Coalescence Phenomenon of Immersed Jets

Claudiu PATRASCU[1], Ioana Laura OMOCEA*[,1], Corneliu BALAN[1]

*Corresponding author
[1]"POLITEHNICA" University of Bucharest, Power Engineering Faculty, Hydraulics Department, REOROM Group
Splaiul Independenţei 313, 060042, Bucharest, Romania
claudiu.t.patrascu@gmail.com, ioana.omocea@upb.ro*, corneliu.balan@upb.ro

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Abstract: *The present paper investigates the immersed jet behavior. Jets of water and water - glycerol mixtures are studied. Two jets are placed in contact. The jets collision creates flow patterns depending on velocity and liquid properties; the two jets can remain in contact, but separated (non-coalesced) for low flow rates, or coalesced in a single larger jet. The resulting jet can exhibit breakup. The breakup phenomenon of a single jet is investigated and breakup length is measured. The influence of the liquid properties on the phenomena evolution is evidenced by varying the concentration of glycerol in the glycerol - water solution.*

Key Words: *immersed jet, colliding jets, coalescence, jet breakup, breakup length.*

1. INTRODUCTION

Liquid jets are an ideal probe for the liquid properties, such as viscosity or surface tension [1]. In the context of today's environment, understanding how multiphase systems are acting provides the main knowledge for finding optimal solutions. In this framework, to see what happens when water penetrates a hydrophobic fluid, such as oil, is of high interest.

Coalescence is defined as the mixing phenomenon of two identical or miscible fluids placed in contact to minimize the surface energy. It employs physical and chemical principles, along with dynamic principles of fluid interfaces. Equally common, but perhaps less often noticed, are examples wherein two liquid volumes that would normally be expected to unite do not, if only temporarily [2, 3]. Lord Rayleigh was probably the first to perform an extended study of temporary non-coalescence between fluid jets.

Two fluid jets can be coalescent, non-coalescent or even can bounce of each other upon collision [3]. Two separate jets collision creates flow patterns depending on the velocity and liquid properties; the two jets can remain in contact, but separated (non-coalescence) for low flow rates, or they can coalesce in a single larger jet (coalescence phenomenon). The resulting jet can experience instability and, eventually, breakup into drops. This phenomenon is known as Rayleigh instability. This instability is due to the interaction between the fluid discharging from the nozzle and the surrounding medium properties.

Understanding these phenomena increase the equipment's efficiency, liquid transportation, mixing of two liquids, diffusion or inoculation of one liquid into another. The jets non-coalescence problem was revised by Wadhwa and Jung [3, 4].

Multiphase processes in which coalescence and breakup of jets is of huge interest are widely encountered in nature, technology and basic science, such as medical diagnostics, emulsification, DNA sampling, cosmetics, sprays, jet engine technology and combustion processes [5].

Previous studies regarding the non-coalescence of colliding jets presented the non-coalescence phenomenon of liquid jets in air [3]. Until now, breakup of both Newtonian and non - Newtonian jets into droplets was extensively studied in the literature, covering mostly their evolution in the air [2, 4, 6]. Both theoretical and experimental aspects regarding the injection of a liquid jet in a gaseous medium were first studied by Lord Rayleigh [1, 5].

In the present paper, the jets of water or water - glycerol mixtures are oblique colliding in mineral oil. First, the methodology and materials are presented. The results of oblique colliding laminar jets are presented. Viscosity was increased by modifying the concentration of glycerol in the mixture to emphasize the viscosity's influence on the transition from non-coalescence to coalescence.

The critical dimensionless numbers that capture the transition, Reynolds and Webber are then determined. A chapter is dedicated to breakup of a immersed jet, the exact moment when the perturbations appear and the initial jet breakup into droplets, respectively. Maximum breakup length was also the investigated function of Reynolds and Capillary number and fluids properties.

2. MATERIALS AND METHODS

Experiments studied used organic oil as the medium in which mixtures of water and glycerol were used for studying colliding jets and jet breakup. Maximum volumetric concentration of glycerol in water was 60%, limited by the syringe pump to prevent the motor to stall.

Pure glycerol is dense and viscous ($887\ \mathrm{kg/m3}$ and 0.59 Pas). By adding glycerol in water we increased the viscosity and density of the mixture. For each type of oil - mixture interface, the interfacial tension was measured with the pendant drop method.

