Binary water droplet collision study under conditions typical for nuclear reactors

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Abstract

During the course of a hypothetical severe accident in a Pressurized Water Reactor (PWR), spray systems are used at the top of the containment to ensure a mixing of the atmosphere, to reduce the total pressure, to cool down the containment walls, and to wash-out the suspended fission products. The efficiency of the spray system depends on the evolution of the droplet size distribution in the containment, in particular because of possible droplet collision.

This presentation is concerned with the various outcomes of binary droplet collisions under various gas conditions, simulating those of a hypothetical nuclear reactor accident. The purpose of the present work is thus to extend the previous results on water droplet collision by studying a wider range of parameters typical of reactor conditions and to analyze those that can be involved in the bouncing regime.

Keywords: collision, coalescence, bouncing, droplet, water, Weber, density, viscosity, Ohnesorge, Knudsen

Introduction

Spray systems are emergency devices designed for preserving the containment integrity in case of a severe accident in a Pressurized Water Reactor. These systems are used to prevent overpressure, to cool down the enclosure atmosphere, to remove fission products and to enhance the gas mixing in case of hydrogen presence in the reactor containment. The efficiency of these sprays depends partially on the evolution of the droplet size distribution in the containment, due to gravity drag forces, heat and mass transfers with the surrounding gas, and droplet collisions. Spray systems in reactor applications are composed of over 500 interacting water droplet sprays with droplet diameters range from 100 to 1000 µm. They are used under pressure (2-3 bar) at temperature between 20 and 60 °C, and under gaseous mixture composed of water steam, hydrogen and air.

This paper is concerned with water droplet coalescence. According to literature (Orme [1], Figure 1), five collision regimes can be distinguished: coalescence with minor deformation, bouncing, coalescence with major deformation, reflexive and stretching separation. In most studies, the collision process is characterized by three parameters: the Weber number We_s, the dimensionless impact parameter b and the diameter ratio Δ, which depend on the large droplet diameter d_l, the small droplet diameter d_s, the droplet relative velocity U, the liquid density ρ_{liq}, the surface tension coefficient σ and the dimensional impact parameter x (Figure 2):

$$We_s = \frac{\rho_{liq} d_s U^2}{\sigma} \qquad b = \frac{2x}{d_l + d_s} \qquad \Delta = \frac{d_s}{d_l}$$

These parameters are used to determine the transition curves between all binary collision outcomes domains.

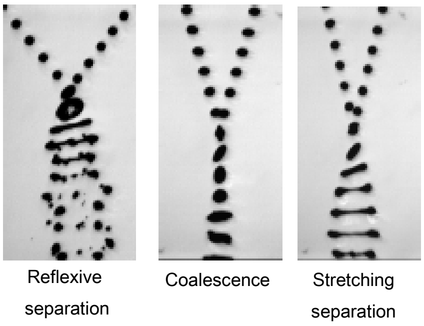

Figure 1. Collision outcome for water droplets under ambient pressure and temperature conditions

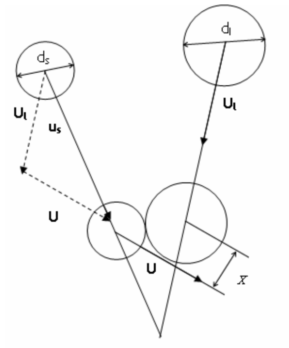

Figure 2. Geometrical sketch of the dimensional impact parameter x

Most available studies concern fuel droplets for a Weber number lower than 250. Only a few studies were performed with water droplets. Ashgriz & Poo [2] used, under ambient conditions, water droplets between 100 and 500 µm in diameter and proposed models for the transition curves in terms of We_s, b, and Δ. These transition curves depend also on the gas conditions, as shown by Qian & Law [3], and on droplet characteristics, as studied very recently by Gotass *et al.* [4].

However, there are no available experimental data for collision outcomes under conditions typical of a hypothetical nuclear reactor accident, i.e. a gas mixture of air, steam and hydrogen, with suspended aerosols (fission products), under a pressure between 1 and 5 bar and a temperature of 60°C up to 140°C. Because of the wide scope of possible collision outcomes under these conditions, a stepwise approach was adopted: the focus here is on the influence of gas properties, i.e. gas mixture composition and total pressure. Gas temperature and aerosol concentration, that can influence the droplet characteristics (viscosity, surface tension), are not considered here, so that the proposed experiments avoid any changes in those parameters. A mixture of air and helium was chosen for simulating air-hydrogen gas mixture conditions in a wider range than in the real case in order to enhance the effects. The experimental data under pressure and some under air-helium mixture conditions were presented and analysed qualitatively at the ILASS 2008 conference, (Rabe *et al.* [5]). It was found that the bouncing regime changes with variations in gas density and viscosity. This analysis was in agreement with the earlier observation of Qian & Law [3].

