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An experimental study of circular sand–water wall jets

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ABSTRACT

Laboratory experiments were carried out to study the effects of sand particles on circular sand–water wall jets. Mean and turbulence characteristics of sand particles in the sand–water wall jets were measured for different sand concentrations c_o ranging from 0.5% to 2.5%. Effects of sand particle size on the centerline sand velocity of the jets were evaluated for sand size ranging from 0.21 mm to 0.54 mm. Interesting results with the range of measurements are presented in this paper. It was found that the centerline sand velocity of the wall jets with larger particle size were 15% higher than the jets with smaller particle size. Concentration profiles in the vertical direction showed a peak value at $x/d = 5$ (where x is the longitudinal distance from the nozzle and d is the nozzle diameter) and the sand concentration decreased linearly for $x/d > 5$. Experimental results showed that the turbulence level enhanced from the nozzle to $x/d = 10$. For sand–water wall jets with a higher concentration ($c_o = 1.5$–2.5%), the turbulence intensity became smaller than the corresponding single-phase wall jets by 34% due to turbulent modulation. A modified logarithmic formulation was introduced to model the longitudinal turbulent intensity at the centerline and along the axis of the jet.

Introduction

Turbulent wall jets have received significant attention in the past given their wide applications in many fields of engineering such as the flow below submerged sluice gates and mixing enhancement (Rajaratnam and Pani, 1974; Mautner, 2004). Considerable research effort has been devoted in the past to study the properties of turbulent wall jets (Rajaratnam, 1976; Launder and Rodi, 1983). Recently, researchers focused more on circular wall jets in various industrial and environmental applications. Some of those applications are in the area of biotechnology such as mixing enhancement in a bioreactor perfusion system (Mautner, 2004) and environmental engineering such as control of air contaminants in ecology (Curd, 1981). In many applications such as, capping underwater waste material in marine environment, a second phase (i.e., solid particles) is added to the wall jets to form sand–water wall jets (Azimi et al., 2014).

Early investigation of Glauert (1956) on a single-phase turbulent wall jet indicated that the wall jet can be analyzed by dividing a jet into a boundary layer and a free jet. This theory was evaluated by using detailed experimental data (Barenblatt et al., 2005). A number of experimental studies were conducted to investigate the mean flow characteristics of circular wall jets such as the growth rate in the axial and lateral directions, axial velocity decay and radial velocity distribution (Rajaratnam and Subramanya, 1967; Sforza and Herbst, 1970; Newman et al., 1972). Rajaratnam and Pani (1974) conducted a series of laboratory experiments and found that the nozzle shape has a great impact on the velocity distributions and the associated length scales of wall jets. Wu and Rajaratnam (1990) showed experimentally that the boundary roughness can significantly change the magnitude of the boundary shear stress and the size of length scales in vertical direction. They found that both axial and transverse velocity profiles and length scales in the transverse plane were almost unaffected by the boundary roughness.

Law and Herlina (2002) found that the transverse length scale for the concentration of the mixture was almost 50% greater than that for the velocity of mixture. They evaluated the effect of Reynolds number (i.e., $R = \rho_w u_o d/\mu$, where ρ_w is the density of water, u_o is the initial jet velocity, and μ is the dynamic viscosity) on the mean flow characteristics of the jets and they concluded that the mean flow is independent of R. Sun (2002) studied the effect of nozzle geometry and he reported that a wall jet from a round nozzle can produce 10–15% larger spreading rate than that from a fully developed round pipe.

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Nomenclature

The following symbols are used in this paper:

a	coefficient
A	cross sectional area of the nozzle, m^2
c	sand volumetric concentration, %
c_m	sand volumetric concentration at the centerline of the jet, %
c_o	sand volumetric concentration at the nozzle, %
C	coefficient
d	nozzle diameter, m
D	diameter of sand particles, mm
D_{50}	sand diameters at which 50% of the sand particles present are finer, mm
F	densimetric particle Froude number
g	acceleration due to gravity, m/s^2
g'	reduced gravity, m/s^2
K, K_1, K_2	coefficients
m_o	mass flux of sand particles at the nozzle, g/s
M	initial momentum flux of the jet, kg m/s^2
n	exponent
Q	sand–water volume flux, m^3/s
Q_o	water volume flux at the nozzle, m^3/s
r	radius of the nozzle, m
R^2	coefficient of correlation
R	Reynolds number
u	velocity of the wall jet at any location, m/s
u_m	centerline sand velocity, m/s
u_{mo}	centerline sand velocity at the nozzle exit, m/s
u_o	initial velocity of the wall jet, m/s
u_{rms}	root-mean-square of velocity of the wall jet, m/s
u_∞	particle settling velocity, m/s
u_*	shear velocity, m/s
x	horizontal distance from the nozzle, m
y	vertical distance from the bed, m
y_{bc}	half-width concentration length scale in vertical direction where $c = {}^1/_2 c_m$, m
y_{bu}	half-width velocity length scale in vertical direction where $u = {}^1/_2 u_m$, m
z	distance from the centerline of the jet in transverse direction, m
z_{bc}	half-width concentration length scale in transverse direction where $c = {}^1/_2 c_m$, m
z_{bu}	half-width velocity length scale in transverse direction where $u = {}^1/_2 u_m$, m
α	ratio of the integrated mass flux to the measured mass flux at the nozzle
μ	dynamic viscosity, kg/(m s)
ρ_s	density of sand, kg/m^3
ρ_w	density of water, kg/m^3
τ_o	bed shear stress, N/m^2
φ	coefficient of the modified Gaussian distribution for velocity
ψ	coefficient of the modified Gaussian distribution for concentration
λ	coefficient of the modified logarithmic distribution for turbulence intensity

