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Breakup of Liquid Jets

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Abstract: For fundamental analysis of the transport of mass or heat in a dispersed system, accurate knowledge of behavior of jet is prerequisite. For generation of high interfacial area breaking of liquid jet into small droplet is necessary. Liquid jet breakup is a complex phenomenon and dependent on many factors like velocity of jet, pressure difference, geometry of nozzle, temperature of both fluid, properties of fluid like their density, viscosity, surface tension, vapor pressure etc. Here different characteristics of jet are discussed. The most important parameter for this phenomenon is the Weber number (We) calculated from the diameter of the large structures. Indeed, the main parameters that can affect the secondary atomization are acceleration of drop by external flow, shear due to the differential speed between liquid and gas and surface tension. In this paper different aspect of jet behavior like jet length, flow regions of free turbulent jet, types of jet disintegration, effect of different variables on liquid jet breakup, etc. are discussed. The major factors which affect the characteristics of jet are viscosity of liquid, turbulence and environmental pressure. The effect of oscillating pressure and cavitations are also discussed. In this paper an attempt is made to present a literature survey on jet breakup.

Key words: factors for jet breakup, liquid jet, breakup of jet, length of jet, primary and secondary atomization.

I. Introduction

The turbulent flow is desired to increase the rate of transfer per unit area or to help dispersion of one fluid to another and to create more interfacial area, for most of mass transfer between gas and liquid. Dispersion of one fluid to another is a complex phenomenon and depends on many factors like velocity of jet, pressure difference, geometry of nozzle, temperature of both fluids, properties of fluid like their density, viscosity, surface tension, vapor pressure, etc.

When a liquid is injected into another fluid at velocity above specific velocity, jet forms. This jet continues to be intact to certain length and then breaks to drop. The breakup of a liquid jet radiating into another fluid was studied by many investigator since century. These drops result into the generation of large new surface. The prediction of dynamics of jet and calculation of quantity and size of drops are very important.

Jet break up has been studied extensively both practically and theoretically. Theoretical development started by elegant analysis of Plateau and Rayleigh. It has been stated by Plateau (1873) that jet breakup in segments having equal length of 2π times of the jet radius. Rayleigh (1879a) and (1879b) explained that hydrodynamic instability is responsible for the jet breakup. Weber (1931) studied the effects of the density of the ambient fluid and liquid viscosity. Further, Tomotika (1935) extended Rayleigh stability analysis to a viscous cylinder surrounded by a viscous fluid and explain about an optimum ratio of viscosities of the jet to the ambient fluid at which jet attains the maximum growth rate. Christiansen and Hixon (1957) studied inviscid liquid jet in inviscid liquid. Chandrasekhar (1961) accounted the liquid viscosity as well as the liquid density, which was not considered by Rayleigh and mathematically proved that as the viscosity increases the breakup rate of jet reduces and drop size increases. They further conclude that breakup of viscous liquid jet is by capillary pinching mechanism under vacuum. (Lin and Reitz 1998). Sterling and Sleicher (1975) studied liquid jets injected into air and analysed the aerodynamic interaction between the jet. and air. They developed an equation for the growth rate.

II. Behavior of jet

Free jet

A free jet, after leaving the nozzle, will entrain the surrounding fluid, expand and decelerate. Approximately, total momentum which is conserved as jet momentum is transferred to the entrained fluid. In the literature it has also been defined that when the cross-sectional area of jet is less than $1/5$ then the cross section of surrounding region then jet is considered to be free jet in case of both fluid, surrounding fluid and jet fluid, are same. While the turbulent jet having Reynolds number greater than 2000 is considered to be a free jet. (Perry et al., 2007)

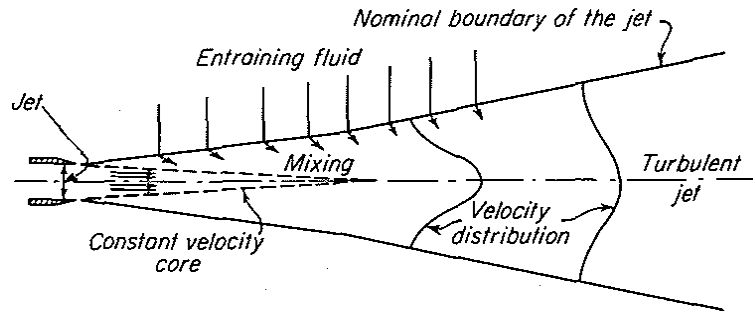
Jet length

The high velocity liquid jet coming out of nozzle situated at the top of ejector flowing through the stagnant fluid surrounding it maintains its identity for a substantial distance (Figure 1). It may be observed for the jet issuing from the nozzle having uniform and constant velocity that

