c_1^2 + 53{,}240\eta^9 c_1^2 - 11{,}616\eta^{10} c_1^2 + 576\eta^{11} c_1^2 + \\ +14{,}236\eta^2 c_2 - 40{,}2494\eta^5 c_2 + 73{,}181\eta^6 c_2 - 57{,}024\eta^7 c_2 \end{pmatrix}. \end{aligned} \tag{23}$$

where the values of constant c_1 and c_2 are determined from the method of least square, as explained in the section basic idea of OHAM, $c_1 = -\,0.3107993431533097$, $c_2 = -\,0.06896949741858062$.

Next, we construct a Homotopy for equation (9), where

$$N = \Pr\left(F(\eta)\frac{d\Theta}{d\eta}\right),\ L = \frac{d^2}{d\eta^2}, \text{ and } g(\eta) = 0. \tag{24}$$

and equating the like powers of p, we find various order problems:

Zeroth-order problem:

$$\Theta_0''(\eta)=0 \quad ; \quad \Theta_0(0)=0,\ \Theta_0(\infty)=1, \tag{25}$$

First-order problem:

$$\Theta_1''(\eta,c_1)=F(\eta)\Pr c_1\Theta_0+\Theta_0''+c_1\Theta_0'' \quad ; \quad \Theta_1(0)=0,\ \Theta_1(\infty)=0, \tag{26}$$

give solutions of equations (25) and (26) with the corresponding boundary conditions are respectively as given by:

$$\Theta_0(\eta)=\frac{\eta}{3}. \tag{27}$$

$$\begin{aligned}\Theta_1(\eta,c_1)=&-0.4524765\Pr\eta\, c_1+0.010146352\Pr\eta^5c_1-0.0018518518\Pr\eta^6c_1+\\&+3.30218911\times10^{-20}\Pr\eta^7c_1+0.000051820\Pr\eta^8c_1-\\&-7.327675570178881\times10^{-6}\Pr\eta^9c_1+8.729746502\times10^{-7}\Pr\eta^{10}c_1-\\&-4.473526616\times10^{-8}\Pr\eta^{11}c_1+9.03742751\times10^{-9}\Pr\eta^{12}c_1-\\&-1.6684482\times10^{-9}\Pr\eta^{13}c_1+7.09139712\times10^{-11}\Pr\eta^{14}c_1.\end{aligned} \tag{28}$$

The second order approximation of equation (9) becomes:

$$\begin{aligned}\Theta=&\frac{\eta}{3}-0.4524765\Pr\eta c_1+0.010146352\Pr\eta^5c_1-0.0018518518\Pr\eta^6c_1\\&+3.30218911\times10^{-20}\Pr\eta^7c_1+0.000051820\Pr\eta^8c_1-7.3276755701\times10^{-6}\Pr\eta^9c_1\\&+8.729746502\times10^{-7}\Pr\eta^{10}c_1-4.47352661\times10^{-8}\Pr\eta^{11}c_1+9.0374275\times10^{-9}\Pr\eta^{12}c_1\\&-1.6684482\times10^{-9}\Pr\eta^{13}c_1+7.09139712\times10^{-11}\Pr\eta^{14}c_1.\end{aligned} \tag{29}$$

Now we construct a Homotopy for equation (14), where

$$L=\frac{\mathrm{d}^3}{\mathrm{d}\eta^3},\ N=\left(2G\frac{\mathrm{d}^2G}{\mathrm{d}\eta^2}-\left(\frac{\mathrm{d}G}{\mathrm{d}\eta}\right)^2\right),\ \text{and}\ \ g(\eta)=1. \tag{30}$$

Equating the terms with the identical powers of p, we obtain different order problems:

Zeroth-order problem:

$$G_0'''(\eta)=-1 \quad ; \quad G_0(0)=0,\ G_0'(0)=0,\ G_0'(\infty)=1. \tag{31}$$

First-order problem:

$$G_1'''(\eta,c_1)=1+c_1-c_1G_0'^2+2c_1G_0G_0''+G_0'''+c_1G_0''' \quad ; \quad G_1(0)=0,\ G_1'(0)=0,\ G_1'(\infty)=0. \tag{32}$$