Densities are evaluated by weighting a volume of liquid (quantified using a Hamilton microsyringe Gastight #1725 of 0.25ml) using a scale Radwag AS 82/220.R2. The viscosity was measured with a rotational rheometer Anton Parr Physica MCR301 using the cone - plate geometry.

The fluids properties are presented in Table 1, along with the capillary length, a, values. All fluids were tested at $25^{\circ}C$. Organic oil's properties (viscosity and density) were relatively determined to those of the water – glycerol mixtures and the variation plotted in Fig.1.

$$a = \sqrt{\frac{\gamma}{\rho g}} \quad , \tag{1}$$

A mechanism with 2 needles was used for the oblique collision. Needles were attached at the end of hoses from the 140 ml syringes. A syringe pump Harvard Apparatus Pump 33 with two syringes was used to maintain the expected flow rates. The mechanism was immersed in organic oil retained in a glass cell.

Needles were mounted on a glass piece and were oriented so that the resulting fluid jet was vertical. The two jets are impacting at an angle of 2α (Fig. 2); $\alpha = 40^{\circ}$. The distance between the central axes of the needles is $1\ cm$.

Table 1. Liquids' Properties at 25°C

Glycerol concentration [%]	*η [Pas]*	*γ[N/m]*	*ρ [kg/m^3]*	*a [mm]*
0	1.00E-03	0.03	1004	1.75
15	0.0015	0.032	1045	1.77
25	0.00225	0.03	1082	1.68
40	0.00412	0.032	1117	1.71
50	0.00845	0.028	1149	1.58
60	0.0131	0.029	1177	1.58
Oil	0.055	-	877.5	-

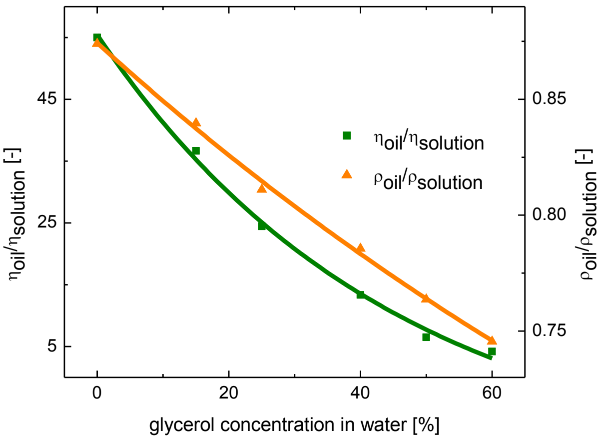

Fig. 1 Dependence of viscosity and density on glycerol concentration in water-glycerol solution.

Jets centerlines intersect, the mechanism is symmetrical and the two jets are identical. If they are not aligned properly, they usually form a helical shape. For the first set of experiments, we increased the Reynolds number from 40 to 400 to clearly establish the critical value at which the two jets become coalescent. For every water - glycerol mixture a set of 5 experiments was performed.

Two identical jets of diameter D, at a flow rate Q and with a certain density, viscosity and interfacial tension, colliding at an angle 2α can become coalescent or not, depending on the Reynolds number.

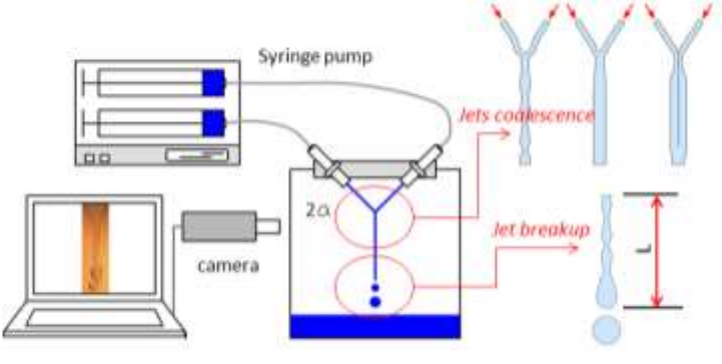

Fig. 2 Sketch of the experimental setup. Coalescence of two colliding jets; Example of water jet in oil and measurement of breakup length, *L*

Movies at normal and high speed were recorded from a perpendicular direction to the jets plane. All experiments were performed at $25^{\circ}\mathrm{C}$. First, we focused on coalescence of two jets. Then, we used the same setup with just one syringe to study the breakup of a single jet.

