CHAPTER 2

LITERATURE SURVEY

Literature pertinent to liquid column breakup that utilizes active control strategies is presented. It has been arranged in four sections, where the first two sections describe the air-assisted atomization of liquid jet and sheet. The subsequent two sections focus on the applications of acoustic excitations for enhancing the disintegration of liquid jet and sheet.

2.1 Air-assisted System

Many experimental and theoretical analysis have been carried out to address the atomization processes associated with twin-fluid atomizers (Lefebvre, 1989; Liu et al., 1993; Chigier, 1993; Lin, 2003). These studies emphasize the influence of co-flowing air on the liquid column that increases the magnitude of the initial disturbances responsible for the hydrodynamic instability at the interface. The primary forces that control interfacial instability are surface tension force, viscous force, aerodynamic force as well as the discontinuous boundaries at the orifice exit (Fraser et al., 1963).

2.1.1 Liquid Jet

Rayleigh (1878) studied the instability of a liquid jet in a quiescent air, and observed that the balance between surface tension and inertia forces control the subsequent development of the jet. At low velocities, due to the dominance of surface-tension force, capillary waves are generated that leads to instability. The Rayleigh breakup occurs at the particular wavelength of perturbation that exhibit highest growth-rate, so that ensuing droplets have diameter larger than the initial jet diameter. Chandrasekhar (1961) extended the Rayleigh model by incorporating effects of viscous and gravitational forces. The results show that, as viscosity increases, the breakup rate reduces
and the drop size increases. Weber (1931) introduced a dimensionless parameter called Weber number, which is defined as the ratio of inertia to surface tension forces. It can be a useful concept for two phase flow analysis, specifically in classifying the atomization regimes. Even though the analysis of Rayleigh (1878) and Weber (1931) did not consider the influence of gravity and aerodynamic shear, their results are valid as long as laminar flow prevails in the liquid phase. Tomotika (1935) explained about an optimum ratio of viscosity of the jet to that of the ambient fluid at which jet attains the maximum growth rate. Ohnesorge (1936) proposed the first classification of different regimes of atomization processes based on Reynolds number and Ohnesorge number, where the Ohnesorge number (Oh) is a dimensionless number that relates the viscous forces to inertial and surface tension forces. In other words, Ohnesorge number is defined as the ratio of square root of the Weber number to the Reynolds number. Accordingly, three regimes namely Rayleigh breakup, wind-induced and atomization zones were classified as depicted in Fig. 2.1.

![Diagram of regimes of atomization processes](image)

**Fig. 2.1:** Mechanism of drop breakup in each regime
Ranz (1956) studied the primary atomization of liquid jet by balancing the inertia and surface tension forces without considering viscous shear stress. Subsequent studies of McCarthy and Molloy (1974) reckoned breakup length as an indicator of stability of the liquid column. Studies of Reitz (1978) focused on experimental characterization of liquid jet atomization using flow visualization techniques. The results include stability variables such as the angle of divergence of the jet and breakup length. It was found that the spray angle and breakup length are strong functions of gas density and liquid viscosity. Reitz and Bracco (1982) studied the influence of liquid inlet pressure, turbulence, and cavitation on interfacial wave instability. Eroglu et al., (1991) measured the breakup length of a liquid jet in an annular coaxial air stream, and observed that the breakup length decreases with increasing aerodynamic shear. The instability responsible for the breakup of a liquid jet in quiescent gas has been modelled by Wu et al., (1995), and subsequently utilized for the quantification of the Sauter Mean Diameter ($D_{32}$) distribution. A correlation for the droplet separation location based on undisturbed length and spread angle was proposed by Mayer and Branam (2004). Their results led to an extended classification of liquid jet breakup regimes.

Ibrahim et al., (2010) developed an analytical model to predict the variation of satellite drop size with respect to aerodynamic Weber number. Avulapati and Venkata (2013) carried out experimental studies on air-assisted impinging jet atomization. The results revealed that the Sauter mean diameter (SMD) is constant beyond a critical gas to liquid flow rate (GLR) and momentum flux ratio. Ren and Marshall (2014) characterized the initial spray from high Weber number impinging jets and developed the drop size scaling laws based on injector geometry. The results highlight the effect of sheet breakup mode on drop size distribution. The fragmentation process of a liquid volume into clouds of droplets has been analyzed by Barreras et al., (2016),
utilizing a non-dimensional parameter known as transition number based on the atomizing pressure.

