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SAND JETS PASSING THROUGH AN IMMISCIBLE INTERFACE

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Abstract: Laboratory experiments were conducted to study the behaviour of sand jets passing through two immiscible fluids (i.e., oil and water), formed by instantaneous release of dry sand particles from various heights above the oil layer. Different air release heights, nozzle diameters, and sand masses were tested. Effects of the characteristics of sand jets in air such as mass flow rate, sand impact velocity, and jet diameter on the evolution of oily sand jets were investigated. It was observed that the impact velocity has an insignificant effect on the variation of frontal velocity of sand jets. It was found that the diameter of sand jet in air is linearly correlated with the nozzle diameter. Evolution of oily sand jets with time was investigated using image processing and boundary visualization techniques. The frontal width and velocity of oily sand jets were measured for different evolution times. Dimensional analysis was performed, and an empirical correlation was introduced to predict the frontal velocity of oily sand jets passing through immiscible layer. The presented formulations can be used for engineering design and validation of numerical models.

1 INTRODUCTION

Multiphase flows involving suspensions of solid particles have been a subject of intense research and are pertinent to many environmental and industrial processes. One particular feature of interest could be magma flows wherein molten particles flow as clusters of particles (Giraut et al., 2014; Mohammadidinani et al., 2017). Magma is a high-temperature fluid or semi-fluid with a mixture of molten and semi-molten rocks, volatiles and solids and could be modeled by a gravity-driven two-phase flow with a considerable density difference entering into water bodies. Since it is difficult to study the behavior of magma flows owing to natural restrictions (e. g., high temperature and vaporized water in the vicinity of magma flows), cluster of particles could be modeled by encapsulated sand particles passing through an oil layer. Oil-sand tailing ponds have been noted as a recent practical example of the flow of sand jets and thermals through an immiscible interface (Miller et al., 2009).

Webster and Longmire (2001) examined the behaviour of glycerin-water jets flowing into immiscible ambient. They found that the forcing frequency and the viscosity ratio between fluids had a strong effect on the flow regime and pinch-off characteristics. The dynamics of negatively buoyant jets in a homogenous immiscible ambient liquid was experimentally studied by Geyer et al. (2011). They injected a jet of dyed water into a rapeseed oil ambient to determine different flow behaviors based on non-dimensional parameters such as Re=$\rho_w U_w D/\mu_w$, Ri=Dg'/u_w^2 and We=$\rho_w u_w^2 D/\sigma$ where the subscript w stands for water, D is nozzle diameter, σ is the interfacial tension coefficient, and g' is the reduced gravity. It was found that Ri is the most dominant parameter to determine the maximum penetration height of the buoyant jets, while the flow behavior was found to be mainly controlled by the Reynolds and Weber numbers.

Nicolas (2002) conducted an experimental study of gravity-driven jets of dense suspensions falling in a stagnant miscible liquid. He observed four different flow regimes referred to as stable jet, unstable jet with blobs formation, spiral jet with dispersion, and atomized jet. Particle Reynolds number, $Rp=(d_p/d_o)R_o$ was found to be a suitable criterion to characterize the flow behavior as well as the dispersion phenomenon where d_p/d_o is the tube-to-particle diameter ratio and R_o is the Reynolds number at the nozzle outlet. Hall et al. (2010) presented experimental measurements of particle velocity and concentration within sand and slurry jets in quiescent water. Their measurements showed that both velocity and concentration profiles are self-similar and fit a Gaussian profile. The centerline sand concentration and particle velocity profiles were found to decay rapidly with a Froude number dependency. The momentum flux of the sand within the jets also revealed a quick decrease throughout the measurement zone. The effect of particle size on the characteristics of sand jets in water was numerically studied by Azimi et al. (2011), and their obtained results were in a good agreement with experimental measurements of Hall et al. (2010). The behavior of sand jet front and its associated fluid motion for a wide range of nozzle diameters and sand particle sizes was studied by Azimi et al. (2012a). It was reported that the jet frontal velocity is a function of nozzle diameter and particle size. A direct correlation was observed between the formation of the frontal shape of sand jet and the particle Reynolds number of sand particles. A computational analysis was carried out by Azimi et al. (2012b) to investigate the effects of nozzle size, initial particle concentration, initial velocity, and particle size on the hydrodynamics of slurry (i.e., sand-water) jets. Their model provided accurate predictions at low particle concentration (less than 8.6%) compared with experimental measurements from the literature.