The breakup length, L (Fig. 2), defined by Eggers and Villermaux, represents the distance from the nozzle over which the liquid jet is still connected [1]. The maximum breakup length was measured from the photos acquired.

The progressive thinning of the thread is driven by capillarity and resisted by inertia and viscosity. The velocity between the jet and the surrounding liquid (oil) is different. Thus, the oil- water (or glycerol – water mixture) is unstable. When the jet column shape becomes unstable it eventually breaks into drops.

Dimensionless numbers used to quantify the coalescence phenomenon and the jet breakup are Reynolds number (Re) of the injected liquid, Webber number (We), Capillary number (Ca):

Re – ratio of inertia and viscous forces:

$$Re = \frac{\rho v d}{\eta}$$

We – relative importance of inertia to interfacial tension:

$$We = \frac{\rho v^2 d}{\sigma}$$

Ca – ratio of viscous forces to interfacial tension:

$$Ca = \frac{\eta v}{\gamma}\ ,$$

along with densities ($\frac{\rho_{oil}}{\rho}$) and viscosities ($\frac{\eta_{oil}}{\eta}$) ratios.

Where: ρ is the water - glycerol mixture density, ρ_{oil} is organic oil density, η_{oil} is organic oil viscosity, η is the mixture viscosity, γ is the interfacial tension between the oil and the mixture, v is the velocity and d is the interior diameter of the needle used for injection.

3. COALESCENCE OF TWO COLLIDING IMMERSED JETS

By increasing the flow rates in the two needles, we observed the critical Reynolds number for jets to coalesce. The oblique collision of two laminar jets creates flow patterns, which depend on jet velocity and liquid properties [7]. For the low flow rates, the two jets remain separated, but in touch. Instead of becoming coalescent, they are getting closer, being separated by a thin film of oil. Due to the jet velocity, the oil is replenished, sustaining the non-coalescence of jets [4]. Increasing the flow rate, the jets unite in one single larger jet for a certain flow rate.

The transition and dependence of dimensionless parameters are thus investigated. Fig. 3 presents the Re and We number for coalescence with increasing glycerol concentration. Increasing glycerol concentration has a decreasing effect on coalescence Re number. We for coalescence is increasing with increasing glycerol concentration in the mixture.

The coalescence of two colliding oblique jets develops because of instabilities at the interface. In the case of water jets or low concentrations of glycerol in water mixture, the inertia dominates and the fluid interface is more unstable. These instabilities are reduced by increasing the glycerin concentration and viscosity, respectively.

The patterns of coalescence for the 6 cases studied (water, water – glycerol mixtures with a volumetric concentration of 15, 25, 40, 50, 60 % glycerol) are described in Fig. 4, where the interface is emphasized.

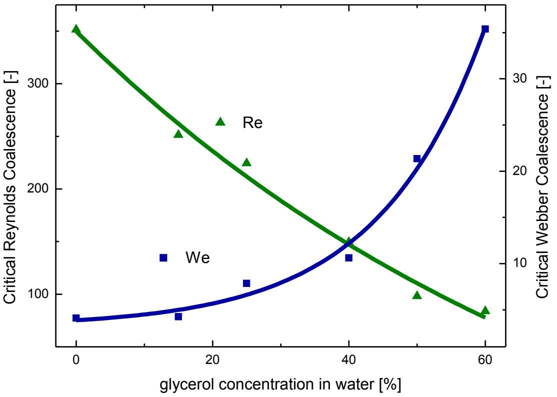

Fig. 3 Critical coalescence Reynolds and Weber number variation with glycerol concentration in water – glycerol mixture

We observed three different patterns of coalescence, one referring to the dominant instabilities after coalescence (for water jets), and the other two referring to small perturbations or a stable resulting jet. Between 40% and 50% glycerol concentration in water a transition regime is observed: the coalescence point is different from the intersection point of the two jets' axis. Increasing the viscosity of the jets, the distance from the intersection point of the imaginary axes of the needles to the coalescence point is increasing.

This phenomenon can be related with the absence of small wave perturbations damped by the liquid viscosity. This can be seen in experiments with mixtures of 50 or 60% glycerol (Fig. 4).

