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Entrainment analysis of a two-phase jet using integral conservative equation

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Abstract

In the present study, experimental results for the mean and fluctuating velocities of a two-phase jet are analyzed using image-based measurements. Eulerian averaged velocities statistics of each phase and the mixture is obtained experimentally. With the recent improvements for describing entrainment in single-phase jets using the mean kinetic energy (van Reeuwijk & Craske (2015)-Kaminski *et.al* (2005)), an expression for entrainment in a two-phase jet is obtained. The Eulerian volume-averaged equations in cylindrical coordinates for axisymmetric flow assumption are used to obtain a relation for the budget of entrainment. Various terms in the budget of entrainment are calculated with experimental results.

Introduction

Two-phase jets occur in a variety of situations (eg: combustion in engines, Fuel-coolant interaction). The dynamics of two-phase jets are often complex involving fragmentation (the injected fluid breaks into drops) and entrainment (the fluid injected induces velocity to the ambient fluid) that are coupled to each other. One of the important feature of the such flow is that after sufficiently large distance from the nozzle, self-similar velocity profile is observed. Due to entrainment of the surrounding fluid, region of non-zero velocity, referred as width of the jet, increases. The mixing between fluids causes the decay in the velocity of both fluids. In present study, variation of spreading rate, decay rate with entrainment will be analyzed using experimental results.

Traditionally, Morton Taylor Turner (MTT) entrainment approximation (*i.e.* entrainment velocity = α centerline velocity) is used to describe the entrainment in free turbulent flows. For two-phase jet, Cossali (2001) initially propose a model for cumulative mass entrainment K_e . This model considers Bernoulli equations for separate liquid and gas flows with additional terms for interaction using an assumption of constant spray angle. Recently Hinterbichler *et.al* (2020), using simplifications on the same methodology stated an analytical solution. Energy consistent relation of entrainment is stated by van Reeuwijk & Craske (2015) and Kaminski *et.al* (2005) for the single-phase jets, relating it to turbulence production, axial momentum and axial change in the velocity profile. In the present paper, we try to extend the energy-consistent methodology to determine entrainment for the two-phase jet. With know entrainment coefficient, the spreading rate and velocity decay for a two-phase jet are also obtained.

Experimental methodology.

Investigation of a two-phase jet is usually difficult due to its opacity. But in the present experiments, we use fluids with matched refractive index. Therefore no light deviates and optical diagnostics with laser is possible. One such fluid is manufactured by Cargille industries, referred to as Cargille fluid having an optical index equal to water. The Cargille fluid is injected into a water tank through a 5 mm nozzle. The density of Cargille fluid is 1.9 times (1896.52 kg/m^3) of water and its viscosity is 24.98 times ($26.02 \text{ mPa}\cdot\text{s}$) of water. The surface tension between the water and Cargille is, $\sigma = 0.0265 \text{ N/m}$.

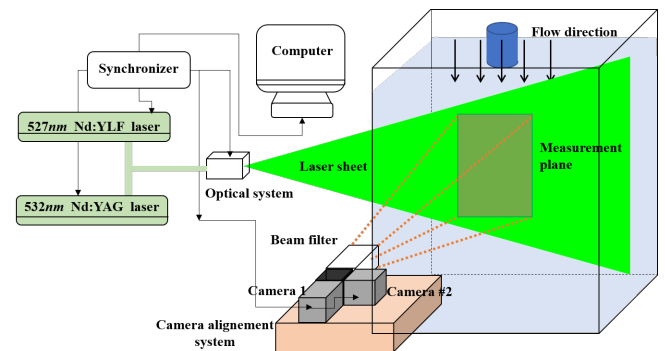


Figure 1: Place here the figure caption.

The schematic of the experimental setup used is shown in figure 1. As two fluids with the same refractive index are used, two cameras are used. Camera 1 is provided with a high pass filter ($\lambda \geq 530 \text{ nm}$) and Camera 2 is provided with a low pass filter ($\lambda \leq 530 \text{ nm}$). Both the cameras view the same measurement area. A dye Pyromethene 597 having the emission peak near $\lambda = 597 \text{ nm}$ is mixed with Cargille fluid

and PIV seeding particles (Polyamid Seeding Particles) are mixed with water. Camera 1 and Camera 2 can be synchronized with Laser 1 (with emission at $\lambda = 527$ nm in figure 1) and Laser 2 (with emission at $\lambda = 532$ nm in figure 1) respectively. On using only Laser 2 with the stated optical filters viewing at the same time instant, Camera 1 only records LIF signal of Cargille and Camera 2 only records PIV signal of reflected by seeding particle in water.