- The velocity remain uniform and constant in the core
- the area of core decreases with distance from the nozzle,
- the core is bounded by an increasing turbulent jet, in which the radial velocity decreases with distance from the centerline of the jet,
- the core is shrinking and disappears at some distance from the nozzle,
- but the turbulent jet maintains its integrity further than the point at which the core disappeared however its velocity steadily decreases,
- the radial velocity in the jet decreases and a pressure increases in as per the Bernoulli principle

There is simultaneous surrounding fluid enters into the jet and is absorbed, accelerated and blended into the enlarged jet. This process is called *entrainment*.

Figure 1 : Flow of a submerged circular jet (Rushton and Oldshue, 1953).



In this process there are also strong shear stresses at the boundary of the jet and the surrounding liquid. Due to these stresses strong eddies are generated at the boundary and create considerable turbulence, which causes the intimate mixing action. It is also established that liquid flow at high velocity and entrainment of large quantity alone do not sufficient for thorough mixing. Enough time and space is must for the streams to mix together satisfactorily by the mechanism of entrainment. (McCabe et al., 1993)

Liquid jet break-up length

Breakup length of round liquid jet was measured by Eroglu et al. (1991) in annular coaxial air streams. They further observed that the decreasing breakup length with increasing Weber number and they also found that liquid jet length increases by increasing Reynolds number. They gave following expression:

$$\frac{L}{2a} = 0.5We_L^{-0.4}Re_g^{0.6} \quad (1)$$

where a = central tube inner radius and L = liquid intact length. Here Weber (We) and Reynolds numbers (Re) are based on gas and liquid relative velocity.

In similar attempt numerical analysis of jet breakup is performed by Kazuya et al. (2004) using the Moving Particle Semi-implicit (MPS) method in x - y two dimensions. Effects of the Weber number and the Froude number on the jet breakup length agree well with experimental data. The breakup length with gravity is from 70 to 80% of the experimental data. They expressed L/D as the following expression:

$$\frac{L}{D} = 2.2We^{0.28}Fr^{0.78} \quad (2)$$

where L , D , We and Fr are jet breakup length, nozzle width, Weber number and Froude number, respectively. However, the coefficient 1.2 by the MPS method is a little smaller than experimentally obtained values 1.5 for alcohol and 3.0 for water.

Richards et al. (1994) compared results obtained experimentally and numerically for jet length till break up as well as jet and drop shapes. He concluded that numerical method shows a greater sensitivity of jet length to Reynolds number.

Flow regions of free turbulent jet

Tuve (1953) and Davies (1972) have explained break up length differently. A turbulent free jet is normally considered to be consisting of four flow regions that are:

- Region of flow establishment is up to the 6.4 times nozzle diameter. In this region there is a core having conical shape and the velocity is same as at the discharge of the nozzle. As jet proceed away from the discharge of the nozzle, slowly boundary between jet and surrounding reduces to centerline. Here this region is considered to be terminated.
- Next transition region is up to the 8 times diameter of nozzle.
- Region of established flow is the foremost region of the jet. Here, the radial velocity profile is self-conserving with respect to centerline velocity.
- In terminal region centerline velocity reduces rapidly. For air jets, the residual velocity will reduce to less than 0.3 m/s which is considered to be still air.

Several researchers (Tie et al., 2011; Pfeifer et al., 2010; Leick, 2008; Yongyingsakthavorn et al., 2004; Smallwood and Gulder, 2000; Kufferath et al., 1999; Wolfe et al., 1964) have reported the jet behavior.

III. Types of primary atomization

The liquid jet behavior is a critical step in mass and heat transfer operations. There are mainly three categories of mechanisms (Meyers, 2006) of jet disintegration namely:

Mechanical primary atomization

Liquid jet is injected at high speed through a small hole in a gaseous medium at rest. This type of atomization is supposed to have very strong difference in pressure between the upstream and downstream of the orifice. This type of jet is also called free jet. This type of atomization of jet is used in jet ejectors.