Turbulence characteristics of circular wall jets were investigated in detail by many researchers (Swamy and Bandyopadhyay, 1975; Herlina and Law, 2002). Swamy and Bandyopadhyay (1975) showed experimentally the existence of the three regions of potential core, the characteristic decay and the radial-type decay which was introduced by Sforza and Herbst (1970). Sforza and Herbst (1970) reported that the turbulence level in a three-dimensional wall jets is relatively higher than that in two-dimensional wall jets and free jets. Previous investigations indicated the importance of the nozzle geometry on the mean characteristics of turbulent wall jets; however, experimental studies of Padmanabham and Gowda (1991a, 1991b) showed that the turbulence profiles are relatively unaffected by the nozzle geometries and the concept of similarity can be applied for the turbulence quantities farther away from the nozzle. The experimental results of Herlina and Law (2002) on a circular wall jet showed that the turbulence profiles were not self-similar at a distance of 50 nozzle diameters from the orifice.

Mean and turbulence characteristics of two-phase turbulent jets are affected by the characteristics of the second phase such as solid concentration and particle size (Muste et al., 1998; Jiang et al., 2005; Wang et al., 2009; Azimi et al., 2012a). Muste et al. (1998) investigated the effect of particles on the mean and turbulence characteristics of the sand–water vertically downward jets with a relatively low sand concentration of $c_o = 0.04\%$ and particle size range of $D_{50} = 0.5$–0.6 mm. Experimental investigations of Jiang et al. (2005) on vertical sediment-laden turbulent jets (i.e., $c_o = 0.04\%$, $D_{50} = 0.05$–0.075 mm) indicated that the sediment concentration along the centerline of the jet increases with the particle size and decreases with the initial sediment velocity. Wang et al. (2009) studied the effect of particle size on the hydrodynamic characteristics of the solid–gas turbulent jets for particle concentrations ranging from 0.14–0.24% and wide particle size range of $D_{50} = 0.075$ –1.232 mm. They found that the smaller particles have more impact on the turbulence attenuation than large particles and the turbulent intensities of jets with large particles ($D_{50} = 1.1$ –1.232 mm) are close to the turbulence intensity of single-phase jets.

Many experimental studies have been focused on the hydrodynamics of single-phase wall jets but less attention has been made to investigate the sand–water turbulent wall jets in detail. The present paper investigates the mean and turbulent characteristics of turbulent circular sand–water wall jets. Effects of sand concentration on sand velocities and concentration distributions in the axial, vertical and transverse directions are studied. Effect of sand particle size on the axial velocity decay is presented, together with laboratory results of sand velocity fluctuations and the effects of sand concentration on turbulence level. It should be noted that the results of this study are applicable for sand concentration ranging from 0.5% to 2.5% and sand particles size ranging from 0.21 mm < D_{50} < 0.54 mm.

Experimental design

Experiments were carried out in a square Plexiglas tank with 1.12 m sides and 0.285 m height. Experimental setup consists of a funnel-shaped sand hopper with a mechanical vibrator (Syntron, C2R3S) which was mounted on the top of the water tank and a cylindrical chamber to mix sand particles with water. In all cases, sand particles were added at a constant rate and mixed with the water in the cylindrical chamber. The mixed sand–water flow was pumped by a progressive cavity pump (Seepex, 1-6L-BN) to form the sand–water wall jet through a nozzle with a diameter, d of 12 mm. The nozzle was located at the bottom of the tank and parallel to the bed. Fine blasting sand particles (Sil Industrial Minerals Inc., Edmonton, Canada) with three different median