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Investigations of Lighter Fluid Jet Injection Velocity on Dip Depth Formed at Surface of Heavier Butt Fluid

Zahid H Khokhar[+,*], Mamdouh A Al-Harthi[1], Amjad A Shaikh[1], A. Abdurraheem[2], Bekir S Yilbas[3]
[1]Department of Chemical Engineering, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia, [2]Institute Research, King Fahd University of Petroleum & Minerals, Saudi Arabia, toazeez@gmail.com, [3]Mechanical Engineering, KFUPM, Dhahran-31261, Saudi Arabia
[+]zahidhkhokhar@yahoo.com, *Corresponding email: zahedhk@gmail.com

Abstract—In this work, we modeled a system of two fluids of different densities contained in an open boundary. A jet injection of a lighter fluid is introduced at suitable location to the system. The injection velocity of the jet influenced the surface of the fluid contained in the system. This heavier fluid surface deformation is investigated in terms of relation between the surface dip formed of the butt fluid and variation of jet injection velocity. The dip depth and shape of dip both depend upon the density of the butt fluid as well as of injected fluid and outflow location.

***Index Terms*—Jet, Injections, Cleaning, Density, Surface Science.**

I. INTRODUCTION

Fluid blown onto a secondary fluid is a natural occurring phenomenon. From wind storms to leaking from any container fracture, it is occurring in industry as well as in daily life. Primary fluid may be gas, gas with solid objects or liquid. Secondary (butt) fluid may be the same or different. The density of secondary fluid is a resistance to primary fluid flow. This may stop, divert or engulf the primary fluid depending upon its density. Lighter fluid may be primary and heavier fluid may be secondary or vice versa. From medical human sciences to cleaning the pipelines in petroleum industry, both types of phenomena are occurring and researchers are doing their chores and assignments to study and explore these.

Reference [1] studies impact flows and loads on ship-deck structures. They investigate shipping of water on the deck of a vessel in head-sea conditions and zeru-forward speed by experimental and numerical means. They address in their study the role of hydro-elasticity in the case of fluid impacting against a vertical wall. Reference [2] develops a finite-difference/front-tracking method for computational modeling of impact and spreading of a viscous droplet on dry solid walls. The method is first tested for the spreading and relaxation of a droplet from the initial spherical shape to its final equilibrium conditions for various values of Eotvos number. Then they applied it to impact and spreading of glycerin droplets on wax and glass substrates and compared the results with experimental data showing a good agreement. Reference [3] investigates contact time of an incident particle hitting a 2D bed of particles. The contact time for a particle hitting a bed of particles arranged in a rectangular and a hexagonal array is measured experimentally and is calculated numerically based on the discrete element method. The incident particle and the bed particles are of the same size and material. They find that the contact time is proportional to the number of bed layers in case of a rectangular bed array and independent of the number of bed layers in case of a hexagonal bed of particles and it is inversely proportional to the impact speed. Reference [4] studies direct simulation of sound and underwater sound generated by a water drop hitting a water surface using the finite difference lattice *Boltzmann* method. They modify two-particle immiscible fluid model to simulate sound in the gas phase and underwater simultaneously. They successively detect sounds propagating into the gas and liquid phases in earlier stage after the collision and observe the effects of drop shape and gas bubbles. Reference [5] studies drop impacts onto cold and heated rigid surfaces, characterizing the mechanisms of disintegration which occur when individual water and fuel droplets impact onto heated surfaces. Their results evidence that surface topography, wettability and liquid properties combine in a complex way to alter the wetting behavior of droplets at impact at different surface temperatures. Reference [6] experimentally investigates fluid physics of splashing and nonlinear fingerlike instability of large water drops. They report new phenomena of drop impact that differ from the conventional *Rayleigh-Taylor* instability theory. Their experimental data show good agreement with previous work at low Weber number but the number of fingers or instabilities begins to deviate from the RT equation of Allen at high Weber numbers. Reference [7] studies fluid impact on a solid boundary and analyze the hydrodynamic impact due to a column of liquid hitting on a solid wall. Reference [8] studies and investigates numerically a normal impingement of a droplet onto a wall film based on the finite volume solution of the *Navier–Stokes* equations, in their axi-symmetric formulation, expressing the flow field of the two phases, liquid and gas, coupled by the volume of fluid method (VOF) allowing the tracking of the fluid-gas interfaces. Reference [9] presents spray impact onto horizontal flat and rigid surfaces. They use a phase Doppler instrument to measure drop size and two components of velocity directly above the target measuring the average film thickness formed due to spray impact using a high-speed CCD camera.