The LIF signal images obtained from Camera-1 are processed with PTV (Particle tracking velocimetry) method for obtaining velocity, size and volume fraction information of the dispersed phase. Based on the information of the drops, a dynamic mask is created on the corresponding PIV image (obtained from Camera-2) and is processed with PIV algorithm to obtain the velocity of carrier phase (water).

Integral model

Consider a two-phase jet with \hat{w} , $\bar{\rho}$ and \bar{p} as the Eulerian average velocity in the axial flow direction (z), average density and average pressure respectively. Integrating the Eulerian-averaged mass, momentum and volume fraction conservation equation from 0 to ∞ in the radial direction (r), with negligible viscosity, axisymmetric flow assumption and assuming that radial direction velocity is zero at the axis and at far field, the averaged integral equations are stated as,

$$\frac{d}{dz}(Q) = E \quad \frac{d}{dz}(M^g) = 0 \quad \frac{d}{dz}(F_y^g) = 0 \quad (1)$$

$$\begin{aligned} Q &= \int_0^\infty \bar{\rho} \hat{w} r dr & M &= \int_0^\infty \bar{\rho} \hat{w}^2 r dr \\ M^f &= \int_0^\infty \bar{\rho} \hat{w}''^2 r dr & M^p &= \int_0^\infty \bar{p} r dr \\ F_y &= \int_0^\infty \rho_s \hat{w} \bar{Y} r dr & F_y^f &= \int_0^\infty \bar{\rho} \hat{w}'' \bar{Y}'' r dr d\theta \end{aligned} \quad (2)$$

Here, Q is the total mass flow rate in the z -direction integrated over r direction. M^g ($M^g = M + M^f + M^p$) is integral gross momentum and is the sum of contribution from mean flow M and velocity fluctuations M^f and pressure M^p contribution. F_y^g is the flux of volume fraction and is sum of mean (F_y) and fluctuation of volume fraction (F_y^f).

In order to obtain the relation for entrainment, procedure stated by van Reeuwijk & Craske (2015) using mean kinetic energy equation is used. The mean kinetic energy equation is integrated in radial direction from 0 to ∞ . On integration with self similar velocity profile approximation, the entrainment in the jet is stated as,

$$E = \frac{dQ}{dy} = Q \left[-\frac{P_m^g}{G_m^g} + \frac{2}{M} \frac{dM}{dz} + \frac{1}{\gamma_m^g} \frac{d\gamma^g}{dz} \right] \quad (3)$$

$$\begin{aligned} P_m^{uf} &= \int_0^\infty \bar{\rho} \hat{u}'' \hat{v}'' \frac{\partial \hat{w}}{\partial r} r dr & P_m^{wf} &= \int_0^\infty \bar{\rho} \hat{w}''^2 \frac{\partial \hat{w}}{\partial z} r dr \\ P_m^{pf} &= \int_0^\infty \bar{p} \frac{\partial \hat{w}}{\partial z} r dr & G_m &= \int_0^\infty \bar{\rho} \frac{\hat{w}^3}{2} r dr \\ G_m^f &= \int_0^\infty \bar{\rho} \hat{w} \hat{w}''^2 r dr d\theta & G_m^p &= \int_0^\infty \hat{w} \bar{p} r dr \\ \gamma_m^g &= \frac{G_m^g}{\bar{\rho} v_{sc}^3 r_{sc}^2} & v_{sc} &= \frac{M}{Q}; r_{sc} = \frac{Q}{(\rho \bar{M})^{1/2}} \end{aligned}$$

Here, G_m^g is the total flux of kinetic energy of the fluid ($G_m^g = G_m + G_m^f + G_m^p$) in z -direction and is sum of mean kinetic energy (G_m), averaged fluctuation of kinetic energy in z -direction (G_m^f) and pressure contribution to kinetic energy (G_m^p). P_m^g is the gross production of fluctuations contributing from $P_m^{wf} + P_m^{uf} + P_m^{pf}$. P_m^{wf} and P_m^{uf} are production of fluctuation in z and r directions respectively. P_m^{pf} is pressure contribution to gross turbulent production. Based on mean flow quantities, velocity scale (v_{sc}) and flow scale (r_{sc}) are defined. The advantage of using such scales is that for self similar flows if the integrals can be scaled with the mean integrals, the resultant scaled integrals (eg. γ_g) are constant. γ_g is referred as drift coefficient by van Reeuwijk & Craske (2015) and for self similar flow, $\gamma_m \approx \gamma_m^g$ and is constant.

Equation (3) describes the entrainment of the fluid. First-term in the equation (3) is related to the gross turbulent production normalized with the total kinetic energy. The last term includes shape coefficient and describes the effect of change in the shape of velocity profile on entrainment.

Expected Result

All the terms stated in the previous section will be evaluated or simplified using experimental methodology. Hence a budget of the terms contributing to entrainment for a two-phase jets will be present.

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