Breakup characteristics of the liquid sheet formed by impinging jets

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***Abstract*— This paper reports the breakup characteristics of the liquid sheet formed by impinging jets. The problem has been numerically investigated using commercial computational fluid dynamics package ANSYS 14. The mixing characteristics of five different Newtonian fluids with a doublet like-on-like impinging jet injector is analyzed and discussed. The simulations have been carried out for five different Newtonian fluids with different fluid velocities.**

***Keywords*— impinging jet injectors, mixing characteristics, flow structures, Volume of Fluid (VOF).**

NOMENCLATURE

D	Jet diameter, m
L	Preimpingement length, m
U	Jet velocity, m/s
2α	Impingement angle, °
ΔP	Pressure difference
c	Volume fraction
t	Time, s
Re	Reynolds number $\left(\frac{\rho U D}{\mu}\right)$
We	Weber number $\left(\frac{\rho U^2 D}{\sigma}\right)$
Oh	Ohnesorge number $\left(\frac{\mu}{\sqrt{(\rho \sigma D)}}\right)$

Greek Symbols

ρ	Fluid density, kg/m^3
ρ_1	Density of first fluid, kg/m^3
ρ_2	Density of second fluid, kg/m^3
μ	Dynamic viscosity, kg/ms
μ_1	Viscosity of first fluid, kg/ms
μ_2	Viscosity of second fluid, kg/ms
ν	Kinematic viscosity, m^{2}s
σ	Surface tension, N/m
K	Radius of curvature of interface
n	Unit vector normal to interface
δ_s	Dirac delta function

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I. INTRODUCTION

Liquid propellant rocket engines are an important component of the space program. The most important aspects affecting the performance and stability of liquid propellant rocket engines are the atomization and mixing of the fuel and oxidant that are injected into the combustion chamber. Impinging jet injectors are one of the most popular designs due to their inherent simplicity, low fabrication costs, good atomization and mixing characteristics. Liquid propellants (fuel and oxidizer) are injected through small holes in such a manner that the propellants impinge upon each other. Liquid atomization is achieved by the impingement of two identical and cylindrical jets at high liquid jet velocities.

To understand the characteristics of the spray formed by impinging jet injectors, it is crucial to investigate the small leaf-shaped liquid sheet formed around the impingement point, see Fig.1. Deformations caused by the impact of the collision or by viscous effects, density differences and surface tension result in instabilities in the liquid sheet. The liquid sheet gradually becomes thinner and disintegrates into unstable arc-shaped liquid ligaments, which contract by surface tension and finally break into droplets.

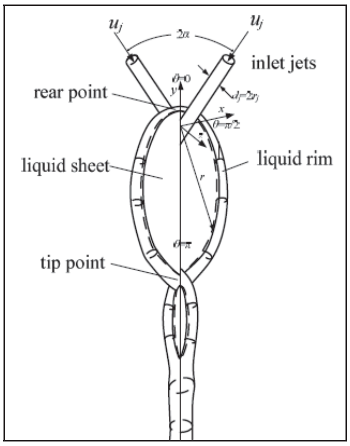

Figure 1: Schematic of the sheet formation

Dombrowski and Hooper [1] conducted experiments to analyze the factors influencing the break-down of sheets formed by the impingement of two liquid jets. It was shown that disintegration generally results from the formation of unstable waves of aerodynamic or hydrodynamic origin. The results of their study indicated that hydrodynamic (or "impact") waves are generated when the Weber number of each jet is above a critical value, and that their formation is independent of the Reynolds number. Linear stability model and finite difference model were developed for the atomization of the impinging jets, sheet and ligament breakup processes by Anderson, Ryan and Santoro [2]. They developed a correlation for drop size as a function of Weber number. Bush and Hasha [3] combined experimental and theoretical investigation to illustrate the fishbone and fluid chain patterns resulting from the collision of laminar viscous jets. They reported the dependence of the flow structures on Reynolds and Weber number. Experiments were performed by Li and Ashgriz [4] to provide understanding of mixing processes and the mechanism in impinging jet atomizers. The volume fraction profiles were used to characterize the mixing processes and determine the quality of mixing. Results showed that two distinct processes control mixing: 1) the ability of the two jets to redirect each other on impact and before atomization (preatomization process) and 2) the turbulent dispersion in the spray region (postatomization process). Jung, Hoath, Martin and Hutchings[5] experimentally analyzed the fluid sheet created by the colliding jets of viscoelastic fluids and observed the effect of elasticity on the formation and fragmentation of liquid sheet. Recently, Chen, Ma and Yang [6] performed numerical simulations and investigated phenomena responsible for the formation of the impact wave. The temporal evolution and spatial development of the injected liquid, including the jet impingement, sheet formation and rupture, and atomization into ligaments and droplets, are examined. It is suggested that the interaction between the two shear layers is the primary cause of the wave dynamics after jet impingement.