### 2.1.2 Liquid Sheet

Savart (1833) carried out the first systematic investigation on liquid sheet instabilities based on balance of forces. In other words, equilibrium between inertial, capillary and gravitational forces determines the interfacial displacement of the self-suspended liquid sheet. Squire (1953), and Hagerty and Shea (1955) emphasized the instability associated with a plane liquid sheet in the presence of ambient gas. Both studies detected two modes of instabilities: the sinusoidal mode, where waves at the upper and lower interfaces are in-phase and the varicose mode in which the waves are out of phase. Their results show that the antisymmetrical perturbation dominates and control the liquid sheet breakup processes. Taylor (1959) predicted the critical radius associated with interfacial waves of liquid sheet as a function of local Weber number. Theoretical and experimental characterization of liquid sheet instability by Fraser et al., (1962) showed that the sheet breakup processes and drop size distributions are influenced by ambient gas density and liquid velocity. Also, it is revealed that liquid turbulence plays a minor role in atomization process either in vacuum or in atmosphere.

The breakup length is considered to be an indicator of the stability of liquid column. Thus, many theoretical and experimental studies emphasize on breakup length measurements. The liquid sheet breakup processes have been studied by Clark and Dombrowski (1972). Analytical solutions pertinent to critical wavelength of disturbance and breakup length for a conical sheet were obtained and it shows good agreement with their empirical data. Arai and Hashimoto (a) (1985) experimentally investigated the disintegration of thin liquid sheet in a co-flowing high-speed air stream. Measurements of breakup length, breakup frequency, drop
velocity and mean droplet diameter have been carried out. An empirical relation for breakup length in terms of sheet thickness, Reynolds number, and Weber number was developed. Senecal et al., (1999) performed a linear stability analysis for a liquid sheet by including the effects of ambient gas, surface tension and liquid viscosity. Results established the validity of their model in predicting liquid spray penetration, breakup length, local SMD and overall spray shape.

A combined numerical and experimental study has been performed on an air-blasted water sheet by Lozano et al., (2001). Based on linear instability analysis, oscillation frequency of the liquid sheet, critical wavelength and amplitude growth rate of perturbations have been obtained. The results confirmed the strong dependence of oscillation frequency on the air speed. Two major breakup regimes are identified in Li and Ashgriz (2006) work, namely capillary and Kelvin-Helmholtz instabilities. Accordingly, droplets formation takes place from the rim of the sheet for capillary instability, whereas for Kelvin-Helmholtz regime, the interaction between the sheet and the ambient air determines the breakup processes. Theoretical and experimental studies of Heislbetz et al., (2007) focused on breakup characteristics of a liquid sheet formed by impinging jets. The theoretical analysis was carried out to determine critical wavelengths and breakup lengths for low and high viscous fluids in a wide range of Weber numbers. A good agreement between theory and experiment was observed only for high viscous liquids.

The consequences of instabilities at the liquid–gas interface results in primary breakup of liquid column, and further disintegration into fine droplets called secondary atomization or spray zone. Complexities associated with this region are drop collisions, evaporation, condensation, and turbulence. The quality of sprays can be gauged by the droplet size, velocity distribution, volume flux, and spray angle. By utilizing diffractively scattered light experiments, Dobbins et
al., (1963) quantified droplet concentration and volume-to-surface mean diameter in the spray zone. Chigier (1983), Bachalo and Houser (1984), and Black et al., (1996) reviewed wide range of commercially available instruments for characterizing the spray structure. It comprises non-optical probing methods and optical techniques that include photography, holography, phase Doppler spray analyzer, interferometry, anemometry, laser Fraunhofer diffraction and tomography. All these techniques enable to measure the particle size and associated droplet velocity. A full-field, time-resolved interferometric laser imaging for droplet sizing (ILIDS) technique for the characterization of sparse, polydisperse spray zone has been effectively utilized by Glover et al., (1995). The studies of Barreras et al., (2006) focused on large-capacity multihole industrial twin-fluid atomizers. Parameters such as discharge coefficient and gas-to-liquid mass flow rate ratio have been tuned to characterize the SMD. A correlation between dimensionless SMD and aerodynamic Reynolds number was obtained. Dejean (2016) utilized laser induced fluorescence, back lighting visualization and light diffraction techniques to characterize the breakup processes of liquid sheet. Empirical correlations for flapping frequency, breakup length and SMD have been obtained. The results show that the breakup length is strongly correlated to liquid flow rate, whereas flapping frequency depends on airflow conditions.