Aerodynamic primary atomization

Liquid jet injected at low speed in the chamber surrounded by a gas jet injected at high speed. This type of coaxial jet is also called assisted jet. This type of atomization of jet is used in high energy venturi scrubber (HEVS).

Impact primary atomization

When atomization is performed by impact of two liquid jets or a liquid jet to a wall, it is called impact primary atomization.

The understanding of the phenomenon of primary atomization is still not clear due to the difficulty in observation of primary fracture of jet in the dense zone of the flow. Moreover there are strong changes in topology of interface and quick transfer between the phases in this zone very rapidly, alter the properties of the drops/bubbles before they reach experimentally observable conditions. However, recently due to the improvement of measurement techniques (holography technology and probes of optical fiber) understanding of the dense fog area has become possible.

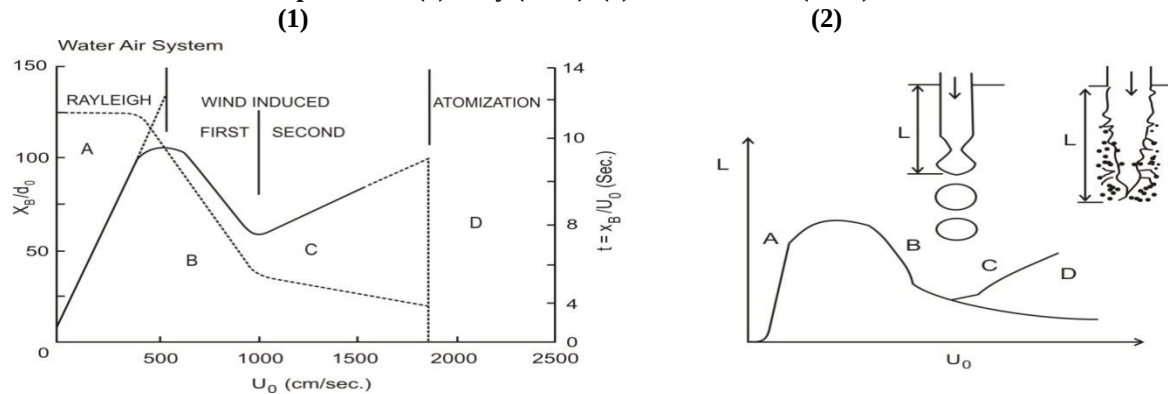
The current study involves mechanical primary atomization by multi nozzle jet ejector. Review of literature published about mechanical primary atomization is given as under:

Mechanical primary atomization

Faeth (1999, 1990) and Reitz and Bracco (1986) have given exhaustive review of literature on mechanical atomization. Ohnesorge and Angew (1936) provided the first classification of different schemes based on the Reynolds and Ohnesorge numbers. Reitz (1978) clarified the uncertainty of classification proposed by Ohnesorge and Angew.

Lin and Reitz (1998) as well Atay (1986, 1987) discussed various regimes of breakup of liquid jets injected into

Figure 2 : Break up time and/or jet breakup length as a function of jet exit velocity
[Adopted from (1) Atay (1986), (2) Lin and Reitz (1998)]



both stagnant and co-flowing gases. Available criteria for the alteration from one regime to another have been reviewed by them. They proposed a convenient method of categorizing jet breakup regimes by considering the length of the coherent portion of the liquid jet or its unbroken length, L , as a function of the jet exit velocity, U , [Refer Figure 2(1) and Figure 2(2)].

They identified four main breakup regimes which were based on combinations of inertia of liquid, surface tension and forces of aerodynamic acting on the jet. The regimes are named as follows

- (1) The Rayleigh regime,
- (2) The first wind-induced regime,
- (3) The second wind-induced regime and
- (4) The atomization regime.

These regimes are summarized as in Table 1.

Region A and B of figure (2) shows that after the dripping flow regime ($We_L > 8$), the breakup length linearly increases in beginning as jet velocity increases till it reaches maximum and then start decreases. It is also clear

that the drops are pinched of having comparable diameter to the jet. These two breakup regimes, which are understood properly, related to the Rayleigh and first wind-induced breakup regimes.