The above review of literatures reveals that most of the work relating to these areas is experimental and only few numerical studies are reported. The breakup characteristics of the liquid sheet formed by impinging jets are very complex phenomenon due to its inherent instability and therefore it needs further investigation. The aim of this work is to numerically investigate the breakup characteristics of the liquid sheet formed by impinging liquid jets using commercial computational fluid dynamics package ANSYS 14 and to classify the various regimes of flow patterns formed during the disintegration of the liquid sheet.

II. Numerical Analysis

The mathematical modeling governing the problem is numerically solved in a three dimensional computational domain using commercially available computational fluid dynamics package ANSYS FLUENT 14 [7] .

The schematic of the proposed model is shown in Fig.2.

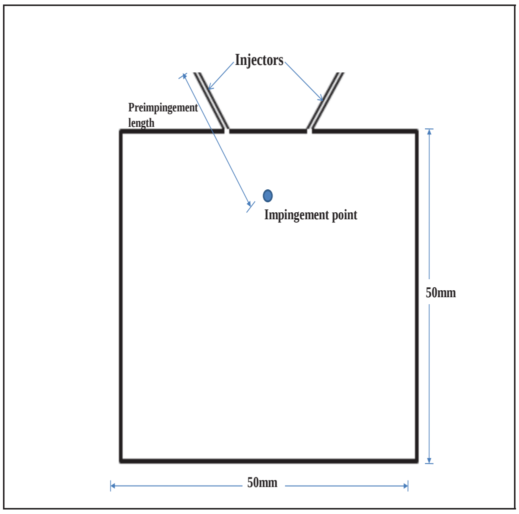

Figure 2: Schematic of the proposed model

For the present work an impingement angle (2α) of 90° and a pre-impingement length (L) of 10 mm have been chosen. The mixing characteristics of the impinging jets were visualized by considering five different fluids. The velocities of each fluid are varied so as to obtain different patterns. Table I shows the list of fluids along with the properties used for numerical simulation. It is worth to mention that for a particular fluid, the Ohnesorge number remains same since it is calculated based on the injector exit diameter D = 0.7 mm.

TABLE I: LIST OF PROPERTIES OF INVESTIGATING FLUIDS

Liquid	μ mNs/m^2	σ mN/m	ρ Kg/m^3	Oh
n-heptane	0.387	19.65	683.6	0.0040
Water	1.002	74.00	998.0	0.0044
n-octane	0.508	21.62	700.0	0.0049
Ethanol	1.074	21.97	789.4	0.0097
Ethylene glycol	16.100	47.99	1113.0	0.0833

The governing equations of flow pertinent to this problem are:

Conservation of mass:

$$\nabla.\mathbf{u} = 0 \quad (1)$$

Conservation of momentum:

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}.\nabla)\mathbf{u} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\mathbf{u} + \sigma\kappa\delta_s n \quad (2)$$

A. Boundary conditions

The boundary conditions are velocity inlet at the inlet of the injectors, pressure outlet at the bottom of the domain and all other surfaces are considered as wall. Computational domain with boundary conditions and grid used for numerical simulation is depicted in the Fig. 3. The computational domain is discretised using unstructured non-uniform quadrilateral cells (7,21,202) consisting of 14,30,630 faces and 1,26,642 nodes.

