International Journal of Greenhouse Gas Control 25 (2014) 151–161

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

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

Experimental study on the friction coefficient of supercritical carbon dioxide in pipes

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ARTICLE INFO

Article history:
Received 17 August 2013
Received in revised form 24 February 2014
Accepted 9 April 2014
Available online 4 May 2014

Keywords:
Supercritical carbon dioxide
Friction coefficient
Physical property
Reynolds number
Roughness

ABSTRACT

This paper has attained friction coefficients of supercritical carbon dioxide (SC-CO_2) with various pressures and temperatures in pipes through experiments, of which the temperature range is 30–150 °C, the pressure range is 3.5–40 MPa, the Reynolds number range is 200–2.0×10^6, and relative roughness of pipeline is 0.005, 0.015 and 0.025, respectively. Temperature and pressure affect viscosity and density of SC-CO_2, then affect the Reynolds number *Re* and make friction coefficients of CO_2 change abruptly near the critical point, but *Re* can reflect variations of viscosity and density comprehensively, therefore, function $\lambda = f(Re)$ can still be used to determine the friction coefficient of SC-CO_2. The experimental relationship between the friction coefficient of SC-CO_2 and *Re* corresponds with the functional relation $\lambda = 64/Re$ in the laminar flow region, for which the absolute average error is 2.39%. In the transition region, compared 5 relations of friction coefficient with the experimental data, it is found that the absolute average error of Churchill's equation is smaller, but when the Reynolds number is larger than 2800, the absolute average error is up to 10.35%. Proposed calculation model of friction coefficient in the transition region is regressed and its absolute average error is 2.81%. In the turbulent region, compared 15 relations of friction coefficient with the experimental data, it is found that Colebrook–White equation as a representative fits in better. The error in the low Reynolds region ($3400 < Re < 11{,}000$) is relatively bigger, but the absolute average error is within 10%. A modified calculation model of friction coefficient, with the absolute average error 1.94%, is proposed based on the experiment data.

1. Introduction

Carbon dioxide as the most important greenhouse gas is attracting people's attention increasingly. Capturing, transportation and storage techniques can reduce emission of greenhouse gases into the atmosphere on a large scale (Grimston et al., 2001; Li et al., 2006; Zhang et al., 2011). During the process of CO_2 injection and sequestration, CO_2 can be in the supercritical state, and the calculation accuracy for friction coefficient of supercritical carbon dioxide (SC-CO_2) will affect the accuracy of pressure drop directly. Besides, SC-CO_2 has been successfully applied in oil and gas well drilling, fracturing and well cleanout (Kolle, 2000; Gupta et al., 2005), so in these engineering designs, determination of the friction coefficient of SC-CO_2 is of the same importance. When the temperature of CO_2 is over 31.5 °C (the critical temperature) and the pressure is over 7.35 MPa (the critical pressure), CO_2 is in the state of supercritical. SC-CO_2 is a special kind of fluid and is of some particular characteristics, density of which can be very high, close to water; while viscosity can be pretty low, close to gases. Physical property parameter of SC-CO_2 can be affected by temperature and pressure, especially near the critical point, density and viscosity vary dramatically. As the Reynolds number is a function of density and viscosity, changes of temperature and pressure will make it vary and then lead to variation of friction coefficient. A great number of scholars have done massive work (Gürol Yıldırım, 2009; Brkić, 2011a,b) aiming at friction coefficient, however, for the one when SC-CO_2 the special fluid is flowing in pipes, research work has rarely been done. In this paper, abundant friction coefficient data by means of the flowing experiment of SC-CO_2 in pipes are attained. Compared with the existing models, a modified calculation model of friction coefficient in different ranges of Reynolds number is proposed based on the experiment data.

A great deal of research has been done on friction coefficient of fluid in pipes since 1930s. In 1933, Nikuradse J. defined the frictional resistant coefficient as a function of Reynolds number and relative roughness through artificial rough pipes experiment. The experimental curves are divided into five regions, which are the laminar flow region, the transition region, the smooth region of turbulent

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http://dx.doi.org/10.1016/j.ijggc.2014.04.014
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Δp	pressure drop in the friction measurement, Pa;
μ	fluid viscosity, Pa s;
L	pipe length, m;
h_f	the route loss, m;
ρ	fluid density, kg/m^3;
g	gravity acceleration, 9.8 m/s^2;
d	pipe diameter, m;
Re	Reynolds number;
λ	Darcy friction coefficient;
v^*	friction velocity, m/s;
v	average velocity of cross section, m/s;
$v_{\max}$	maximum axial velocity in the pipe, m/s;
κ	constant Karman;
C	integral constant;
y	distance from pipe wall, m;
δ	boundary layer thickness, m;
ε	absolute roughness, m;
ΔP	pressure differential of both ends in density measurement, MPa;
h	vertical length of the measuring pipeline, m;
Q	mass flow velocity, kg/s;
E_λ	friction measurement uncertainty.

flow, the rough region of turbulent flow, the transition region of turbulent flow.