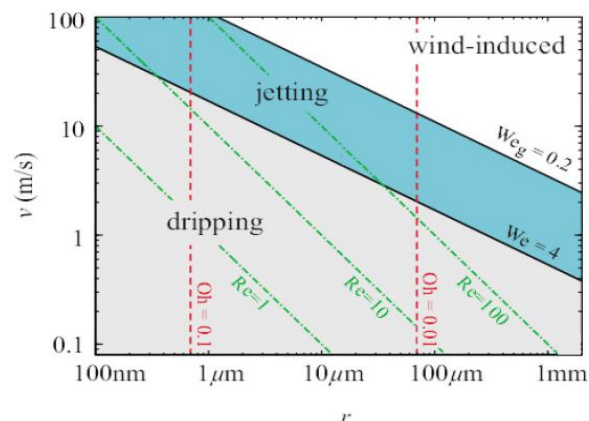
Table 1 : Jet breakup regimes (Lin and Reitz, 1998 and Atay, 1986)

Type of Regime	Jet velocity U_0 , m/sec	Break up length X_B in terms of X_B/d_0	Diameter of drop, d	Webber no, $We_L = \frac{\rho_l U^2 (2a)}{\sigma}$ $We_g = \frac{\rho_g U^2 (2a)}{\sigma}$
Rayleigh Jet Breakup Regime	0 – 5	10 – 110	$d > d_0$	$We_L > 8$ $We_g < 0.4$
First Wind Induced Breakup Regime	5 – 10	110 – 60	$d = d_0$	$0.4 < We_g < 13$
Second Wind Induced Breakup Regime	10 – 18	60 – 100	$d < d_0$	$13 < We_g < 40.3$
Atomization Regime	> 18	0	$d \ll d_0$	$40.3 < We_g$

* U is the relative velocity between jet and gas, d_0 = diameter of nozzle, $2a = d_0$

Hoeve et al.(2010) presented classification of droplet formation regimes graphically as figure 3 . They presented on the radius of jet r vs liquid velocity v .They also plotted Re , Oh and We lines calculated on the property of pure water. The blue colored strip shows droplet formation by

Figure 3:Classification of. droplet formation regimes



the breakup of continuous liquid jet in Rayleigh breaking regime (jetting) which is bounded by a lower and upper critical velocity (indicated by Weber numbers, $We_L=4$ to We_g) . As the jet size decreases the Rayleigh breakup velocity range becomes wider for example for 1 mm jet the range is 0.35 to 2.3 m/s and for 17 and 110 m/s for a 1 μ m jet.

However, there is variation in observation about breakup-length trends beyond the first wind-induced breakup regime. Haenlein (1932) stated that the jet breakup length increases with increasing jet velocity again. [region C in Figure 2], and then suddenly reduces to zero [region D Figure 2] while McCarthy & Malloy (1974) reported that the breakup length discontinues shortening and elongation of the jet with changes in the jet velocity. Castleman (1931) observed that the breakup occurs at some jet diameters from the orifice, while DeJuhasz (1931) claims that disintegration begin within the nozzle itself.

Theories developed for jet breakup have been reported by various investigators as tabulated in Table 2.

Table 2 : References on jet breakup and primary atomization

References	Theory of jet breakup
Ranz (1956)	Breakup by balancing inertial forces with surface tension forces, neglecting viscous shear stress.
Fraser et al. (1962)	Hydraulic atomization of rapidly moving liquid sheet.
Reitz (1978,2004)	Atomization and other breakup regimes of a liquid jet
Ingebo (1991)	Liquid Jet breakup in sonic- velocity gas flow.
Frago and Chigier (1992)	Pulsating and super pulsating breakup process.
Chigier & Reitz. (1996)	Air- blast coaxial atomization.
Kankkunen et al. (1997)	Sheet breakup mechanism of black liquor.
Meier et al. (1997)	Breakup of very low velocity liquid jets.
Geschnr et al. (2001, 2004)	Disintegration of sinusoidally forced liquid jet.
Herrero et al. (2007)	Air blast atomization of swirling viscous annular liquid sheet (alginate solution)

Tie Li et al. (2011), Tamaki et al. (2007, 2010) and Yongyingsakthavorn et al. (2004) have reported that there are still other parameters which effect the breakup of jet: physical properties of fluid, the nozzle geometry, the surrounding gas (stagnant or moving, atmospheric or pressurized).

