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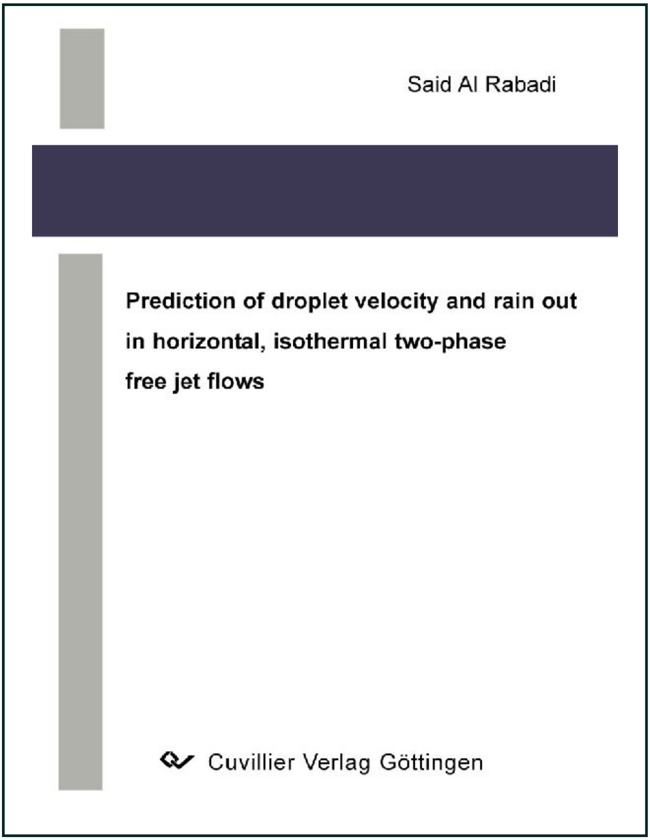

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1 Introduction

The dispersion of two-phase flows has received considerable interest in the industry since they may originate from a leakage of a flange connection, a wall crack or from the accidental release of an industrial unit running under an inadmissible overpressure. Such releases have a potentially hazardous impact on the environment and the personnel health. For risk and hazard assessment, the spread width and the intact length scale of the established jet flow are required for the computer codes utilizing integral, resp., multidimensional balance equations of mass, energy, momentum and species. For solving these equations essential closure parameters in the form of submodels are required, namely, the entrainment coefficient which is characterizing the mixing of the entrained air from the ambient with the free jet flow. Regarding the droplet rain out, a droplet size model must be determined allowing for the definition of a characteristic droplet diameter which, in turn, depends on the self-establishing droplet size spectrum and velocity distribution.

Droplets are generated from the liquid disintegration process in the case of two-phase free jet flow. Concerning the type of the droplet disintegration, it may be caused due to the fluid dynamic shear stress induced by the velocity difference between both phases in the jet flow, or by superimposed violent phase change (flashing) of the liquid or the liquefied pressurized gas. The codes are valid only in narrow parameter boundaries to model two-phase dispersion flows on the physical basis. Hence, there is still a lack of validated descriptive parameters for the effect of fluid properties (viscosity, density, surface tension, droplet coalescence affinity, etc.) on the behavior of two-phase free jet flow.

1.1 Status

The jet flow is accelerated to a certain downstream distance. This is possible by only the air expansion, i.e., higher outlet pressure than that of the ambient. Thus, the expansion induces unstable flow perturbations on the liquid bulk ultimately leading to the breakup. The liquid disintegration is significantly affected by the aerodynamic forces associated with both the co-flowing and the entraining air into the jet. Observations of the droplet deformation in two-phase free jet flow confirm that the interactions between the air stream and the liquid bulk surface are becoming significant. Hence, the air entrainment process is especially enhanced in the jet far field region at a downstream distance of longer than 30 nozzle outlet diameters, due to the contribution of both the co-flowing and the entraining air streams in the two-phase free jet flow. Meanwhile, the effect of the liquid properties, especially the viscosity on the air entrainment in two-phase air/ liquid free jet, is still stochastic. Indeed, the liquid viscosity influences the primary droplet deformation and the secondary breakup through higher shear stresses continuously acting on the droplet surface. The disruptive and the adhesive, resp., conservation forces for each particular droplet compete along with the downstream distance.

