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Journal of Computational and Applied Research
in Mechanical Engineering

jcarme.sru.ac.ir

JCARME

ISSN: 2228-7922

Research paper

Analytical study of heat and mass transfer in axisymmetric unsteady flow by ADM

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Article info:

Article history:

Received: 28/03/2018

Revised: 09/06/2019

Accepted: 12/06/2019

Online: 15/06/2019

Keywords:

Adomian,
Decomposition,
Squeezing flow,
Heat transfer,
Mass transfer.

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Abstract

Finding the solutions for heat and mass transfer problems is significant to reveal the main physics of engineering issues. In this work, the Adomian decomposition method is chosen as a robust analytical method for the investigation of temperature and flow features in a viscous fluid that moves between two parallel surfaces. To ensure the validation of results, the outcome of the Adomian decomposition method is compared with that of the Runge-Kutta method, and reasonable agreement is observed. The comparison confirms that the Adomian decomposition method is a robust and reliable approach for solving this problem. Then, diverse parameters such as Prandtl number and squeeze number are studied. Besides, the effect of chemical reaction parameter, Eckert number, and Schmidt number are comprehensively discussed. Findings reveal that the Sherwood number rises when the chemical reaction parameter and Schmidt number increase. Also, it declines with growths of the squeeze number. Likewise, The findings confirm that the Nusselt number enhances with the rising of the Eckert number and Prandtl number, and it declines when the squeeze number increases.

1. Introduction

In recent decades, scientists applied theoretical methods for solving problems with a simple domain. In fact, the methods are reliable techniques for obtaining the on-hand solution for various scientific problems. Mathematicians then tried to apply the methods for real work

applications. In engineering problems, heat transfer studies are significant due to their effects on the performance of devices such as heat driers, food industries, and microprocessors. Since nonlinear terms exist in most engineering problems, finding reasonable results is crucial for engineering applications. Hence, analytical methods were extensively employed. Among the

semi-exact approaches that applied linearization or discretization, the Adomian decomposition method (ADM) is an efficient approach, and several types of research are done to improve its capability [1, 2]. The main gain of this method is that it can present analytical approximation for a relatively widespread type of nonlinear equations without specific considerations such as linearization, closure approximation, perturbation, or discretization approaches.

Dissimilar to the conventional approaches, i.e., small perturbation and delicate nonlinearity, which modify the nature of the problem due to adjustments, ADM presents a reliable resolution of the engineering problems without any explanation. Therefore, realistic outcomes are obtained by this approach. Various authors have used this technique for solving problems of fluid dynamics. Sheikholeslami et al. [3] used the ADM to study the impact of nanoparticle and magnetic fields on the Jeffery-Hamel flow. They displayed that growing Hartmann number will reduce backflow. Similarly, their results demonstrated that momentum boundary layer thickness rises when nanoparticle volume fraction surges. Jafari et al. [4] offered a modified ADM to resolve nonlinear equations that generated sequences of results with quicker convergence than the series gained by the normal ADM. Allen and Syam [5] examined non-homogeneous and traditional Blasius equations. Hashim [6] applied the ADM for resolving 4th order equations of boundary value problems and the Blasius equation [7]. Arslanturk [8] reviewed this method on the performance of convective straight fins when their thermal conductivity is temperature-dependent. In fact, previous studies just focused on the main theoretical aspects of the problem. Since the main purpose of the analytical studies is to present guidelines for the initial results, it is crucial to find a reasonable outcome for the engineering [9-15].

ADM similarly has been applied by numerous scholars to solve an extensive range of engineering applications such as porous media and fluid flow domain [16-21] and other nonlinear problems [22-27]. In fact, nonlinear problems are widely considered by various researchers to find reliable results [28-33]. Among various topics, heat transfer problems, due to presence of nonlinear terms, are highly considered for evaluation of these approaches [34-39].

The investigation of the transient enfolding of a viscous fluid with constant density between two parallel plates, with respect to time, has been considered as one of the most significant investigations due to its applications [40, 41], for example, hydrodynamical machines, lubrication system and injection molding. The primary study on the squeezing flow under lubrication estimation was stated by Stefan [42]. Lately, because of their requests in numerous divisions of engineering applications, analysis of flow parameters has been improved. Meanwhile, parametric flow analysis of chemical reaction plays a vigorous effect in the chemical process design. The heat transfer properties in the squeezed flow within a porous domain are widely studied by Mahmood et al. [43]. The result of transient chemical reaction on the hydrodynamic of a viscous fluid is measured by Abd-El Aziz [44]. In the other works, Domairry and Aziz [45] studied the magnetohydrodynamic squeezing flow of a viscous fluid between parallel disks. Several researchers applied these methods for non-Newtonian fluid and MHD problems. They found that these approaches present reliable results [46-51].

