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Turbulent pipe flow in the presence of centerline velocity overshoot and wall-shear undershoot

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ABSTRACT

The existence and characteristics of an overshoot phenomenon in the axial velocity distribution that occurs at the centerline of a turbulent pipe flow is investigated and documented by means of numerical simulation. A complementary phenomenon is also encountered in which the axial variation of the wall shear stress experiences an undershoot. These occurrences are not restricted to the case of a uniform velocity profile at the pipe inlet. The magnitude of the inlet turbulence intensity was found to play a major role in the downstream development of the flow. In particular, the magnitude of the overshoot showed a dependence on the value of the inlet turbulence intensity; the higher the intensity value, the lower the magnitude of the overshoot. Evidence was presented that enabled the attribution of the velocity peak and the wall shear undershoot to an initial tendency for the flow to laminarize. In particular, the presence of the velocity peak was related to different patterns of radial flow. When a peak was present, there was a radial inflow of fluid toward the centerline of the pipe followed downstream by a radial outflow from the centerline to the wall. The suppression of the velocity peak was accomplished by a very high value of the turbulence intensity at the inlet which neutralized the tendency towards laminarization. Other evidence of the laminarization tendency was obtained by examining the magnitude of the turbulence viscosity.

1. Introduction

Among the fundamental issues in fluid mechanics that have only been superficially investigated is the occurrence of a local maximum (i.e., an overshoot) in the variation of the streamwise velocity along the axis of a pipe. This phenomenon was detected experimentally about 45 years ago [1] and has been further investigated, primarily by experiment, in the interim. Only three attempts at numerical simulation of the phenomenon have been reported in the literature [2–4]). In these, the flow entering the pipe inlet was assumed to have a perfectly flat velocity profile. Since the impact of a flat inlet profile velocity is also an insufficiently studied issue in fluid mechanics, it was originally thought that the flat profile was connected with the occurrence of the velocity overshoot. In support of this contention, it may be recognized that a flat velocity profile is in conflict with the no-slip condition at the pipe wall. This conflict creates a mathematical singularity, making it impossible to encounter a strictly flat inlet profile velocity experimentally.

The overshoot phenomenon has been sporadically observed in the literature over a span of 50 years. In this regard, it is appropriate to begin with a chronological approach to the literature. Miller (1971) [1] performed an in-depth experimental study of fluid flow in diffusers and a very limited study of flow in a round pipe. From the latter, overshoots in the axial velocity distribution along the pipe centerline were identified. There were no details given of the velocity profile with which flow entered the pipe. Slightly later, in Weir (1974) [5], experiments were carried out in a round pipe preceded by an upstream 16:1 contraction and a velocity overshoot was observed. By making use of a trip ring at the pipe inlet, the overshoot was eliminated.

An experimental study of the effects of various pipe inlet configurations was performed by Sharan [6]. Three inlet configurations were investigated. In all cases, there was a 16:1 upstream contraction in place. The velocity overshoot was observed in the pipe, and the upstream placement of a mesh (gauze) did not have a significant effect on the overshoot. When a sharp change was made in the geometry of the bounding wall of the pipe, the overshoot disappeared. Reichert et al. [7] performed independent experiments to quantify the presence of overshoot. The experimental setup consisted of an 89:1 contraction cone followed by a sand paper trip. The overshoot was observed for both of the investigated Reynolds numbers in that work.

The first numerical investigation of the overshoot phenomenon was due to Walklate et al. [2] who used a highly simplified model (e.g., the transverse momentum equation was altogether ignored). The numerical simulation model was based on an approximation of the original Launder and Spalding k-ε turbulence model. Also of concern is that the

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Nomenclature

A	geometric dimension
B	geometric dimension
D	inlet diameter
F_1, F_2	blending functions in the SST model
H	geometric dimension
L	pipe length
p	pressure
P_k	production term for the turbulent kinetic energy
r	radial coordinate
S	invariant measure of the strain rate
u	velocity component
U	axial velocity
V	radial velocity
u', v', w'	fluctuating velocity component
x	coordinate
y	coordinate
$y+$	non-dimensional near-wall mesh quality metric
z	axial coordinate

Greek symbols

α_1, α_2	turbulence model constants
β_1, β_1, β^*	turbulence model constants
ε	turbulence dissipation
κ	turbulent kinetic energy
μ	molecular viscosity
μ_t	turbulent eddy viscosity
ρ	fluid density
σ_ω, $\sigma_{\omega 1}$, $\sigma_{\omega 2}$	turbulence model constants
σ_κ, $\sigma_{\kappa 1}$, $\sigma_{\kappa 2}$	turbulence model constants
τ	shear stress
ω	specific rate of turbulence dissipation

Subscripts

c	centerline
i, j, k	index notation for Cartesian coordinates
t	turbulent
w	wall

boundary conditions on the velocity at the pipe inlet were not stated. From the simulation results, overshoots were observed at the three investigated Reynolds numbers, with the greatest overshoot occurring at the lowest of the Reynolds numbers. In a formal discussion by Walklate et al. [2] of a paper by Weir [5], conjectures were offered to explain the overshoot phenomenon as follows: overshoot is caused by the initial turbulence level and overshoot is a direct consequence of the presence of intermittency.

