Size and velocity distributions of droplets in an air-water horizontal pipe flow

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Abstract

We investigate the formation and entrainment of droplets occuring in gas-liquid horizontal pipe flows due to the shear applied on the liquid layer by the faster gas stream. Detection and tracking of the droplets is performed by processing the images obtained in the center of the pipe using a high-speed camera. We show that the bag and ligament break-up mechanisms are responsible for the liquid fragmentation. We also discuss in detail the distributions obtained for the size and velocity of the droplets.

Introduction

In several regimes of gas-liquid pipe flow (including wavy-stratified and annular flows), droplets formation is induced by the shear applied on the liquid layer by the faster gas stream. This phenomenon is of interest in many industrial processes, such as oil extraction, for it leads to mass and momentum transfer between the phases [1]. The knowledge of the characteristics of entrained droplets in the dispersed phase is a first step towards a better understanding of the atomization and redeposition processes at the interface. We have therefore investigated these characteristics for a horizontal air-water pipe flow. In this work, we will focus on the flow regime where atomization occurs but the flow still remains stratified. The liquid layer flows on the bottom of the pipe but displays large fluctuations of elevation corresponding to the passage of roll waves. This regime is usually termed “wavy-stratified with atomization”. Though the entrainment of droplets has received considerable attention in the subsequent regime, the annular flow, to our knowledge, no measurement is available up-to-now in the literature for this regime, in part because of the lower impact on the pressure loss of droplets atomization and redeposition.

Materials and Methods

The experiments were performed for an air-water flow in a horizontal pipe (diameter 5cm, length 5m). The different flow regimes occuring in this configuration were mapped out in the plane of the parameters (U_{gs}, U_{ls}), where U_{gs} is the superficial gas velocity and U_{ls} the superficial liquid velocity. We investigate the wavy-stratified regime with atomization in the range $0.06 < U_{ls} < 0.13\,\mathrm{m/s}$ and $13 < U_{gs} < 17\,\mathrm{m/s}$.

Measurements of the pressure loss were carried out for different flow regimes using a differential pressure transducer between two pipe sections located 3m-apart. In parallel, a high-speed camera together with a telecentric lens were used to record the position of the air-liquid interface. Image processing then allowed us to obtain estimations of the liquid layer thicknesses, of the celerity of the roll waves and of their frequencies for different values of U_{gs} and U_{ls}.

The atomization process was investigated using a high-speed camera (6000 images per second). This had to be associated to a 20-ns flash lamp to get motion-blur-free images (especially for the smaller droplets). The volume of observation is located in the center of the pipe. In order to investigate a large range of drop sizes, we used two fields of view: of length 15.4 mm, depth of field 4 mm and resolution 15.02 μm/pix; and of length 8.6 mm, depth of field 1.6 mm and resolution 8.38 μm/pix. With the latter, droplets as small as 30μm in diameter could be measured. Image calibration and processing were then used to discriminate the droplets present in the volume of observation from those which were out-of-focus thanks to a gradient-based method and to retrieve their equivalent diameter from their area in the image. Together with the droplet detection program, a droplet tracking routine was developed using a multi-hypothesis method [2] in order to follow the droplets along a sequence of images and to obtain their vertical and horizontal velocities. Both programs were implemented using the Matlab Image Processing Toolbox.

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Results and Discussion

As illutrated in figure 1, video recordings revealed that primary atomization mainly occurs through two mechanisms: bag- and ligament-breakup, like in the case of a single drop [3] or of a liquid jet sheared by a high-velocity gas stream [4]. In the present case, however, the characteristic sizes of the ligaments and bags varies from a few millimeters to a few centimeters. Therefore, the range of size of droplets produced can be expected to be quite large. We also observed that secondary atomization due to collisions between drops (or even drop break-up) is a frequent phenomenon that may have a greater importance in the reduction of droplets sizes than previously considered. An example of collision of two drops is shown figure 2.

Digital image processing allowed us to measure the probability density functions of droplets sizes and velocities. It appears that the droplets size distributions are more peaked and have heavier tails than the corresponding fitted (log)normal distribution. Notably, the distribution presents a heavy tail at large drop diameters (> 0.5 mm), which gives the predominant contribution to the mass of entrained droplets. Analysis of the joint distributions of sizes and horizontal velocities revealed that the most numerous droplets (diameters about 100μm) travel at a velocity close to the gas speed, while large drops travel at much lower velocities. The corresponding distribution of vertical velocities is also non-Gaussian, displaying exponential power tail-off. Moreover, the power of the exponent is not the same in the two tails and the distribution exhibits a smooth peak at a negative velocity value (≈ -0.5 m/s) between these two tail regimes. It appears that droplets of large size are responsible for the larger weight of positive vertical velocities. However, most droplets ($\approx 70\%$) present negative vertical velocities. The introduction of a characteristic life time of the droplets allowed us to shed some light on the shape of the distributions by separating drops that are still accelerating, and probably freshly atomized, from those that have already reached their terminal velocity.

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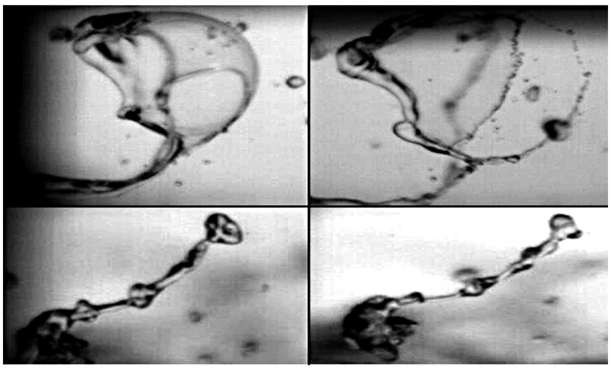

Figure 1. Primary atomization: upper figures: bag break-up; lower figures: ligament break-up.

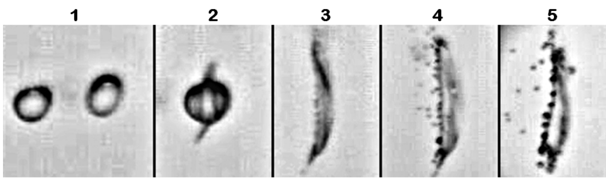

Figure 2. Secondary atomization: impact of two droplets in the dispersed phase.