Second-order problem:

$$\begin{gathered}G_2'''(\eta,c_1,c_2)=c_2-c_2G_0'^2-2c_1\,G_0'G_1'+2c_2G_0G_0''+2c_1G_1G_0''+c_1G_1''G_0+c_2G_0'''+G_1'''+c_1G_1''',\\ G_2(0)=0,\ G_2'(0)=0,\ G_2'(\infty)=0,\end{gathered} \tag{33}$$

the solutions of equation (31-33) with the corresponding boundary conditions are respectively as:

$$G_0(\eta)=\frac{1}{12}(11\eta^2-2\eta^3), \tag{34}$$

$$G_1(\eta,c_1)=\frac{\left(13{,}608\eta^2c_1-77\eta^6c_1+6\eta^7c_1\right)}{15{,}120} \tag{35}$$

$$G_2(\eta,c_1,c_2)=\frac{1}{179{,}625{,}600}\begin{pmatrix}161{,}663{,}040\eta^2c_1-914{,}760\eta^6c_1+71{,}280\eta^7c_1+\\+676{,}314{,}441\eta^2c_1^2-1{,}812{,}888\,\eta^6c_1^2+71{,}280\eta^7c_1^2-\\-66{,}550\eta^9c_1^2+13{,}068\eta^{10}c_1^2\;-648\eta^{11}c_1^2+\\+161{,}663{,}040\eta^2c_2-914{,}760\eta^6c_2+71{,}280\eta^7c_2\end{pmatrix}. \tag{36}$$

The second order approximation for velocity field in axisymmetric flow is:

$$\tilde{G}(\eta,c_1,c_2)=\frac{1}{12}(11\eta^2-2\eta^3)+\frac{\left(13{,}608\eta^2c_1-77\eta^6c_1+6\eta^7c_1\right)}{15{,}120}+\frac{1}{179{,}625{,}600}\begin{pmatrix}161{,}663{,}040\eta^2c_1-914{,}760\eta^6c_1+71{,}280\eta^7c_1+\\+676{,}314{,}441\eta^2c_1^2-1{,}812{,}888\,\eta^6c_1^2+71{,}280\eta^7c_1^2-\\-66{,}550\eta^9c_1^2+13{,}068\eta^{10}c_1^2\;-648\eta^{11}c_1^2+\\+161{,}663{,}040\eta^2c_2-914{,}760\eta^6c_2+71{,}280\eta^7c_2\end{pmatrix}, \tag{37}$$

where $c_1=-0.255792696846651$, $c_2=-0.027530840462981345$.

Finally, we construct a Homotopy for equation (15), where

$$L=\frac{\mathrm{d}^2}{\mathrm{d}\eta^2},\;\; N=2\Pr\left(F(\eta)\frac{\mathrm{d}\theta}{\mathrm{d}\eta}\right),\text{ and }\; g(\eta)=0, \tag{38}$$

and obtained different order problems as in the previous all cases:

Zeroth-order problem:

$$\theta_0''(\eta)=0\quad;\quad\theta_0(0)=0,\,\theta_0(\infty)=1, \tag{39}$$

First-order problem:

$$\theta_1''(\eta,c_1)=2G(\eta)\Pr c_1\theta_0+\theta_0''+c_1\theta_0''\quad;\quad\theta_1(0)=0,\,\theta_1(\infty)=0, \tag{40}$$

the solutions of equation (39-40) with the corresponding boundary conditions are respectively as:

$$\theta_0(\eta)=\frac{\eta}{3}. \tag{41}$$

$$\begin{aligned}\theta_1(\eta,c_1)=&-0.9049531\Pr\eta c_1+0.0202927\Pr\eta^5c_1-0.0037037\Pr\eta^6c_1+\\&+6.60437\times10^{-20}\Pr\eta^7c_1+0.0001036\Pr\eta^8c_1-\\&-0.000014655\Pr\eta^9c_1+1.74594930\times10^{-6}\Pr\eta^{10}c_1-\\&-8.9470532\times10^{-8}\Pr\eta^{11}c_1+1.807485501\times10^{-8}\Pr\eta^{12}c_1-\\&-3.3368963\times10^{-9}\Pr\eta^{13}c_1+1.4182794\times10^{-10}\Pr\eta^{14}c_1\end{aligned} \tag{42}$$

The first order approximation for temperature distribution in case of axisymmetric flow is:

$$\theta = \frac{\eta}{3} - 0.9049531\Pr\eta c_1 + 0.02029227\Pr\eta^5 c_1 - 0.0037037\Pr\eta^6 c_1 + \\ +6.60437\times10^{-20}\Pr\eta^7 c_1 + 0.0001036\Pr\eta^8 c_1 - 0.00014655\Pr\eta^9 c_1 + \\ +1.74594930\times10^{-6}\Pr\eta^{10} c_1 - 8.9470532\times10^{-8}\Pr\eta^{11} c_1 + 1.807485501\times10^{-8}\Pr\eta^{12} c_1 - \\ -3.3368963\times10^{-9}\Pr\eta^{13} c_1 + 1.4182794\times10^{-10}\Pr\eta^{14} c_1. \quad (43)$$

4 CONCLUSION

In this work, we use Optimal Homotopy Asymptotic Method for the titled problem. The velocity field for plane stagnation and axisymmetric stagnation flows are derived. The numerical procedure of the solution of the problem is given in Table 1, which are plotted in Fig. 1.