The key purpose of the present work is to use the ADM to obtain reasonable answers for nonlinear differential equations [51-55]. This work initially explains the ADM for the solving of the nonlinear equations [56-61]. Then, a model is presented and the definitions and boundary conditions are presented. Next, the non-dimension process of equations are briefly explained. Among various complicated problems, the problem of mass and heat transfer within the transient squeezing flow between parallel surfaces is significant. In this work, the concentration and temperature profiles are compared and the effect of the important parameters on the hydrodynamic and flow features is comprehensively explained.

2. Equations and units

In solving each engineering problems, finding the governing equations and recognition of the main parameters are the main step for solving the problem. In this work, the heat and mass transfer analyses of the transient 2-dimensional squeezing flow are chosen for the evaluation of this method [62-65]. In this domain, it is

assumed that the fluid is incompressible and viscous between the infinite parallel surfaces. As shown in Fig. 1, the two surfaces are located at $z = \pm \ell(1 - \alpha t)^{1/2} = \pm h(t)$. For $\alpha > 0$, the two surfaces are squeezed till they reach $t = 1/\alpha$, and the two surfaces are disconnected in $\alpha < 0$. In this problem, the effects of viscous dissipation and heat production are considered because friction of shear in the flow is preserved. This outcome is significant when the fluid flowing at a high velocity or fluid is mainly viscous. This specific characteristic happens at a high Eckert number ($\gg 1$). The chemical reaction of the transient reaction rate in mass transfer equations is also considered. Furthermore, flow is assumed symmetric.

According to these assumptions, the governing equations for mass, momentum, energy, and mass transfer in the unsteady two-dimensional flow of a viscous fluid are:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{1}$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right), \tag{2}$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right), \tag{3}$$

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{k}{\rho C_p} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \frac{\nu}{C_p} \left(4 \left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)^2 \right), \tag{4}$$

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = D \left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \right) - K_1(t)C. \tag{5}$$

In these equations, u and v are the velocities in x and y directions, respectively, T is the temperature, C is the concentration, p is the pressure, ρ is the fluid density, ν is the kinematic viscosity, k is the thermal conductivity, C_p is the specific heat, D is the diffusion coefficient of the diffusing species, and $k_1(t) = k_1(1 - \alpha t)$ (see [16]) is the time-dependent reaction rate. The relevant boundary conditions are:

$$\begin{aligned} C = 0, \quad v = v_w = dh/dt, \quad T = T_H, C = C_H \quad \text{at } y = h(t), \\ v = \partial u / \partial y = \partial T / \partial y = \partial C / \partial y = 0 \quad \text{at } y = 0. \end{aligned} \tag{6}$$

The following parameters are presented:

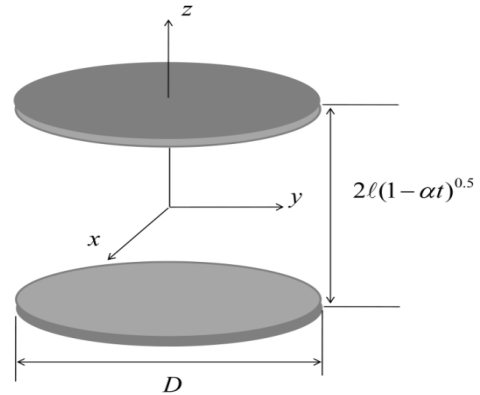


Fig. 1. Geometry of problem.

$$\begin{aligned} \eta = \frac{y}{[\ell(1 - \alpha t)^{1/2}]}, \quad u = \frac{\alpha x}{[2\ell(1 - \alpha t)]} f'(\eta), \\ v = -\frac{\alpha t}{[2\ell(1 - \alpha t)^{1/2}]} f(\eta), \quad \theta = \frac{T}{T_H}, \quad \phi = \frac{C}{C_H} \end{aligned} \tag{7}$$