Most of the recent researches assessed the underwater release of sediments in both stagnant and cross-flow ambient conditions (Rugabber, 2000; Gu and Li, 2004; Gensheimer et al., 2012); however, the effect of air release height has not been completely studied. Zhao et al. (2012) investigated the impact of air release height on the underwater behavior of sediment thermals in a stationary body of water. Three different phases of motion were observed for the evolution of sediment clouds: initial acceleration phase, self-preserving phase, and dispersive phase which found to resemble the behavior of particle clouds released without initial momentum into stagnant water studied by Rahimipour and Wilkinson (1992). It was found that although increasing the air release height accelerated the transition between the phases, the growth rate of the thermal within the self-preserving phase had no dependency on the air release height. Hydrodynamics of particle cloud and the effects of air release height and mass of particles on the motion of particles were recently studied by Moghadaripour et al. (2017a, 2017b). They converted sand mass into a length scale L where L is the pipe length filled with sand particles. It was found that L/d_o and the release height of particles significantly change the width and the frontal velocity of particle clouds in water.Recently, some studies have been devoted to the dynamics of sand jets entering into a two-layer system of immiscible fluids. A Notable example is a work of Mohammadidinani et al. (2017) where the evolution of oily sand jets and cloud formation were investigated using different oil layer thicknesses, nozzle diameters, and sand masses. They observed that Reynolds number and normalized oil thickness play the most important role in the evolution of oily sand jets. The objective of the present conference paper is to investigate the effects of air release height on the growth and motion of particles passing through an immiscible interface.

2 DIMWNSIONAL ANALYSIS

The motion of sand jets passing through an immiscible layer is controlled by the properties of background fluids, the physical characteristics of sand particles, and the initial release conditions. Frontal width w, and velocity u_f of particles passing through the oil-water interface can be formulated as:

$$w, u_f = f_1(m, d_o, h, u_o, \rho_w, \rho_{oil}, \rho_s, \mu_w, \mu_{oil}, D, h_{oil}, c_o, g, t) \quad (1)$$

where m is the mass of sand particles, d_o is the inner diameter of nozzle, h is the air release height, u_o is the velocity of sand particles after the interface, ρ_w, ρ_{oil}, and ρ_s are the densities of water, oil, and sand particles, respectively, μ_w and μ_{oil} are the dynamic viscosities of water and oil, respectively, D is the mean particle size, h_{oil} is the thickness of oil layer, c_o is the initial volumetric concentration of particles, g is the acceleration due to gravity, and t is time.A narrow range of particle size (i.e., 0.250 mm≤D≤0.297 mm) was used in this study to reduce the number of unknown variables. The mass of sand particles m can be converted into a length scale L, where L is the length of the pipe filled up with sand particles to form an aspect ratio of L/d_o and can be formulated as:

$$L = \frac{4m}{c_o \pi \rho_s d_o^{\,2}} \quad (2)$$

For certain particle size, the frontal velocity of turbulent thermals is a function of buoyancy F_B and distance from the water surface to the front of particle cloud x (Batchelor, 1954) with a scaling relationship described as:

$$u_f \sim F_B^{\,1/2} x^{-1} \quad (3)$$

A time T can be introduced using the particle settling velocity of individual sand particles u_∞ to include the effect of particle size D as:

$$T = \frac{F_B^{\,1/2}}{u_\infty^{\,2}} \quad (4)$$

The velocity of sand particles at the nozzle exit can be related to the nozzle diameter using the orifice equation $u_n = c(gd_o)^{1/2}$ where c is a constant coefficient. Cai et al. (2010) proposed a coefficient of 0.68 for $d_o/D \geq 40$ and 0.6 for $d_o/D \leq 40$. Considering the structure of free-falling velocity of a single particle, and assuming that the air release height plays an important role in the frontal velocity of sand jets, a non-dimensional air release height can be introduced as:

$$\eta = \frac{2gh}{u_n^{\,2}} \quad (5)$$

Based on dimensional analysis, Reynolds number R can be defined to describe the balance between the inertia and viscous forces. Effect of Reynolds number on characteristics of jet flows was found to be significant (Webster and Longmire, 2001; Nicolas, 2002; Azimi et al., 2012a, 2012b). Reynolds number can for oily sand jets be formed as:

$$\mathrm{R} = \frac{u_i d_o (\rho_s - \rho_{oil})}{\mu_{oil}} \quad (6)$$

Therefore, by grouping controlling parameters in Eq. (1), dynamics of oily sand jets can be studied using the following non-dimensional parameters as

$$w, u_f = f_2\left(\frac{t}{T}, \frac{L}{d_o}, \eta, \mathrm{R}\right) \quad (7)$$