Table 1

Comparison between numerical results and the results obtained by using OHAM in plane stagnation flow and axisymmetric stagnation flow

η	$F'(\eta)$ (RK-4)	$F'(\eta)$ (OHAM)	$G'(\eta)$ (RK-4)	$G'(\eta)$ (OHAM)
0.1	0.11826	0.119616	0.12619	0.130563
0.2	0.22661	0.229304	0.24239	0.25113
0.3	0.32524	0.329235	0.34863	0.361718
0.4	0.41446	0.419679	0.44499	0.462374
0.5	0.49465	0.500984	0.53160	0.553184
0.6	0.56628	0.573568	0.60871	0.634286
0.7	0.62986	0.637901	0.67663	0.705877
0.8	0.68594	0.694494	0.73577	0.768227
0.9	0.73508	0.743891	0.78666	0.821678
1.0	0.77787	0.786653	0.82987	0.866651
1.1	0.81487	0.823354	0.86608	0.903647
1.2	0.84667	0.854573	0.89598	0.933248
1.3	0.87381	0.880881	0.92032	0.956108
1.4	0.89681	0.902838	0.93983	0.972948
1.5	0.91617	0.920988	0.95522	0.984548
1.6	0.93235	0.935853	0.96718	0.991732
1.7	0.94578	0.947923	0.97631	0.995347
1.8	0.95684	0.95766	0.98316	0.996252
1.9	0.96588	0.96549	0.98822	0.995288
2.0	0.97322	0.971797	0.99190	0.993255
2.2	0.98386	0.981165	0.99635	0.98881
2.4	0.99055	0.987923	0.99847	0.987386
2.6	0.99464	0.993354	0.99940	0.990822
2.8	0.99705	0.997711	0.99979	0.997239
3.0	0.99843	1	0.99993	1

The results obtained from OHAM can be more improved by increasing the constant $c_i's$ in the auxiliary function. Also, the solutions for temperature distribution in case of plane stagnation and axisymmetric stagnation flows are obtained. The solution obtained from OHAM is reasonably accurate and satisfies the boundary conditions for different Prandtl numbers as shown in Figs. 2 and 3. Figures 4 and 5 represented the physical behavior of the Prandtl number by providing results that the temperature increases as the Prandtl number increases.

In this study all the results obtained from OHAM is logically good and converge to the exact solution as the constant $c_i's$ increased in the auxiliary function. This method provides us a suitable way to control the convergence of the series solution using the auxiliary constants ($c_i's$) which are optimally determined.

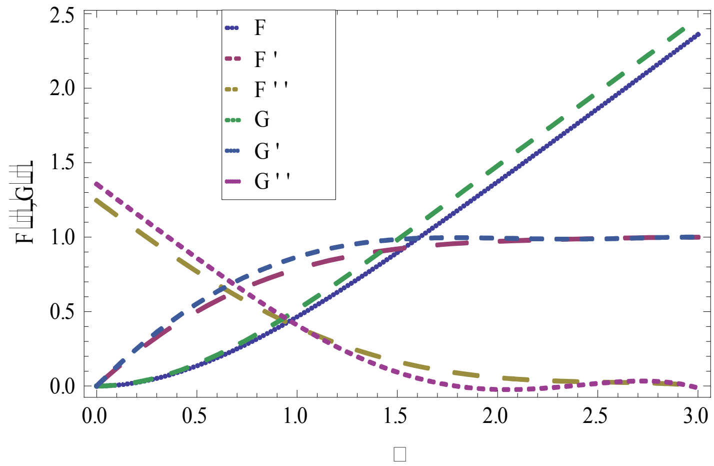

Fig. 1 – Profile of plane stagnation flow and axisymmetric stagnation flow.