The above reviews highlight the relevance of primary breakup processes in controlling the quality of spray that subsequently determines the combustion efficiency. Therefore, experimental measurements of breakup length, spray angle and void fraction are imperative in optimizing the injector designs. It has to be noted that the present approach utilizes data directly obtained from flow visualization, rather than relying on expensive particle analyzers as commonly used in spray research, for example, the studies of Durst et al., (2012). Visualization
comprises both backlighting method and laser light sheet technique, which exploit a setup similar to the studies of Garlick and Jasuja (2009). However, in the present investigation, the laser light sheet is used to illuminate different cross sections of the spray zone, whereas the backlighting enables extracting a stability variable such as the breakup length and spray angle. The recorded images were subsequently processed, and with appropriate normalization, a universal function for the void fraction has been attained. The void fraction results can be used for inferring the length at which complete atomization occurs. In essence, the present study provides simple and inexpensive procedure to characterize secondary atomization. Even though spray characteristics under atmospheric conditions differ significantly from pressurized chamber settings, nevertheless, the present data may enable in estimating the minimum size of a combustion chamber during design stages.

2.2 Acoustic System

2.2.1 Liquid Jet

The process of liquid jet disintegration into spray can be enhanced by active control strategies such as acoustic excitations, especially for low Weber number flows. Many practical flows belong to low Weber number category, for example, drug delivery, electronic cooling, agricultural sprays, coatings and drop impact studies. For any acoustic source, the pressure wave behavior in the cavity strongly depends on specific atomizer system. This in turn necessitates the universality of results, without limiting to a particular setup.

Miesse (1955) investigated the effect of transverse and longitudinal acoustic modulations on liquid jets. For the frequency range of 20 Hz to 500 Hz tested, the results identified the existence of an optimum frequency that can effectively influence the liquid column. Subsequent studies of Buffum and Williams (1967) fine-tuned the pressure wave at resonant frequencies of
the system, thereby significantly altering a turbulent liquid jet. In order to gain a better understanding of stability of rocket engine combustors, effects of acoustic oscillations on jet breakup frequency were examined both analytically and numerically by Heidmann and Groeneweg (1969). The analysis considers an axial liquid jet in a cylindrical chamber under different acoustic modes.

The deformation of jets under acoustic action has been further explored by Abramov et al. (1987), Hoover et al. (1991) and Bauckhage et al. (1996). Their results exhibited the complete transformation of a perturbed jet or sheet into a droplet. The numerical simulations of liquid jet subjected to transverse and longitudinal acoustic modes were carried out by Heister et al. (1997). It revealed that efficient acoustic energy transfer occurs at the second mode natural frequency of the liquid column. Davis and Chehroudi (2007) tested the influence of acoustic field on a coaxial jet. By utilizing high-speed imaging, the study validated the effect of nozzle geometry and flow physics in the vicinity of injector exit that ultimately leads to combustion instability in cryogenic rocket engines. By effectively exploiting longitudinal acoustic oscillations under resonant conditions of the system, Sujith (2005) carried out experiments relevant to low Weber number flows.

Acoustic radiation Bond number to predict jet flattening that leads to atomization through various modes of instabilities was proposed by Baillot et al., (2009). That is, rapid atomization is initiated by three main phenomena: intrinsic instability, Faraday instability, and membrane breakup. Acoustic radiation Bond number (Bo) criterion determines the acoustic pressure threshold above which the cylindrical jet flattening occurs. In other words, it is a measure of radiation pressure, which can counter balance the surface tension effect to induce the flattening of the round jet into a sheet. A similar study by Carpentier et al., (2009) utilizing transverse
acoustic perturbations on a cylindrical liquid jet corroborated the sequence of events that culminates into atomization.

### 2.2.2 Liquid Sheet

Liquid fuel is discharged to the combustion chamber from atomizer in the form of a liquid jet or a liquid sheet. Unlike liquid jet, a 2D liquid sheet configuration possesses a high ratio of surface-to-mass liquid phase at the nozzle exit. So that, a proper triggering of perturbations at the interface can enhance fuel-air mixing that subsequently improves combustion efficiency. Various techniques have been developed to improve the atomization quality in combustion systems. This includes passive or active control strategies, such as different flow geometries at the injector outlet or imparting energy through external sources. By this way, fine sprays can be generated at low fuel injection pressure. Acoustic excitations applied to a liquid sheet can be perceived as an active control strategy, because of its effectiveness in altering the surface tension-dominated flow structure in the initial stages.