IV. Effect of various variables on liquid jet breakup

Effect of the environmental pressure

Reitz and Bracco (1986) noted that the atomization regime can be obtained for low-speed fluid when it is injected into a highly pressurized environment. The length of intact surface decreases with increasing environmental pressure to a certain value.

Faeth (1990, 1995), Tseng et al (1992a, b), and Ruff et al (1992) studied the structure of an atomized spray in a pressurized environment. Atomized spray in a pressurized environment shows a very dense area, called the liquid core, at the outlet of ejector. Chehroudi et al. (1985) found that the faster rate of mixing results in high pressures of the surrounding environment. However, these effects are relatively low. Faeth (1999) noted that for $\rho_L / \rho_G < 500$ the aerodynamic forces influence the atomization. Similar study was also done recently by Kufferath et al. (1999).

Effect of turbulence

Properties of jet are highly dependent on the state of development of the turbulence at injector outlet. Faeth (1995) confirms this by varying the output conditions of the jet. It seems that mixing rates are increased greatly in the layer of liquid mixture with the degree of turbulence of the liquid jet. Wu et al. (1995) and Wu and Faeth (1995, 1993) proposed an analysis for fully turbulent jets developed at injector outlet, to estimate the average Sauter diameter (SMD) of drops produced early in the process of atomization and position of primary rupture. Wu et al. (1995) assume that the drops are formed when the kinetic energy of the smallest eddy is comparable to the energy of surface tension necessary to form a drop of similar size. This principle was already envisaged by Kolmogorov (1949). Similar effect of turbulence has also been studied by Kufferath et al (1999).

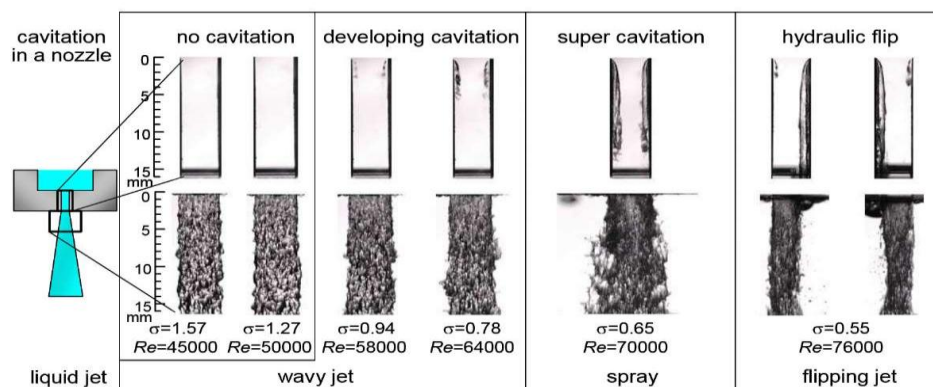
Effect of liquid viscosity

In general, increasing the viscosity of the fluid must tend to delay breakup of the liquid jet as it balances the forces of inertia. Indeed, this parameter is taken care in the calculation of the Reynolds number of the liquid. Reitz and Bracco (1982) studied the influence of the viscosity of liquid by varying the proportion of glycerol and water in the liquid phase. They showed that instabilities are strongly dampened when the viscosity increases resulting in the formation of a laminar liquid jet. The angle of the fog is not influenced by changes in viscosity. Finally, the position of the primary break shifts downstream. Lefebvre (1989) showed that the viscosity plays a role in the average diameter of drops formed. It was noted that the SMD increases with viscosity. Indeed when the viscosity increases, the internal turbulence of the fluid decreases and leads to an increase in wavelength of instabilities. This then results in a thickening (of liquid) produced disintegration as a result of the primary atomization. However, established atomization regime (high Reynolds number and Weber number), it appears that viscosity does not influence the primary atomization phenomenon but only influences the secondary breakage. Tamaki and Shimizu (2002) studied effect of kinematic viscosity (0.66×10^{-6} to 20×10^{-6} cSt). They studied the break up length and Sauter mean diameter (SMD) of highly viscous liquid sprayed at injection pressure up to 15 MPa. They concluded that the disintegration behavior of the spray and the spray characteristics are independent of kinematic viscosity. They have invented new atomization enhancement nozzle (sharp edge with additional gap and bypass) which is able to atomize highly viscous liquid at low injection pressure. Similar conclusion was made by Krzeczowski (1980) in the study of measurement of liquid droplet disintegration mechanism. Contrary to this Herrero et al. (2007) concluded that when viscosity decreases there is shorter breakup length.