The purpose of this work is to extend the experimental database under an air-helium gas mixture, and to perform a quantitative analysis of the results in terms of appropriate dimensionless numbers.

Experimental set-up and conditions

A widely used experimental method for investigating droplet collision (see e.g. Ashgriz & Poo [2], Estrade [6]) consists in producing two calibrated droplet streams with converging trajectories. Periodic binary droplet collisions then are observed and recorded. Our droplet stream generators are made of a steel tube ended by an iridium plate with a calibrated hole. A piezoelectric cell provides, with an appropriate modulation of the applied electric signal, a mechanical perturbation of the liquid jet. A growing instability along the jet ends up in the break-up of the water filament and the formation of droplets. This technique provides water droplets with specified diameters, ranging from 200 to 700 µm. Droplet velocities used in this study are between 1 and 5 $m.s^{-1}$ and droplet stream collision angles between 10 and 95°. Collisions are recorded by two cameras (for the front and side views). A large number of collisions are recorded by back-lighting the scene with a very short stroboscopic flash. Picture sequences are collected for image post-processing by a software that is appropriate for treating a large amount of data. More information can be found in Rabe [7].

One set of experimental conditions was performed under pressurized air, the total pressure ranging from 1 to 3.5 bar. For these experiments, the experimental set-up described above was introduced in a pressurized vessel built at ONERA Toulouse research centre. Results are described in detail in Rabe *et al.* [5]. For those experiments, 220 µm droplets were used with a droplet size ratio of unity. Another set of data was obtained under various air-helium mixtures (with 10, 50 and 85% in volume of helium in air) at atmospheric pressure. The experimental set-up was then confined in a large transparent Plexiglas® enclosure. Results for a 50% volume concentration were presented [5]. New results under helium conditions will be given in this paper. Droplet sizes of 260 µm are used with a droplet size ratio of unity for the air-helium tests.

Experimental results and comparison with former modelling

Experimental results under a pressure lower than 3.5 bar and for three air-helium mixtures are presented in Figure 3 and Figure 4. It is observed that the separations between the coalescence, reflexive and stretching separation regions are not significantly different from the one obtained for atmospheric conditions, i.e. from the Ashgriz and Poo model [2]. Figure 3 also shows that the Ashgriz and Poo model for transition between coalescence and both separation regimes could be used for such conditions for Weber number We_s from 30 to 120 and low impact parameter (lower than 0.7-0.8). However, for lower Weber number and higher impact parameter, a bouncing regime appears clearly. An increase in pressure leads to an extension of this regime that replaces coalescence at both low Weber number and impact parameter. These conclusions correspond to those formulated by Qian and Law [3] for higher pressures (3 to 12 bar). Since the present study is performed under lower pressure conditions, it provides an extension of former results by increasing the past database.

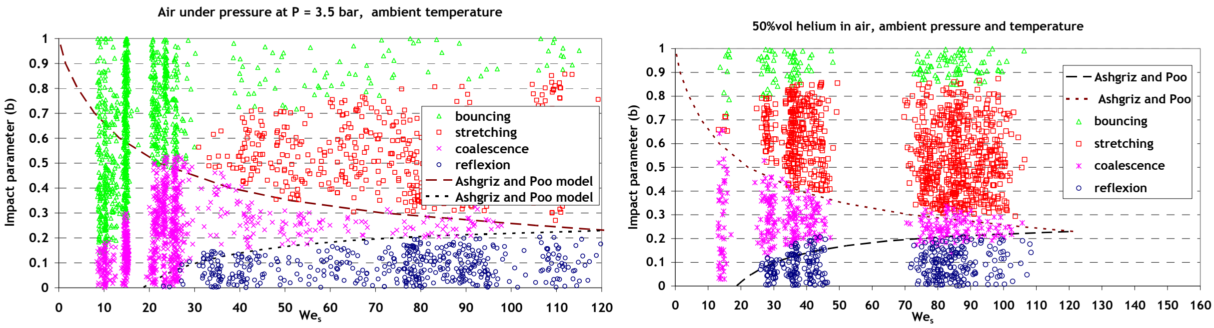

Figure 3. Results under pressure (left, from [5], *d* = 220 µm, P_{abs} = 3.5 bar) and air-helium mixture (right, *d* = 260 µm, air-50%vol helium), Δ = 1. Comparison with Ashgriz and Poo [2] for coalescence and separation regimes transitions