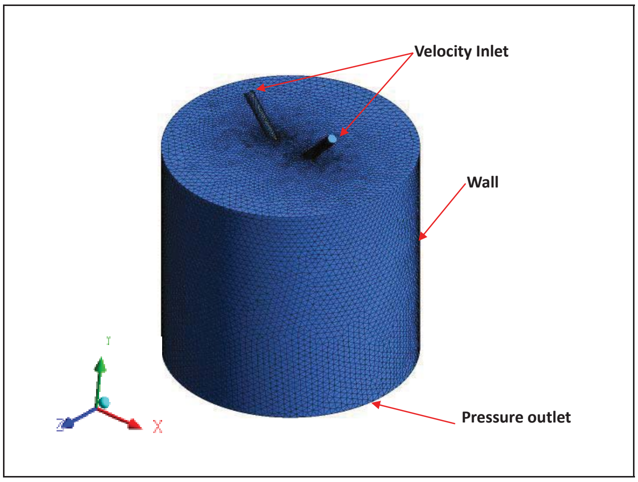

Figure 3: Computational domain and grid

B. Numerical solution procedure

In the present computation the transient solver options available in the FLUENT solver has been used for solving the governing partial differential equations. Pressure based option with first order upwind discretization scheme has been selected for the present computation. A Volume of Fluid (VOF) model is used to trace the multi-fluid interface. The VOF model can model two or more immiscible fluids by solving a single set of momentum equations and tracking the volume fraction of each of the fluids throughout the domain [7]. The density and viscosity in each cell of the interface is calculated in FLUENT as:

$$\rho\,(c) = c\,\rho_1 + (1 - c)\,\rho_2 \quad (3)$$

$$\mu\,(c) = c\,\mu_1 + (1 - c)\,\mu_2 \quad (4)$$

where c is the volume fraction used to track the multi-fluid interface. These functions are present in the built-in library of the Ansys software and are calculated automatically for all iterations. To calculate the volume fraction of the interface, a special interpolation treatment, in geometric reconstruction schemes, is employed [7]. A schematic of the interface shape of geometric reconstruction is shown in Fig.4.

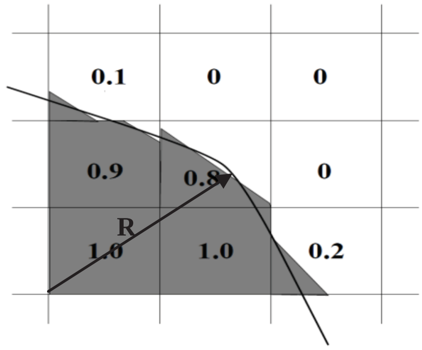

Figure 4: Interface shape of geometric reconstruction

C. Grid indepedence study

In order to obtain an optimum grid for numerical analysis a grid independence study conducted for the impinging jets of n-heptane. The results show that the maximum velocity at the impinging point is insensitive beyond a grid size of 7,21,202. The final grid used for numerical simulation is 7,21,202 cells consisting of 14,30,630 faces and 1,26,642 nodes.

TABLE II: GRID INDEPENDENCE STUDY FOR N-HEPTANE (RE 3,710, WE 219 & OH 0.0040)

Case	No. of cells	Maximum velocity(m/s)
1.	6,62,130	2.60
2.	**7,21,202**	**2.80**
3.	8,51,727	2.81

III. RESULTS AND DISCUSSIONS

Numerical simulations were performed for different fluids and the velocity of impinging jets was varied from 1.1m/s to 27.03 m/s. The ranges of dimensionless parameter conducted in this study are $208 \leq Re \leq 20{,}890$, $29 \leq We \leq 6{,}950$ and $0.0040 \leq Oh \leq 0.0833$.

For all fluids tested different breakup patterns could be observed with increasing jet velocity, and thus increasing Reynolds number and Weber numbers. These patterns are not identical for all fluids, but nevertheless similarities can be found.