Replacing the above variables into Eqs. (2 and 3) and then disregarding the pressure gradient from the resulting equations give:

$$f^{iv} - S(\eta f''' + 3f'' + ff'' - ff''') = 0, \tag{8}$$

Using Eq. (7), the Eqs. (4 and 5) transform to the subsequent equations:

$$\theta'' + \text{Pr} S(f\theta' - \eta\theta') + \text{Pr} Ec(f''^2 + 4\delta^2 f'^2) = 0, \tag{9}$$

$$\phi'' + Sc S(f\phi' - \eta\phi') - Sc\gamma\phi = 0, \tag{10}$$

and boundary conditions are as follows:

$$\begin{aligned} f(0) = 0, \quad f''(0) = 0, \quad \theta'(0) = 0, \\ \phi'(0) = 0, \quad f(1) = 1, \quad f'(1) = 0, \\ \theta(1) = \phi(1) = 1, \end{aligned} \tag{11}$$

where S , Pr , Ec , Ec , and γ are the squeeze number, the Prandtl number, the Eckert number, the Schmidt number, and the chemical reaction parameter, respectively. These parameters are determined as:

$$\begin{aligned} S = \frac{\alpha \ell^2}{2\nu}, \quad \text{Pr} = \frac{\mu C_p}{k}, \quad \text{Ec} = \frac{1}{C_p} \left(\frac{\alpha x}{2\ell(1 - \alpha t)} \right)^2 \\ Sc = \frac{\nu}{D}, \quad \gamma = \frac{k_1 \ell^2}{\nu}, \quad \delta = \frac{\ell}{x}, \end{aligned} \tag{12}$$

The main parameters for the evaluation of hydrodynamic feature of the low are the Nusselt

number, skin friction coefficient, and Sherwood number, and they are calculated as follows:

$$C_f = \frac{\mu \left(\frac{\partial u}{\partial y} \right)_{y=h(t)}}{\rho_w^2}, \quad Nu = \frac{-lk \left(\frac{\partial T}{\partial y} \right)_{y=h(t)}}{kT_H}, \quad Sh = \frac{-lk \left(\frac{\partial C}{\partial y} \right)_{y=h(t)}}{DC_H} \quad (13)$$

In terms of Eq. (7), the followings can be obtained:

$$\begin{aligned} l^2 / x^2 (1-\alpha t) \text{Re}_x C_f &= f''(1), \\ \text{Re}_x &= \rho_w x / \mu \\ \sqrt{1-\alpha t} Nu &= -\theta'(1), \\ \sqrt{1-\alpha t} Sh &= -\phi'(1). \end{aligned} \quad (14)$$

3. Details of ADM

By considering equation $F u(t) = g(t)$, where F denotes an overall nonlinear ordinary, the linear terms are decomposed into $L + R$, where L is simply invertible and R is the remained of the linear operator. Thus, the equation can be presented as [51]:

$$Lu + Nu + Ru = g \quad (15)$$

where Nu specifies the nonlinear terms. By resolving Eq. (15) for Lu , since L is invertible, it can be written as:

$$L^{-1}Lu = L^{-1}g - L^{-1}Ru - L^{-1}Nu \quad (16)$$

L^{-1} is a twofold indefinite integral If L is a second-order operator. By solving Eq. (16), Eq. (17) is obtained:

$$u = A + Bt + L^{-1}g - L^{-1}Ru - L^{-1}Nu \quad (17)$$

where A and B are factors of integration. These factors are determined by the boundary or initial conditions. ADM adopts the solution u , and it could be extended into infinite series as:

$$u = \sum_{n=0}^{\infty} u_n \quad (18)$$

Similarly, the Nu term will be written as bellows:

$$Nu = \sum_{n=0}^{\infty} A_n \quad (19)$$

The singular Adomian polynomials are defined by A_n . By determining A_n , next element of u can be calculated as:

$$u_{n+1} = L^{-1} \sum_{n=0}^n A_n \quad (20)$$

Lastly, after a few iterations and receiving adequate correctness, the solution can be stated by Eq. (17). In this equation, the Adomian polynomials could be produced by numerous methods. Now, the subsequent recursive formulation is applied:

$$A_n = \frac{1}{n!} \left[\frac{d^n}{d\lambda^n} \left[N \left(\sum_{i=0}^n \lambda^i u_i \right) \right] \right]_{\lambda=0}, \quad n = 0, 1, 2, 3, \dots \quad (21)$$

As this technique does not alter linearization, the generated solution is overallly more accurate than those attained by shortening the model of the physical problem.

4. Implementation of ADM

Consistent with Eq. (15), Eqs. (8-10) can be rewritten as follows:

$$\begin{aligned} L_1 f &= S(\eta f''' + 3f'' + ff'' - ff'''), \\ L_2 \theta &= -\text{Pr} S(f\theta' - \eta\theta') - \text{Pr} Ec(f''^2 + 4\delta^2 f'^2), \\ L_3 \phi &= -Sc(f\phi' - \eta\phi') + Sc\gamma\phi. \end{aligned} \quad (22)$$

where the differential operator L_1, L_2 and L_3 are given by $L_1 = \frac{d^4}{d\eta^4}, L_2 = \frac{d^2}{d\eta^2}$ and $L_3 = \frac{d^2}{d\eta^2}$, respectively. Assume the inverse of the operator $L_i (i=1, 2, 3)$ is exist and from 0 to η it can be integrated, i.e.:

$$L_1^{-1} = \int_0^\eta \int_0^\eta \int_0^\eta (\bullet) d\eta d\eta d\eta, \quad L_2^{-1} = \int_0^\eta \int_0^\eta (\bullet) d\eta d\eta, \quad L_3^{-1} = \int_0^\eta \int_0^\eta (\bullet) d\eta d\eta. \quad (23)$$