Reference [10] analyzes the evolution of the deforming liquid surface following the impact of a drop onto a film of the same liquid numerically using a boundary integral method assuming axi-symmetric, in viscid flow and obtained at times much smaller than the impact time scale, jetting behavior in the neck region where the drop meets the film when the Weber number is large enough suggesting the possibility of bubble entrapment with occurrence of a train of bubble rings from repeated near-reconnection events as the neck moves radially outwards under jetting conditions. Reference [11] develops a finite-difference/front-tracking method for computational modeling of impact and spreading of a viscous droplet on dry solid walls. They focus their numerical method to treat partially wetting substrates for axi-symmetric problems. In this study we modeled a system of two fluids contained in one boundary. A jet of a lighter fluid is introduced at suitable location to the system. The injection velocity of the jet introduced influences the surface of the fluids contained in the system. System used is partially and fully filled with secondary fluid. This influence is investigated in terms of relation between the surface dip generated of the butt fluid and variation of jet velocity. The dipping depth and shape of dip and density of the butt fluid as well as outflow location available for hitting fluid are target studies to accomplish. Velocity variation influence on hitting butt fluid, its impact on butt fluid, its penetration and other flow characteristics mingling with each other after injection are further interests in the work scope. Theoretical and experimental observations will draw more lines to investigate or vice versa.

II. METHODS

Two different geometries are constructed. One is small and second is bigger. Smaller geometry is of width 10 mm with depth of 4.0 mm. A jet is introduced of 0.5 mm. The second geometry is large of depth $4.0*10^4$ mm and width $1.0*10^4$ mm using Gambit preprocessor. At the top a jet of $0.5*10^3$ mm is introduced. Geometry is spaced axi-symmetric with steady time using viscous model. Turbulence model used is standard k-epsilon. Fluent 6.2.16 is used to solve the system of equations. VOF multiphase model is used to predict the solution. Density ratio of lighter to heavier fluid is 1.225 to 2.548 (1:2). The heavier fluid is double dense than lighter fluid.

The system contains heavier fluid at bottom from $2.0*10^4$ mm to $4.0*10^4$ mm depth. At top of system from top out flow at zero to mid $2.0*10^4$ mm depth the lighter fluid is introduced. The depth of dip is measured by plotting volume fraction of heavier fluid along center line of the geometry which is also the center line of depth. At $2.0*10^4$ mm depth of the system the volume fraction of heavier fluid is zero and that of lighter fluid is one. As jet is introduced at the top of the system at zero depth, it approaches towards the surface of heavier fluid and hits it and makes a dip changing the volume fractions at that position. Either the penetration of lighter fluid is a measure of dip depth or the displacement of heavier fluid is a measure the dip depth. For this evaluation, plots are made for both penetration of lighter fluid and displacement of heavier fluid. Agreement of calculation is found between them.

III. MATERIALS

Table 1 shows the materials used for numerical experiments. Properties with method and value used are listed in the table. Heavier fluid is carbonyl-sulfide and the lighter fluid is air. In smaller geometry case heavier fluid is liquid-water. The H/L density ratio is 2.08 for carbonyl-sulfide and air. The molecular weight equation is HFmw: LFmw:: 60.07455:28.966. The H/L mw ratio is 2.073968.

Table 1: Materials used and their Properties

Sr	Material	Property	Units	Method	Value(s)
1	carbonyl-sulfide (fluid)	Density	kg/m3	constant	2.548
		Cp (Specific Heat)	j/kg-k	constant	755
		Thermal Conductivity	w/m-k	constant	0.0104
		Viscosity	kg/m-s	constant	1.2e-05

		Molecular Weight	kg/kgmol	constant	60.07455
		L-J Characteristic Length	angstrom	constant	0
		L-J Energy Parameter	k	constant	0
		Thermal Expansion Coefficient	1/k	constant	0
		Degrees of Freedom		constant	0
		Speed of Sound	m/s	none	#f
2	air (fluid)	Density	kg/m3	constant	1.225
		Cp (Specific Heat)	j/kg-k	constant	1006.43
		Thermal Conductivity	w/m-k	constant	0.0242
		Viscosity	kg/m-s	constant	1.7894e-05
		Molecular Weight	kg/kgmol	constant	28.966
		L-J Characteristic Length	angstrom	constant	3.711
		L-J Energy Parameter	k	constant	78.6
		Thermal Expansion Coefficient	1/k	constant	0
		Degrees of Freedom		constant	0
		Speed of Sound	m/s	none	#f