A. Breakup patterns

Comparing the obtained images three different breakup patterns could be identified, which are presented in the following:

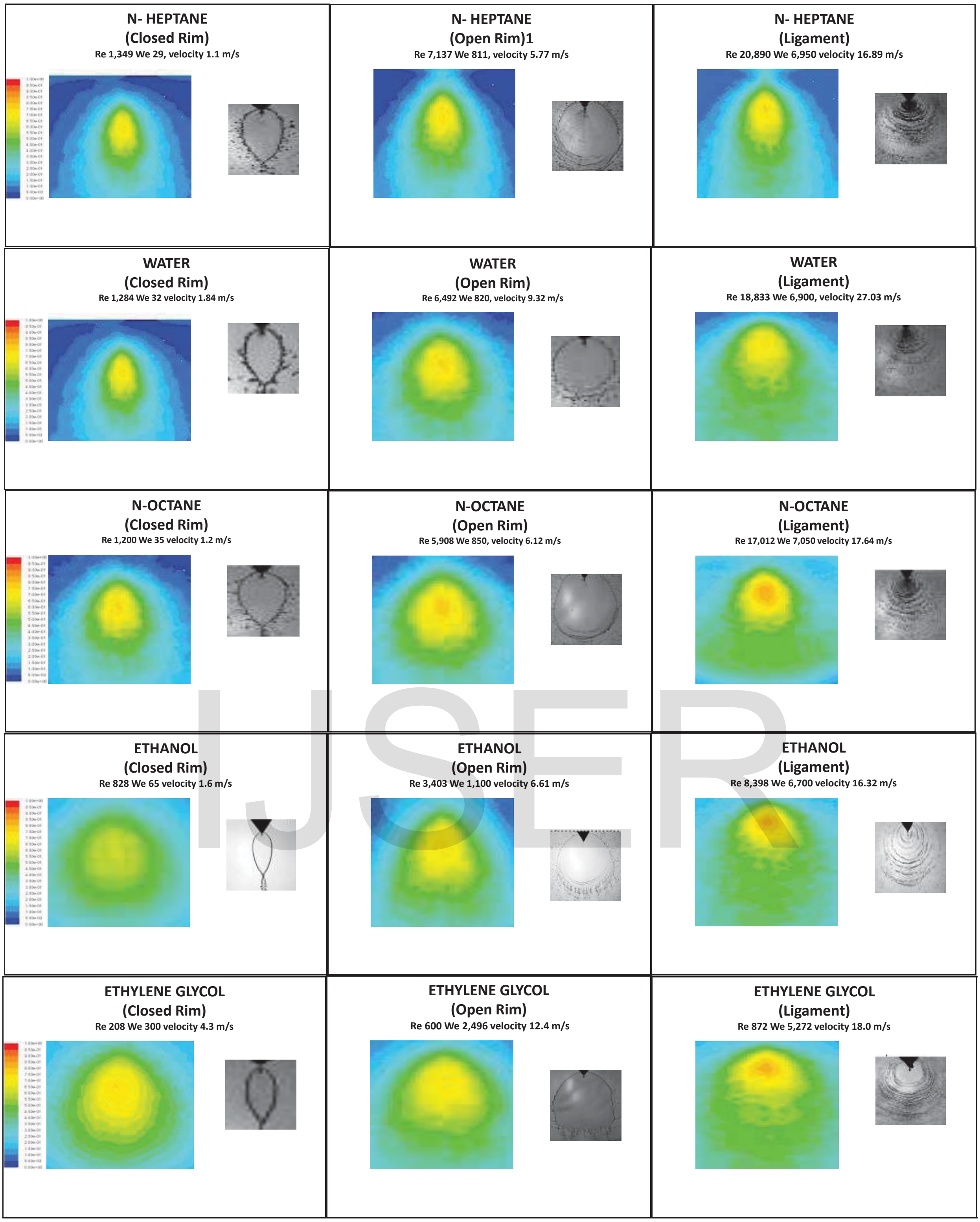

Figure 5: CFD images of breakup patterns – Volume Fraction

Experimental results are shown on right hand side - Bailardy *et al.*[8]

