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Mol solution for transient turbulent flow in a heated pipe ☆

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Abstract

A computational fluid dynamics (CFD) code, based on direct numerical simulation (DNS) and method of lines (MOL) approach previously developed for the prediction of transient turbulent, incompressible, confined non-isothermal flows with constant wall temperature was applied to the prediction of turbulent flow and temperature fields in flows dominated by forced convection in circular tubes with strong heating. The code was parallelized in order to meet the high grid resolutions required by DNS of turbulent flows. Predictive accuracy of the code was assessed by validating its steady state predictions against measurements and numerical results available in the literature. Favorable comparisons obtained reveal that the code provides an efficient algorithm for DNS of non-isothermal turbulent flows.

Keywords: Direct numerical simulation (DNS); Non-isothermal flows; Method of lines (MOL); Turbulent flows; Transient flows

1. Introduction

Continuous advances in large scale computers, numerical methods and post-processing environments over the past two decades have led to the application of Direct Numerical Simulation (DNS), which is the most accurate and straightforward technique, to the prediction of turbulent flow fields. However due to the fact that fine space and time resolutions are needed for DNS, both accurate and efficient numerical techniques and high performance computers are required for the simulation in short computation time. The former can be achieved by increasing the order of spatial discretization method, resulting in high accuracy with less grid points, and using not only highly accurate but also a stable numerical algorithm for time integration. The method of lines, the superiority of which over finite difference method had already been proven [1], is an alternative approach that meets this requirement for the time dependent problems. The latter requirement is met by either supercomputers or parallel computers which require efficient parallel algorithms.

In the MOL approach, the system of partial differential equations (PDEs) is converted into an ordinary differential equation (ODE) initial value problem by discretizing the spatial derivatives together with the boundary conditions using a high order scheme and integrating the resulting ODEs using a sophisticated ODE solver which takes the burden of time discretization and chooses the time steps in such a way that maintains the accuracy and stability of the evolving solution. The most significant advantage of MOL approach is that it has not only the simplicity of the explicit methods but also the superiority of the implicit ones unless a poor numerical method for the solution of the ODEs is employed. MOL has been used extensively to solve PDEs since its first appearance in the former Soviet Union in 1930 and has been successfully applied to the solution of Navier–Stokes equations in both vorticity-stream function and primitive variables form. Considering the emphasis on the prediction of transient turbulent flows, a new CFD code satisfying the abovementioned requirements was recently developed for the DNS of 2D incompressible separated internal flows in regular and complex geometries. The code

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Nomenclature

c_p	specific heat capacity	$cm^2 \cdot K^{-1} \cdot s^{-2}$
D	diameter	cm
g	gravitational acceleration	$cm \cdot s^{-2}$
i	grid index in r direction	
j	grid index in z direction	
k	thermal conductivity	$gr \cdot cm \cdot s^{-3} \cdot K^{-1}$
L	length of the pipe	cm
$\dot{m}$	mass flow rate	$gr \cdot s^{-1}$
NR	number of grid points in r direction	
NZ	number of grid points in z direction	
p	pressure	$gr \cdot cm^{-1} \cdot s^{-2}$
q^+	dimensionless heating rate	
r	distance in radial direction	cm
Re	Reynolds number	
t	time	s
t_p	user defined print time	s
Δt	time step	s
T	temperature	K
u	axial component of the velocity	$cm \cdot s^{-1}$
v	radial component of the velocity	$cm \cdot s^{-1}$
z	distance in axial direction	cm

Greek letters

ρ	density	$gr \cdot cm^{-3}$
ν	kinematic viscosity	$cm^2 \cdot s^{-1}$
ϕ	dependent variable transformed into 1D array	

Subscripts

in	inlet
max	maximum
NEQN	number of equations
w	wall

Superscripts

n	present time level

uses the MOL approach in conjunction with (i) an intelligent higher-order multidimensional spatial discretization scheme which chooses biased-upwind and biased-downwind discretization in a zone of dependence manner (ii) a parabolic algorithm which removes the necessity of iterative solution on pressure and solution of a Poisson type equation for the pressure (iii) an elliptic grid generator using body-fitted curvilinear coordinate system for application to complex geometries. Predictive accuracy of the code was assessed on various laminar and turbulent isothermal flow problems by validating its predictions against either measurements or numerical results available in the literature [2,3]. Favorable comparisons were obtained on these isothermal problems. First application of the code to a non-isothermal problem was the simulation of flow and temperature fields of a suddenly started laminar flow in a pipe with sudden expansion with hot wall at uniform temperature [4]. Although the results showed expected trends, validation of the code was not possible due to the absence of data.

Considering the interest in numerical simulation of transient turbulent non-isothermal flows in advanced power reactors, gas turbines, heat exchangers etc., the predictive accuracy of the code is tested by applying it to the simulation of turbulent, non-isothermal, axisymmetric flow of air through a strongly heated pipe for which experimental data are available on two entry Reynolds numbers and three different heating rates yielding conditions considered to be turbulent, sub-turbulent and laminarizing [5]. In order to meet the extensive grid requirement of DNS of turbulent flows, the code was parallelized by using domain decomposition strategy. To the authors' knowledge, a parallel implemented DNS code based on MOL for turbulent non-isothermal flows is not available to date.

2. Governing equations

The Navier–Stokes equations for transient two-dimensional incompressible non-isothermal flows in cylindrical coordinates are as follows:

continuity:

$$\frac{\partial u}{\partial z} + \frac{v}{r} + \frac{\partial v}{\partial r} = 0 \tag{1}$$

z-momentum:

$$\begin{aligned}\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial z} + v\frac{\partial u}{\partial r} &= -\frac{1}{\rho}\frac{\partial p}{\partial z} + \nu\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial z^2}\right)\\ &\quad + \frac{1}{\rho}\left(\frac{\partial v}{\partial z} + \frac{\partial u}{\partial r}\right)\frac{\partial \mu}{\partial r} + \frac{2}{\rho}\left(\frac{\partial u}{\partial z}\right)\frac{\partial \mu}{\partial z} + g_z\end{aligned} \tag{2}$$

r-momentum:

$$\begin{aligned}\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial z} + v\frac{\partial v}{\partial r} &= -\frac{1}{\rho}\frac{\partial p}{\partial r} + \nu\left(\frac{\partial^2 v}{\partial r^2} + \frac{1}{r}\frac{\partial v}{\partial r} - \frac{v}{r^2} + \frac{\partial^2 v}{\partial z^2}\right)\\ &\quad + \frac{2}{\rho}\left(\frac{\partial v}{\partial r}\right)\frac{\partial \mu}{\partial r} + \frac{1}{\rho}\left(\frac{\partial v}{\partial z} + \frac{\partial u}{\partial r}\right)\frac{\partial \mu}{\partial z} + g_r\end{aligned} \tag{3}$$

energy:

$$\begin{aligned}\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial z} + v\frac{\partial T}{\partial r} &= \frac{k}{\rho c_p}\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}\right)\\ &\quad + \frac{1}{\rho c_p}\left(\frac{\partial T}{\partial r}\right)\frac{\partial k}{\partial r} + \frac{1}{\rho c_p}\left(\frac{\partial T}{\partial z}\right)\frac{\partial k}{\partial z}\end{aligned} \tag{4}$$