3 EXPERIMENTAL SETUP

Experiments were performed in a 0.4 m square glass-walled tank with 1 m height in the Multi-Phase Flow Research Laboratory (MFRL) at Lakehead University. The experimental tank was filled with tap water with a temperature of 23±0.5 °C, density of ρ_w=997.5 kg/m^3, and dynamic viscosity of μ_w=0.9321×10-3 Pa.s. The water in the tank was maintained at a constant depth of 0.87 m for all experiments using a drain valve. The water surface was covered with a 0.03 m layer of canola oil, h_{oil}, to form an immiscible layer. The density and dynamic viscosity of canola oil used in this research were measured by a Sigma 700 tensiometer (Biolin Scientific, Finland) and were ρ_{oil}=908 kg/m^3, and μ_{oil}=56.8×10-3 Pa.s, respectively.

The release height from the oil layer surface h was adjusted at 0.2, 0.4 and 0.6 m using the adjustable frame. Three nozzle sizes with a nominal diameter of 8, 12 and 16 mm were used in these experiments. Sieve analysis was employed to select relatively uniform sand particle size. Sand particles had a density of ρ_s=2540 kg/m^3, an averaged unpacked sand concentration of c_o=0.6, and a nominal diameter of D=0.275 mm with a uniformity coefficient of 1.31. Experimental details and non-dimensional parameters are listed in Table 1.

Table 1: Experimental details of oily sand jets and non-dimensional parameters for D=0.275 mm.

Test no.	h (m)	d_o (mm)	m (g)	L (m)	L/d_o	u_n^* (m/s)	R	η
1	0.2	8	5	0.065	8.16	0.19	433	108.1
2	0.2	8	8.5	0.111	13.88	0.19	433	108.1
3	0.2	8	10	0.131	16.33	0.19	433	108.1
4	0.2	8	12	0.157	19.59	0.19	433	108.1
5	0.2	12	10	0.058	4.84	0.23	649	72.1
6	0.2	12	15	0.087	7.26	0.23	649	72.1
7	0.2	12	20	0.116	9.67	0.23	649	72.1
8	0.2	12	25	0.145	12.09	0.23	649	72.1
9	0.2	16	5	0.016	1.02	0.27	865	54.1
10	0.2	16	10	0.033	2.04	0.27	865	54.1
11	0.2	16	15	0.049	3.06	0.27	865	54.1
12	0.2	16	30	0.098	6.12	0.27	865	54.1
13	0.4	8	5	0.065	8.16	0.19	612	216.3
14	0.4	8	8.5	0.111	13.88	0.19	612	216.3
15	0.4	8	10	0.131	16.33	0.19	612	216.3
16	0.4	8	12	0.157	19.59	0.19	612	216.3
17	0.4	12	10	0.058	4.84	0.23	918	144.2
18	0.4	12	15	0.087	7.26	0.23	918	144.2
19	0.4	12	20	0.116	9.67	0.23	918	144.2
20	0.4	12	25	0.145	12.09	0.23	918	144.2
21	0.4	16	5	0.016	1.02	0.27	1223	108.1
22	0.4	16	10	0.033	2.04	0.27	1223	108.1
23	0.4	16	15	0.049	3.06	0.27	1223	108.1
24	0.4	16	30	0.098	6.12	0.27	1223	108.1
25	0.6	8	5	0.065	8.16	0.19	749	324.4
26	0.6	8	8.5	0.111	13.88	0.19	749	324.4
27	0.6	8	10	0.131	16.33	0.19	749	324.4
28	0.6	8	12	0.157	19.59	0.19	749	324.4
29	0.6	12	10	0.058	4.84	0.23	1124	216.3
30	0.6	12	15	0.087	7.26	0.23	1124	216.3
31	0.6	12	20	0.116	9.67	0.23	1124	216.3
32	0.6	12	25	0.145	12.09	0.23	1124	216.3
33	0.6	16	5	0.016	1.02	0.27	1498	162.2
34	0.6	16	10	0.033	2.04	0.27	1498	162.2
35	0.6	16	15	0.049	3.06	0.27	1498	162.2
36	0.6	16	30	0.098	6.12	0.27	1498	162.2