Operating with L_i^{-1} on Eq. (21), and subsequently applying boundary condition on it, the following equation is obtained:

$$\begin{aligned}
 f(\eta) &= f(0) + f'(0)\eta + f''(0)\frac{\eta^2}{2} + f'''(0)\frac{\eta^3}{6} + L^{-1}(N_1u), \\
 \theta(\eta) &= \theta(0) + \theta'(0)\eta + L^{-1}(N_2u), \\
 \phi(\eta) &= \phi(0) + \phi'(0)\eta + L^{-1}(N_3u).
 \end{aligned}
 \tag{24}$$

where N_iu are introduced as:

$$\begin{aligned}
 N_1u &= S(\eta f''' + 3f'' + ff'' - ff'''), \\
 N_2u &= -\text{Pr} S(f\theta' - \eta\theta') - \text{Pr} Ec(f''^2 + 4\delta^2 f'^2), \\
 N_3u &= -Sc(f\phi' - \eta\phi') + Sc\gamma\phi.
 \end{aligned}
 \tag{25}$$

ADM presented the following expression:

$$\begin{aligned}
 f(\eta) &= \sum_{m=0}^{\infty} f_m(\eta), \quad f(\eta) = \sum_{m=0}^{\infty} f_m = f_0 + L^{-1}(N_1u) \\
 \theta(\eta) &= \sum_{m=0}^{\infty} \theta_m(\eta), \quad \theta(\eta) = \sum_{m=0}^{\infty} \theta_m = \theta_0 + L^{-1}(N_2u) \\
 \phi(\eta) &= \sum_{m=0}^{\infty} \phi_m(\eta), \quad \phi(\eta) = \sum_{m=0}^{\infty} \phi_m = \phi_0 + L^{-1}(N_3u)
 \end{aligned}
 \tag{26}$$

To limit the components of $f_m(\eta), \theta_m(\eta)$ and $\phi_m(\eta)$, the $f_0(\eta), \theta_0(\eta)$ and $\phi_0(\eta)$ are determined by using the boundary condition of Eq. (11) :

$$\begin{aligned}
 f_0(\eta) &= a_1 \frac{\eta^6}{6} + a_2 \eta, \\
 \theta_0(\eta) &= a_3, \\
 \phi_0(\eta) &= a_4. \\
 f_1(\eta) &= \frac{1}{30} S\eta^5 a_1 + \frac{1}{2520} S a_1^2 \eta^7, \\
 \theta_1(\eta) &= -\frac{1}{30} \text{Pr} Ec \delta^2 \eta^6 a_1^6 + \\
 &\left(-\frac{1}{12} \text{Pr} Ec a_1^2 - \frac{1}{3} \text{Pr} Ec \delta^2 a_1 a_2 \right) \eta^4 \\
 &- 2 \text{Pr} Ec \delta^2 a_2^2 \eta^2, \quad \phi_1(\eta) = \frac{1}{2} Sc \gamma a_4 \eta^2.
 \end{aligned}
 \tag{27}$$

$f_m(\eta), \theta_m(\eta)$ and $\phi_m(\eta)$ for $m \geq 2$ are

defined in the similar method from Eq. (25). Then, using

$$f(\eta) = \sum_{m=0}^{\infty} f_m(\eta), \quad \theta(\eta) = \sum_{m=0}^{\infty} \theta_m(\eta) \quad \text{and}$$

$\phi(\eta) = \sum_{m=0}^{\infty} \phi_m(\eta)$ following equations are obtained:

$$\begin{aligned}
 f(\eta) &= \sum_{m=0}^{\infty} f_m(\eta) = a_1 \frac{\eta^6}{6} + a_2 \eta + \frac{1}{30} S\eta^5 a_1 + \\
 &\frac{1}{2520} S a_1^2 \eta^7 + \dots, \\
 \theta(\eta) &= \sum_{m=0}^{\infty} \theta_m(\eta) = a_3 - \frac{1}{30} \text{Pr} Ec \delta^2 \eta^6 a_1^6 \\
 &+ \left(-\frac{1}{12} \text{Pr} Ec a_1^2 - \frac{1}{3} \text{Pr} Ec \delta^2 a_1 a_2 \right) \eta^4 - \\
 &2 \text{Pr} Ec \delta^2 a_2^2 \eta^2 + \dots, \\
 \phi(\eta) &= \sum_{m=0}^{\infty} \phi_m(\eta) = a_4 + \frac{1}{2} Sc \gamma a_4 \eta^2 + \dots
 \end{aligned}
 \tag{29}$$