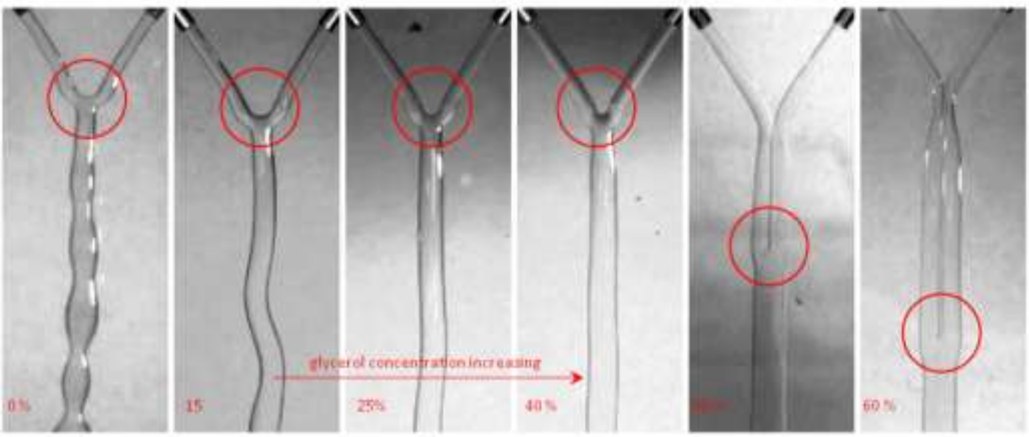

Fig. 4 Experimental results. Patterns of the coalescence of two jets; Coalescence point depending on glycerol concentration.

4. BREAKUP OF ONE SINGLE IMMERSED JET

The resulting jet from the coalescence of the two oblique jets exhibits breakup. One single jet was separately studied to observe Rayleigh instabilities of the jet. The results for a water jet in organic oil medium are presented in Fig. 5. A series of perturbations wavelength can be distinguished in the images. The jet's lead has a round shape, prior to drop formation.

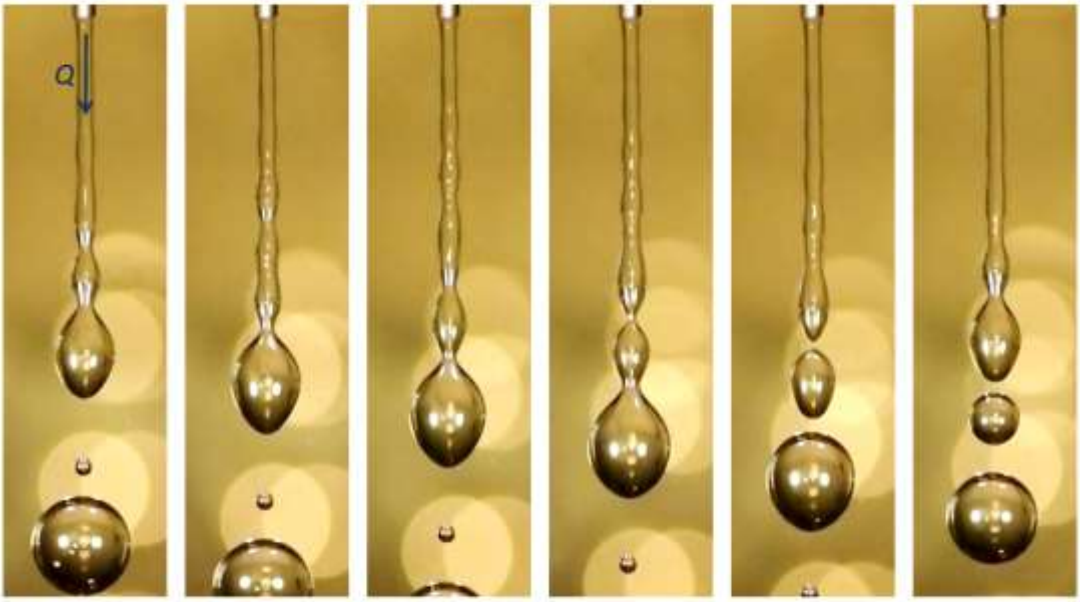

Fig. 5 Breakup of water jet in oil; constant flow rate $Q = 10\ ml/min$; needle diameter 0.838; each two frames are separated by $80\ ms$

