Submerged Jet Mixing in Nuclear Waste Tanks: A Correlation for Jet Velocity

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ABSTRACT

Experimental studies were carried out in jet-stirred slurry tanks to correlate the influence of nozzle diameter, initial jet flow velocity, submerged depth of jet, tank diameter and slurry properties on the jet axial velocity.

The tanks used in the experimental work had diameters of 0.3 m (1-ft) and 2.13 m (7-ft). The fluids emerged from nozzles of 0.003 m and 0.01 m in diameter, 1/8-inch and 3/8-inch respectively. The examined slurries were non-Newtonian and contained 5 weight percent total insoluble solids. The axial velocities along the centerline of a submerged jet stream were measured at different jet flow rates and at various distances from the nozzle orifice (16 to 200 nozzle diameters) utilizing electromagnetic velocity meter.

A new simplified correlation was developed to describe the jet axial velocity in submerged jet-stirred tanks utilizing more than 350 data points. The Buckingham Pi theorem and non-linear regression method of multivariate approximation, in conjunction with the Gauss-Jordan elimination method, were used to develop the new correlation. The new correlation agreed well with the experimental data obtained from the current study. Good agreement was also possible with literature data except at large distances from the nozzle as the model slightly overestimated the jet axial velocity.

The proposed correlation incorporates the contributions of system geometry, fluid properties, and external forces. Furthermore, it provides reasonable estimates of jet axial velocity.

INTRODUCTION

The purpose of this technical brief is to provide a simplified correlation for predicting back of the envelop estimates for jet axial velocity in jet-stirred tanks. The correlation was developed with the help of experimental data generated in large (7-ft diameter) and small (1-ft diameter) tanks utilizing simulant nuclear waste slurries.

The proposed correlation was compared to other accepted correlations in the literature. Below is a brief description of these correlations and relevance to the current application. Churnetski [1] conducted experimental work at the Savannah River Laboratory's 30-meter-diameter mock-up waste tank utilizing surrogate waste and sludge in order to develop a correlation for jet axial velocity. Churnetski [1] proposed Eq. (1) to estimate jet axial velocity:

$$V_x = \frac{C_1}{x} V_o D_o e^{-C_2 [\tan(\frac{1}{2\theta})]^2} \qquad \text{(Eq. 1)}$$

where C_1 and C_2 are dimensionless constants, D_o is the diameter of the jet nozzle, V_o is the initial jet velocity, whereas tan (*1/2θ*) was given by Donald and Singer [2] as a function of kinematic viscosity as follow:

$$\tan\left(\frac{\theta}{2}\right) = 0.238\nu^{0.133} \qquad \text{(Eq. 2)}$$

where ν is in the units of stokes. Due to the similarity between Churnetski’s application and the current study, it was found justifiable to use the Eq. (1) for comparison and validation purposes. Churnetski gave the values of constants C_1 and C_2 in Eq. (1) as 40 and 6.2 respectively. However, when the calculated average velocity from the model was compared to the current experimental data, values of 3 for C_1 and 6.2 for C_2 were observed to better fit the current data.

Rushton [3] developed a model based on Abramovich’s [4] theoretical equation for dimensionless velocity, V_x/V_o, a correlation by Donald and Singer for the jet expansion angle, and literature data for jet axial velocity reported in thirteen references. Rushton [3] proposed the following equation to predict jet axial velocity:

$$\frac{V_X}{V_O} = 1.41\,(\mathrm{Re})^{0.135}\,\left(\frac{D_o}{X}\right) \qquad \text{(Eq. 3)}$$

Equation (3) is a modification of Abramovich’s theoretical equation.

Folsom and Ferguson [5] studied jet mixing of two liquids having the same density. They proposed the following equation to describe the axial centerline velocity:

$$V_x / V_o = 5.13\left(\frac{D_o}{X}\right) \qquad \text{(Eq. 4)}$$

Unlike the other previous models discussed in this section, Eq. (4) does not indicate proportionality between (V_x/V_o) and $\nu^{0.135}$.