On the other hand, analytical approaches involving the disintegration of the liquid bulk and the assessment of the jet breakup length are still a questionable general validity for the two-phase air/ liquid dispersion flows. The two-phase predictive models for droplet size and velocity include simplifications which may be applied to single-phase flow or two-phase dispersion experiments performed with a liquid phase of relatively low viscosity. Further uncertainties also remain regarding the extrapolation of the laboratory results to large scale releases which might occur in real industrial releases with fluids of a relatively higher viscosity.

1.2 Aim

In the frame of this work a two-phase entrainment model based on the upstream flow conditions of an air/ high viscosity liquid phase will be developed. This model accounts for the droplet formation process under the effect of the interactions between the turbulent air flow and the liquid bulk. Furthermore, the model validates the influence of the liquid phase properties, especially the influence of viscosity on the droplet velocity, rain out and air entrainment. Essentially, it would provide sufficient information to better understand the dispersion flow behavior and to assess the reproductive accuracy in comparison with other predictive models.

1.3 Thesis structure

In the next chapter, the characteristics of the single- and two-phase free jet flows will be reviewed to understand the conceptual aspects of such flow kinds. The related work in the field of two-phase air/ liquid free jets will be studied in the third chapter to shed light on the trials that are relevant to this subject. The experimental investigations with a description of the instrumentation and the methodology as well as the experimental results such as the mean droplet velocity and size spectra will be presented in the fourth chapter. Later on the analytical investigations involving self-proposed correlations and the derivation of trends are to be discussed in the fifth chapter. The sixth chapter focuses on the implication of the results along with the drawbacks encountered in the model validity and recommendations for further work. The seventh and the final chapter is a summary of the most important results.

2 Characteristics of single- and two-phase free jet flows

Free jet flows are established with particular behavior of mixing the content of the free jet with the surrounding, i.e., entraining the ambient fluid into the jet flow. For the sake of illustration, single-phase free jet flow is described in the next section.

2.1 Single-phase free jet flow

The release of a single-phase from a nozzle is considered as turbulent flow, where the Reynolds number, calculated based on the outlet conditions, is in excess of 5000 - 8000. Fig. 1 depicts the classification of air entrainment into the jet flow as was previously investigated. According to Chiang et al. [12], Epstein et al. [21], Hirst [36], Muralidar [73], Ooms [76], Schefer et al [89], Tickle et al. [99] or Woodward [114], the entrainment process can be classified into three main regimes dominated by:

1. Momentum. The jet flow is typically characterized in this regime by a dispersion flow originates from a venting nozzle to the ambient, where the storage pressure is normally higher than that of the ambient. At the nozzle outlet, this pressure difference will be converted into other forms mostly the kinetic energy. Consequently, the jet flow will be establishing with a significant outlet velocity higher than that of the ambient. With the nozzle downstream distance, the mean jet velocity will decrease due to mixing of the jet content with the ambient. The degree of mixing or so called the entrainment in this regime provides the potential for the decrease of the mean jet velocity and, hence, the rate of momentum transfer between the jet flow and the ambient.

2. Buoyancy/ gravity. The entrainment process is influenced in this regime to a great extent by the physical properties of the jet content, especially in the case of dense fluid dispersion of a distinctly different density from that of the ambient. The jet flow losses its momentum to the surrounding. The jet flow raises in the ambient due to the buoyancy effects in case of lower fluid density than that of the ambient, or settles down under the gravity force in case of high fluid density. At the final stage of this regime, the jet flow touches the ground level leading to wet the contact area and forming the liquid pool.

3. Atmospheric turbulence. The jet flow in this regime is sufficiently mixed and approaches an asymptotic condition close to that of the ambient. In reality, an alteration in the thermal or in the turbulent state of the atmosphere may happen leading to the evaporation from the pool. The entrainment is then affected to a great extent by the ambient state.

