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# Numerical study of three-dimensional droplet impact on a flowing liquid film in annular two-phase flow

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## HIGHLIGHTS

- 3D droplet deposition process in annular flow is studied in detail.
- 3D simulation of droplet impacting on flowing liquid film with a shallow angle.
- Atmospheric and high pressure conditions are taken into account for two cases.
- A new CV-FE method is employed for 3D interfacial flows with surface tension.
- The numerical framework also features an anisotropic adaptive mesh algorithm.

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## ABSTRACT

Annular flow with liquid entrainment occurs in a wide variety of two-phase flow system. A novel control volume finite element method with adaptive unstructured meshes is employed here to study three-dimensional droplet deposition process in annular two-phase flow. The numerical framework consists of a 'volume of fluid' type method for the interface capturing and a force-balanced continuum surface force model for the surface tension on adaptive unstructured meshes. The numerical framework is validated against experimental measurements of a droplet impact problem and is then used to study the droplet deposition onto a flowing liquid film at atmospheric and high pressure conditions. Detailed complex interfacial structures during droplet impact are captured during the simulation, which agree with the experimental observations, demonstrating the capability of the present method. It is found that the effect of the ambient pressure on the fluid properties and interfacial tension plays an important role in the droplet deposition process and the associated interfacial phenomena.



## 1. Introduction

Droplet impact on solid or liquid interface is a ubiquitous phenomenon in many engineering applications, such as inkjet printing, spray painting and coating, spray cooling, internal combustion engines, liquid atomization and cleaning (Yarin, 2006). Although this fascinating fluid mechanics problem and its associated phenomena have enjoyed significant attention in the literature, much less attention has been given to droplet impact in annular two-phase flows.

In annular two phase gas-liquid flow, part of the liquid phase flows as a liquid film on the channel walls and the remaining liquid flows as droplets entrained in the gas core of the flow. Droplets are continually being entrained from the film surface and are redeposited back onto the surface. In annular flow, the 'dryout', 'burnout' or Critical Heat Flux (CHF) condition corresponds to the drying out of the liquid film which occurs when the evaporation rate of the film exceeds that required to evaporate liquid flowing along the film from upstream plus the liquid which is transported to the film by deposition of droplets (from those which are entrained in the vapour core of the flow). If the (heated) surface becomes dry, then there is a characteristic upwards excursion of wall temperature which signals the occurrence of the CHF condition. A special case is that of upstream dryout where the CHF condition occurs

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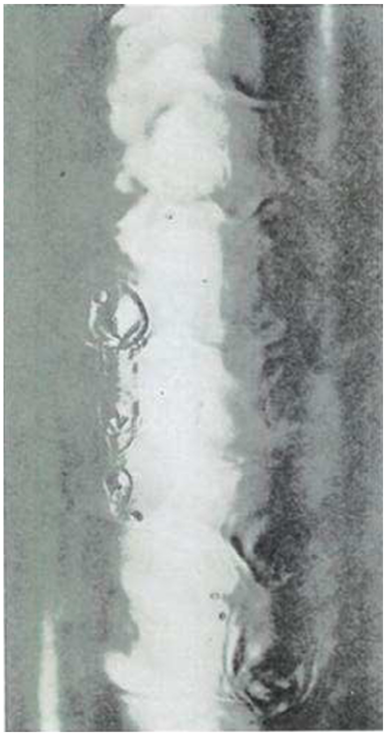

Fig. 1. Experimental picture in annular two-phase flow (Cousins and Hewitt, 1968) of depositing liquid film for a mean gas velocity of 28 m/s.