Effect of cavitation The phenomena of cavitation can be expressed as the formation of vapor pockets (or bubbles) as a result of lowering pressure in a liquid jet. Cavitation is observed in nozzles of liquid atomizer. This question has been studied by many researchers. (Tamaki, 2009, Tamaki et al. 2001, 1998; Sou et al., 2009, 2007, 2006; Schmidt, 1997; Soteriou et al., 1995; Hiroyasu et al., 1991; Chaves et al., 1991; Bergwerk, 1959). As a result of many experiments conducted by many researchers, it has been determined that strong turbulence in the nozzle hole, induced by the cavitation phenomena, contribute enormously to the disintegration of the liquid jet. Sou et al. (2007) investigated the effect of cavitation on the flow in the nozzle and liquid jet atomization. They concluded the findings as (Refer Figure 4):

1. Cavitation in the nozzles and liquid jet can be classified into the four regimes
 - (i) No cavitation having wavy jet,
 - (ii) Developing cavitation having wavy jet,

Figure 4: Images of cavitation in a 2D nozzle and liquid jet (water) (Suo et al., 2006)



- (iii) Super cavitations having spray jet and
- (iv) Hydraulic flip having flipping jet.
2. Liquid jet near the nozzle exit depends on cavitation regime
3. Cavitation and liquid jet are not strongly affected by Re
4. Surface tension (σ) and strong turbulence induced by the collapse of cavitation clouds near the exit play an important role in ligament formation.

In 2009, Sou et al. concluded after analyzing their results that cavitation length L_{cav}/L and jets are not strongly affected by Re but by σ .

Sou et al. (2008) after using the high-speed visualization concluded that since the pressure in the cavitating bubbles is much lower than ambient pressure, bubbles collapse either before reaching the surface of the liquid jet or immediately after reaching downstream of the nozzle. Park et al. (2008) noticed that super cavitation formation along the internal nozzle wall influences the external flow pattern and droplet formation.

Tamaki et al. (1998) observed that when cavitation takes place in a nozzle, it contributes greatly to the disintegration of the liquid jet. Leroux et al. (1996) studied the stability of Newtonian liquid jets and confirmed that the jet atomization is strongly influenced by the fastest growing wavelength in the radial direction

Effect of oscillating pressure field on liquid jet

McCormack et al. (1965) and Crane et al. (1964) studied the effect of mechanical vibration on the breakup of a liquid jet. They concluded that the application of mechanical vibration having the appropriate frequency range of small vibration, acceleration values can induce small pressure fluctuations and cause a capillary instability. Similarly with higher acceleration values there is substantial effect on radial velocity of liquid jet.

Barreras et al. (2002) studied the effect of ultrasonic vibrations on water atomization when excited with waves in the MHz range. They found that diameters of the resulting droplets are of the order of few microns. They used Malvern diffractometer to calculate droplet size distribution. There has been extensive study on the response of a bubble to a continuous oscillating pressure field. Neppiras (1980) explained that in the presence of oscillating pressure waves generated by an acoustic field, existing bubbles or cavities are subjected to both expansion and contraction.

Sindayihebura and Bolle (1998), Brennen (1995), Lin and Woods (1991), Knapp et al., (1970), McCormack et al., (1965) and Crane et al., (1964) have also studied the effect of vibration on the breakup of jet.

V. Secondary atomization

Physical process of disintegration of structures from the primary atomization to form multiple droplets is called secondary atomization. When a spherical liquid drop is subjected to a convective gas flow, it will initially become flattened due to pressure difference between the stagnation points at the front and rear of the drop and the lower pressure at the drop center. In addition to this distortion, the dynamic pressure exerted on the drop by gas flow also causes the drop to vibrate, and may cause it to breakup. The most important parameter for this phenomenon is the Weber number (We) calculated from the diameter of the large structures. Indeed, the main parameters that can affect the secondary atomization are acceleration of drop by external flow, shear due to the differential speed between liquid and gas and surface tension.