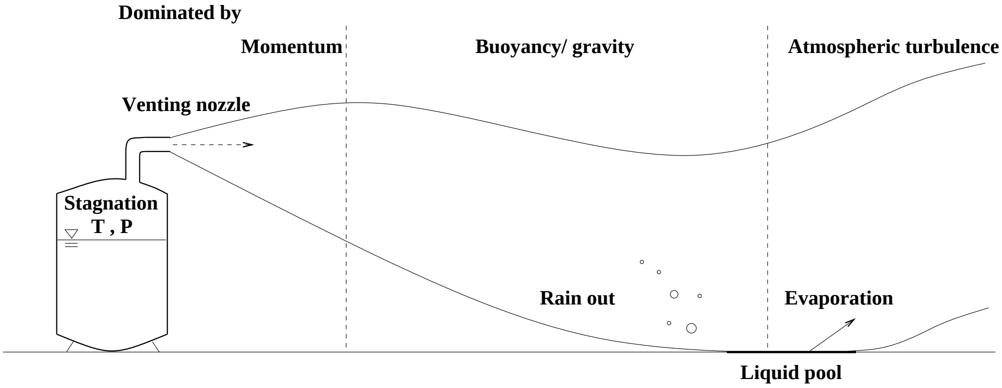

Fig. 1: Classification of air entrainment into a turbulent dispersion from a nozzle (dimensions of the Momentum dominated regime are overscaled)

For an estimation of the dominating length of each regime, Chiang et al. [12] and Epstein et al. [21] proposed field criteria to distinguish between the domination boundaries of the Momentum and the Buoyancy/ gravity regimes. In the near field, they define the Momentum length scale, while the Buoyant length scale was suggested for the far field regime. The length scales were determined according to the following correlations

$$L_{Moment} = \frac{u_{jet} \cdot d_{Nozzle}}{u_{Nozzle} \cdot C_{Ent,\,Moment}}$$

$$L_{Buoy} = \frac{g \cdot u_{jet} \cdot d_{Nozzle}^2 \cdot \left(T\left(P_{outlet}\right) - T\left(P_{ambient}\right)\right)}{u_{Nozzle}^3 \cdot T\left(P_{ambient}\right) \cdot C_{Ent,\,Buoy}} \quad ,$$

where L_{Moment} and L_{Buoy} are the Momentum and the Buoyant length scales. u_{jet} is the mean jet velocity. $C_{Ent,\,Moment}$, $C_{Ent,\,Buoy}$ are the entrainment coefficients for the regimes dominated by Momentum and Buoyancy/ gravity effects. The Momentum length scale was determined by the downstream location where the jet velocity approaches that of the ambient. While, the Buoyant length scale was determined based on the downstream distance where the evaporation of the dispersed fluid is obvious. In the study by Epstein et al. [21], the entrainment process dominated by Momentum and Buoyancy/ gravity effects were only considered and given the values of 0.1, resp., 0.5 to the entrainment coefficient. The Atmospheric turbulence effects were neglected since the phase change was presumed to be established within the Buoyant/ gravity dominated regime. In general, the proposed values for the entrainment coefficient vary according to their definition. The entrainment coefficient is typically defined according to two common entrainment models used in the dispersion codes, namely the Morton et al. [72] and Ricou et al. [86] definitions. For illustration, a single-phase air free jet flow into the ambient will be considered. The definitions of the entrainment coefficient according to these models read

$$C_{Ent} = \frac{u_{Air(P_{ambient})}}{u_{Air_{jet}}} \qquad \text{Morton et al. [72]}$$

$$C_{Ent} = \frac{u_{Air(P_{ambient})}}{u_{Air_{jet}}} \sqrt{\frac{\rho_{Air(P_{ambient})}}{\rho_{Air_{jet}}}} \qquad \text{Ricou et al. [86]}$$

Here $u_{Air(P_{ambient})}$ and $u_{Air_{jet}}$ are the air velocity of the ambient and the jet flow. Webber et al. [107] and Buchlin et al. [9] illustrate in a detailed comparison of the above entrainment models an appropriate selection of the values for the single-phase entrainment coefficient. The only difference between these definitions is that Ricou et al. [86] accounts for the density ratio of the ambient air to that of the jet while Morton et al. [72] disregards the effect of the density ratio on the entrainment. Indeed, the predictions by these models are apparently different when applied to the case of free jet flow of fluid with physical properties distinctly differ from those of the ambient air. In total, the applicability of the relevant entrainment model will differ according to the regime of interest.