upstream of the end of the heated section; this situation may occur where the heat flux is decreasing with distance and signifies the existence of a local balance between droplet deposition and evaporation, with the flow of liquid along the film towards the dryout point being zero. One method of measuring the rate of deposition of the droplets is to extract the liquid film and to study the rate of buildup of a new liquid film by subsequent deposition. The new liquid film must, of course, be such that large waves are absent and the entrainment rate is zero. This technique was first employed by Cousins and Hewitt (1968) but was subsequently extended to high mass flow rates by Owen et al. (1985) and by Hewitt and Govan (1990). An alternative method for determination of the rate in heated systems is to determine the position of upstream dryout in a non-uniformly heated tube (Bennett et al., 1967). In the case of the non-uniformly tube and at the upstream location of dryout, there is equality between the rate of evaporation and the rate of deposition. Results obtained by the two methods were in agreement and showed the strong decrease of deposition coefficient with increasing droplet concentration. Hewitt and Govan (1990) correlated both deposition coefficient and entrainment rate and were able to track the change in film flow rate with position in the channel. This allowed prediction of the conditions under which the film flow rate became zero, corresponding to the onset of dryout (at the end of the channel in the case of a uniformly heated channel and, depending on the heat flux distribution, upstream dryout or dryout at the end of the channel). A comprehensive review on the droplets in annular two-phase flow can be found in Azzopardi (1997).

Annular flow with liquid entrainment occurs in a wide variety of two-phase flow system. Only few studies have reported the droplet deposition process for naturally entrained droplets back onto the liquid film. Cousins and Hewitt (1968) reported extensive and detailed measurements of droplet deposition in air-water annular flow and the results suggest that, in the case of deposition in annular flow at low film flow rates, all of the liquid deposited remains attached to the film at the wall. This result is surprising in that droplets are often seen to bounce from a wall liquid layer (as exemplified by droplets impinging on a falling liquid film). The experimental results seem to show that, in the presence of the high gas velocities characteristic of annular flow, the droplets do not bounce: rather, they are more slowly decelerated and leave a streak as they impinge on the film and slow down to be part of the film. The evidence from the experiments (as shown in the example in Fig. 1) is that all the droplets are absorbed into the film. This total absorption is an important feature of models for film dryout. Pham et al. (2014) performed backlit visualisation of gas-sheared liquid film on the outer surface of a cylinder – part of a rod bundle. They presented a number of impact events with formation of a liquid ligament and creation of secondary droplets. Alekseenko et al. (2014) investigated droplet impacts in downward annular flow using laser-induced fluorescence (LIF)-technique in one longitudinal section of the pipe. They have measured maximum depth and width of the craters, created by impacting droplets, together with spreading velocities and typical lifetime in a wide range of experimental conditions. Cherdantsev et al. (2014) studied the three-dimensional wavy structure and liquid entrainment for gas-sheared liquid film in an horizontal rectangular duct. Recently, Cherdantsev et al. (2017) studied droplet impacts in horizontal gas-sheared liquid film using LIF technique. The parameters of impacting droplets and local film thickness were measured in both longitudinal and transverse coordinates with highly-resolved spatial and temporal resolution. Two main scenarios were identified including a crater appears on film surface for large angle impact and a long narrow furrow appears for shallow angle impact.

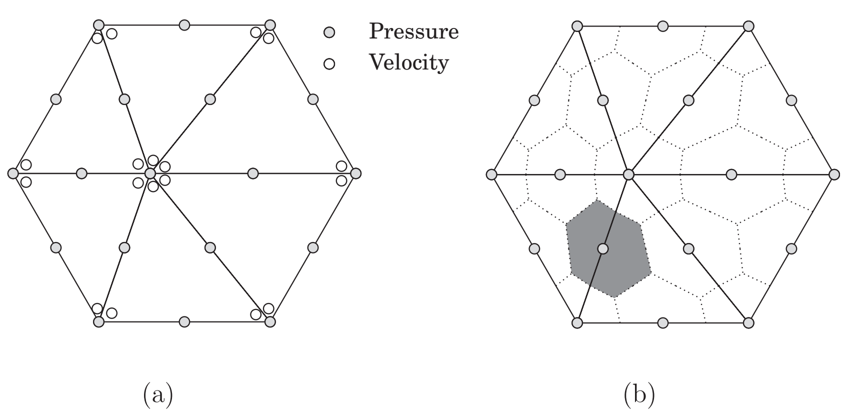


Fig. 2. (a) Finite element used to discretise the fluids equations. The central position of key solution variables are indicated here for the $P_1DG$-$P_2$ element pair (Pavlidis et al., 2016); (b) diagram showing the relationship between intersecting control volumes (shaded area) and elements for the $P_2$ element.