IV. RESULTS AND DISCUSSIONS

Figure 1 shows the smaller geometry of depth 4 *mm* with width 10 *mm*. Air jet is introduced at top of 0.5 *mm*. Half of the system is filled with water-liquid whereas the half at top is filled with air. The dip can be seen at the surface of water where the air jet is hitting. To study this dip in detail a larger geometry is constructed and ran for air-carbonyl sulfide system with varying air jet velocities. Dip formation is seen and it is directly proportional to hitting velocity of air jet to the surface of secondary butt fluid. Figure 2 shows the grid of larger geometry. The area where jet is flowing and hitting the butt fluid and where the formation of dip takes place, an almost ten times mesh refinement is done. It is shown in Figure 2. Figure 3 shows the dip formed by hitting air jet with velocity of $28*10^3$ *mm/s* to the surface of carbonyl sulfide. For two more velocities the numerical run was done without changing any other parameter. The dip formed is measured by air fraction at symmetric middle line. Where the air fraction is zero that is the bottom of dip and surface of heavier fluid is the top of dip which is at $20*10^3$ *mm* from either bottom of geometry or top of geometry. The air hitting the butt fluid not only makes the dip but also splashes back on their contact interface.

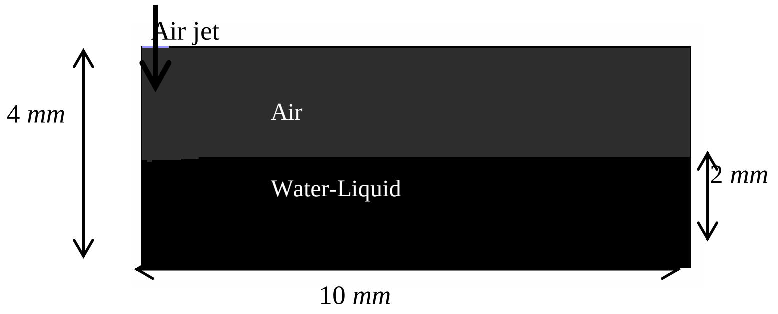

Figure 1: Basic, Small geometry, Air hitting the water surface creating a seeable dip. (Density ratio Air: water-liquid: 1: 800)

Table 2: Dip Depth Formed In On Surface of Heavier Fluid for Different Velocities of Lighter Fluid Using VOF and Mixture Multiphase Model

Case	Velocity, mm/s	Dip Depth, min, mm (VOF, Mixture)	Dip Depth, max, mm (VOF, Mixture)
1	$28*10^3$	$1.875*10^3$,$1.875*10^3$	$2.5*10^3$,$2.5*10^3$
2	$48*10^3$	$3.5*10^3$,$3.5*10^3$	$4.*10^3$, $4.*10^3$
3	$58*10^3$	$3.875*10^3$,$3.875*10^3$	$4.25*10^3$,$4.25*10^3$