As mentioned in Eq. (28), the precision of the ADM solution rises by growing the number of solution terms (m). To attain the final solution for Eq. (28), $a_i, (i=1,2,3,4)$ with a boundary condition at $\eta=1$ must be initially calculated. E.g., constant values are attained as follow:

$$\begin{aligned}
 a_1 &= -2.099635946, \\
 a_2 &= 1.423330239, \\
 a_3 &= 1.628275971, \text{ and} \\
 a_4 &= 0.6581746879
 \end{aligned}$$

when:

$$S = \text{Pr} = Ec = Sc = \gamma = 1 \text{ and } \delta = 0.1.$$

5. Results and discussion

After the governing equations are determined, the ADM as a reliable technique is applied to analyze hydrodynamic characteristics of viscous squeezed fluid between parallel surfaces. This method could predict reasonable results for the nonlinear equations. Now, the different aspects of the results are comprehensively studied. Fig. 2 displays errors for $f(\eta), \theta(\eta)$, and $\phi(\eta)$ versus η when other significant parameters are fixed. This plot also displays that extreme errors

values occurs at $\eta=0.6$ and $\eta=1$, respectively. Fig. 3, Tables 1 and 2 compare results of the numerical method with those of the ADM when diverse values of significant parameter is demonstrated.

The influence of the squeeze number on the velocity profile is also revealed in Fig. 4. One of the main crucial parameters in this problem is squeeze number. It is significant to mention that the squeeze number (S) pronounces the displacement of the surfaces ($S > 0$ belongs to the plates moving apart, while $S < 0$ belongs to the surfaces moving together (the so-called squeezing flow)). As the surfaces move apart, velocity rises with growth in the squeeze number when $\eta > 0.5$, while it declines when $\eta < 0.5$.

Reverse patterns are detected when the surfaces close together. Consistent with Eq. (14), $f''(1)$ presents the skin friction coefficient. As perceived from Fig. 4, skin friction coefficient declines as the squeeze number intensifies. According to the industrial viewpoint, the power outflow elaborates in the production of motion of surfaces, and it is diminished when S is negative.

As explained in the text, there are significant results that should also be investigated to reveal the main effects of various parameters. Fig. 5 displays the outcome of the Prandtl number, Eckert number and squeeze number on the profile of temperature. It is found that increasing the squeeze number can be associated with some changes such as a decrease in the kinematic viscosity, a rise in the spacing between the surfaces, and a growth in the speed at which the surfaces move.

The obtained results also show that when $S < 0$, thermal boundary layer thickness intensifies as the absolute degree of the squeeze number rises. In addition, thermal boundary layer thickness declines with the rise in $|S|$ when $S > 0$. It is apparent that the thickness of the temperature boundary layer is relatively high when the surfaces become close. It is also found that the rise of squeeze number can be relevant to growth in the distance between the surfaces, the reduction of the kinematic viscosity, and an increase in the velocity at which the surfaces move.

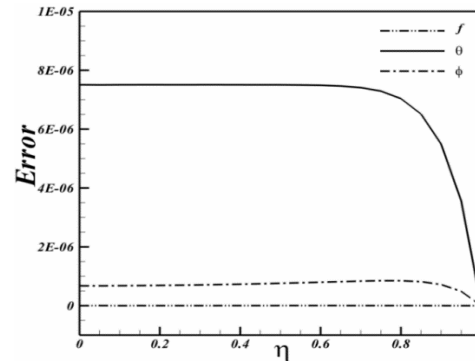


Fig. 2. Error for $f(\eta), \theta(\eta)$ and $\phi(\eta)$ versus η when $S = Ec = 1, \delta = 0.1, \gamma = 1, Sc = 1$ and $Pr = 1$.

