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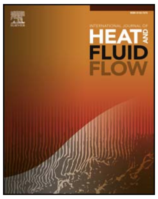

Laminar similarities between accelerating and decelerating turbulent flows

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ABSTRACT

An experimental study of a pipe flow ramping monotonically between two turbulent states has been undertaken. Ensemble-averaged mean and turbulent flow quantities obtained from two-component particle image velocimetry and hot-film anemometry measurements have been presented. It is shown that the time-developments of the mean and turbulence quantities in accelerating and decelerating flows are similar during an initial stage following the transients. Specifically, the mean perturbation velocity (defined as the surplus/deficit from the initial value) can be described using self-similar expressions. The duration of this initial stage is shown to be a decreasing function of the dimensionless parameter $\delta = \nu/u_{\tau 0}^2(1/U_{b0})\mathrm{d}U_b/\mathrm{d}t$. Data from studies of linearly accelerating and decelerating flows as well as impulsively accelerating and decelerating flows have been used to validate the results, covering four orders of magnitude of δ. The highest initial Reynolds number investigated in this study (35,700) is, however, relatively low thus requiring further studies at high Reynolds numbers to assure the universality of the results. We have also shown that the time-developments of the mean and turbulent quantities between an accelerating and a decelerating flow loose their similarity as the transient proceeds beyond the initial stage. The departure was explained by the time-evolvement of the production of turbulence kinetic energy, which exhibit differences between the two types of transients.

1. Introduction

Conditions of transient turbulent flows occur at an increasingly higher rate in hydraulic machinery due to the ongoing installation of intermittent resources of renewable energy. The unpredictable nature of wind and solar power forces the hydraulic machines to frequently change their operating condition, and consequently the flow rate, for balancing the frequency of the electrical grid. The machines were not originally built for such transient operation conditions, as such, a better understanding of transient flows is needed to assure their long-time functioning. The subject of transient flows is, however, not only interesting from the perspective of a hydraulic engineer. A better understanding of unsteady turbulent flows may, in the end, also lead to a better understanding of its steady counterpart, for which many unanswered questions still remain. A different type of unsteady flow that is equally interesting from a practical as well as from a fundamental view is when a non-zero mean flow is perturbed by periodic unsteadiness; i.e., a pulsating flow. In the present paper, we focus our attention solely on turbulent flows subjected to a monotonic change in the flow rate. Specifically, the response of the mean and turbulence fields under conditions of transient pipe flow will be experimentally investigated.

For laminar flows, analytical solutions for various types of unsteady flows and geometries can readily be derived from the Navier-Stokes equations. Uchida (1956) and Zielke (1968) derived solutions for pulsating and transient laminar pipe flows, respectively. For their turbulent counterparts, unfortunately, but not surprisingly, no analytical solutions have been found so far. Instead, investigations of the reaction of a turbulent flow subjected to a time-varying forcing have traditionally been conducted by means of experimental studies (see, e.g., Tardu et al., 1994; Mao and Hanratty, 1986; Brereton et al., 1990 for a pulsating flow and Maruyama et al., 1976; He and Jackson, 2000; Greenblatt and Moss, 2004 for a transient flow). However, the rapid development of supercomputers has enabled studies of unsteady turbulent flows using either direct or large-eddy numerical simulations (abbreviated DNS and LES henceforth). The detailed information made available by these numerical techniques has led to a substantially increased understanding of unsteady flows; see He and Seddighi (2013) and Seddighi et al. (2014) for a transient flow and Manna et al. (2012, 2015) and Weng et al. (2016) for a pulsating flow, to name a few. Despite the recent advances, many outstanding issues remain unanswered.

Specifically, for pulsating flows, a puzzling feature is the robustness of the time-averaged flow quantities. For, as long as the bulk flow does not reverse direction, the time-averaged quantities do not differ, or

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differ only marginally, from their steady counterparts (Brereton et al., 1990; Weng et al., 2016; Sundstrom et al., 2016). The robustness prevail even in the case of relaminarization and local flow reversal during part of the oscillating cycle (Scotti and Piomelli, 2001; Tardu et al., 1994). Another puzzling feature of a pulsating turbulent flow is a paradoxical behaviour of the wall shear stress in the range $0.006 < \omega^+ = \omega\nu/\bar{u}_\tau^2 < 0.02$, of non-dimensional frequencies. ω, ν and $\bar{u}_\tau$ denote, respectively, the circular forcing frequency, the kinematic viscosity and the time-averaged friction velocity. The paradoxical behaviour is manifested by a reduction in the amplitude of the oscillating component of the wall shear stress in a turbulent flow compared to in a laminar flow exposed to the same sinusoidal pressure gradient. Turbulence is thus reducing friction, which is contrary to most other situations involving wall-bounded flows.

An intriguing and yet largely unexplored feature of a temporally accelerating turbulent channel flow, which was first observed by He and Seddighi (2013), is that the time-evolvement between the two turbulent states bears marked similarity with the laminar to turbulent bypass transition. The similarities between the transient channel flow and the bypass transition were confirmed by Talha and Chung (2015) using LES as well as by Jung and Kim (2017) using DNS. He et al. (2016) confirmed the similarity also in the case of an accelerating pipe flow. It has been established that the mean and turbulence fields evolve in three stages following a temporal acceleration. Typical characteristics of the flow in Stage 1 are: a laminar-like evolution of the mean velocity, a minimal response of the Reynolds shear stress, a significant increase of the streamwise turbulent velocity fluctuations due to elongation and amplification of the pre-existing turbulence structures, and negligible increase of the energy redistribution to the wall-normal and spanwise/circumferential components owing to delays in the response of the pressure-strain. In the second stage, the pressure-strain responds rapidly to the new conditions, resulting in the formation and merging of turbulent spots and a rapid increase of the wall-normal and spanwise turbulent velocities. During the third stage, both the mean and the turbulence fields converge toward their steady distributions dictated by the final Reynolds number.

