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Determining velocity and friction factor for turbulent flow in smooth tubes

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ABSTRACT

The most popular explicit correlations for the friction factor in smooth tubes are reviewed in this paper. The friction factor for the turbulent flow in smooth tubes is required in some correlations when calculating the Nusselt number. To calculate the friction factor, the velocity profile in a turbulent smooth wall-tube must be estimated at first. The radial velocity distribution was determined using either universal velocity profile found experimentally by Reichardt or by integration the momentum equation using the eddy diffusivity model of Reichardt. The friction factor obtained by using the universal velocity profile gives better results than that obtained from the momentum equation when compared with the Prandtl—von Kármán—Nikuradse equation. Based on the velocity profiles proposed by Reichardt the friction factor was calculated as a function of the Reynolds number and subsequently two formulas for the friction were proposed. They have satisfactory accuracy when comparing with the implicit Prandtl—von Kármán—Nikuradse equation. Thus, it was concluded that the universal velocity profile proposed by Reichardt will provide good results when it is taken into account while integrating the energy conservation equation. There is also a considerable number of experimental correlations for the friction factor in smooth tubes. All these relationships were compared with the experimental data and with the implicit Prandtl—von Kármán—Nikuradse equation that is considered as a standard to test the explicit approximations. The Colebrook and Filonienko explicit correlations are widely used when calculating the Nusselt number for the turbulent flow but they have noticeable errors for small Reynolds number ranged from 3000 to 7000 for the Colebrook relation and from 3000 to 30,000 for the Filonienko relation. For this reason, a new simple and accurate correlation for the friction factor for Reynolds numbers between 3000 and 10^7 is proposed in the paper.

1. Introduction

The determination of a friction factor in turbulent tube flow is essential not only to pressure drop calculations in pipelines and heat exchangers [1] but also is needed for calculating the Nusselt number in turbulent tube flow [2,3]. The correlations for the friction factor ξ can be found experimentally based on the measured pressure drop in a tube over a given distance or on the measured radial velocity profile. The latter way of the friction factor determining is also important in driving the heat transfer correlation because it allows to choose the most appropriate velocity profile indirectly. Solving the energy conservation equation using accurate universal velocity profile will yield the Nusselt numbers as functions of the Reynolds and Prandtl numbers that are consistent with the experiment.

Blasius was the first who proposed an explicit correlation for turbulent tube flow that is valid for Reynolds numbers between 3000 and 10^5. The Blasius correlation is still in use [4]. Sheikholeslami et al. [5] studied turbulent flow and heat transfer in the air to water double-pipe heat exchanger. The Blasius formula was used to calculate the friction factor needed for the estimation of the heat transfer by the Gnielinski correlation. Only about 20 years later, an implicit relationship for determining the friction factor was developed by Prandtl, von Kármán, and Nikuradse (PKN) [6–8]. The PKN equation for the friction factor for the turbulent flow in a smooth tube is widely accepted and has become a model equation for explicit approximations. The PKN correlation is implicit in ξ because the friction factor ξ appears on both equation sides. In other words, it is a nonlinear algebraic equation that must be solved either iteratively or graphically. This inconvenience can be circumvented using a numerous explicit approximation to the PKN

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Nomenclature

c_1, c_2	constants
d_w	inner diameter of a circular tube, $d_w = 2r_w$, m
e_i	relative difference
i	node number
k	turbulence kinetic energy, N/(s m^2)
L	distance between pressure taps, m
n	number of nodes in the finite difference grid
p	pressure, Pa
PKN	Prandtl–von Kármán–Nikuradse
r	radial coordinate, m
r_w	inner radius of the tube, m
r^2	coefficient of determination
r^+	dimensionless radius, $r^+ = ru_\tau/\nu$
R	dimensionless radius, $R = r/r_w$
Re	Reynolds number, $Re = w_m d_w/\nu$
u_τ	friction velocity, $u_\tau = \sqrt{\tau_w/\rho}$, m/s
w_m	mean velocity
w_x	velocity component in the x direction
$\overline{w}_r$, $\overline{w}_x$	time averaged velocity component in the x and r direction, respectively, m/s
x	a spatial coordinate in Cartesian or cylindrical coordinate systems, m
y	a spatial coordinate in a Cartesian system or distance from distance from the wall surface, m
y^+	dimensionless distance from the tube wall, $y^+ = yu_\tau/\nu$