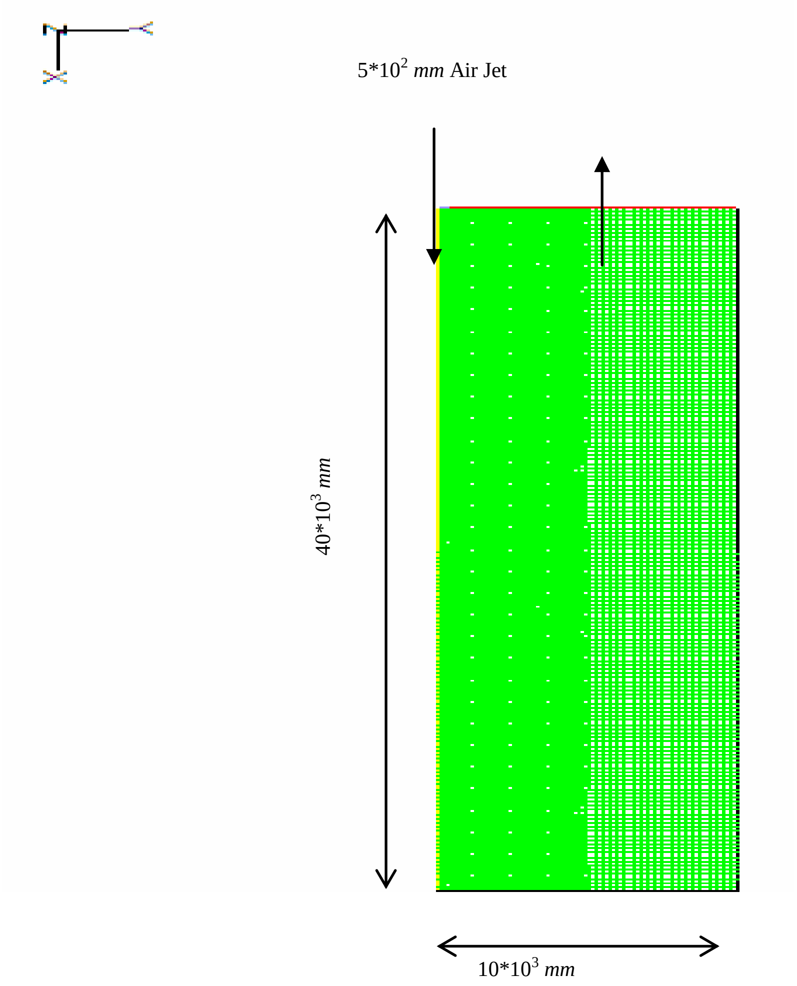

Figure 2: Scale Up Geometry, Refined Mesh at Area Of Direct Jet Contact, at Dip Formation and at Part Of Interest Of Geometry.

Figures 1 and 3 show the dip formation by hitting lighter fluid jet velocity of $28*10^3$ mm for smaller and larger geometries filled with water and carbonyl sulfide respectively. These figures are contour of volume fraction. Figure 2 is the refined mesh grid of bigger geometry with inlet jet position. Figures 1 and 3 show that half of the continuum is filled with lighter fluid at the top and at the bottom half heavier fluid is contained. At top a jet of lighter fluid is introduced with different velocities and it is penetrating into bottom heavier fluid.

The three zones clearly visible are at bottom heavier fluid zone and at top lighter fluid zone and the dip zone generated by lighter fluid injection into heavier fluid. There is a small intermediate zone along dip in between lighter fluid and heavier fluid attached with dip. This zone formation also depends upon the density difference of the two fluids. Its direction and expansion is also influenced by the outflow direction of lighter fluid. Lighter hitting fluid dip and a small comparable region in between lighter and heavier fluid can also be seen in volume fraction contours. It is found that dip depth is proportional to velocity of injected jet. Table 2 shows the dip depth for different velocities. As the velocity of lighter jet is increased the dip depth is increased. It also shows comparisons of depth measured by using two different multiphase models. Mixture model and VOF model almost predicted the same dip dept for equal number of nodes selected. Mixture model is more efficient model than VOF model. Figure 3 is the volume fraction contours of lighter fluid. A plot is shown in Figure 4 comparing the dip depth measurements for two models. At higher velocity both behave almost similar consuming the time to get the solution converged. The running speed is also better of mixture model than VOF during numerical runs. Maximum dip formation exists at some higher velocity as well as a minimum velocity also exists where dip formation starts.

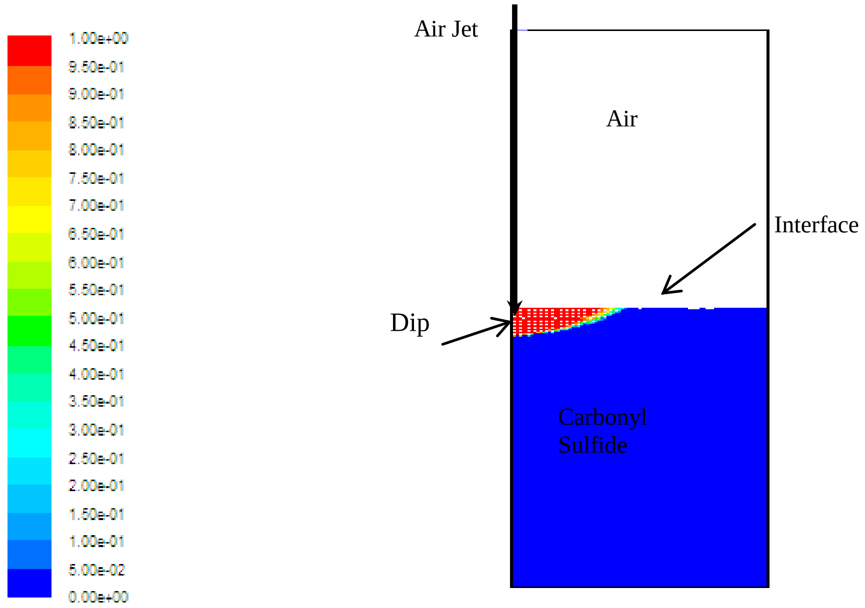

Figure 3: Dip formed at jet velocity 28*10^3 mm/s. Air volume fraction contours (density ratio air-carbonyl sulfide :: 1:2)

