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Relationship between roughness height in use with Colebrook roughness function and the internal wall surface roughness parameters for stainless steel pipes

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ABSTRACT

Flow tests were conducted on a total of 7 commercial stainless steel (SS) pipes of two sizes: 114.3 mm and168.3 mm O.D., and lengths of approximately 5 m, sourced from different manufacturers. The working fluid is a pipeline quality natural gas at a pressure range of 4700–5100 kPa(g), and flow rates resulting in Reynolds number (based on respective pipe I.D.) ranging between 8×10^6-23×10^6. The experimentally determined friction factor (λ) allowed calculation of the roughness function (RF), and determination of the effective roughness height (k_s) in use with the Colebrook RF correlation. It was found that the commercial (SS) pipes exhibit different surface roughness characteristics that produce higher λ and higher k_s than that of commercial carbon steel (CS) pipes having the same roughness parameter represented by the root mean square of the surface roughness element (R_q). It was found that the main contributor for the increase in λ or k_s for the SS pipes over the CS pipes is the generally relatively low values of the roughness parameter RS_m, which characterizes the frequency of the surface modulation along the length of the pipe surface. The lower the RS_m, the higher the modulation frequency, and the higher λ or k_s. A correlation between k_s in use with the Colebrook RF or λ, and R_q was developed for commercial SS pipes in the form; $k_s = 2.2907R_q + 0.1029R_q^2$(both k_s and R_q in µm).

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1. Introduction

Langelandsvik et al. (2008) suggested that the relationship between the characteristic roughness height (k_s) in use with the roughness function (RF) of either (Nikuradse, 1933) or (Colebrook, 1939), and the roughness parameter described by the r.m.s. of the roughness element profile (R_q), for turbulent flow in pipes is $k_s = 1.6R_q$. Shockling et al. (2006) found that this relationship to be $k_s = 3R_q$ for a honed aluminum pipe. Application of the two relationships could lead to approximately 15% difference in the pressure drop in turbulent pipe flows. This raised a question in the gas pipeline industry due to its significant implication from economic and operational perspectives.

Recently, (Botros, 2016) conducted flow tests on a total of 11 commercial carbon steel (CS) pipes of two sizes; 114.3 mm and 168.3 mm O.D. and provided data to enable the development of a more definitive relationship between k_s and R_q. These tests were conducted on high pressure pipeline quality natural gas mixtures in the range of Reynolds number (based on pipe internal diameter, D) of $Re_D = 9 \times 10^6$-16×10^6. For these commercial carbon steel pipes, it was found that the relationship between k_s for use with Colebrook RF correlation and R_q, takes the form $k_s = 1.306R_q + 0.078R_q^2$ (both k_s and R_q in µm). This correlation covers a range of R_q from 2.7 µm to 12.5 µm, a range which is typically found in commercial carbon steel pipes.

For stainless steel (SS) pipes, however, preliminary results from (Botros, 2016) on two SS pipes indicated that other surface roughness parameters such as RS_m need to be assessed to better predict the values of k_s for these pipes. The roughness parameter RS_m is defined in (ISO 4287, 1997; ANSI ASME B46.1, 2009) as the arithmetic average of the width of all roughness elements along the evaluation length determined from distance between successive peaks rising above, or valleys dropping below, a pre-defined profile height typically taken as ±10% of R_z. The roughness parameter, R_z, represents the sum of the largest profile peak height and the largest profile valley height within a sampling length, also as defined in

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(ISO 4287, 1997; ANSI ASME B46.1, 2009). A third parameter that was found to be of significance is the normalized third moment of the roughness height above the mean, known as R_{sk} (or skewness), defined as:

$$R_{sk} = \frac{1}{R_q^3}\frac{1}{n}\sum_{i=1}^{n} h_i^3 \tag{1}$$

where, h is the profile height above the mean value of the roughness profile. Note that R_a (the arithmetic mean of the absolute roughness height $|h|$) is less important with regards to turbulent pipe flow correlations. This is because it does not reveal the nature of the peaks vs. valleys in the roughness profile nor its modulation frequency, both of which are key contributors to k_s.

The present paper describes an extension of the flow test program by (Botros, 2016) to a total of 7 commercial SS pipes of the same two sizes: 114.3 mm and 168.3 mm O.D. and lengths of approximately 5 m. The working fluid is a pipeline quality natural gas drawn from a pipeline running through the test facility. The test pressure ranges between 4700 and 5100 kPa(g), and flow rates resulting in Re_D ranging between 8×10^6-23×10^6. The experimentally determined friction factor (λ) allowed calculation of the RF, as will be shown later in the paper, which is then used to determine the effective roughness height (k_s) in use with the Colebrook RF correlation. The theoretical background Section gives a brief account of this approach. Once k_s is determined for each of the 7 SS pipes and averaged over the respective test flow range, it is then correlated to the internal surface roughness of these pipes characterized by R_q, RS_m and R_{sk} measured by a standard stylus surface profiler (Mitutoyo, model SJ-210).

