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Numerical simulation of laminar breakdown and subsequent intermittent and turbulent flow in parallel-plate channels: Effects of inlet velocity profile and turbulence intensity

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ABSTRACT

The nature of flow development in a parallel plate channel has been investigated by making use of a newly developed model of intermittency. That model, taken together with the RANS equations of momentum conservation, the continuity equation, and the SST turbulence model, was employed to provide a complete chronology of the development processes and the derived practical results. A major focus of the work is the effect of inlet conditions on the downstream behavior of the developing flow. It was observed that the flow development process depends critically on the specifics of the inlet conditions characterized here by the shape of the velocity profile and the magnitude of the turbulence intensity. Two velocity profile shapes (flat and parabolic), are regarded as limiting cases. Similarly, two turbulence intensities, Tu = 1% and 5%, are employed. From the standpoint of practice, the relationship between the friction factor and the Reynolds number is most significant. It was found that this relationship reflects that of standard practice for only one of the investigated cases (flat velocity profile, Tu = 5%). For the other cases (flat profile, Tu = 1% and parabolic profile, Tu = 1% and 5%), the breakdown of laminar flow is delayed and the onset of full turbulence occurs rather abruptly at Re ∼10,000. Three unique fully developed flow regimes are existent, depending on the inlet conditions and on the value of the Reynolds number. In addition to the standard laminar and fully turbulent regimes, another regime, *fully developed intermittent*, can occur. Specifically, in the latter regime, laminar and turbulent flows occur intermittently.

1. Introduction

Although flow in large-aspect-ratio rectangular ducts may be considered a mature area of fluid flow research, a careful appraisal reveals the contrary. For example, the considerable ambiguity in the nature of the fluid flow at the duct inlet has a significant effect on its downstream behavior [1]. In fact, a careful assessment of the relevant literature indicates that aside from [2], only qualitative descriptions of the inlet conditions are given. As a second illustration of the uncertainties associated with the available information about flow in flat rectangular channels, it has been pointed out in [3] that the hydraulic diameter is not the optimal characteristic dimension in the Reynolds number and friction factor.

In the present research, a non-empirical, quantitative approach is taken to the fluid flow in a parallel-plate channel, which is the limit of large-aspect-ratio ducts. The objective of the present work is to numerically simulate and predict the breakdown of laminar flow, the ensuing intermittent flow, and the attainment of a fully developed regime which may be either intermittent or fully turbulent. The dependency of these outcomes on the nature of the flow field at the duct inlet will be explored by varying the turbulence intensity and the shape of the velocity profile. Other characteristics that will be explored include the locations of laminar breakdown and the attainment of fully developed flow.

The literature on fluid flow in flat rectangular ducts and parallel-plate channels can be classified into three categories. One of these encompasses papers in which empirical information is given on the friction factor and its dependence on the Reynolds number [2–11]. Some of these papers used the height of the duct as the characteristic dimension whereas others utilized the hydraulic diameter. In [3], which is a retrospective view of an accumulation of data, it was suggested that the optimal characteristic dimension is 2/3 of the traditional hydraulic diameter. In many of the cited references, no mention was made of the conditions at the duct inlet. In those cases where a qualitative description was given, the sharp-edged inlet was used. The exception is that of [2]. There, a careful control of the turbulence intensity was achieved by the

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Nomenclature

A	transitional model constant
E	model destruction terms
H	channel height
F_1, F_2	blending functions in SST model
p	pressure
P	model production term
Re	Reynolds number based on hydraulic diameter and average velocity
S	absolute value of the shear strain rate
Tu	turbulence intensity
u	x velocity
U	average velocity
υ	y velocity
x,y	coordinate directions

Greek symbols

β_1, β_2	SST model constants
ω	specific rate of turbulence dissipation
μ	dynamic viscosity
κ	turbulent kinetic energy
Π	intermittency adjunct function
γ	intermittency
ρ	density
σ	Prandtl number

Subscripts

turb	turbulent

use of screens, a honeycomb, and a contraction ratio of 24:1 upstream of the duct. The contraction also compresses the boundary layers, so that it may be expected that the velocity profile at the duct inlet was relatively flat with high velocity gradients adjacent to the bounding walls. Notwithstanding the aforementioned uncertainties, a general consensus of the results of [2–11] is that laminar breakdown in flat rectangular ducts occurs for a Reynolds number on the order of 2500–4000, where the Reynolds number is based on the mean velocity and the hydraulic diameter.