1)Closed Rim:

For n-heptane, which is a fluid with a very low Ohnesorge number, at low injection velocities, low Reynolds number (1,349) and Weber number (29) a flat sheet with a distinct rim is produced perpendicularly to the plane of the two impinging jets. This Closed Rim pattern formed from the impingement point, where the jets collide and the liquid expands radially creating a flat and thin sheet, perpendicular to the jets collision plane, bounded by a distinct and pronounced rim. Chen, Ma, and Yang[6] stated that the surface tension forces are that what holds together the rim, which may be an explanation why distinct rims can be observed in the low Weber region.

2) Open Rim :

For higher velocities, higher Reynolds number (7,137) and Weber number (811) a flapping motion of the lower part of the sheet breaks up the rim so that the two sides of the rim are not anymore in contact. In Open Rim pattern, the sheet is not totally surrounded by a distinct rim and this flapping motion of the lower part of the sheet is caused by a Kelvin-Helmholtz instability[2,3,4].

3) Smooth Sheet Ligaments :

Further increase in velocity, Reynolds number (20,890) and Weber number (6,950), Smooth sheet pattern of droplet dominated direct sheet decay, a periodic separation of bow-shaped structures (also called ligaments) from the sheet occurs, which subsequently decay into droplets downstream. The separation of these ligaments is supported by the occurrence of holes in the sheet, which grow in size. It can be seen that this instability generates wavy structures, which lead to the breakup.

These patterns are compared with the experimental results of Bailardi, Negri and Ciezki [8] and found to be in agreement which establishes the correctness of the proposed methodology, (VOF) in solving mixing problems. Similar patterns are obtained for other fluids of different Reynolds numbers and Weber numbers. A complete CFD image of breakup patterns for different fluids is depicted in Fig. 5.

B. *Regime diagram*

In order to classify the regime in which different patterns are formed, a Reynolds vs. Weber numbers diagram is plotted and presented in Fig. 6. The Ohnesorge number of the used fluids increases moving from right to left in the diagram in a range from 0.0040 (n-heptane) to 0.0833(Ethylene Glycol).

Closed Rim mode occurs in the region below Weber number of 300. The low Weber indicates that in this region the surface tension forces are dominant in comparison to the inertial forces. The surface tension forces are that what holds together the rim, which is the explanation for distinct rims observed in the low Weber region [6].

Open Rim pattern is identified in the Weber number range from 811(n-heptane) to 2,496(ethylene glycol). It is noticed that Open Rim regime expands to a higher Weber numbers as the Ohnesorge number increases. In this regime, as the Weber number increases, the sheet become broader and lower part of the sheet opens up.

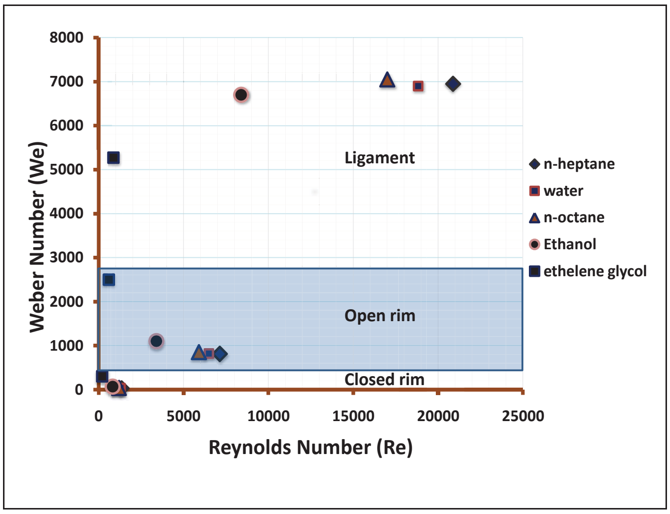

Figure 6: Different regimes of impinging liquid jets

The break up mode of Smooth Sheet with Ligaments pattern was found in the Weber number range from 5,272 to 7,050. A periodic separation of sheet occurs during this regime before the atomization. At these velocities, the sheet started to subject an aerodynamic instability that generates the flapping motion of the sheet.