The overall mass balance on the jet flow considering the entrainment processes in the three regimes reads

$$\frac{d[\rho \cdot u \cdot A]_{jet}}{ds} = \dot{M}_{Ent,\,Total} = \dot{M}_{Ent,\,Moment} + \dot{M}_{Ent,\,Buoy} + \dot{M}_{Ent,\,Atmos}$$

$$= \frac{\pi}{2} \cdot d_{jet}(s) \cdot \rho_{Air(P_{ambient})} \cdot \Big(C_{Ent,\,Moment} \cdot u_{jet}(s) + u_{Air(P_{ambient})} (C_{Ent,\,Buoy} + C_{Ent,\,Atmos}) \Big) \quad ,$$

where $\dot{M}_{Ent,\,Total}$ is the total entrainment rate. $d_{jet}(s)$ and $u_{jet}(s)$ account for the jet diameter and the velocity with the downstream distance. The total entrainment rate into the jet flow is taken as the summation of the three individual entrainment rates. $C_{Ent,\,Moment}$, $C_{Ent,\,Buoy}$ and $C_{Ent,\,Atmos}$ are the entrainment coefficients for the Momentum, the Buoyancy/ gravity and the Atmospheric turbulence dominated regimes. Typical values for these entrainment coefficients are listed in Tab. 1.

Model	$C_{Ent,\,Moment}$	$C_{Ent,\,Buoy}$	$C_{Ent,\,Atmos}$
Muralidar [73]	0.081	0.5	1.0
Tickle et al. [99]	0.074	0.6	1.0
Ooms [76] and Chiang et al. [12]	0.057	0.5	1.0
Woodward [114]	0.04	0.2	0.25

Tab. 1: Typical values for the entrainment coefficients in the Momentum, Buoyancy/ gravity and Atmospheric dominated regimes

Clearly, the value stated for the entrainment coefficient in the Momentum dominated regime is relatively lower than those for the other regimes of Buoyancy/ gravity and Atmospheric turbulence. This is attributed to the smaller jet periphery in comparison to that in the other regimes. For instance, Muralidar [73] had chosen the entrainment coefficient as 0.081, 0.5 and

1.0 for $C_{Ent,Moment}$, $C_{Ent,Buoy}$ and $C_{Ent,Atmos}$. The Momentum dominated regime entrainment coefficient had been chosen to match the experiments by Ricou et al. [86]. Tickle et al. [99] proposed a model for single-phase dense gas dispersion flows proposing values of 0.074, 0.6 and 1.0 for the entrainment coefficient in the Momentum, the Buoyancy/ gravity, resp., the Atmospheric turbulence dominated regimes. Accordingly, the entrainment coefficient follows the Morton et al. [72] model, where no consideration is given to the jet properties variations from those of the ambient. Ooms [76] and Chiang et al. [12] assumed the value of 0.057 for the entrainment coefficients in the Momentum dominated regime obtained from stack gas releases data, while the entrainment coefficient for the Buoyancy/ gravity and for the Atmospheric turbulence regimes are identical to those used by Muralidar [73]. The entrainment coefficients were given values of 0.04, 0.2 and 0.25 by Woodward's model [114] in the Momentum, the Buoyancy/ gravity and the Atmospheric dominated regime. In general, these models propose different values for the entrainment coefficients in order to fit the experimental data in the relevant regime, as well as to account for the jet flow changes with the downstream distance. Many industrial applications focus on the entrainment process in the momentum dominated region. This fact will be described in more details in the next section.

2.1.1 Gas free jet flow

The idealized behavior of a stationary, compressible, subcritical, single-phase gas free jet flow from a nozzle into a quiescent ambient with the same pressure, is depicted in Fig. 2. Downstream of the nozzle, an idealized time-averaged mean boundary is established between the jet flow and the ambient. It is highly unstable and subject to rotational flow instabilities that eventually lead to the formation of large scale vortical structures as indicated by the arrows. The interaction of these structures with the surrounding produces strong flow fluctuations, entraining ambient fluid into the jet fluid, and enhancing the mixing. The jet flow is, by convention, characterized by three distinct regions. The Core region with a conical velocity profile in which only the centerline nozzle outlet velocity is preserved. Ultimately, the core region disappears at a downstream distance of about five nozzle outlet diameters. Further downstream, the flow enters the Transition region where the jet boundary spreads due to the entrainment. Then the jet flow ideally establishes a rotationally symmetric velocity profile, or what is called the bell-shaped velocity distribution. The maximal axial velocity is found on the jet centerline.

The velocity decreases in the radial direction towards the jet periphery to equalize - on average - to that of the surrounding, if a quiescent ambient does not prevail. The so called half jet spread angle, $\beta_{0.5}$, is the inclination angle of the line that passes through the half way point of the maximum velocity at each axial distance and the jet centerline. The half jet spread angle is related to the entrainment coefficient that characterizes the amount of the entrained gas into the jet, and the corresponding self-establishing virtual origin that is determined by the downstream distance between the intersection point and the nozzle outlet.