EXPERIMENTAL SETUP

Materials

A non-radioactive surrogate slurry was used to simulate the nuclear waste sludge. The surrogate slurry consisted of insoluble hydroxides of iron, aluminum, and manganese and exhibited sticky, brown, gelatinous characteristics with particle sizes of few microns. The concentration of the insoluble solids in the slurries was maintained at 5% wt.

A Hakke RS75 concentric-cylinders rotational rheometer with Rotovisco model RT20 was used to evaluate the rheology of the experimented slurries at room temperature. The shear rate applied during the rheological evaluation was in the range from 0.1 s^{-1} to 450 s^{-1}.

The behavior of the examined slurries was better described by the power law model, $\tau = K \gamma^n$, where $K = 0.0003$ and $n = 1.53$. More experimental data for several fluids of a wide range of power law parameters will be needed in order to capture the influence of the two parameters in the power law model on the behavior of the jet stream and its axial velocity. Due to the lack of such experimental data, the concept of equivalent viscosity, $\mu_{E,}$ was utilized in developing the new simplified correlation. The equivalent viscosity was identified as the slope of the straight line starting from the origin with the least variances from the experimental rheological data.

Large Tank Setup

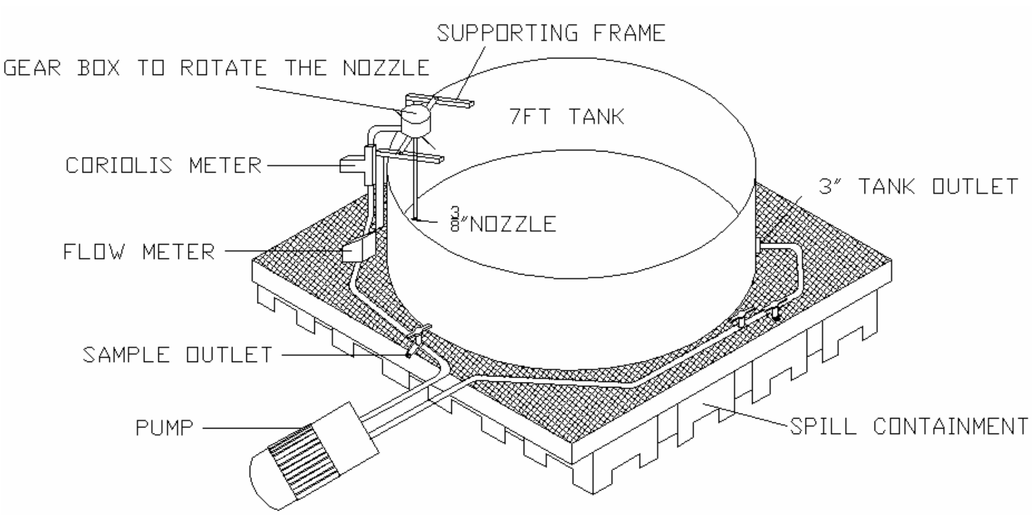
The simulant sludge was transferred from 55-gallon drums to a 2.13 m (7-ft) diameter tank made of polyethylene . A positive displacement pump was used to circulate the examined slurry. The pump was used to withdraw the slurry from the tank before ejecting it back into the tank through a bidirectional nozzle 0.01 m (3/8 inch) in diameter. The maximum flow rate of allowed through the nozzle was 57 L/min (15 gal/min). The fluid height in the tank varied from 0.08 m to 0.13 m (3 inch to 5 inch). Figure 1-a illustrates an isometric diagram of the large tank setup. The nozzle was placed 0.025 m (1 inch) above the bottom of the tank in the horizontal plane so that the axis of the jet stream was parallel to the tank bottom. The height of the slurry in the tank varied between 6" and 8". The nozzle was positioned so that its axis, hence the jet axis, lied on top of the tank centerline (axis).

The jet axial velocity in this tank was measured by means of electromagnetic velocity meter (model 2000 Flo-Mate by Marsh-McBirney Inc., Maryland, USA) which had a probe diameter of 1-inch. The meter had a range of -0.15 m/s to 6 m/s (–0.5 f/s to 20 ft/s) with ±2% accuracy.

