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BUBBLE FORMATION IN A CO-FLOWING AIR-WATER STREAM

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Summary The present work investigates the generation of bubbles in a co-flowing air-water stream from the analytical as well as the experimental point of view. We first study the effect of the outer shear layer on the stability properties of two co-flowing streams of different density moving with different velocities. On the second part of the work we concentrate on the non-linear mechanisms leading to the formation of bubbles. The analytical results given by a model proposed here are compared with experiments.

Laminar co-flowing streams are present in many natural processes as well as engineering applications such those taking place in chemical reactors and modern material manufacturing among others. In particular, the present study focuses on some new aspects related to the formation and stability of laminar, coaxial gas-liquid jets of great relevance in bubble generation processes. Several mechanisms, previously unexplored in the literature, are expected to influence the formation of bubbles in a submerged coaxial air-water jet configuration. More precisely, we study the influence of the outer shear layer generated by the difference of velocity between the external co-flowing liquid stream and the quiescent surrounding liquid from the analytical as well as the experimental point of view. The variety of mechanisms appearing in the bubble generation problem suggests the idea of isolating and exploring them separately. Thus the different aspects analyzed in this work are summarized as follows.

We first studied the stability of two coflowing streams with finite crosstream extent in a cylindrical geometry. Transition curves from convective to absolute instability were obtained in terms of the control parameters, namely, inner to outer fluid density ratio, S, outer fluid to inner fluid velocity ratio, Λ, and, more importantly, external to internal nozzle diameter ratio, a. A new mode of instability caused by the external shear layer included in the velocity profile was identified. It was also found that this mode was responsible for triggering the absolute instability of configurations considered convectively unstable in the limit $a \to \infty$. Moreover, it was shown that, when $\Lambda = 1$, the critical density ratio necessary to sustain absolute instability in axisymmetric jets decreases with the diameter ratio as $S_c \propto a^{-4}$. In more general situations, where $\Lambda \neq 1$, two modes of instability associated respectively with the inner and the outer shear layers coexist. The analysis revealed that the outer shear layer has a significant effect on the stability of the internal interface, especially for light jets, corresponding to $S < 1$, when a is sufficiently close to unity. Furthermore, a new region of absolute instability was described in the a–Λ–S parameter space.

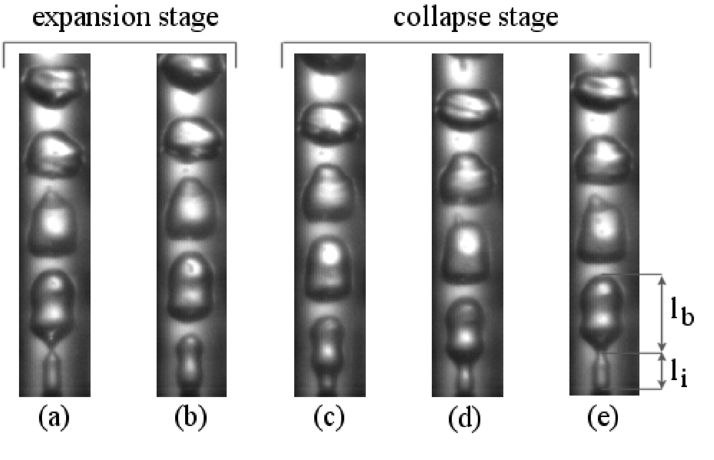

Figure 1. Temporal sequence of images illustrating the two different stages of the bubble formation process, namely *expansion stage* and *collapse stage*. Here l_i and l_b indicate the length of the intact ligament and the bubble respectively.

Once the effect of the external shear layer was described, we concentrated on the formation of bubbles in a co-flowing stream of water, $S = 10^{-3}$, without external shear layer. In this particular problem, the experiments were performed by discharging a water co-flow, which surrounded an air stream, directly into a stagnant air atmosphere. This simplified problem revealed different features which, to our knowledge, had never been reported before. More precisely, two different flow regimes were identified depending on the liquid (outer fluid) to gas (inner fluid) velocity ratio, $u_l/u_g = \Lambda$. For small values of Λ, a *bubbling regime*, characterized by a periodic bubble formation, was found. On the other hand, for values of the velocity ratio larger than a critical one which depends on the gas Weber number, $\Lambda > \Lambda_c$, a *jetting regime* with a long, stable gas jet forming inside the core of the liquid stream was observed. The transition between both regimes