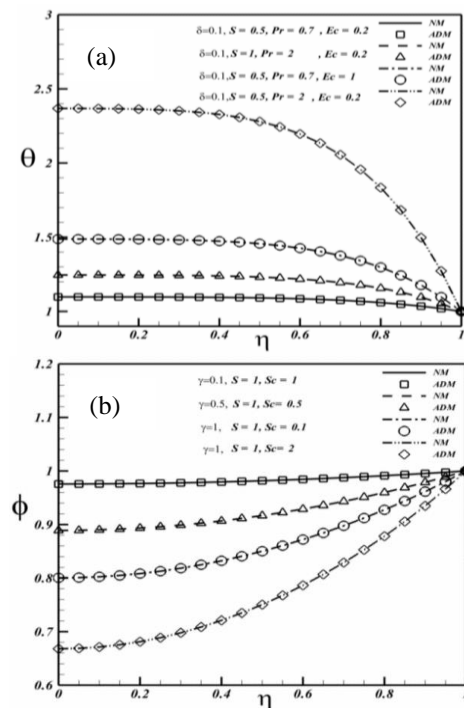


Fig. 3. Comparison between (a) numerical and, (b) ADM solution results.

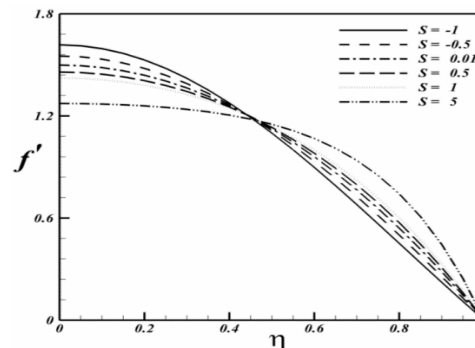


Fig. 4. Effect of the squeeze number on the velocity profile.

Table 1. Comparison between the numerical results and ADM solution for $f(\eta), \theta(\eta)$ and $\phi(\eta)$ when $S = 0.5, Ec = 0.2, \delta = 0.1, \gamma = 1, Sc = 1$ and $Pr = 0.7$.

η	$f(\eta)$			$\theta(\eta)$			$\phi(\eta)$		
	NM	ADM	Error	NM	ADM	Error	NM	ADM	Error
0	0	0	0	1.097532	1.097524	0	0.653436	0.653437	0
0.1	0.145385	0.145385	2.43E-10	1.097465	1.097458	7.51E-06	0.656705	0.656705	6.8E-07
0.2	0.288260	0.288260	1.86E-09	1.097179	1.097172	7.51E-06	0.666529	0.666529	6.9E-07
0.3	0.426066	0.426066	2.83E-09	1.096409	1.096401	7.51E-06	0.682963	0.682964	7.07E-07
0.4	0.556143	0.556143	3.86E-09	1.094689	1.094682	7.51E-06	0.706108	0.706108	7.31E-07
0.5	0.675682	0.675682	4.56E-09	1.091321	1.091313	7.51E-06	0.736111	0.736112	7.62E-07
0.6	0.781671	0.781671	4.54E-09	1.085316	1.085308	7.49E-06	0.773188	0.773189	7.99E-07
0.7	0.870846	0.870846	4.05E-09	1.075322	1.075315	7.41E-06	0.817636	0.817637	8.37E-07
0.8	0.939640	0.939640	3.53E-09	1.059519	1.059512	7.04E-06	0.869860	0.869860	8.5E-07
0.9	0.984134	0.984134	1.61E-09	1.035483	1.035478	5.49E-06	0.930404	0.930405	7.18E-07
1	1	1	0	1	1	0	1	1	0

Table 2. Comparison between the numerical results and ADM solution for $f(\eta), \theta(\eta)$ and $\phi(\eta)$ when $S = 1, Ec = 1, \delta = 0.1, \gamma = 1, Sc = 1$ and $Pr = 1$.

η	$f(\eta)$			$\theta(\eta)$			$\phi(\eta)$		
	NM	ADM	Error	NM	ADM	Error	NM	ADM	Error
0	0	0	0	1.628962	1.628276	0.000686	0.658171	0.658175	3.33E-06
0.1	0.141982	0.141982	2.67245E-08	1.628521	1.627835	0.000686	0.661463	0.661466	3.35E-06
0.2	0.281844	0.281844	5.16693E-08	1.626762	1.626077	0.000686	0.671342	0.671345	3.4E-06
0.3	0.417380	0.417380	7.25832E-08	1.622311	1.621625	0.000686	0.687829	0.687832	3.48E-06
0.4	0.546214	0.546214	8.87184E-08	1.612646	1.611960	0.000686	0.710964	0.710968	3.6E-06
0.5	0.665708	0.665708	9.81879E-08	1.593714	1.593028	0.000686	0.740827	0.740831	3.75E-06
0.6	0.772872	0.772872	9.85931E-08	1.559320	1.558635	0.000685	0.777554	0.777558	3.93E-06
0.7	0.864254	0.864254	8.72818E-08	1.500179	1.499501	0.000678	0.821372	0.821376	4.12E-06
0.8	0.935839	0.935839	6.25974E-08	1.402502	1.401857	0.000645	0.87264	0.872644	4.21E-06
0.9	0.982926	0.982926	2.58639E-08	1.245862	1.245355	0.000507	0.931908	0.931911	3.61E-06
1	1	1	0	1	1	0	1	1	0