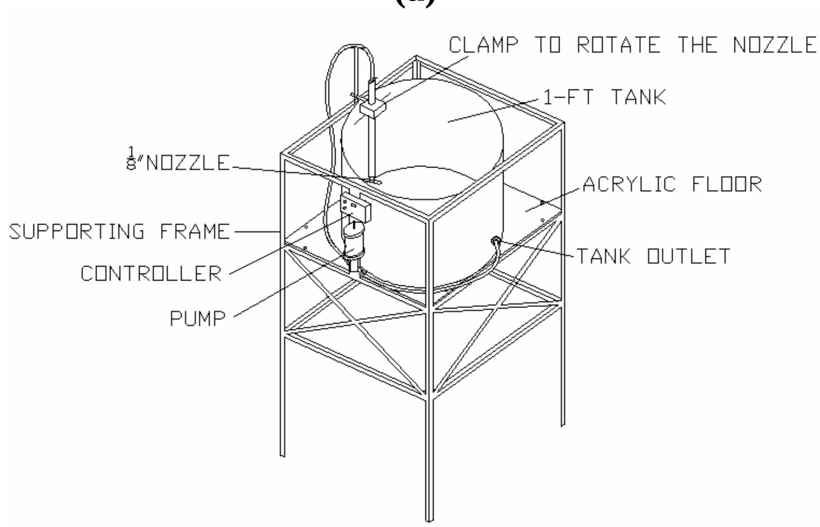
Small Tank Setup

The 0.3 m (1-ft) diameter tank was made of clear acrylic. Figure 1-b illustrates an isometric diagram of the small tank setup. The slurry was circulated in the tank by a variable speed pump. The pump was used to withdraw the fluid from the tank. The fluids were then ejected back into the tank through a 0.003 m (1/8 inch) diameter bidirectional nozzle. The nozzle had no compartments to condition the fluid prior to ejection. The nozzle was placed 0.013 m (½ inch) above the bottom of the tank, in the horizontal plane so that the axis of the jet stream was parallel to the tank bottom. The fluid height was kept constant at 0.025 m (1 inch) throughout the experiments. The pump flow rate varied from 0.5 L/min (0.13 gal/min) to 2.2 L/min (0.67 gal/min). The jet axial velocity in the small tank was measured at several distances from the nozzle orifice along the jet axis. During this study there was no intent to measure the radial velocity on either side of the jet axis. The nozzle was positioned so that its axis, hence the jet axis, lied on top of the tank centerline (axis).

The jet axial velocity in this tank was measured using an electromagnetic velocity meter (model 523, Marsh-McBirney Inc., Maryland, USA). The velocity meter consisted of a transducer probe 0.013 m (½-inch) in diameter which measures flow in a plane normal to its longitudinal axis and presents this flow as two analog voltages for the *x* and *y* orthogonal components. The meter had a range of ±3 m/s (±10 ft/s) with ±2% accuracy and resolution of 0.002 m/s (0.006 ft/s).



(a)



(b)

Fig. 1. Isometric diagrams of the experimental setup, a) 7-ft diameter tank, b) 1-ft diameter tank

CORRELATION DEVELOPMENT AND VALIDATION

More than 350 experimental data points were utilized to correlate the velocity to the system geometry and fluids properties. The Buckingham Pi theorem was used to identify all possible dimensionless groups (Pi terms) that influence the velocity and should be involved in the final correlation. Based on the Buckingham Pi theorem, six dimensionless groups were defined as D_T/x, D_T/D_O, D_T/H, V_X/V_O, Reynolds Number (Re) = $D_O V_O \rho/\mu$, and Froude Number (Fr) = $\frac{V_o}{\sqrt{g H}}$.

Equation 5 below is the final working equation for jet axial velocity:

$$\frac{V_x}{V_0} = 0.97 \, Re^{0.22} \, Fr^{0.09} \left(\frac{D_T}{D_o}\right)^{-1.6} \left(\frac{D_T}{H}\right)^{0.93} \left(\frac{D_T}{X}\right)^{0.6} \qquad \text{(Eq. 5)}$$

It is clear that the jet velocity is a stronger function of the nozzle diameter, height of fluid in the tank, and distance from the nozzle than viscous and gravitational forces. In general, the velocity along the centerline of the jet is proportional to $D_o^{1.82}$ and inversely proportional to both $H^{0.975}$ and $X^{0.6}$.