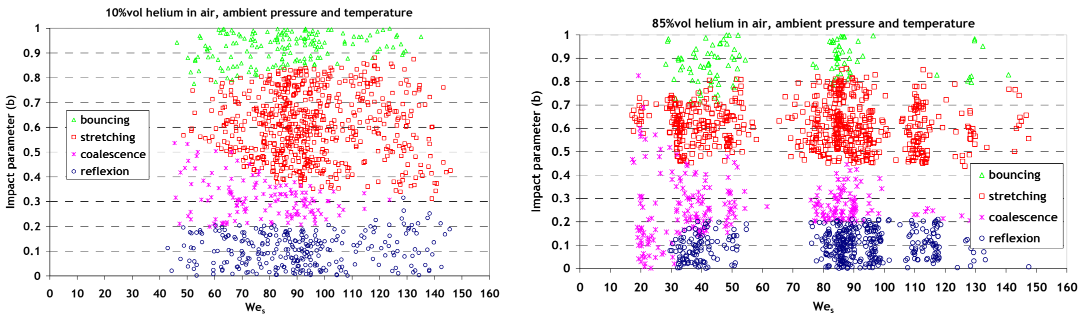

Figure 4: Experimental results under 10 and 85%vol helium in air

Our experimental results may also be compared to Estrade's empirical relationship [6] describing the bouncing transition:

$$We_{coal/bouncing} = \frac{(1+\Delta^2)(4\Phi_c - 12)\Delta}{\chi\,(1-b^2)}$$

with $\Phi c = fct(\Psi_c)$, χ is the fraction of volume interaction and b the impact parameter defined in [6].

The Ψ_c constant in Estrade's relationship was adjusted so as to fit our data. Results are presented in Figure 5. These results show that the Ψ_c constant should be modified when changing the gas environment.

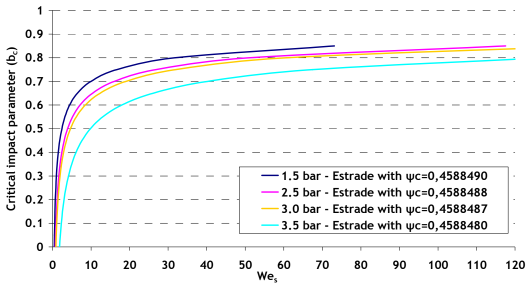

Figure 5: Estrade's relationship [5] for bouncing transition, fitted to our experimental data for pressurized gas.

Analysis of the bouncing transition and discussion

This section focuses on the analysis of the bouncing transition curve in the standard (We-b) chart. The bouncing transition curve for each experimental condition was obtained in two steps. The first step consisted in determining, on the basis of the experimental data, the critical impact parameter b_c relative to the bouncing transition for each value of the Weber number. An experimental 'raw data' curve was obtained for this critical impact parameter. The second step consisted in searching for a fitting curve based on these raw data. An example of this post-processing is given in Figure 6. The same data processing was then performed for all experimental data, so that a (We-b_c) curve was plotted for each gas condition. The corresponding (We-b_c) curve was also extracted from Qian and Law [3] and all transition curves are merged in Figure 7. It is observed that this (We-b_c) representation does not allow to fit all experimental data under various gas conditions. This was a known result on the basis of Qian and Law experiments, but these effects are clearly also observed for conditions typical for nuclear reactor accidents. A modelling of the influence of the gas conditions on droplet collision outcomes is clearly needed.

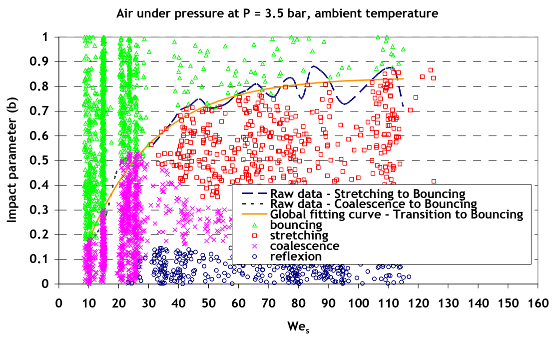

Figure 6: Example of critical impact parameter fitting curve, compared to the raw data curve and the experimental data

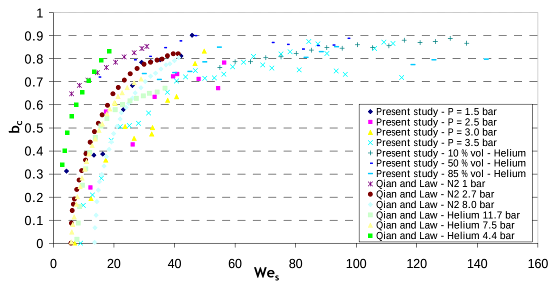

Figure 7: Bouncing transition curves obtained from various gas conditions used in this study and obtained by Qian and Law

With this goal in view, we then looked for a direct influence of some parameters when gas pressure and composition are changed. Gas density and viscosity should play a role (as mentioned in Qian and Law [3]), but as observed in Figure 8, there is no clear relation between the evolution of the shape of these transition curves and the variation of these parameters. It should be mentioned that these figures use a new formulation for the Weber number, proposed by Rabe *et al.* [8], which takes into account the energies of both droplets; for equal droplets, this so-called 'symmetric Weber number' We is 48 times lower that the classical Weber number used in droplet collisions studies.

