International Journal of Heat and Mass Transfer 95 (2016) 525–534

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

New friction factor equations developed for turbulent flows in rough helical tubes

Houjian Zhao, Xiaowei Li *, Xinxin Wu

Key Laboratory of Advanced Reactor Engineering and Safety of Ministry of Education, Collaborative Innovation Center of Advanced Nuclear Energy Technology, Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 17 July 2015
Received in revised form 7 December 2015
Accepted 16 December 2015
Available online 31 December 2015

Keywords:
Helical tube
Curvature ratio
Friction factor
Relative roughness
Turbulent flow

ABSTRACT

Helical tubes are widely used and there lacks friction factor equations for turbulent flows in rough helical tubes. Turbulent flows in rough helical tubes were investigated theoretically in this paper. Friction factor equations for transitionally and fully rough regime turbulent flows in rough helical tubes were derived based on the logarithmic velocity distribution law. The parameters of the equations were obtained by regression analysis of experimental data of Clancy (1949) and verified by experimental data of McElligott (1948). The characteristics of the friction factors in rough helical tubes were discussed based on the equations. Friction factors of helical tubes are influenced by Reynolds numbers, relative roughnesses and curvature ratios. The friction factors of rough helical tubes can also be divided into a transitionally rough regime and a fully rough regime according to the roughness height and the Reynolds number like that for straight tubes. Roughnesses have greater effects on the transition from the transitionally rough regime to the fully rough regime than that of curvature ratios. Roughness effects on friction factors increase with the increasing of the curvature ratio and the Reynolds number.

1. Introduction

Helical tubes are widely used in chemical, petroleum and nuclear industries due to the advantages of compact structures, high heat transfer coefficients and good thermal expansion performances. In nuclear industries, helical tubes are usually used in steam generators [3–5], especially for gas cooled reactors. Flows in helical tubes are more complex than those in straight tubes. Secondary flows occur in helical tubes in the cross section due to the centrifugal force, which causes more friction losses.

Since the classical works by Dean [6,7], flows in smooth curved tubes have been extensively studied. Dean obtained an approximate solution through perturbation over the Poiseuille flow in straight tubes and introduced the Dean number. Gnielinski [8] presented equations for laminar flows and turbulent flows to calculate the friction factors and heat transfer coefficients in helical tubes. Results were compared with experimental data from literature and the deviations were less than 15%. Srinivasan [9] measured the pressure drops of water and oil in helical tubes and developed equations to predict friction factors for laminar, transition and turbulent flow regions. Ju et al. [10] evaluated the hydraulic characteristics in small bending radius helical tubes. Friction factor correlations were obtained by regression analysis of the experimental data and the results showed that the critical Reynolds number for laminar flow to turbulent flow transition in helical tubes was much greater than that in straight tubes. Yamamoto et al. [11] investigated flows in helical tubes with large pitches numerically and experimentally. Simulations agreed well with experimental data and showed that two vortices transformed into one single vortex as the pitches increase. Hart et al. [12] presented a friction factor chart for flows in curved tubes which covered the laminar flow region and turbulent flow region and derived an equation to calculate friction factors. Grundman [13] developed a practical friction factor diagram for helical tubes which accounted for curvature ratio effects. The diagram also offered a graphic view of the flow conditions and other parameters. Mishra and Gupta [14] investigated the pitch effects on pressure drops in helical tubes. Pressure drops were measured and equations for friction factors were derived using the modified Dean number. They concluded that the pitch effects could be eliminated by using the modified curvature diameter. Ito [15] measured the frictional pressure drop of turbulent flows in smooth curved tubes with zero pitch and derived an equation using the 1/7th power velocity distribution law and an equation using the logarithmic velocity distribution law, which have been used widely for engineers [16].

---

* Corresponding author. Tel.: +86 10 62784825; fax: +86 10 62797136.
E-mail address: lixiaowei@tsinghua.edu.cn (X. Li).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.12.035

Nomenclature

Notations

Cur	curvature ratio (dimensionless)
f_c	friction factors for curved tubes (dimensionless)
K_s	average wall surface roughness (m)
M	mass flow rates (kg s^{-1})
P	static pressure (Pa)
r_0	tube inner radius (m)
R	helical radius (m)
R_c	modified helical radius (m)
V	velocity magnitude in curved tubes (m s^{-1})
V_r	velocity magnitude in the r direction (m s^{-1})
V_θ	velocity magnitude in the θ direction (m s^{-1})
V_φ	velocity magnitude in the φ direction (m s^{-1})
V_*	$(\tau_w/\rho)^{1/2}$, friction velocity (m s^{-1})
V_m	mean axial velocity (m s^{-1})
y	distance normal to the wall (m)
y_0	distance normal to the wall where the velocity magnitude is zero (m).
τ_w	wall shear stress (N m^{-2})
τ_θ	wall shear stress in the θ direction (N m^{-2})
τ_φ	wall shear stress in the φ direction (N m^{-2})

