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ORIGINAL ARTICLE

Modified Adomian decomposition method for solving the problem of boundary layer convective heat transfer

Yassir Daoud, Ahmed A. Khidir*

Faculty of Mathematical Sciences and Statistics, Alneelain University, Algamhoria Street, P.O. Box 12702, Khartoum, Sudan

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Abstract In this paper, we apply a new modification of the Adomian decomposition method for solving the problem of boundary layer convective heat transfer with viscous dissipation and low pressure gradient over a at plate. The technique is based on the standard Adomian decomposition method and the Chebyshev pseudospectral method. Comparisons are made between the pro-posed technique, the standard Adomian decomposition method, and the numerical solutions to demonstrate the applicability, validity, and high accuracy of the present approach. The results demonstrate that the new modification is more efficient and converges faster than the Adomian decomposition method.

1. Introduction

Many problems in the fields of physics, engineering, and biology occurs linearly, most occur nonlinearly. Compared to nonlinear equations, linear equations can be easily solved, finding analytical solutions to nonlinear problems on finite or in finite domains is one of the most challenging problems. Such problems do not usually admit closed form analytic solutions and in most cases we resort to finding approximate solutions of the problems using numerical or analytical approximation techniques. Common numerical and analytical methods used for solving nonlinear BVP's include, among others, the Runge-Kutta methods, finite difference, cubic Hermite finite element, pseudo-spectral, Chebyshev-collocation and the finite element method. These methods have their shortcomings, including instability, and hence the last few decades have seen the popularization of a number of new

*Corresponding author. Tel.: +249912897411.

E-mail address: ahmed.khidir@yahoo.com (Ahmed A. Khidir).

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perturbation or non-perturbation techniques such as the Lyapunov artificial small parameter method [1], the homotopy perturbation method [2,3], the homotopy analysis method [4] and Adomian decomposition method [5].

More studies have been applied and developed to solve various nonlinear problems that cannot be solved by analytical methods by Sinan and Necdet [6–8] and Abdelhalim et al. [9–12].

The Adomian decomposition method (ADM) was first presented in the 1980s and it has been efficiently used to solve linear and nonlinear problems such as differential equations and integral equations [13,14]. The method provides the solution as an in finite series in which each term can be easily determined. The rapid convergence of the series obtained by this method is thoroughly discussed by Ref. [15]. Adomian decomposition method has led to several modifications on the method made by various researchers in an attempt to improve the accuracy or expand the application of the original method [16–21]. There are some of the main limitations of the Adomian decomposition method that it has limited choice of acceptable linear operators and initial approximations and it must chosen to be simple in order to ensure that the higher order deformation differential equations can be easily integrated using high-performance computers and symbolic computation software. Complicated initial approximations and linear operators may result in higher order deformation equations that are difficult or impossible to integrate under the Adomian decomposition method. For such problems, the method of highest order differential matching in which an auxiliary linear operator matching the highest derivative of the linear part of the governing nonlinear differential equation is prescribed.

In this work, we improved the Adomian decomposition method in order to address some of the perceived limitations of the Adomian decomposition method. The proposed method, herein referred to as the spectral Adomian decomposition method (SADM). This technique proposed standard way of choosing the auxiliary linear operators and initial approximations of the solution. The proposed method is based on the blending of the Chebyshev pseudo-spectral methods and the Adomian decomposition method. The application of the SADM leads the differential equations to a system of algebraic equations that are easy to solve when compared to a system of ordinary differential equations obtained by the ADM. We have applied the new modification to find an approximate solution of nonlinear differential equation governing boundary layer convective heat transfer with low pressure gradient in the presence of viscous dissipation to show the efficiency of the SADM in comparison with the ADM.

2. Problem statement

Boundary layer flow over a at plate is governed by the continuity and the Navier-Stokes equations. Under the boundary layer assumptions and a constant property assumption, the continuity and Navier-Stokes equations become [22]:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{dp}{dx}+\upsilon\frac{\partial^2 u}{\partial y^2} \quad (2)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{dp}{dx}+\frac{\upsilon}{c_p}\left(\frac{\partial u}{\partial y}\right)^2 \quad (3)$$

where u and v are the velocity components along the x and y axis, respectively, T denote the temperature, υ is the kinematic viscosity of the porous medium, α is the thermal diffusivity, ρ is the liquid density and c_p is the specific heat capacity.

The boundary conditions are given by

$$\left.\begin{array}{llll} u=0, & v=0, & T=0 & \text{at } y=0 \\ u\to U_\infty, & & T\to T_\infty & \text{as } y\to\infty \end{array}\right\} \quad (4)$$

The system of partial differential Eqs. (1), (2) and (3) is converted into ordinary differential equations using the following similarity transformations

$$\psi=\sqrt{\upsilon x U_\infty}f(\eta),\quad \eta=y\sqrt{\frac{U_\infty}{\upsilon x}},\quad T=T_\infty+(T_w-T_\infty)\theta(\eta) \quad (5)$$

The continuity Eq. (1) is satisfied by introducing a stream function ψ such that

$$u=\frac{\partial\psi}{\partial y}\text{ and } v=\frac{\partial\psi}{\partial x} \quad (6)$$

Substituting Eq. (5) into the governing partial differential equations gives

$$f'''+\frac{1}{2}ff'+\lambda=0 \quad (7)$$

$$\frac{1}{Pr}+\theta''+\frac{1}{2}f\theta'+Ecf''^2=0 \quad (8)$$

The corresponding boundary conditions are

$$\left.\begin{array}{llll} f(\eta)=0, & f'(\eta)=0, & \theta(\eta)=1 & \text{at } \eta=0 \\ f'(\eta)\to 1, & & \theta(\eta)\to 0 & \text{as } \eta\to\infty \end{array}\right\} \quad (9)$$

where the prime symbol represents the derivative with respect to η, λ is the pressure gradient, Pr is the Prandtl number, Ec is the Eckert number (viscous dissipation parameter), These parameters are defined as

$$\lambda=-\frac{1}{\rho}\frac{x}{U_\infty}\frac{dp}{dx},\quad Pr=\frac{\upsilon}{\alpha},\quad Ec=\frac{U_\infty^2}{c_p(T_w-T_\infty)}$$

3. Fundamentals of Adomian decomposition method (ADM)

In this section, the review of the standard Adomian decomposition method [23–26] is presented. We start by consider the following differential equation,

$$Lu(x)+Ru(x)+N(u(x))=g(x)$$