1.1. Laminar flow region

When fluid makes laminar flow movement in pipes, according to formula Hagen–Poiseuille, the frictional head loss can be achieved:

$$h_f = \frac{32\mu L v}{\rho g d^2} \tag{1}$$

According to formula Darcy–Weisbach, Eq. (2) can be obtained:

$$h_f = \lambda \frac{L}{d}\frac{v^2}{2g} \tag{2}$$

The analytic expression of λ in the laminar flow region can be achieved by the simultaneous Eqs. (1) and (2),

$$\lambda = \frac{64}{Re} \tag{3}$$

Accuracy of the analytic expression of λ in the laminar flow region was verified by Hagen (1839) through the flow experiments by fine copper tube and Poiseuille (1840) through the capillary experiments.

1.2. Transition region

The transition region is the transitional zone for laminar flow to turbulent flow. When fluid flow in transition region, its flow pattern is extremely complex and many factors affect the friction coefficient. Experiment results indicate that friction coefficient data is scattered, laws are difficult to summarize. Many scholars have acquired some empirical or semi-empirical formulae according to experimental data, including P.M. Зайченка, Shen and Zhu (1986) and Manadilli (1997). Furthermore, a lot of scholars have proposed some relations for friction coefficient applicable to all the Reynolds number ranges, including the transition region. Churchill (1977) and Goundar and Sonnad, 2008 are representatives. Those equations are listed in Appendix A.

1.3. Turbulence region

The time-average velocity profile in the turbulence region includes logarithmic form and exponential form. Von Kármán (1930) and Prandtl (1932) gave the logarithmic form of the current velocity distribution.

$$v = \frac{v_*}{\kappa}\ln y + C \tag{4}$$

The exponential form of the time–average velocity profile can be demonstrated as below:

$$\frac{v}{v_{\max}} = \left(\frac{y}{\delta}\right)^{1/n} \tag{5}$$

The exponential law and logarithmic law for the time–average velocity of turbulent flow are essentially uniform and can be convertible. They are derived from the similar theory, revealing the internal coupling relationship between the law of velocity distribution and on-way resistance.

(1) Smooth region of turbulent flow

In this region, the friction coefficient is only related to Re, not ε/d. Blasius (1911) used the 1/7 power exponential function of velocity distribution, combining with the experimental data, to derive the friction coefficient formula. On the basis of logarithmic function velocity distribution, Prandtls (1949) acquired the friction coefficient calculation formula combining with experimental data of Nikuradse (1993). Zagarola and Smits (1998) proposed the relation of friction coefficient in the hydraulic smooth region. Mckeon et al. (2005) proposed a relation of friction coefficient in the hydraulic smooth region by using viscous correction. The related equations are listed in Appendix B.

(2) Rough region of turbulent flow

In this region, the friction coefficient is only decided by ε/d, having nothing to do with Re. According to the turbulent fluctuation similarity assumption, combining with Nikuradse, 1993 experimental data, Von Kármánm (1921) derived the equation also listed in Appendix B.

(3) The mixing friction region of turbulent flow

The calculation formula of friction coefficient in this region takes viscous force and inertia force into consideration. Through changing various pipe wall roughness and Reynolds numbers, many scholars acquire the relation of friction coefficient in the condition of turbulent flow by analysis of data regression according to experimental data, and this study method makes it applicable to calculation of friction coefficient in the smooth zone of turbulent flow and in the rough zone as well.

Colebrook and White (1937) proposed a relation of friction coefficient in the mixing friction region of turbulent flow on the basis of logarithmic function velocity distribution formula.

In fact, Colebrook–White equation is the synthesis of Prandtl equation (B-2) and Von Kármán equation (B-5). In terms of mathematical correlation $\lg(A+B) \neq \lg A + \lg B$, but Colebrook–White equation, with a satisfactory accuracy, has been broadly applied in engineering.

Moody (1947) proposed an approximate approach for calculation of friction coefficient in the light of the implicit function Colebrook. Wood (1966) brought forward a relation of friction coefficient with the similar exponential form to Moody's. Chen (1979) issued a relation of friction coefficient applicable to the range of all Reynolds numbers and relative roughness. Zigrang and Sylvester (1982) adopted the same method as Chen's, and their formula included three internal iterations. Haaland (1983) issued an explicit empirical relationship of friction coefficient in the turbulent flow region, similar to Colebrook–White. Serghides (1984) proposed