In fact, the secondary atomization controls the size of the drops in the spray. Two methods of disintegration processes are often treated separately, but, actually they are not clearly distinct from each other.

Faeth (1995) noted the existence of the two processes in the dense region close to the surface of the fast moving liquid jet and found a strong presence of small spherical drops confirming the rate of secondary atomization. The phenomenon of secondary atomization began as soon as the liquid structures (fragments, drops...) are grabbed up in liquid jet (results of the primary atomization) and become unstable. They are immediately subject to acceleration, due to momentum transfer with the gas.

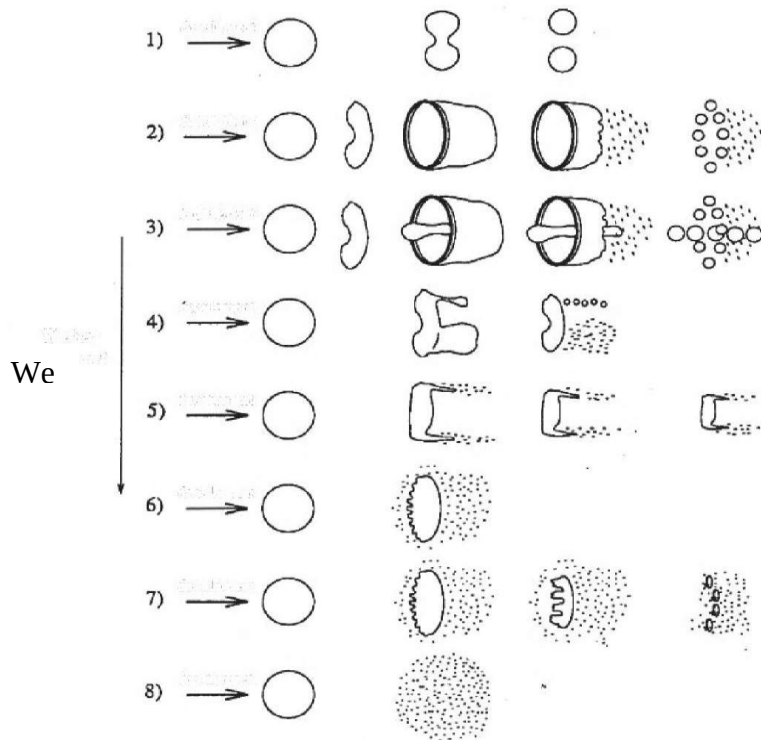
Regimes of secondary atomization

Many experimental studies (Meyers, 2006; Gokalp et al., 2001, 2000; Gokalp and Chauveau, 2000; Zheng and Jasuja, 1994; Mansour and Chigier, 1994, 1993; Krzeczowski, 1980; Krauss, 1970; Ranger and Nicholls, 1969; Engel, 1958; Lane, 1951; Hinze, 1949) have identified different regimes of secondary atomization. The secondary atomization may be categorized better with the Weber number.

These modes of secondary atomization are generally distinguished as follow:

- **The deformation regime (case 1 of Figure 5)**
This type of atomization appears at lower Webber number. The deformation of the drop is a result of the imbalance between the dynamic pressure applied on the drop and the surface tension force. While the speed of the flow surrounding drop increases the dynamic pressure applied on the drop also increases and that tends to distort it. The drop curvature increases in turn leading to the amplification of surface tension
- **The "Bag break-up" regime (cases 2 and 3 of Figure 5)**
Bag break up occurs when the surface tension over compensates for the dynamic pressure applied on the surface of the drop. At breakpoint, flattened drop widens to form a sac which stretches in the direction of

the flow. As a result of disruptions to the flow, the bag drills leading gradually to its disintegration into fine droplets