*Velocity at the nozzle exit was calculated based on $u_n=c(gd_o)^{1/2}$ where c=0.68 for $d_o/D\geq40$ and 0.6 for $d_o/D\leq40$

Three minutes of relaxation time was allowed between each experiment to dampen oil-water interface fluctuations. During the relaxation time, all the oil and water droplets from the previous experiment were settled; thus, there was no memory impact on the next experiment. Two different types of light sources were employed for boundary detection and image recording of oily sand jet evolution. The evolution of sand jets passing through the oil-water interface was recorded using a high-speed camera (Photron-FASTCAM, 1024PCI-100KC) with a resolution of 1024×1024 pixels. The camera was equipped with a 15-55 mm AF-S Nikkor, 1:3.5-5.6 GII (Nikon, Japan) lens to capture images. Raw images were captured with a frame rate of 250 fps and a shutter speed of 0.004 sec. The area of interest was a rectangle of 0.25 m ×

0.20 m and located below the water surface. Obtained images were turned to negative for better visualization. Images were imported to AutoCAD to determine the frontal width and velocity of sand jets.

4 RESULTS

Figure1 shows the dependence of the frontal velocity of sand jets in air u_i on the air release height h. Our observation revealed that the frontal velocity of sand jets was affected by the drag force and was found to be u_i=0.95(gh)$^{1/2}$ for the air release height ranging from 0.2 m to 0.6 m. It could be explained by the fact that the porosity of particles caused the air resistance and reduced the frontal velocity by 5% ofthe fall velocity. It was found that the particles mass flow rate had no effect on frontal velocity of sand jets in air.

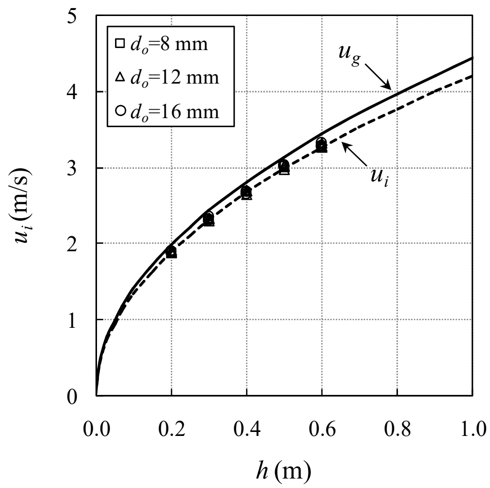

Figure 1: Relationshipbetween frontal velocity of sand jet in the air and release height.

Observations by Cai et al. (2010) showed that the jet front was being accelerated with negligible air resistance and the size of the sand particles did not appear to affect the velocity of the jet front.The relationship between the mass flow rate of sand particles and the nozzle size is shown in Fig. 2. The mass flow rate of particles from an orifice under the gravitational conditions is dependent on the orifice diameter and independent of the particle head if the height is large enough (Ogata et al., 2001). Beveloo et al. (1961) introduced an empirical equation for circular orifice as:

$$\dot{m} = 0.538\,\rho_b \left(d_o - 1.4D\right)^{5/2} \sqrt{g} \quad (8)$$

where ρ_b is the bulk density of unpacked particles and g is the acceleration due to gravity.

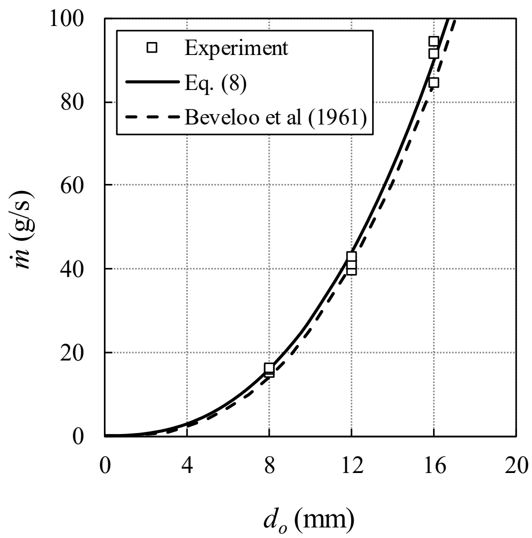

Figure 2: Relationship between mass flow rate of sand jet and nozzle diameter.