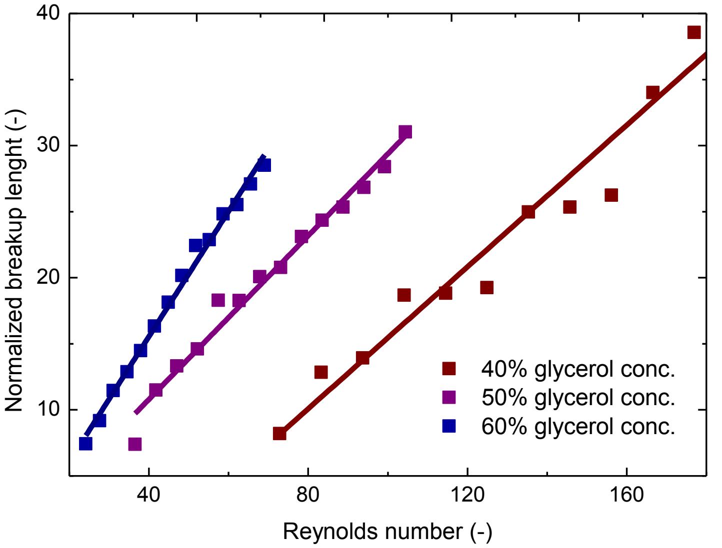

Fig. 6 – Parameter L/D1 dependence on Reynolds number for three difference glycerol concentration in water

The volume of this drop increases, then the breakup occurs. The same behavior and response was also observed in the case of glycerol – water mixtures.

The maximum breakup length, L, was measured from the image data. It was normalized with the needle diameter, D. Parameter L/D variation with Re and Ca number are plotted in Fig. 6 and Fig. 7, respectively.

Results were compared for three different glycerol concentrations (40%, 50% and 60%). The experimental data plotted show that the normalized breakup length has a linear dependence on Re and Ca number.

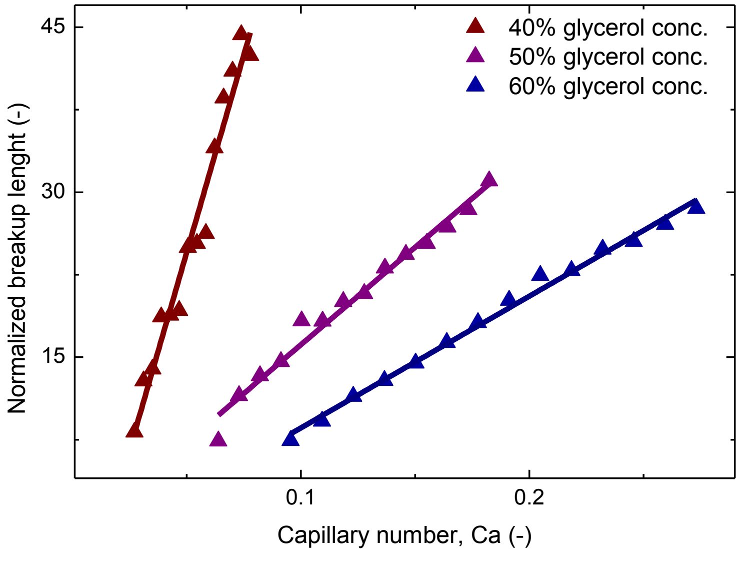

Fig. 7 Parameter L/D_1 dependence on Reynolds number for three difference glycerol concentrations in water

5. CONCLUSIONS

An experimental work has been performed in order to study the viscosity influence, the ratio between the jet viscosity and the surrounding fluid viscosity on the dynamics of two jets. Organic oil was used as a surrounding medium for water and water – glycerol mixtures. The viscosity of the jets was increased by adding glycerol in water.

The coalescence of colliding jets is usually explained by the thinning of the film that separates the jets. At a certain thickness the Van der Waals forces become important and the coalescence takes place.

We captured different patterns of immersed oblique jets coalescence. For low glycerol concentrations the jets present perturbations.

The coalescence point is observed at different distances from the imaginary intersection of the two jets axis.

This distance between the imaginary needle axis intersection and the equilibrium joint point increases with the viscosity in the glycerol mixture.

The resulting jet from the coalescence experiences jet breakup. The breakup (breakup parameters, like breakup length, L) of the resulting jet can be predicted if the liquids properties are known.

Our future work will be focused on the breakup of the resulting jet and the measurements of the drops formed. Also, the same response has to be studied for the non – Newtonian fluids.

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