- **The " Bag break-up" regime (cases 4 and 5 of Figure 5)**

There are two theories explaining this type of disintegration. The first (Hwang et al., 1996) assumes that the disintegration of the liquid fragment is due to the uprooting of the boundary layer that forms on the surface of the drop as a result of the shear with the gas stream. The second theory (Hinze, 1955, 1959; Liu and Reitz, 1997) is based on the elongation of the ends of the drop in the direction of flow. Capillary waves are then formed on the surface of the drop which leads to the production of ligaments in the direction of the flow which will disintegrate drops. **Figure 5: Different schemes of secondary atomization (Meyers, 2006)**

- **The "Catastrophic break-up" regime (cases 6, 7 and 8 of Figure 5)**

This involves high speed. The process takes place in two stages. First low wavelength disturbances (type Rayleigh-Taylor instabilities) are formed on the upstream surface of drop because of its high acceleration. And then Kelvin - Helmholtz instabilities occur leading to the formation of several ligaments bursting into droplets.

There exist some other theories of secondary break up for different specific situations. Hopfinger (2001) considers only three scenarios of secondary breakage: breakage by shear, breakage by the turbulence of the gas and breakage by collision between the drops.

The criteria for transition between regimes

The transition between these different regimes is often defined through two dimensionless numbers. Many authors use Weber number and Reynolds number for distinguishing regimes.

Gelfand (1996) proposes the following criteria to test the regime:

- $0.2 \leq We/\sqrt{Re} \leq 1$: deformation and rupture first type
- $1 \leq We/\sqrt{Re} \leq 20$: failure by shear plan
- $We/\sqrt{Re} \geq 20$: catastrophic failure

Gokalp et al. (2001) have also studied and presented the criteria of transition between regimes.

Time of breakup of drops to droplet

An important parameter characterizing the phenomenon of secondary atomization is the time of "breakup". This is the interval of time between the formation of drops and their disintegration to droplets. A first expression is given by Hinze (1955, 1959):

$$t_b = \frac{K_b d_i}{2\Delta U} \sqrt{\left(\frac{\rho_l}{\rho_g}\right)} \quad \text{where } 0.2 < K < 2 \quad (3)$$

O'Rourke and Amsden (1987) proposed a model (TAB: Taylor Analogy Breakup) based on the Taylor instabilities theory. The drop is regarded as a mass-spring system where the external force is the aerodynamic force of the gas, the call back spring force is the force of surface tension and the damping force of the system is fixed by the viscosity of the liquid. They get a similar equation as above where the value of constant K equal to $\sqrt{3}$. Similar study was done by other scientists also. Krzeczkowski (1980) plotted time vs. We for methanol, water, ethanol, butanol, 50% aqueous solution of glycerin and glycerin and compared the results with other researchers (Littaye, 1943; Engel, 1958; Levich, 1962). The results are different from the earlier reported work. However Engel's formula fits somewhat to his results.

VI. Summary and recommendations

Liquid jet first disintegrate to small droplet which is termed as primary atomization. Then of disintegration of structures from the primary atomization to form multiple droplets is called secondary atomization. The Two methods of disintegration processed are often treated separately, but, actually they are not clearly distinct. The phenomenon of secondary atomization begins as soon as the liquid structures (fragments, drops...) are grubbed up in liquid stream (results of the primary atomization) and become unstable. They are immediately subject to acceleration, due to exchange of quantity of movement with the gas.

- The length of jet is a inverse function of Weber number and direct function of Reynold number and Froud number.
- The length of jet is a inverse function of Weber number and direct function of Reynold number.(Eroglu et al. (1991))
- Free turbulent jet have four regions: Region of flow establishment, transition region, established flow region and terminal region.
- There are three type of primary atomization: mechanical, aerodynamic and impact.
- Secondary atomization has four regimes: deformation regime ($0.2 \leq W_e/\sqrt{R_e} \leq 1$), bag break-up regime, bag break-up regime and catastrophic break-up regime ($W_e/\sqrt{R_e} \geq 20$).
- Time of breakup may be calculated by co-relation given by Hinze (1955, 1959)

$$t_b = \frac{K_b d_l}{2\Delta U} \sqrt{\left(\frac{\rho_l}{\rho_g}\right)} \quad \text{where } 0.2 < K < 2$$

- The jet length and time of break up are the function of different factor such as: geometry of ejector, viscosity, velocity of jet, surface tension, surrounding pressure, oscillating pressure etc.
- cavitation in the nozzles and liquid jet have four regimes and effect type of jet..

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