International Journal of Heat and Mass Transfer 103 (2016) 661–671

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Time evolution of surface roughness in pipes due to mass transfer under different Reynolds numbers

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ARTICLE INFO

Article history:
Received 19 May 2016
Received in revised form 23 June 2016
Accepted 3 August 2016
Available online 11 August 2016

Keywords:
Surface roughness
Mass transfer
Scallop development

ABSTRACT

Experiments were performed using a dissolving wall method to characterize the development of surface roughness in pipes at Reynolds number from 50,000 to 200,000. The test sections had a lining of gypsum that dissolved to flowing water in a closed flow loop. The tests were run over sequential time periods for each Reynolds number. At the end of each time period, the inner surface topography was measured using X-ray CT scans. Scallops are seen to initiate on the surface over time and then subsequently grow spatially and in depth with time. The surface was divided into smaller local areas and a scallop initiation time was introduced so that a common time datum from initiation could be used to characterize the time development of the roughness. The peak-to-valley roughness height was found to scale well with time when normalized by the turbulent inner scales. There is an initial period of slower growth rate in the roughness height, followed by a period of relatively higher growth rate. The growth of the integral length scale of the scallops is different, with an initial rapid growth followed by a much slower growth rate. The streamwise spacing of the scallops estimated from the density is approximately 1000 wall units as the scallops saturate the surface. There is a good correlation between the roughness height and the wear when normalized by the turbulent inner scales.

1. Introduction

Surface roughness plays an important role in the momentum and mass transfer at the wall, with a significant enhancement in the mass transfer rates for flow over rough walls [1–4]. Experimental studies have been performed to investigate the roughness effect on mass transfer using different types of predefined surface roughness, mainly using electrochemical methods for the mass transfer measurements. The artificial surface roughness includes V-grooves [1], sandpaper-roughened [2], square rib [3] and erosion-corrosion roughened surfaces [4]. In addition to the roughness height, the ratio of pitch to height, size and frequency of the roughness elements were found to affect the mass transfer.

For the case of mass transfer on a soluble surface, the surface roughness develops naturally due to the mass transfer to the bulk flow, which subsequently affects the momentum and mass transfer and vice versa. The most common natural roughness pattern is a densely packed array of intersecting, saucer-shaped depressions or pits, usually called 'scallops' [5]. In geological fields, scalloped cave channel walls are commonly seen in karst systems or ice caves due to the fluid flow [6]. Early studies indicated that the natural physical scallop length was correlated to the fluid flow velocity during the scallop development [5–7]. Surface defects or imperfections on the surface are thought to be responsible for initialization of scallops. Goodchild and Ford [7] found the mean length of stable scallops (L) correlated with the mean flow velocity with a value (LU/υ) of approximately 11,500, showing that the scallop length was inversely proportional to the flow velocity. Blumberg & Curl [6] performed experiments on soluble gypsum surfaces and found the normalized wavelength (Lu_τ/υ) to be approximately 2200. Thomas [8] later analyzed roughness data from a large variety of sources in both natural geological fields (granular bed, rock, ice, plaster) and man-made industrial plants (metal pipes) and proposed the dimensionless average streamwise spacing ($\lambda u_\tau/\upsilon$) of ripples or scallops was approximately 1000. The streamwise spacing proposed by Thomas [8] is close to the scallop characteristic length when the scallops or ripples are fully developed.

In industrial piping systems, the scalloped patterns formed in metal pipes [9,10] due to flow accelerated corrosion (FAC) are very similar to those found in geological fields. The pipe wall thinning rates are found to be enhanced by the increase in mass transfer due to the scallops developing on the surface. The mass transfer

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.08.004
0017-9310/

Nomenclature

AR	aspect ratio
C_w	gypsum concentration at the wall [g/l]
C_b	gypsum concentration in the bulk flow [g/l]
C_{b0}	initial gypsum concentration in the bulk flow [g/l]
D	inner diameter of test section [mm]
D_s	density of scallops [/m^2]
e	roughness height [mm]
e_s	equivalent sand-grain roughness height [m]
$e_{p\text{-}v}$	peak to valley roughness height [mm]
e_{rms}	RMS roughness height [mm]
f_D	Darcy friction factor
L	length of roughness element [mm]
Re	Reynolds number
r	local radius of test section [mm]
r'	local radius of test section after wavelet [mm]
t	time from roughness initiation [s]
t_{exp}	experimental time [s]
t_m	mixed time scale [s]
t_{mod}	modified time scale [s]
t^+	dimensionless time normalized by inner time scale
U	mean velocity [m/s]
u_τ	friction velocity [m/s]
W	width of roughness element [mm]
z	streamwise distance [mm]