Beside validation with other accepted correlation in literature, the new correlation was also validated utilizing independent experimental data of jet axial velocity developed by Barker [6], and Shekarriz et al. [7, 8]. Barker [6] reported experimental data on jet axial velocity for both water and dilute polymer solutions. He used two nozzles of 0.64 cm and 1.91 cm diameters. Reynolds number at the nozzles ranged from 5000 to 50000. Axial velocity measurements were obtained by a laser-Doppler velocimeter.

Shekarriz et al. [7, 8] investigated the decay of jet axial velocity for water and pseudo plastic solution of polymer in water. The experimental work took place in a rectangular tank (0.3 m X 0.6 m X 0.4 m). He reported experimental data on jet axial velocity for both water and pseudo plastic fluids. The jet was injected through a 0.357 cm diameter nozzle. The initial jet velocity ranged from 2.43 to 8.54 m/s. His measurements of axial velocity were obtained by a laser-Doppler Velocimeter.

RESULTS

Figure 2 illustrates sample results obtained in the 7-ft diameter tank at initial jet velocity of 5.3 m/s (17.4 ft/s). In order to obtain a sense of confidence in the new correlation, the predictions obtained from the new correlation were compared to their corresponding experimental values and to those obtained by equations developed by Churnetski [1], Folsom and Ferguson [5], and Rushton [3]. Figure 2 shows that the new correlation is in good agreement with the experimental data. For example, in the region close to the nozzle (16 D_o), the measured dimensionless velocity, V_x/V_o, had a value of 0.11 while the new model predicted a value of 0.16.

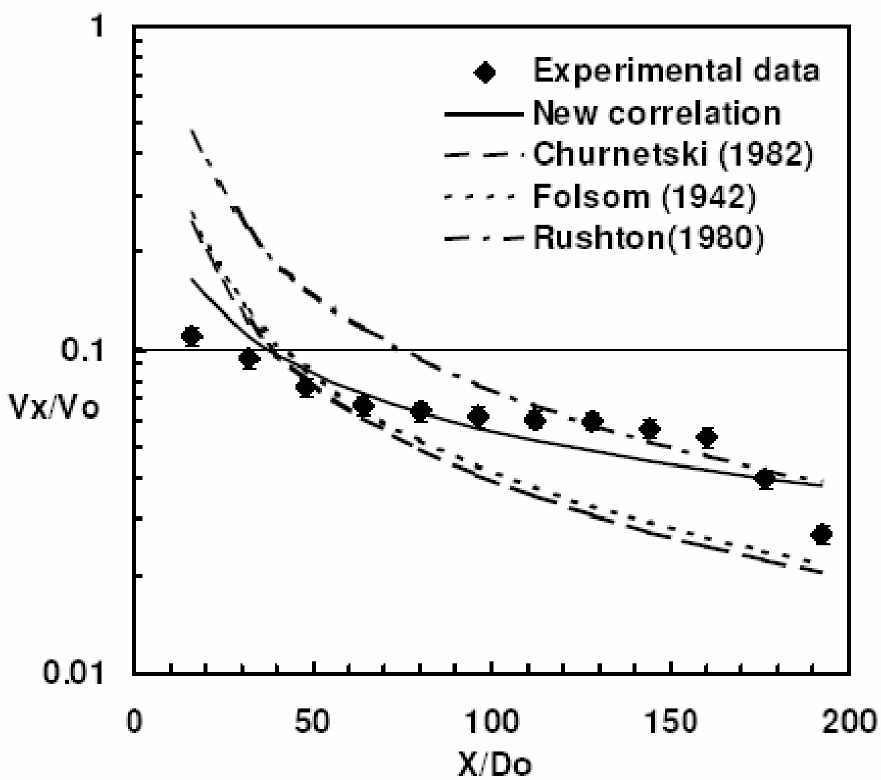


Fig. 2. Comparison between measured and predicted axial velocity in the 7-ft tank, Re = 19000

The corresponding values obtained by Churnetski [1], Folsom and Ferguson [5], and Rushton [3] correlations were 0.25, 0.26, and 0.47, respectively. The correlations used by Churnetski and Folsom and Ferguson overestimated point velocities at distances less than 48 D_o from the nozzle and underestimated it at distances greater than 80 D_o. The Rushton model overestimated point velocity at distances less than 112 D_o from the nozzle. The velocity along the centerline of the jet in the current study decayed gradually up to 60 D_o, then it remained fairly constant until 150 D_o. From that point forward the velocity decreased steeply. The steep reduction in the velocity may be associated to the reverse flow created by the counter rotating eddies in the tank.