Detailed studies on the time evolution of the mean and turbulence fields following a temporal deceleration have received relatively limited attention, though. A few notable exceptions are the works by Maruyama et al. (1976) who studied the response of the turbulence following a step decrease in flow rate, Shuy (1996) who studied the wall shear stress in a decelerating pipe flow and He and Jackson (2000) who performed laser Doppler velocimetry measurements of all three components of the velocity in a linearly decelerating flow. The laminar characteristics of the mean velocity that are present in an accelerating flow have been confirmed to exist also in a decelerating flow. Specifically, Ariyaratne et al. (2010), used a $k - \epsilon$ turbulence model to verify the laminar-like behaviour, whereas Mathur (2016) verified the behaviour by performing a number of DNS of low-Reynolds-number flows undergoing impulsive and linear decelerations.

From the foregoing presentation it appears that, despite the advances of experimental and numerical tools, decelerating turbulent flows have received relatively little attention in comparison to accelerating and pulsating flows. However, both from a fundamental as well as an engineering viewpoint, decelerating flows are equally interesting as the two aforementioned unsteady flows. To partially resolve this imbalance, the current study presents two-component particle image velocimetry (PIV) measurements and hot-film wall shear stress measurements performed in decelerating and accelerating turbulent pipe flows. The purpose is to illuminate similarities between decelerating and accelerating flows, which are particularly pronounced in the early phases following the commencement of the transients. We will also discuss dissimilarities between the flows, which become increasingly more important as the transients proceed. The data will also serve as a valuable tool for verifying the performance of turbulence models in transient flows.

Table 1
Experimental conditions for the case of a decelerating flow. ΔT denotes the ramp-time over which the transient was effective. Indices 0 and 1 refer to the initial and final values, respectively. The * in the second column signifies that the final value of Re_τ had not been reached when the measurements ended. In the naming convention, 'D', 'P' and 'H' denote deceleration, PIV and Hot-film, respectively. Note that $Re_{\tau0}$ differs among cases having equal Re_0 because of uncertainties in the measurement of τ.

$Re_{\tau0}$	$Re_{\tau1}$	Re_0	Re_1	ΔT^+	$\Delta T\,(s)$	δ	Case
484	*	17,100	7900	663	6.1	0.00084	DP1
480	*	17,100	7900	320	3	0.0017	DP2
860	350	32,400	11,400	792	2.6	0.00082	DH1
960	440	35,700	13,300	1144	3	0.00055	DH2
695	297	24,400	9300	580	3	0.0011	DH3
685	295	24,400	9300	383	2	0.0016	DH4
800	430	29,700	14,500	525	2	0.00097	DH5

2. Experimental arrangement and instrumentation

2.1. Test facility

The main elements of the flow loop was a 700 l tank, a piping system through which the working fluid was supplied, the test section and an Oberdorfer N1100 gear pump. The test section consisted of three flush-connected pieces of circular Plexiglas pipes, 0.1 m in diameter and 10 m in total length. After passing the test section, the working fluid returned to the collector tank from which it was pumped back into the flow loop once more. Transient flow rate excursions were produced by varying the supply voltage to the pump in such a way to achieve the desired bulk flow variation.

Two measurement campaigns have been performed. One campaign in which PIV was used to measure the radial and axial velocities, and one campaign in which the wall shear stress was measured using hot-film anemometry. As summarized in Tables 1–3, a total number of 19 combinations of initial to final Reynolds numbers and ramp times have been investigated. The respective Reynolds numbers are defined as $Re = U_b D/\nu$ and $Re_\tau = u_\tau R/\nu$. U_b, D and R denote the bulk velocity, the pipe diameter and the pipe radius, respectively. Owing to experimental difficulties in achieving an exactly linear flow rate excursion, all transients were close to, but not strictly linear as illustrated in Fig. 1(a). The parameters characterizing each case are thus the time over which the transient was effective, ΔT, respectively, the initial (Re_0) and final (Re_1) Reynolds numbers. The measurements performed using hot-film anemometry were designed to cover a range of the non-dimensional parameter $\delta = \nu/u_{\tau0}^2(1/U_{b0})\mathrm{d}U_b/\mathrm{d}t$ as large as possibly allowed by the experimental setup. $\mathrm{d}U_b/\mathrm{d}t$ denotes the bulk velocity acceleration, and the subscript '0' refers to the value prevailing before the commencement of the transient. For the PIV measurements, the restriction in the design of the experiments was to not lose the seeding particles between the two images.

The cases investigated using hot-film anemometry were performed in the test section as described previously. For the PIV measurements, however, a one meter long section made of fluorinated ethylene propylene (FEP) was installed to enable near-wall measurements of the velocity. FEP has an index of refraction of approximately 1.34, which is close to that of water, having a refractive index of 1.33. The optical distortions at the curved pipe surface were effectively removed by (i)

Table 2
Experimental conditions for the case of an accelerating flow. ΔT denotes the ramp-time over which the transient was effective. Indices 0 and 1 refer to the initial and final values, respectively. In the naming convention, 'A' and 'P' denote acceleration and PIV, respectively. Note that $Re_{\tau0}$ differs because of uncertainties in the measurement of τ.

$Re_{\tau0}$	$Re_{\tau1}$	Re_0	Re_1	ΔT^+	$\Delta T\,(s)$	δ	Case
243	470	7900	17,100	170	6.1	0.0065	AP1
248	470	7900	17,100	85	3	0.013	AP2