Relation between Velocity Profile and Friction Factor at High Reynolds Number in Fully Developed Pipe Flow

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ABSTRACT

Pipe flow, which is one of the canonical wall-bounded flows, finds wide application in engineering fields. Because knowledge of the physics of pipe flow is very important to achieve effective fluid transport, many studies on fully developed turbulent pipe flow have been performed since the early 1900s. However, even the functional form for the mean velocity profile remains incomplete because of the Reynolds number effect, as summarized by Kim (2012). One of the reason for the inconsistency of the velocity profile formulae is that the wall shear stress used for the scaling of the velocity profile is also inconsistent among previous experiments. Obtaining the wall shear stress (or equivalently the friction factor) is important for not only pipe flows but also for wall-bounded flows in general. The second reason of the inconsistency is the Reynolds number dependency of the velocity profile formula. As investigated in other type of the wall bounded flows, boundary layer and channel flow, the constants in the velocity profile formula are influenced by Reynolds number. To discuss the universality of the velocity profile, the pipe flow experiments at higher Reynolds number region is required. In this paper, new experimental results for the friction factor and the velocity profile at high Reynolds number up to \(10^7\) are presented. The Reynolds number dependency of the constants in the formulae of the friction factor and the velocity profile are discussed using the experimental result. Furthermore, to show the reliability of the experimental results, the higher level consistency of the measurement data between the friction factor and velocity profile is presented.

In this experiments, the Hi-Reff (High Reynolds number actual flow facility) (Furuichi et al, 2009) was used. The working fluids in this facility is water. The feature of this facility is high Reynolds number and high accurate flowrate measurement. The maximum Reynolds number based on diameter of pipe is \(Re_D=2\times10^7\) (based on friction velocity, \(Re=3\times10^5\)). The flow rate is measured by the static gravimetric method or the reference flowmeters calibrated by the weighing tank. The uncertainty of the flow rate ranges from 0.060% to 0.10% with the coverage factor of \(k=2\). The velocity profile was measured by using laser Doppler velocimetry (LDV). The examined Reynolds number ranges \(Re_D=3.9\times10^4 - 1.1\times10^6\) \((Re=1.0\times10^3 - 2.1\times10^5)\). The friction factor is obtained by the measurement of the pressure drop between two pressure taps installed in smooth pipes with \(D=100\) mm and 387 mm. The examined Reynolds number for the friction factor measurement ranges \(Re_D=7.1\times10^3 - 1.8\times10^7\) \((Re'=2.3\times10^2 - 2.7\times10^5)\). The detail of experimental results are shown in the reference (Furuichi et al., 2015).

Using the experimental results, the Reynolds number dependence of the Kármán and the additive constants (\(\kappa\) and \(B\)) respectively) is investigated as shown in the figure. The behaviors of both constants are found to change at approximately \(Re_D=3\times10^5 - 5\times10^5\). Both constants vary in the bulk Reynolds number region \(Re_D<5 \times 10^5\) \((Re<10^4)\) and remain invariant at values of \(\kappa=0.383\) and \(B=4.335\) with changing Reynolds number for \(Re_D>5\times10^5\) \((Re>10^4)\). The consistency between the velocity profile and the friction factor is investigated by integrating the velocity profile data. The velocity profile data are fitted by the log law, and the equation for the friction factor is derived by integrating the fitted equation of the velocity profile. This friction factor equation is found to suitably represent the friction factor data, with the equation deviating from the friction by less than 1%. This analysis indicates that the friction factor for \(10^4<Re_D<10^7\) cannot be expressed by a unique equation for the velocity profile based on the log law because the Kármán and the additive constants have Reynolds number dependence at low Reynolds numbers \((Re_D<3\times10^5)\). At high Reynolds numbers \((Re_D>5\times10^5)\), the friction factor can be expressed by a unique equation, which yields \(\kappa=0.383\) and \(B=4.335\). This friction factor behavior is consistent with the behavior of the constants in the mean velocity profile.

REFERENCES