Greek symbols

δ	local wear on pipe inner surface [mm]
θ	crosswise angle in the azimuthal direction [°]
λ_{str}	streamwise spacing of roughness element [mm]
ν	kinematic viscosity [m^2/s]
ρ	Gypsum density [kg/m^3]

Subscripts

+	length scale normalized by wall unit (ν/u_τ)

on surfaces with naturally developing roughness has been experimentally studied using dissolving wall methods with naphthalene sublimation in air [11,12] and gypsum dissolution in water [13,14]. The mass transfer results with predefined roughness [1–4] have not been compared to those on dissolving walls, primarily because of the difficulties of characterizing the temporal development of the roughness and mass transfer. Thus, there is uncertainty when using correlations developed for predefined roughness to predict the mass transfer on surfaces with naturally developing roughness. Mazhar et al. [14] investigated the change of roughness and mass transfer by using different gypsum test sections tested for different times. The roughness height was found to decrease slightly with increasing Reynolds number. Using a dissolving gypsum surface, Villien et al. [15] observed the length scale of scallops decreased, while the density of scallops increased with increasing flow rate; however, this was not quantified. Wang et al. [16] recently developed a non-destructive measurement technique to quantify the scalloped surface and the corresponding mass transfer using X-ray CT scans. They used the method for flow in a S-bend at a Reynolds number of 300,000 [17] and determined that regions of high mass transfer corresponded to regions of higher roughness and the ratio of streamwise spacing to roughness height was very different in the different regions.

One challenge in quantifying the temporal development of the roughness is in selecting the appropriate roughness parameters to characterize the surface. A typical surface contains a range of spatial wavelengths, which can be decomposed to surface form, waviness and roughness. The decomposition can be done using a number of surface filtering methods, such as 2RC, Gaussian, spline, morphological, and wavelets [18]. Wavelet analysis allows space-frequency localization, which is well suited for multi-scale analysis of surface roughness [19,20]. The proper selection of the local sampling area is also important so that it provides both local information as well as be sample independent [21]. The roughness height is typically characterized by the arithmetic mean deviation, root-mean-square deviation and ten point peak to valley height while the topography is often characterized by the skewness and kurtosis [21,22]. The spatial length scales of roughness can be characterized by the autocorrelation lengths from two-dimensional autocorrelation functions [21], while the spatial distribution can be characterized by the number of roughness elements or scallops in a unit area.

The objective here is to investigate the time evolution of the roughness due to dissolution from a solid soluble pipe wall under different Reynolds numbers. Experiments were performed using 203 mm diameter straight pipe test sections at Reynolds numbers of 50,000, 100,000 and 200,000. The wall dissolving method using gypsum dissolution to water at 25 °C was used, with a Schmidt number of 1200. The surfaces before and after each run time were measured non-destructively using X-ray CT scans.

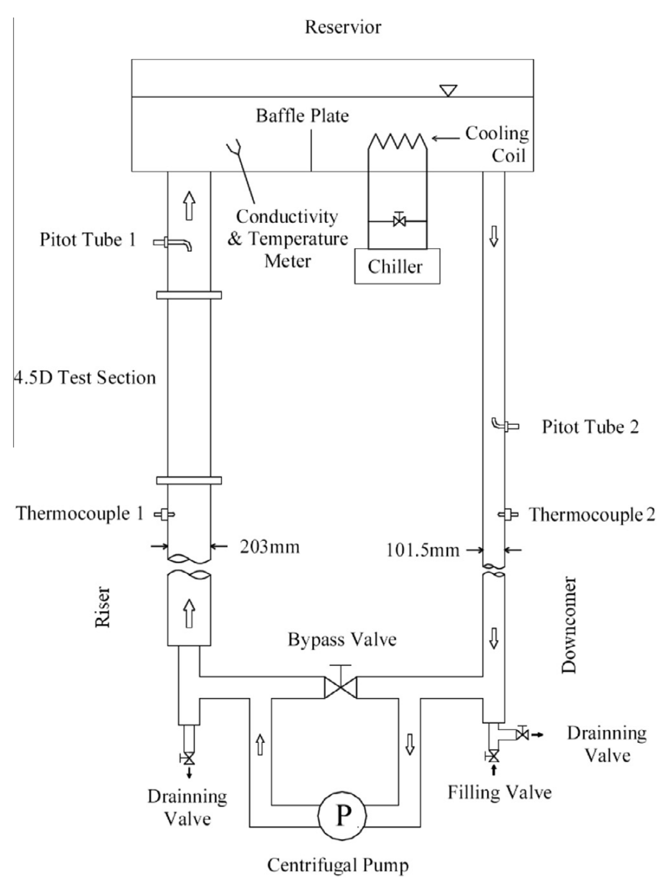

Fig. 1. Schematic of test facility.