A narrow range of particle size was used in this study; therefore, the effect of particle size was excluded from the calculation of mass flow rate and Eq. (8) was rewritten as:

$$\dot{m} = 0.538\rho_b(d_o)^{5/2}\sqrt{g} \quad (9)$$

which was found to be in a better agreement with the present measurements with the average error of ±3%. Fig. 3 shows the relationship between the nozzle diameter d_o and the diameter of sand jet in air d_j. As can be seen, the diameters of sand jets in air were found to be smaller than the nozzle diameters. Experimental observation indicated that a linear formulation could appropriately describe the relationship between the sand jet diameter in air and the nozzle diameter as:

$$d_j = 0.5d_o - 0.813 \quad (10)$$

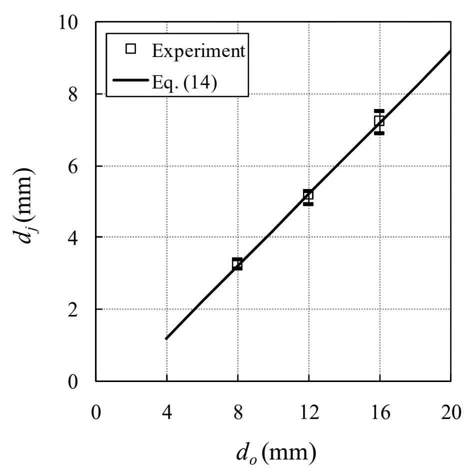

Figure 3: Relationship between diameter of sand jet in the air and nozzle diameter.

A non-dimensional time scale t^* was defined to study the transitional effects of jets' evolution where at t^*=1 all particles passed through the oil layer and each image shows a time lag of 4×10^{-3} s from the onset of release. Fig. 4 shows the effect of air release height on the evolution of oily sand jets for d_o=12 mm at two different non-dimensional time scales t^*=0.4 and 0.8. Some cloud bursting was observed when sand particles were released from a height of h=0.2 m (Fig. 4(a)). In this case, sand particles descended as a mixture of encapsulated clusters of particles and individual particles.

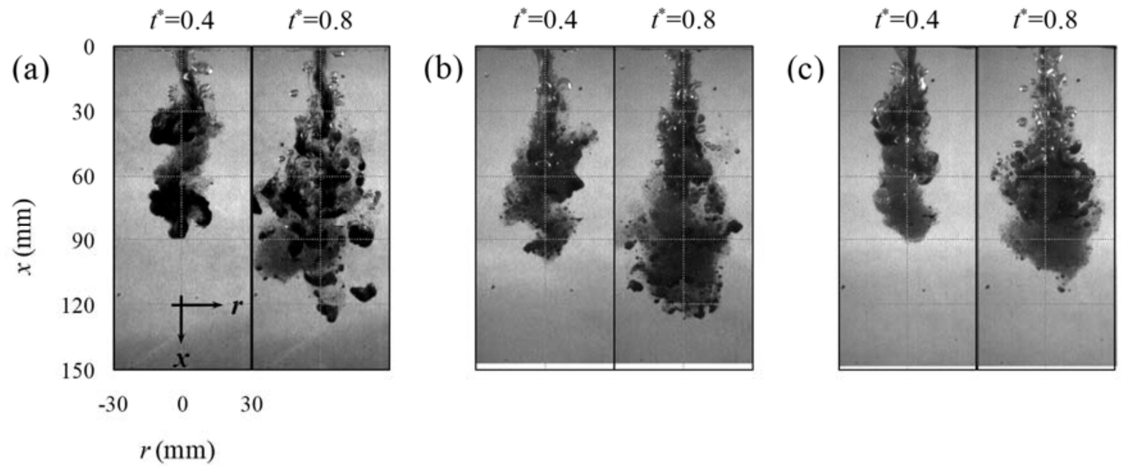

Figure 4: Effect of air release height on the evolution of oily sand jets for d_o =12 mm at different non-dimensional time scale t^*: (a) h=0.2 m; (b) h=0.4 m; and (c) h=0.6 m.