Sufficient information on the subject was available by 1981 to enable Klein [8] to write a review article. In that article, the papers in which overshoots had been detected were set forth; those papers have already been cited here. A conclusion was stated by the author that the conditions upstream of the pipe inlet play a decisive role with regard to the presence or absence of overshoot.

An experiment using flowing water as the working fluid was performed by Salami (1986) [9]. The flow was delivered to the pipe inlet by means of a conical contraction with a 25:1 area ratio. Three flow rates were investigated, and overshoot was observed for all the cases. It was found that the higher the flow rate, the overshoot occurred closer to the inlet.

A considerable time lapse occurred between the work of Salami and the next published paper on the overshoot phenomena, which appeared in 2007 and was authored by Doherty et al. [10]. This paper [10], described experiments with five-mesh screens and 60-grit sandpaper used as a means to get a uniform low turbulence level at inlet of the pipe. The net outcome of this setup was the presence of a slight overshoot in the centerline velocity.

The last two papers that were unearthed in the literature survey were both numerical studies. In Anslemet et al. (2009) [3], the conducted simulation was based on FLUENT software in which the velocity profile at the inlet was assumed to be uniform (flat) across the entire section. The simulations were performed for several Reynolds numbers, all of which resulted in velocity overshoots. Kumara (2010) [4], also used FLUENT software and a flat velocity profile as the basis of numerical simulations for a range of Reynolds numbers between 14,000 and 270,000. Velocity overshoots were encountered at all Reynolds numbers, with greater overshoot values at lower Reynolds numbers. The Kumara paper is the only one which displayed the effect of the overshoot phenomenon on the wall shear stress. That effect was an undershoot. Kumar [4] conjectured a cause of the velocity overshoot being related to an acceleration of the turbulent flow before becoming fully developed. In none of these investigations was any concern expressed about the turbulence intensity at the pipe inlet.

Attention is now turned to a graphical display of the experimental data that was discussed in the foregoing, and Fig. 1(a) and (b) have been prepared for this purpose. To achieve a compact presentation, several sets of data are plotted in each figure. Fig. 1(a) displays the data of Weir et al. [5], Sharan [6], and Reichert & Azad [7]. Among these data, those of Reichert are at lower Reynolds numbers and exhibit the greatest overshoot. As will be demonstrated shortly, the trend of greater overshoot at lower Reynolds number is one of the findings of the numerical simulations. The data of Sharan [6] and of Weir et al. [5] fall in the same range of higher Reynolds numbers. The Weir et al. [5] data display a much higher level of overshoot than do those of Sharan [6] and are close to the lower Reynolds number overshoots of Reichert & Azad [7]. This ordering suggests that the Weir data may be an outlier. The two sets of data due to Sharan are mutually supportive. One of these data sets were collected in the presence of an upstream mesh (gauze) but seemingly without effect.

In Fig. 1(b), the designators used by Salami [9] to describe the Reynolds numbers of his data are ambiguous. However, it is believed that "low" denotes a Reynolds number of approximately 700, and "high" indicates a value of about 200,000. The Miller [1] data correspond to much higher Reynolds numbers. Taken together, the data displayed in Fig. 1 strongly support the notion that larger overshoot is achieved at lower Reynolds numbers. It also appears that smaller Reynolds numbers lead to the location of maximum overshoot to be moved further downstream.

The foregoing figures clearly establish that the centerline velocity overshoot is a real phenomenon. The displayed data appear to indicate a trend whereby the lower Reynolds numbers lead to a greater overshoot closer to the pipe inlet. Except for one set of data, all of the experimental data displayed in Fig. 1(a) and (b) correspond to flow in the turbulent regime.

The goal of the research described here is to investigate the velocity overshoot phenomenon. In that regard, flowing fluid will be supplied to the inlet cross section by means of fittings and conduits, giving rise to realistic inlet velocity profiles. In addition, consideration will be given to idealized uniform (flat) velocity profiles that are commonly encountered in the published literature. The outcome of this research can be of benefit to modern large-scale experimental facilities employing sizable piping systems [11–13].