Besides, the thickness of the thermal boundary layer decreases when the Prandtl number intensifies. In low Prandtl numbers ($Pr \ll 1$), the substance is liquid, and thermal diffusivity is high while viscosity is low. On the other side, when the Prandtl number ($Pr \gg 1$) is high, the substance similar to high-viscosity oils. The existence of viscous dissipation effects meaningfully raises the temperature. The influence of the Eckert number on the thickness

of thermal boundary layer is close to the Prandtl number.

In order to analyze the heat transfer in this problem, the Nusselt number as the main non-dimensional number should be investigated. Fig. 6 compares the Nusselt number profile for different values of the squeeze number, Eckert number, and Prandtl number.

As depicted in Fig. 6, the variation of temperature gradient in the vicinity of the wall significantly varies as the Prandtl number

changes. In addition, the effect of squeeze number pronounces more as the Prandtl number is raised. As shown in the plot, the effect of squeeze number is not noticeable in low Prandtl number. Meanwhile, the effect of the Eckert number is also significant on the results. In contradict to the effect of the Prandtl number, the effect of the squeeze number is not substantial as the squeeze number increases.

In order to evaluate real-time momentum and mass diffusion convection procedures, the Schmidt number (Sc), as the ratio of momentum diffusivity (kinematic viscosity) and mass diffusivity is analyzed. This non-dimensional number clearly characterizes fluid features.

Fig. 7 displays the impact of chemical reaction parameter and the Schmidt number on the concentration profiles. When $Sc > 1$, growing Schmidt number reduces the concentration in the centerline but reverse characteristic is detected when $Sc < 1$. It is worthy to note that $\gamma > 0$ signifies the destructive chemical reaction and $\gamma < 0$ exemplifies the generative chemical reaction. Besides, concentration reduces as destructive chemical reaction parameter is raised while it increases with increasing of chemical reaction parameter.

Moreover, the fragile molecular diffusivity and the stripper boundary layer thickness are the main reasons for the slow rise of Sc (Fig. 8). Consequently, the Sherwood number rises with the growth of the Schmidt number. Obtained results also show that the impact of chemical reaction parameter on the Sherwood number is the same as the Schmidt number.

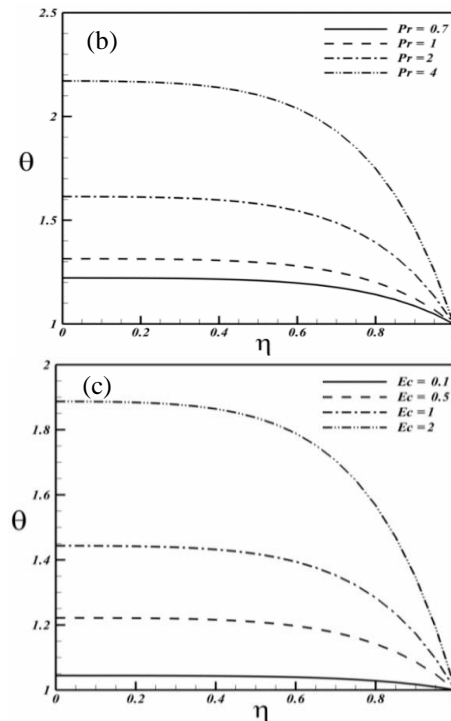
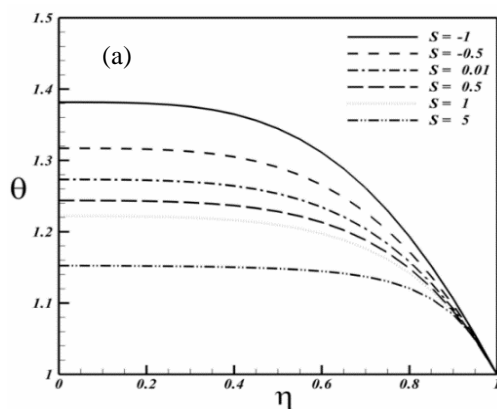


Fig. 5. Effect of the squeeze number, Prandtl number, and Eckert number on the temperature profile when (a) $Ec = 0.5, Pr = 0.7$; (b) $Ec = 0.5, S = 1$; and (c) $Pr = 0.7, S = 1$, and $\delta = 0.1$.