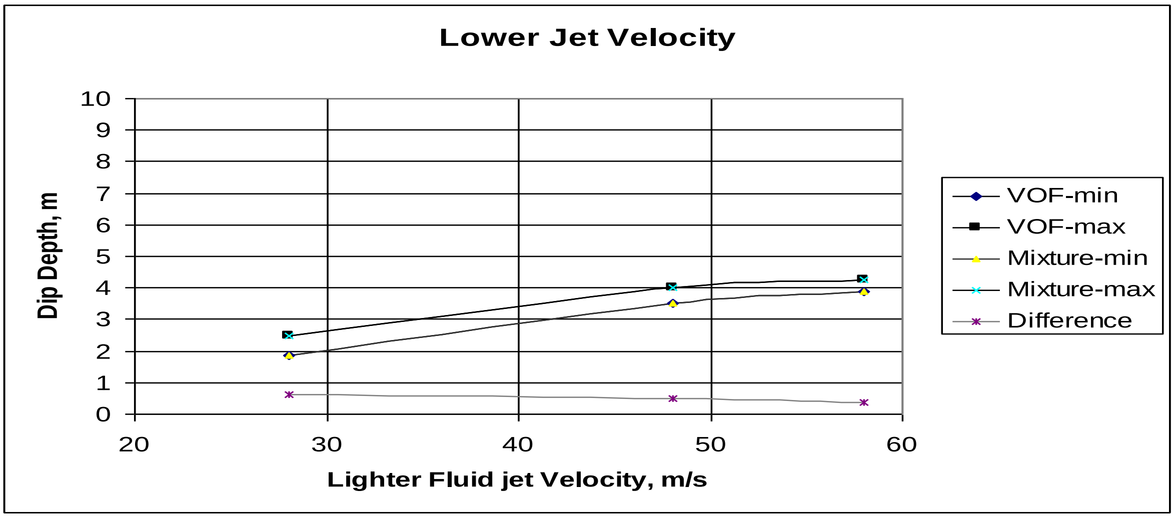

Figure 4: A Plot of Dip Depth Measure for VOF and Mixture Model at Different Velocities Showing Also the Mixed Region in Dip for Comparably Lower Velocity

V. CONCLUSION

Geometries are constructed and simulated. For both geometries, both VOF and mixture numerical models presented similar results but former is more efficient than the other to study the jet penetration into different fluids. The density of a fluid has effect. The penetration of lighter fluid into heavier fluid not only depends upon its velocity but also the direction of its outflow. The depth of dip formed during jet penetration into secondary fluid depends upon the jet velocity. Bottom surface of dip and the shape of dip formed may be influenced by the jet stream outflow. Formation of dip influenced throughout the butt fluid. The dip interface movement may be studied dynamically. The surfaces and interfaces between both major fluids may have some wavy par. The density ratio of two fluids may be related to dip depth. Cleaning for reuse of any fluid container may be simulated. Surface reactions are controlled by dip depth control. Different geometric shapes for same conditions may be studied and may be effective for different fluids depending upon the fluid's characteristics. More than two fluids or phases may be modeled to explore various applications.

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AUTHOR BIOGRAPHY

Zahid H I Khokhar
CHEM-3399, PE, Chemical Engineering, Pak Engineering Council
P-2420, St # (19), Farooq West CRd. Faisalabad-38060, zahidhkhokhar@yahoo.com,2-11-2012
*Corresponding email: zahedhk@gmail.com

Mamdouh A Al-Harthi
Chemical Engineering, King Fahd University of Petroleum & Minerals, Dhahran-31261, Saudi Arabia
mamdouh@kfupm.eud.sa

Amjad A Shaikh
Department of Chemical Engineering,
King Fahd University of Petroleum & Minerals, Dhahran-31261, Saudi Arabia

Abdulazeez Abdurraheem
Research Institute, King Fahd University of Petroleum & Minerals, Dhahran-31261, Saudi Arabia
toazeez@gmail.com

Prof Bekir S Yilbas
Mechanical Engineering, King Fahd University of Petroleum & Minerals, Dhahran-31261, Saudi Arabia