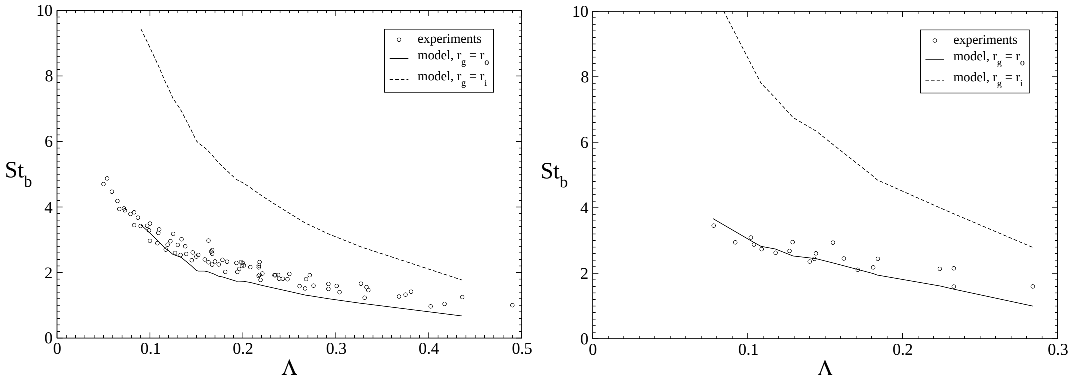

Figure 2. Comparison between the experimentally measured bubble formation frequency and that obtained by the developed model.

was satisfactorily explained in terms of a change in the absolute or convective nature of the instabilities. Regarding the bubbling regime, systematic experiments were performed to characterize the bubbling frequency and the gas ligament intact length, l_i. It was shown, both through experimental evidence and theoretically, that gas compressibility effects were essential during the initial stages of the bubble formation process. Thus, the process was divided into two different stages, namely the *expansion stage* and the *collapse stage*. A sequence of a bubble growth and pinch-off, including the expansion and the collapse stages, is depicted in figure 1. The first stage was theoretically studied by means of the compressible, one-dimensional Navier-Stokes equations for the gas flow, both inside the needle and the bubble. The study revealed that, similar to what happens in a water-hammer phenomenon, the gas pressure inside the bubble initially increased to values of the order of $\Delta p = \rho_g c_0 u_g (1-\Lambda)$ caused by the rapid pinch-off of the previous bubble. Here ρ_g is the gas density, c_0 is the sound speed at the air injection conditions and u_g is the gas injection velocity. Furthermore, the initial overpressure Δp decreased with time due to the bubble growth caused by the liquid acceleration. Since it was observed that compressible effects only took place during the expansion stage, the gas flow inside the bubble could be treated as being approximately incompressible during the rest of the process. In addition, a model to determine the bubbling frequency was developed taking into account the liquid inertia thanks to the use of the Rayleigh-Plesset equation in a cylindrical geometry. It has to be pointed out that the condition that determined the numerical frequency in our model was the neck collapse. This approximation was significantly different from that followed in other related works such those of [2], [1] or [3], where the bubble detachment was imposed as an ad-hoc condition. Experimental results of the dimensionless break-up frequency, St_b, is shown in figure 2 along with the results given by our one-dimensional model.

To conclude, once the different experimentally observed features of the simplified problem were satisfactorily explained, we faced the more complex problem of considering the influence of the external shear layer in the bubble generation process. For this purpose, we injected the co-flowing liquid stream into a stagnant liquid vessel. Similarly to what was observed in the previous simplified problem, two different flow regimes were obtained. In the first regime, occurring for low enough values of the velocity ratio, the flow was observed to be highly periodic due to the non-linear expansion-collapse mechanism described above. Although, in the second regime, which appeared for higher values of the velocity ratio, the flow was also nearly periodic, its presence was qualitatively well explained by the existence of an absolute instability in the system triggered by the external shear layer formed between the liquid coflow and the stagnant surrounding liquid atmosphere.

CONCLUSIONS

The formation of bubbles in a cylindrical co-flowing configuration was investigated here. It was determined that the outer shear layer caused by the difference of velocity between the outer water stream and the stagnant water of the reservoir could trigger the formation of bubbles if the outer diameter of the co-axial nozzle was not sufficiently larger than the inner one. In addition the characteristic of an air-water stream under the assumption of infinitely large outer to inner jet diameter ratio was studied. Under those conditions, two different regimes were described, namely *bubbling* and *jetting*. Furthermore, similar to what happens in a water hammer phenomenon, the bubbling regime was observed to be initially influenced by the overpressure generated by the rapid pinch-off of the previous bubble. The analytical results were satisfactorily compared with the experimental ones.

References

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