As the air release height increases, sand particles gain more momentum as they pass through the immiscible interface. Therefore, the effects of the excess momentum overcome the impact of the oil layer resistance. In this condition, oily sand jets evolve like steady buoyant thermals and the sediment concentration becomes dilute (Fig. 4(b) and 4(c)).

In addition, the higher air release elevation, the more instabilities and air bubble escape from the tailing section. It can clearly be observed that the overall growth of suspension jets was independent of the air release height within the experimental variations which is consistent with observations of Zhao et al. (2012) on the effect of air release height on the growth rate of the sediment thermals in water. One could explain it by the fact that the additional kinetic energy induced from the higher release height is mostly dissipated to rupture oil layer covering sand particles. Consequently, there is no energy left to have an impact on the overall growth of sand jets.

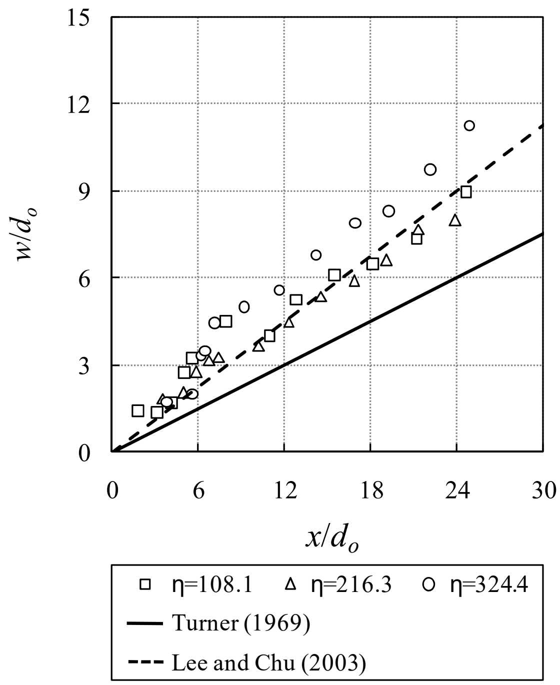

Figure 5: Effect of air release height on the variation of normalized width of oily sand jets $w/d_o$with normalized distance x/d_o for L/d_o=16.3.

The effect of air release height on the variation of the frontal width of oily sand jets for L/d_o=16.3 is demonstrated in Fig. 5. The growth rate of single-phase water jets which are pure momentum-driven flows (Turner, 1969) and the growth rate of thermals of heavy salt which represent pure buoyancy-driven flows (Lee and Chu, 2003) were included in Fig. 5 for comparison. For both shorter release heights (η=108.1 and 216.3) the normalized frontal width of oily sand jets revealed growth trends similar to single-phase buoyant thermals whereas, for the highest elevation (η=324.4), the spreading rate increased and reached 0.45. A physical interpretation is that sand particles gain more momentum as they are released from a higher elevation. This enhances instability of oily sand jets as they pass through the oil-water interface which results in enhancement of the growth rate of the normalized frontal velocity of oily sand jets.

The velocities of sand jet front issued from 8 and 12 mm nozzles were normalized with the settling velocity of particles, and variations of the normalized frontal velocity with t/T were shown in Figs. 6(a) and 6(b), respectively.As can be seen from Fig.6(a), at the early stage, the frontal velocity of sand jets increased with increasing the air release height due to higher impact energy at the interface layer. The ratio of the jet frontal velocity to the particle settling velocity close to the water surface was found to be 20, 35, and 40 for air release heights of 0.2, 0.4, and 0.6 m, respectively.