Greek symbols

Δp	pressure drop, Pa
Δy^+	dimensionless spatial step
ε	turbulence dissipation rate, N/(s m^2)
ε_τ	eddy diffusivity for momentum transfer (turbulent kinematic viscosity), m^2/s
μ	dynamic viscosity, kg/(m s)
κ	the von Kármán constant
ν	kinematic viscosity, $\nu = \mu/\rho$, m^2/s
ξ	Darcy–Weisbach friction factor
ρ	fluid density, kg/m^3
τ	shear stress, Pa
τ_w	shear stress at wall surface, Pa

Subscripts

m	mean
i	node number
w	wall surface

Superscripts

–	time averaged
+	dimensionless

equation [1,9–11]. Even a larger number of explicit correlations was proposed for implicit Colebrook–White equation used to determine the coefficient of friction in the rough pipes. Many comparisons of explicit approximations to the Colebrook–White equation were conducted over the past two decades. Examples of such comparative reviews can be publications [1,9–11]. Unfortunately, the explicit equations for rough pipes cannot be used for smooth pipes, since they were derived for the relative surface roughness greater than zero.

Petukhov and Kirillov [2,12] proposed in 1958 a formula for the Nusselt number and suggested to use the explicit correlation of Filonienko [13] for calculating the friction factor. Gnielinski [14] extended the application of the Petukhov–Kirillov equation to lower Reynolds numbers and continued to calculate the friction factor using the Filonienko correlation. Since that time, the Filonienko correlation is widely utilized in the calculation of the Nusselt number for the transitional and turbulent flow in tubes [15–24]. Mirth and Ramadhyani [15] applied the Gnielinski [14] correlation in conjunction with the Filonienko friction factor to calculate the water-side heat transfer coefficient inside the tubes of a finned-tube chilled-water cooler. In all the experiments, high water mass flow rates were maintained to provide a turbulent flow of water. Fernando et al. tested a mini channel aluminum tube heat exchanger for water-to-water operation [16]. They found that the Nusselt numbers obtained in the experiment agree with those predicted by the Gnielinski correlation [14] within an accuracy of ±5% in the transition Reynolds number range of 2300–6000. The friction factor was calculated using the Filonienko approximation.

A lot of papers is devoted to the intensification of heat exchange in tubes [17–22].

Li et al. [17] measured the turbulent tube flow in a micro-fin tube using water and oil. The friction factor and Nusselt numbers in a smooth tube were first estimated experimentally and compared with the Filonienko and Gnielinski correlations, respectively, to validate the experimental set-up and data reduction procedure. The Reynolds numbers varied from 2500 to 90,000 for water and from 2500 to 12,000 for oil. The results of measurements and calculations agree very well, even for small Reynolds numbers near $Re = 2500$. The maximum relative differences between the measured friction factor and the empirical correlation by Filonienko does not exceed 10%. Similar experiments were carried out by Li et al. with rough tubes [18]. As in the previous study [17], the measurements were conducted for the turbulent flow of water in a smooth tube. The Reynolds number varied from 7000 to 90,000. Differences between measured and calculated friction factors using the Filonienko formula are small. Li et al. [19] used the Filonienko correlation to show the increase in the friction factor of the discrete double inclined ribbed tubes in relation to the smooth pipes. In the paper of Ji et al. [20] developed turbulent heat transfer in internal helically ribbed tubes is studied experimentally. To test the reliability of the test facility, the experimental results of the friction factor were firstly compared with the Filonienko correlation. The relative discrepancy between the experimental data and Filonienko predictions was within ±5% for the Reynolds number ranged from 8000 to 90,000.

Flow heat transfer and pressure drop measurements in doubly enhanced tubes were conducted with water and ethylene glycol in the laminar-transition turbulent flow regime by Raj et al. [21]. The aim of the study was to investigate the usefulness of doubly enhanced tubes for lower duty heat exchangers in the laminar-transition-turbulent flow regime. To check out the experimental set-up and the data processing methodology, the tube-side heat transfer and friction factor were first determined in a 2590 mm long copper smooth tube with an inner diameter of 15.88 mm. Turbulent flow friction factors determined experimentally for deionized water compared to within ±5% of the friction factors predicted by the Filonienko equation.

The paper by Zhang et al. [22] reported the thermo-hydraulic