Figure 3 illustrates a validation of the new correlation with experimental data generated by Shekarriz et al. [7, 8] for jet axial velocity of both Newtonian and non-Newtonian fluids. Figure 5 also illustrates the corresponding predicted jet axial velocity obtained by using Rushton [3] and Folsom and Ferguson [5] equations.

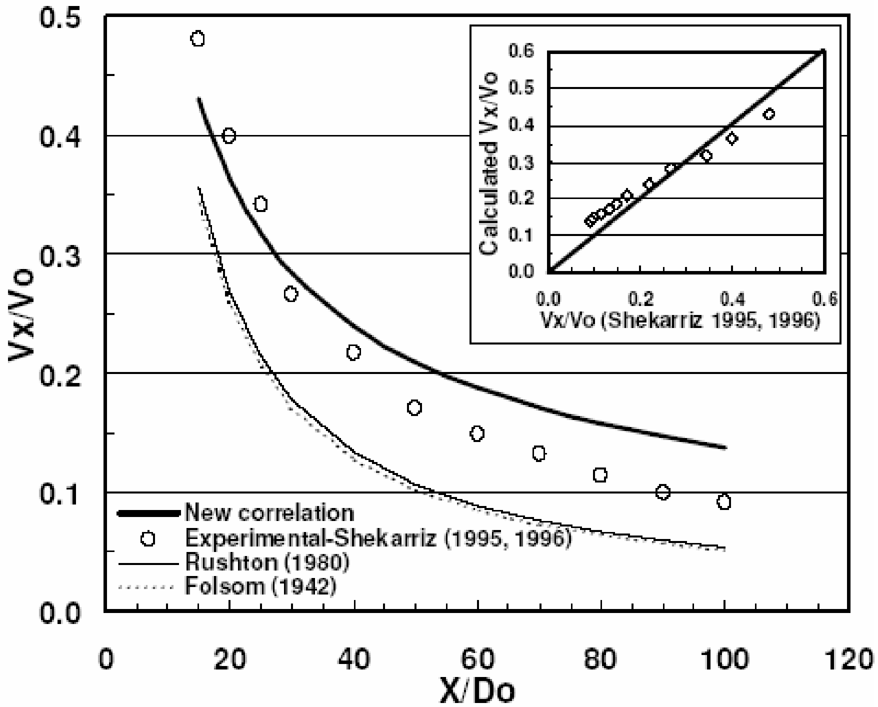


Fig. 3. Validating the new correlation with experimental data developed by Shekarriz et al. [7, 8]

It can be seen from Fig. 3 that the new model agreed with Shekarriz et al. [7, 8] experimental data up to a distance equal to 40 nozzle diameters. At greater distances, the model continued to reasonably describe the trend of the experimental data but slightly overestimated the jet axial velocity. Rushton [3] and Folsom and Ferguson [5] equations both underestimated the jet velocity regardless of the distance from the nozzle.

The plot in the upper right corner of Fig. 3 shows the level of discrepancy between Shekarriz et al. [7, 8] experimental and calculated jet axial velocity obtained from the proposed correlation. The discrepancy between the two sets of velocity data increased slightly as the distance from the nozzle was increased.

Figure 4 illustrates a comparison between calculated axial velocity data and their corresponding experimental data developed by Barker utilizing a nozzle of 1.91 cm in diameter with exit velocity of 3.4 m/s. Figure 4 also illustrates the corresponding predicted jet axial velocity obtained by using Rushton [3] and Folsom and Ferguson [5] equations. The new correlation described the trend of the experimental data reasonably. However, it overestimated the experimental data at relatively large distances from the nozzle. On the other hand, while Rushton equation provided better estimates for the jet velocity, Folsom and Ferguson equation underestimated the jet velocity near the nozzle and agreed with the experimental data at distances larger than 15 nozzle diameters.