Dombrowski and Fraser (1954) identified factors influencing the disintegration of liquid sheets generated by the single-hole fan-spray nozzle and the spinning disk by utilizing visualization studies. The morphology of breakup is strongly related to the liquid properties as well as initial turbulence level. The photographic records reveal the dominance of shear-driven waves that control the intermediate stages of breakup processes. By introducing forced vibrations in a fan-spray nozzle, Crapper and Dombrowski (1984) have developed a simple technique for obtaining the growth rate of low amplitude waves at any distance from a nozzle orifice. They concluded that the resulting drop size may be affected by both amplitude and natural frequencies associated with the vibrating nozzle. The experiments carried out by Mansour and Chigier (1991)
focused on aerodynamic instability of liquid sheets generated by a twin-fluid atomizer. It has been observed that, when the natural frequency of the oscillating liquid sheet matches with the vibrational frequency of the atomizer, resonance will occur. Hence, rapid flapping of the liquid sheet takes place that may augment spray angle.

Better understanding of liquid sheet stability and disintegration characteristics enables the effective exploitation of external sources, such as acoustic excitations, to improve atomization. Chung et al., (1998) studied the breakup of a conical liquid sheet that is modulated by a piezoelectric driver by utilizing stroboscopic technique. The influence of fluid viscosity, driving frequency, and input perturbations power on liquid sheet breakup was examined. The results indicate that the breakup length decreases with increasing input modulation power only at resonant frequency, which was found to be 10 kHz. The research work of Rhys (1999) emphasized the fragmentation of swirl co-axial liquid sheets and flat sheets under acoustic field. Photography, laser light scattering, and phase-Doppler particle analyzer techniques were applied to understand the mechanism of ligament shedding associated with the respective configurations. Accordingly, it was shown that flat and swirling coaxial sheets can shed ligaments in a periodic manner by acoustic excitation. Villermaux and Clanet, (2002) characterized the drop size decay with increasing liquid sheet velocity, and observed that the decay rate is higher with flapping than the stable case.

The effect of acoustic perturbations on the disintegration of air-assisted liquid sheet was studied by Sivadas et al., (2003). It demonstrates the effectiveness in suppressing the dominance of gravitational and surface tension forces. At an optimum frequency, acoustic perturbations create flapping effect on the liquid column and enhance the breakup processes. Messina and
Acharya (2006) characterized the velocity field and spreading rate of an acoustically modulated liquid spray injected from circular and elliptical nozzles. It was observed that under acoustic forcing, the jet spreading for circular and elliptical nozzles is greatly enhanced and thus, the quality of atomization is improved. The impact of sinusoidal acoustic perturbations on the liquid sheet breakup was investigated experimentally and theoretically by Tirumkudulu et al., (2008). The results exhibit that for a particular Weber number and decibel level, the sheet responds to a set of specific frequencies, which may be due to the resonance of the thicker sections of the liquid sheet.

Mulmule et al., (2010) studied the influence of acoustics on thin planar liquid sheets formed by impinging two collinear water jets. Experiments have been performed over a range of Weber number, forcing frequency and sound pressure level (SPL). For a given Weber number and acoustic frequency, there is a threshold SPL below which the sheet will not respond. Tirumkudulu and Manjula (2013) carried out linear stability analysis for radially expanding liquid sheet without considering the inertial effect of surrounding gas. The investigation applied stability equations for the sinuous and the varicose modes of sheet deformation under acoustic forcing. It has been observed that the sinuous mode is unstable for all frequencies and Weber number, whereas varicose mode remains to be stable for all frequencies, and convected at the speed of liquid jet. Their subsequent experimental data (Manjula et al., 2015) validated the theory and found to be in good agreement for sinuous mode. However, they were unable to substantiate the experimental data for varicose mode.

The aforementioned studies recognized the existence of an optimum frequency at which effective acoustic energy transfer to the liquid column take place. However, with a wide range of
atomizer geometries in practical use, the acoustic behavior in the cavity also varies, and accordingly the significant frequency depends on the specific configuration. Therefore, to extend the application of results, one must seek functional correlations that are independent of test conditions. In the present investigation, based on dimensional analysis, non-dimensional parameters were generated to characterize the primary stability variable. The study utilized axisymmetric cavity of an air-assisted atomizer, with variable wind-pipe length ($L_{wp}$). The dimensionless breakup length data is related to non-dimensional combination of forces arising from acoustic perturbations, inertia, surface tension and gravitational effects. In doing so, a better collapse of data can be accomplished. The analysis consists of flow visualization techniques to characterize liquid column breakup length ($L_b$) for perturbed and non-perturbed cases.