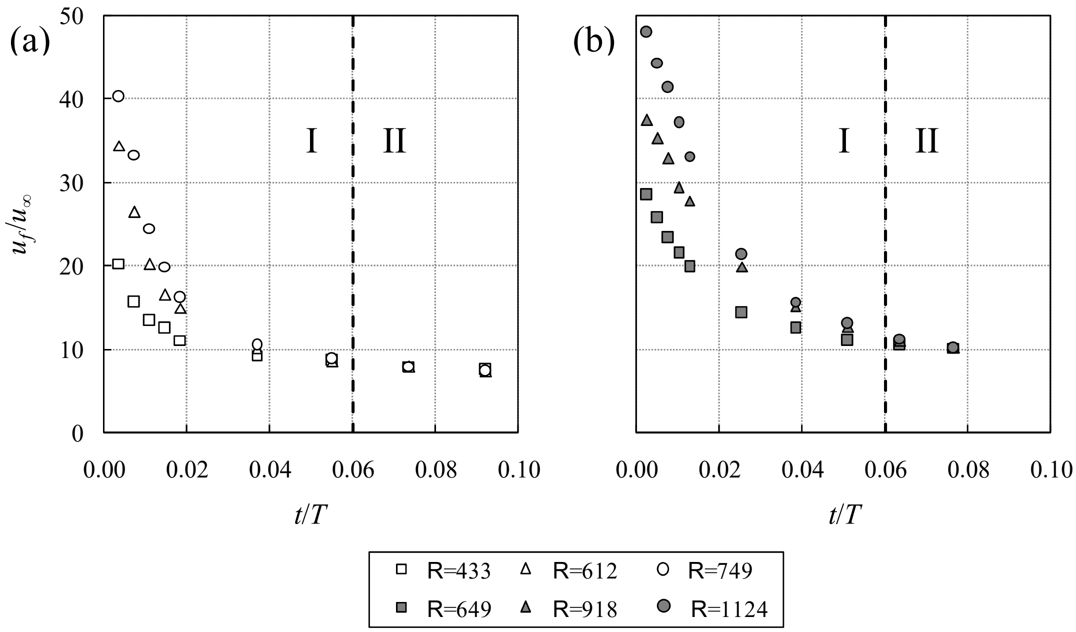

Figure 6: Variation of normalized frontal velocity with normalized time: (a) d_o=8 mm; (b) d_o=12 mm.

The effect of impact energy became less pronounced as sand jets moved downward and dissipated at t/T≈0.04. The frontal velocity reached a plateau equal to $8u_\infty$ almost after t/T=0.06. For the jets issued from a 12 mm nozzle (Fig. 6(b)), the u_f/u_∞ ratio at the early stage found to be higher than that of an 8 mm nozzle owing to the higher initial velocity at the nozzle exit. Considering the variation of the normalized frontal velocity along the jet axis points out that the frontal velocity discharging from smaller nozzles reached the plateau regime faster compared to bigger nozzles which is in a good agreement with the results obtained by Azimi et al. (2012a).