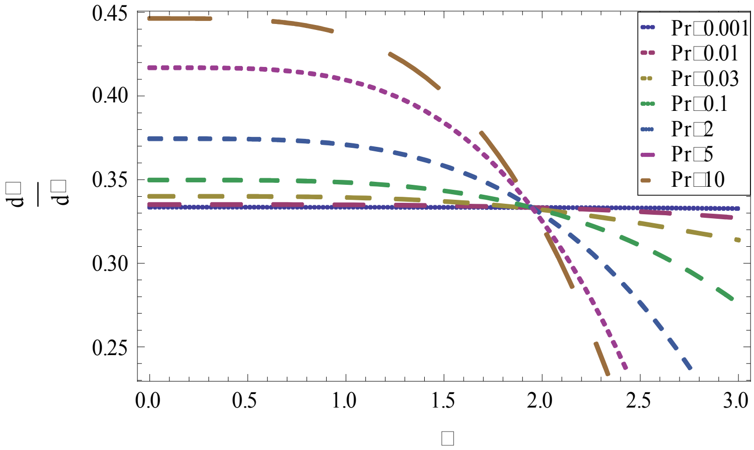

Fig. 2 – Profile of temperature distribution in case of plane stagnation flow for different values of Prandtl numbers.

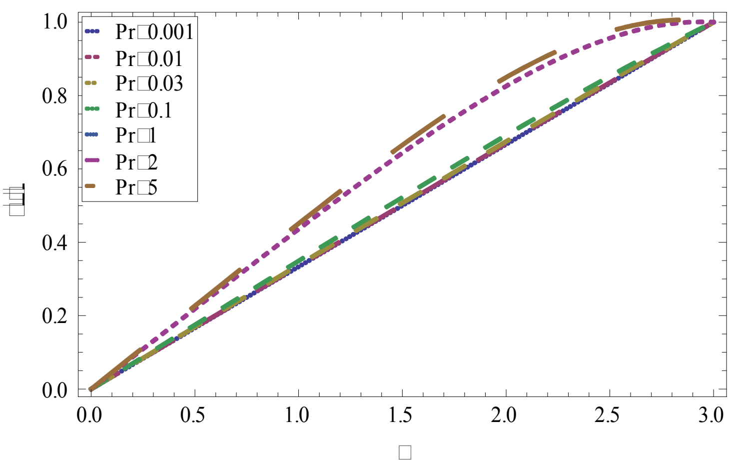

Fig. 3 – Profile of temperature distribution in differential form for plane stagnation flow
for different values of Prandtl numbers.

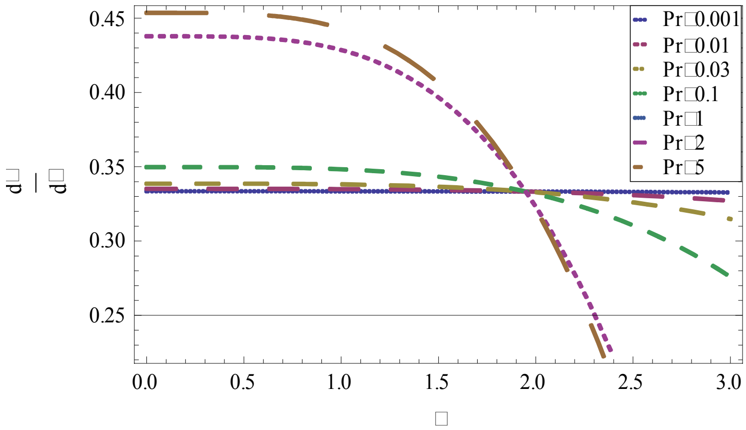

Fig. 4 – Profile of temperature distribution in case of axisymmetric stagnation flow for different values of Prandtl numbers.

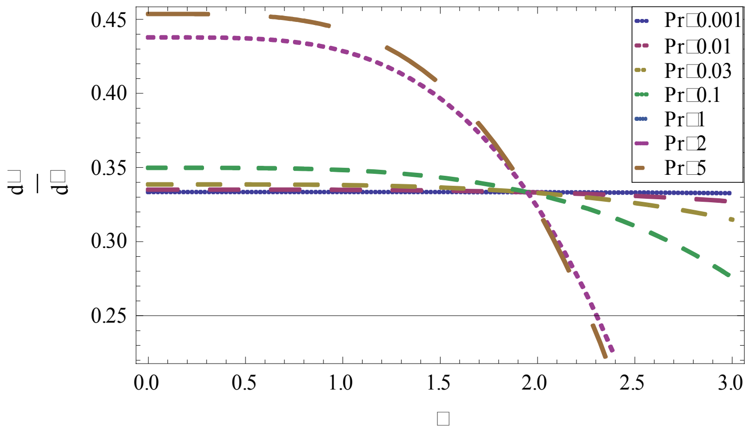

Fig. 5 – Profile of temperature distribution in differential form for axisymmetric stagnation flow for different values of Prandtl numbers.

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