It is worth to mention that the maximum velocity occur at the point of impact of jets. This can be clearly seen from the velocity distribution plotted in Fig. 7.

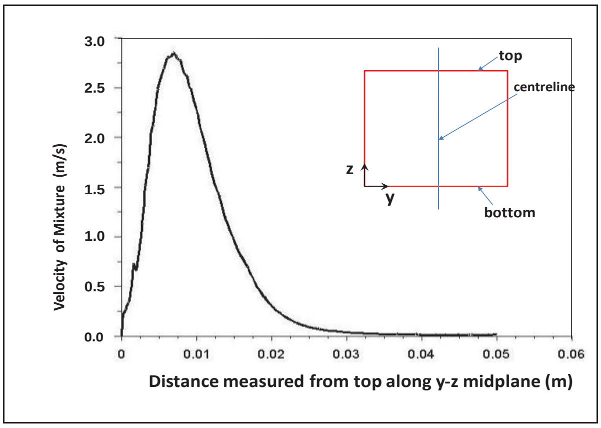

Figure 7: Velocity distribution along yz-midplane

The combustion stability and thrust performance of liquid propellant rocket engines depends on the atomisation and mixing of the fuel and oxidant that are injected into the combustion chamber. Faster the breakup process better mixing characateristics and enhanced combustor performance. An important parameter which affects this breakup characteristics is the breakup length.

C. *Breakup Length*

Breakup length of the liquid sheet is defined as the length from the injector to the breakup point at which ligaments are separated from the liquid sheet. For each fluid, simulations have been performed for different velocities. However each fluid has a distinct Ohnesorge number. As seen from Fig. 8, as Ohnesorge number increases, the breakup length increases. The fluid with higher Ohnesorge number has high velocity which causes the fluid particles to remain in contact for longer distance and therefore breakup length increases.

Breakup of the liquid sheet to smaller ligaments is due to the instability. Study this phenomenon of stability analysis has to be done which is beyond the scope of this work.

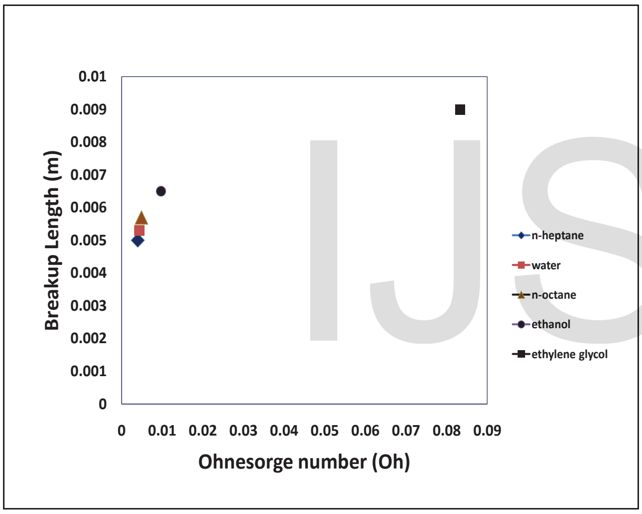

Figure 8: Breakup length Vs Ohnesorge number

IV. CONCLUSION

The numerical simulations have been conducted to study the breakup characteristics of impinging jets of five different fluids. The salient features of the study are:

- The breakup patterns obtained by the numerical simulations are compared with the experimental results of Bailardi, Negri and Ciezki[8] and is found to be in good agreement.
- Three different breakup patterns identified – Closed Rim, Open Rim and Smooth Sheet Ligament.
- Closed Rim pattern is detectable in the region of below Weber number of 300. Surface tension forces hold together the rim results in Closed Rim in the low Weber number region.
- It is noticed that as the Ohnesorge number increases, Open Rim regime expands to a higher Weber numbers due to decrease in surface tension forces.
- As the viscosity increases, the disturbances grow slower which results in an increase in the breakup length.

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