2. Theoretical background

In turbulent pipe flow, when the roughness height (k_s) is relatively low with respect to the viscous sub-layer thickness, the flow near the wall is termed ‘hydraulically-smooth’, indicating that there is no effect of wall surface roughness (McKeon et al., 2004). As k_s and Re_D increases, the flow becomes transitionally-rough, and λ becomes higher than the corresponding smooth value (λ_s) and depends on both k_s and Re_D (Schultz and Flack, 2007; Flack et al., 2012). At much higher Re_D, the flow becomes fully rough, where λ becomes independent of Re_D (Kunkel et al., 2007; Bradshaw, 2000). In the transitionally rough regime, there has been significant debate about the relationship between λ, Re_D and k_s, e.g. (McKeon et al., 2005). The only way to obtain this relationship is from experiment as each surface element profile affects the near wall flow field in a different way. A case in point is (Nikuradse, 1933) experiments, which showed that for surfaces represented by closely packed, uniform sand of different grain sizes, the flow was hydraulically-smooth for $k_s^+ \leq 5$, transitionally-rough for $5 < k_s^+ < 70$, and fully-rough for $k_s^+ \geq 70$. Here, k_s^+ is known as the roughness Reynolds number $= k_s/\delta$, where δ is the viscous length scale defined as ν/u_τ, ν is the fluid kinematic viscosity, $u_\tau = \tau_w/\rho$, τ_w is the wall shear stress, and ρ is the fluid density; hence $\delta = D/(\mathrm{Re_D}\lambda/8)$.

Colebrook (1939), however, showed that commercial pipe surfaces do not behave like closely packed, uniform sand, and developed a correlation based on experiments on rough pipes performed by (Colebrook and White, 1937), in addition to other data obtained from pipes in commercial use. This correlation takes the following implicit form, although there are other forms, extensively reviewed by (Afzal, 2007; Afzal et al., 2013):

$$\frac{1}{\sqrt{\lambda}} = -2\log\left(\frac{k_s}{3.71D} + \frac{2.51}{\mathrm{Re}_D\sqrt{\lambda}}\right) \tag{2}$$

The increase in λ above λ_s is known as the roughness function (RF), which is observed experimentally as a negative term ($-\Delta U^+$) in the “log-law” expression for rough-wall boundary layer defined as (Hama, 1954):

$$U^+ = \frac{1}{\kappa}\ln\left(y^+\right) + B - \Delta U^+ \tag{3}$$

where, $U^+ = U/u_\tau$, U is the local flow velocity, $y^+ = y/\delta$, y is distance from the pipe wall, the von Karman's constant $\kappa = 0.421$ and the constant $B = 5.6$ (McKeon et al., 2004). In order to extract the roughness function, ΔU^+, from a measured λ, the following similarity-law of (Granville, 1987) for fully developed turbulent pipe flows is commonly applied:

$$\Delta U^+ = \sqrt{\frac{8}{\lambda_s}} - \sqrt{\frac{8}{\lambda}} \tag{4}$$

where, λ_s is the friction factor for a smooth wall determined at the same $\mathrm{Re}_D\sqrt{\lambda}$, which is best expressed by (Zagarola and Smits, 1998):

$$\frac{1}{\sqrt{\lambda_s}} = 1.930\ \log\left(\mathrm{Re}_D\sqrt{\lambda_s}\right) - 0.537 \tag{5}$$

3. Experimental setup

The test program includes flow tests on 7 different commercial SS pipes of two sizes: 114.3 mm and 168.3 mm O.D. (DN100 and DN150, respectively), sourced from different manufacturers. Characteristics of the 7 commercial SS pipes tested are given in Table 1, which include 3 pipes of size 114.3 mm O.D. (pipes 1,2 and 3) and 4 pipes of size 168.3 mm O.D. (pipes 4,5,6 and 7).

Tests were carried out at the high pressure Gas Dynamic Test Facility (GDTF) in Didsbury, Alberta, Canada with natural gas drawn from a gas pipeline going through the facility (Karnik et al., 2000). The average gas pressure ranged from 4700 to 5100 kPa(g) and temperature from 12 to 14 °C. An online gas chromatograph is employed to measure the gas mixture composition every 5 minutes during each test. Table 2 gives an example of the gas mixture composition, which did not vary significantly during the tests.

Details of the high pressure test section are shown in Fig. 1, where the flow is from right to left. Natural gas is diverted from the main facility test loop of size DN200. A perforated type flow conditioner, Canada Pipeline Accessories Type 50E (Karnik et al., 1999), is used upstream of the test section, allowing for approximately 5091 mm and 5434 mm separation between it and the first port (A) of the differential pressure measurements for the 114.3 mm O.D. and 168.2 mm O.D. pipes, respectively. This translates to ~50D separation in the case of the 114.3 mm O.D. pipes and ~35D separation in the case of the 168.3 mm pipe. These separation lengths are considered sufficient to ensure fully developed flow at the first differential pressure measurement port A (Karnik, 1995). Two opposite pressure measurements holes are drilled at each port location (A and B in Fig. 1); these are at 3 o'clock (ports 1&2) and 9 o'clock (ports 3&4) to allow for two differential pressure measurements to be taken simultaneously with two differential pressure transducers to check for repeatability. The axial distance between ports A and B for the differential pressure measurements are also given in Table 1 for each spool. Details on the instrumentation specifications, calibration, cleaning of each tested spool before testing, surface profile measurements, experimental procedure, data acquisition and uncertainly analysis are given in (Botros, 2016). The measured roughness parameters were: R_q, R_z,

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