The second category into which work on laminar breakdown can be placed is highly mathematical and deals with the response of the parabolic velocity profile to various types of disturbances [12–17]. Noteworthy is the result that for two-dimensional disturbances, the breakdown of laminar flow was found to occur at Re $\sim$15,000. This seemingly high Reynolds number reflects the fact that no account has been taken of the nature of the flow at the inlet of the duct and that a pre-existing parabolic profile was the starting point to which disturbances were applied.

In the third category are experimental works whose focus is the verification and elucidation of the stability theory [18–20]. In all of these works, artificial disturbances were introduced, either by an electromagnetic solenoid or by a vibrating ribbon. The outcomes of these experiments were inconsistent in that for [19–20], the critical Reynolds number was below that of linear stability theory, whereas in [18], the breakdown occurred at Reynolds numbers consistent with stability theory.

In a recent publication [21], the authors have dealt with a companion problem to that being considered here, namely, the fluid flow in a round pipe which undergoes transitions from laminar-to-intermittent transitional flow and from transitional flow to either fully developed intermittent or fully developed turbulent flow.

2. Simulation model

The geometry of the model is two-dimensional with a symmetry plane extending along the half-height of the channel. The velocity at the inlet will be prescribed along with the turbulence intensity. Two limiting velocity profiles will be employed. One of these is a uniform profile which is intended to represent the limiting profile for a fully developed turbulent flow. The second profile is the parabolic distribution which corresponds to a fully developed laminar flow. It is believed that these two limits are sufficient to reveal the trend-wise dependence of the downstream physical processes on the shape of the inlet velocity profile. In addition, the turbulence intensity was varied over the range from 1% (low) to 5% (high).

2.1. Governing equations

To implement the goals of this study, use has been made of a transition model devised by Menter and co-workers [22–24]. That model, when used in conjunction with the shear stress transport (SST) turbulence model, provides a complete picture encompassing all unidirectional flow regimes. The Menter model was designed to deal with external flows; it was modified in [21] to be applicable to internal flows. Its validity for such use was verified by comparison with both experimental data and with empirical correlations. That verification has encouraged its application here.

The total description of the model involves a set of seven partial differential equations for a two-dimensional flow. The first of these represents conservation of mass, while the second and third are the Reynolds-averaged Navier–Stokes equations.

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\rho\left(\frac{\partial(u^2)}{\partial x}+\frac{\partial(u\upsilon)}{\partial y}\right) = -\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left((\mu+\mu_{turb})\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left((\mu+\mu_{turb})\frac{\partial u}{\partial y}\right) \tag{2}$$

and

$$\rho\left(\frac{\partial(u\upsilon)}{\partial x}+\frac{\partial(\upsilon^2)}{\partial y}\right) = -\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left((\mu+\mu_{turb})\frac{\partial \upsilon}{\partial x}\right) + \frac{\partial}{\partial y}\left((\mu+\mu_{turb})\frac{\partial \upsilon}{\partial y}\right) \tag{3}$$

The next pair of equations represents the SST turbulence model which has been modified to accommodate the intermittency γ. The intermittency is the multiplier of the turbulent production term P_κ.

$$\frac{\partial(\rho u\kappa)}{\partial x}+\frac{\partial(\rho\upsilon\kappa)}{\partial y} = \gamma\cdot P_\kappa-\beta_1\rho\kappa\omega+\frac{\partial}{\partial x}\left[\left(\mu+\frac{\mu_{turb}}{\sigma_\kappa}\right)\frac{\partial\kappa}{\partial x}\right] + \frac{\partial}{\partial y}\left[\left(\mu+\frac{\mu_{turb}}{\sigma_\kappa}\right)\frac{\partial\kappa}{\partial y}\right] \tag{4}$$

and

$$\frac{\partial(\rho u\omega)}{\partial x}+\frac{\partial(\rho\upsilon\omega)}{\partial y} = A\rho S^2-\beta_2\rho\omega^2+\frac{\partial}{\partial x}\left[\left(\mu+\frac{\mu_{turb}}{\sigma_\omega}\right)\frac{\partial\omega}{\partial x}\right] + \frac{\partial}{\partial y}\left[\left(\mu+\frac{\mu_{turb}}{\sigma_\omega}\right)\frac{\partial\omega}{\partial y}\right]+2(1-F_1)\rho\frac{1}{\sigma_{\omega2}\omega}\frac{\partial\kappa}{\partial x}\frac{\partial\omega}{\partial x} + 2(1-F_1)\rho\frac{1}{\sigma_{\omega2}\omega}\frac{\partial\kappa}{\partial y}\frac{\partial\omega}{\partial y} \tag{5}$$