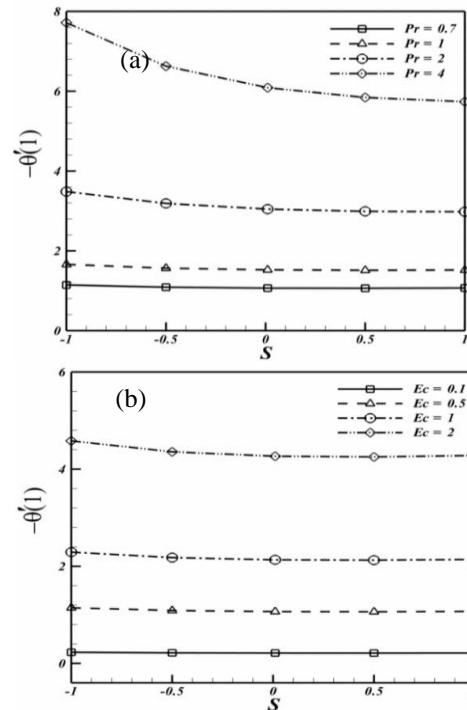


Fig. 6. Effects of the squeeze number, Prandtl number and Eckert number on the Nusselt number when (a) $Ec = 0.5$; (b) $Pr = 0.7$.

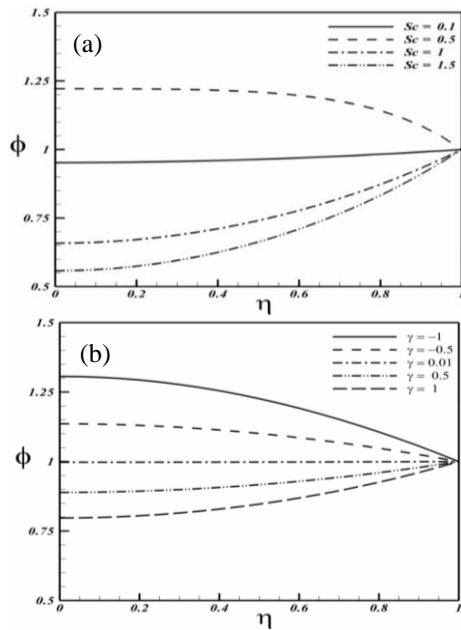


Fig. 7. Effects of Schmidt number and chemical reaction parameter on concentration profiles when (a) $S=1, \gamma=1$;(b) $S=1, Sc=1$.

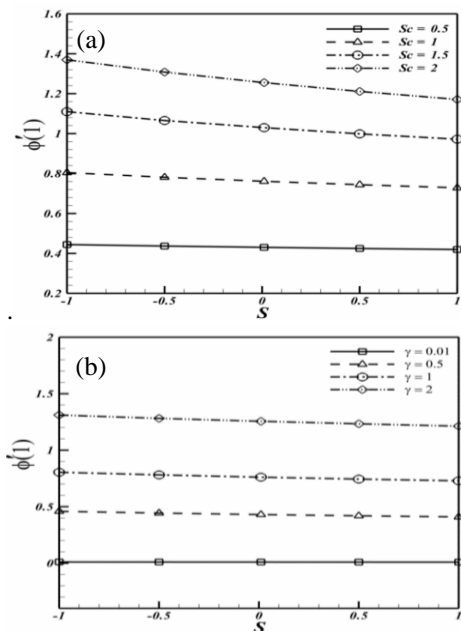


Fig. 8. Effects of the squeeze number, Schmidt number and chemical reaction parameter on the Sherwood number when (a) $\gamma=1$;(b) $Sc=1$.

6. Conclusions

In this research, ADM is used to study and analyze mass and heat transfer of the unsteady squeezing flow through parallel surfaces. A

comprehensive comparison between the obtained results with those of the numerical method (4th order Runge-Kutta technique) is done, and it is found that there is a good agreement. The findings confirm that the Nusselt number directly varies with change of the Eckert number and the Prandtl number, but it has an opposite relationship with the squeeze number. Furthermore, the obtained results reveal that the chemical reaction parameter and the Schmidt number are raised when the Sherwood number increases. However, the Sherwood number declines as the squeeze number increases.

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How to cite this paper:

A. Hassanvand, Mojtaba Saei Moghaddam, M. Barzegar Gerdroodbary and Younes Amini, "Analytical study of heat and mass transfer in axisymmetric unsteady flow by ADM," *J. Comput. Appl. Res. Mech. Eng.*, Vol. 11, No. 1, pp. 151-163, (2021).

DOI: 10.22061/JCARME.2019.3456.1399

URL: https://jcarme.sru.ac.ir/?_action=showPDF&article=1066