Greek letters

α, β, γ	constants in the friction factor equation
δ	thickness of boundary layer (m)
ε	relative roughness, $\varepsilon = K_s/r_0$ (dimensionless)
θ	angels in the cross section
μ	dynamic viscosity (kg s^{-1} m^{-1})
ρ	density (kg m^{-3})
φ	angles in the axial direction

Subscripts

1	at the edge of the boundary layer
c	curved rough tubes
c, r	helical rough tubes
c, s	helical smooth tubes
rough	fully rough regime
str, r	straight rough tubes
trans	transitionally rough regime
w	near the wall

Flows in helical tubes also have been investigated numerically. Austin and Seader [17] solved the Navier–Stokes equation in the stream-function form using the finite difference method to simulate steady, incompressible and fully developed flows in helical tubes. They presented a correlation for pressure drops in terms of the Dean number. Soeberg [18] simulated laminar flow in helical tubes based on the symmetry of the secondary flow and investigated the velocity profile changes which were influenced by the Dean number. Liu and Masliyah [19] and Yamamoto et al. [20] simulated the flows in helical tubes with finite pitches and found the friction factors would increase as the curvature ratios increase. However, the factors would decrease as the pitches increase. Yanase et al. [21] used the Forier–Chebyshev spectral method to analyze the stability of the two-vortex and the four-vortex solutions for flows in slightly curved tubes and found that the two-vortex solution was stable in response to any small disturbances, while the four-vortex solution was unstable to asymmetric disturbances. Lai et al. [22] simulated turbulent flows in curved tubes and found that there were three vortex pairs in the cross section. One was the Dean-type vortex pair. Another existed in the tube core and was caused by the pressure imbalance. The third was near the outer wall and was the turbulence driven secondary flow. Manlapaz and Churchill [23] simulated laminar flows in coiled tubes with a finite pitch and developed a friction factor equation for the laminar flow region. Ivan and Michele [24] simulated turbulent flows using $k-\varepsilon$, SST k—ω and RSM—ω models. Pressure drops were in excellent agreement with experimental data when using SST k—ω and *RSM*—ω models, but results were unsatisfactory when using $k-\varepsilon$ model with wall functions.

To the authors' knowledge, most previous studies did not consider the roughness effects on friction factors in helical tubes. There are no reported equations for calculating the friction factors in rough helical tubes. However, most helical tubes used for industries are commercial tubes with different height of roughness. Many investigations have been done on flows in rough straight tubes which can be taken as the bases for investigation on rough helical tubes. Nikuradse [25] experimentally investigated turbulent flows in rough straight tubes by roughening the tubes with uniform sand grains. At high Reynolds numbers, the results agreed well with others' experimental data for commercial tubes. However, the results deviated from the performances of commercial tubes at moderate Reynolds number. Colebrook and White [26] investigated turbulent flows in roughened straight tubes experimentally and found Nikuradse's [25] deviations from the commercial tubes were due to the uniform roughness in tubes. Then Colebrook [27] presented an implicit equation to calculated friction factors in rough straight tubes. The equation was widely used to calculate friction factors for turbulent flow in rough straight tubes. Many researchers [28–32] obtained explicit equations to calculate the friction factors in rough straight tubes with specific limits. Moody [33] presented a composite friction factor chart of all flow regions for rough straight tubes which was widely used in engineering. For rough helical tubes, Clancy [1] measured the pressure drops in rough helical tubes and straight tubes and found friction factors were influenced by Reynolds numbers, helical diameters and roughness heights. McElligott [2] compared friction factors in rough helical tubes and friction factors in rough straight tubes with comparable roughness. The results showed that friction factors in helical tubes depended more on roughnesses than on curvature ratios.

This paper describes a theoretical investigation on turbulent flows in rough helical tubes and derived friction factor equations considering the roughness effects, curvature ratios and Reynolds numbers. The equations can predict the friction factors accurately compared with literature data. The comprehensive effects of roughnesses and curvature ratios on the friction factor are also discussed based on the equations.

2. Equation derivation

2.1. Physical model and mathematical description

Fig. 1 shows a helical tube schematic with the main parameters and a secondary flow illustration. The helical radius is defined as R, the tube inner radius is defined as r_0 and the helical pitch is defined as b. When the helical pitch is small compared with the helical diameter, torsion effects can be neglected at moderate Reynolds