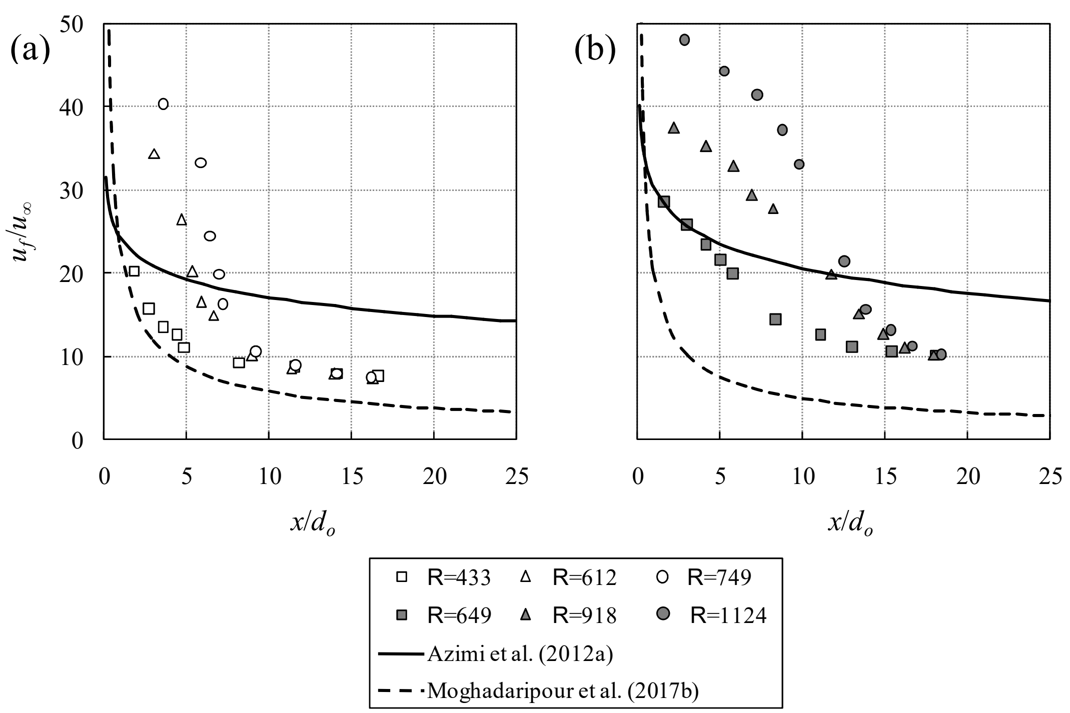

Figure 7: Variation of normalized frontal velocity u_f/u_∞ with x/d_o: (a) d_o=8 mm; (b) d_o=12 mm.

Multivariable regression analysis indicated that the normalized frontal velocity could be appropriately described by:

$$\frac{u_f}{u_\infty} = \phi\left[\frac{t}{T}\left(\frac{18\mu_w d_o}{(\rho_s - \rho_w)D^2 u_n}\right)\right]^{-[0.001\eta + 0.28]} \quad (11)$$

with the regression coefficient of correlation of R^2=0.912. The values of ϕ are 5.75 and 7.75 for d_o=8 mm and 12 mm, respectively.

Fig. 7 shows the variations of the normalized velocity u_f/u_∞ with x/d_o for sand jets released from 8 and 12 mm nozzles. The variations of the velocity for sand jets discharged from a 16 mm nozzle were eliminated from Fig. 7 due to uncertainties observed while measuring the frontal velocities. Prediction curves of sand jet frontal velocities with x/d_o from experimental study of Azimi et al. (2012a) for $L/d_o \approx \infty$ and Moghadaripour et al. (2017b) for $0.8 < L/d_o < 15$ were included for comparison.

As can be seen, at the early stage, frontal velocities of oily sand jets for higher air release heights (i.e., 0.4 m and 0.6 m) were higher than the frontal velocities of continuous sand jets since higher air release heights result in higher initial velocities. As jets travel further in the ambient water, the excesspotential energy is consumed and frontal velocities of oily sand jets fall under the frontal velocities of continuous sand jets. In this stage, sand particles descend either as a number of encapsulated clusters of particles or as a mixture of individual particles and encapsulated groups of particles. In both cases, oily sand jets descend with a velocity that is much faster than the particle settling velocity which was found to be $8u_\infty$ for the former case and $10u_\infty$ for the latter one. Azimi et al. (2012a) indicated a group settling velocity of $5u_\infty$ for $L/d_o \approx \infty$, while Moghadaripour et al. (2017a) reported $1.3u_\infty$ for $0.8 < L/d_o < 40.1$.

5 CONCLUSION

A series of laboratory experiments were carried out to study the dynamics of particles passing through an immiscible oil-water interface. The air release height and a fix oil layer thickness were used to control the initial momentum of gravity-driven sand jets and particle clouds.Our observation showed that the frontal velocity of sand jets in air was 5% less than the fall velocity of particles for the air release height ranging from 0.2 m to 0.6 m. Variations of the mass flow rate of particles from an orifice with the orifice diameter were studied and it was found that the mass flow rate can be estimated using an empirical formulation with ±3% error.

For both shorter release heights (η=108.1 and 216.3), it was found that the normalized frontal width of oily sand jets grew similar to single-phase buoyant thermals and the spreading rate increased for the highest release height and reached 0.45. The effects of air release height and Reynolds number on variations of the frontal velocity with time were studied. It was found that the effect of impact energy became less pronounced as sand jets moved downward and dissipated at $t/T \approx 0.04$. The frontal velocity reached a plateau equal to $8u_\infty$ almost after t/T=0.06.

Empirical formulation was proposed using multivariable regression analysis to predict the frontal velocity of oily sand jets.Dimensional analysis was performed and an empirical correlation was introduced to predict the frontal velocity of oily sand jets passing through immiscible layer. The proposed formulation can be used for validation of numerical models.

6 ACKNOWLEDGMENTS

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