The plot in the upper right corner of Fig. 4 shows the comparability between experimental and calculated jet axial velocity for the same nozzle but with nozzle exit velocities of 1.22, 2.57, and 3.4 m/s and distances ranging from 8 to 31.5 nozzle diameter. It can be seen that the new correlation behaves well in comparison to experimental data and provides a reasonable estimates for the jet axial velocity.

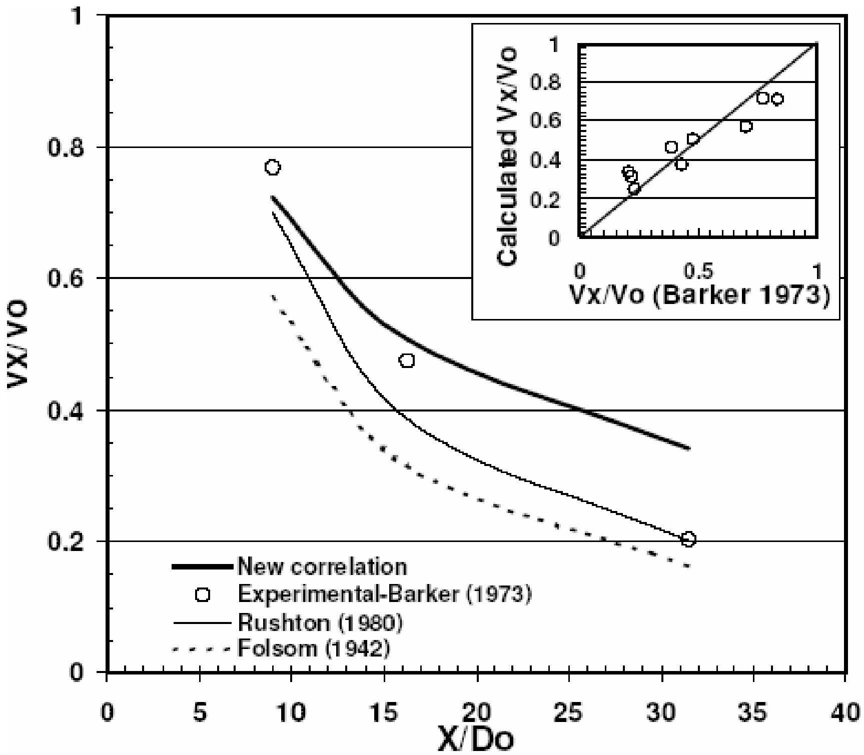


Fig. 4. Validating the new correlation with experimental data developed by Barker [6]

CONCLUSIONS

An experimental investigation of the influence of system geometry, slurry properties, and external forces on the mixing in jet-agitated tanks was undertaken. A simplified correlation was developed to describe the axial velocity along the centerline of a submerged jet stream. The new model agreed well with experimental data developed in the current study.

When compared to other accepted correlations in literature, the new correlation behaved reasonably and provided good estimates of the jet axial velocity. Furthermore, the new correlation had good agreement with literature data at certain distances from the nozzle. However, it slightly overestimated the jet axial velocity at large distances from the nozzle orifice. The new model considered in this study was developed utilizing experimental data for jets of relatively low initial Reynolds numbers. While the new model works well for a system of low solid content (5% wt), it was not validated with systems of high solid concentrations.

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NOMENCLATURE

D	tank diameter, m
Fr	Froude number
g	gravitational acceleration, m/s^2
H	height of liquid above the center of the nozzle orifice, m
Re	Reynolds number
V	velocity, m/s
X	axial distance from nozzle orifice, m

Greek Symbols

ρ	density, Kg/m^3
μ	viscosity, Pa s
ν	kinematic viscosity, stokes
θ	angle jet expansion, radian

Subscripts

E	equivalent
o	initial at the nozzle orifice
T	tank
x	axial

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