The influence of the Ohnesorge and Knudsen numbers is presented in Figure 9. The Ohnesorge number is based here on the gas density and the droplet size:

$$Oh = \frac{\mu_g}{\sqrt{\rho_g \, d \, \sigma}}$$

The Knudsen number is based on the gas mixture mean free path and the droplet diameter. Recent studies (Bach *et al.* [9]) suggest that it is a key parameter for bouncing. As observed in the figure, there is no clear relationship between our results and these dimensionless parameters. In any case, the representation of the bouncing boundary in terms of (We-b_c) is not sufficient and the influence of gas parameters should be introduced in some way.

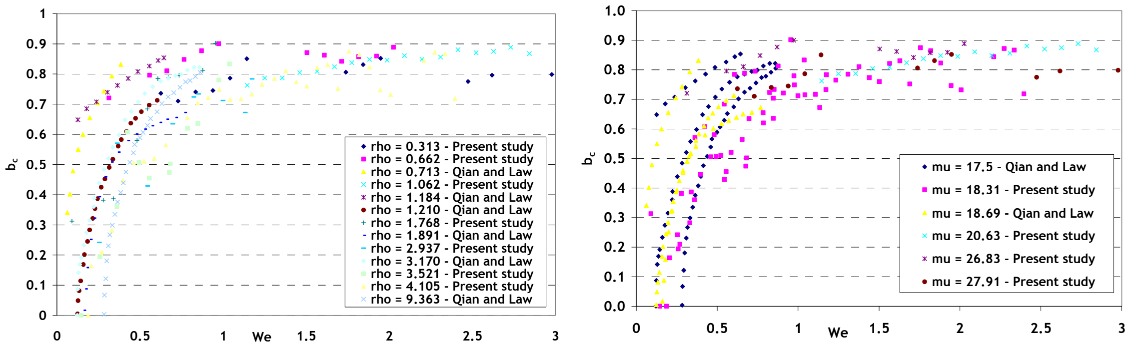

Figure 8: Bouncing transition curves obtained from various gas conditions used in this study and obtained by Qian and Law [3], plotted for increasing gas density (rho, kg/m^3) and gas dynamic viscosity (mu*10^6, Pa.s)

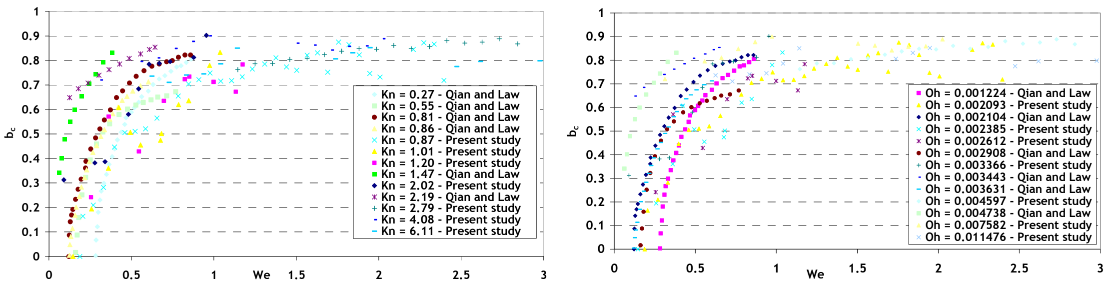

Figure 9: Bouncing transition curves obtained from various gas conditions used in this study and obtained by Qian and Law [3], plotted for increasing gas Knudsen (Kn*10^4) and Ohnesorge numbers (Oh)

In order to obtain a unified chart in terms of the critical impact parameter and another dimensionless number, various combinations were tried (product of Weber number and Ohnesorge number, product of Weber number and Knudsen number, etc.), but no significant grouping arose. Obviously, more theoretical investigations are needed in order to merge those results into a single bouncing transition curve, if such a single curve is ever sufficient.

Nevertheless, in order to formulate an empirical relation that could be used for industrial applications, the following correlation is proposed (Figure 10):

$$b_c = 0.82 - \frac{0.26}{\left(0.93 + 5\, We^{0.92} Oh^{0.56}\right)^{20}}$$

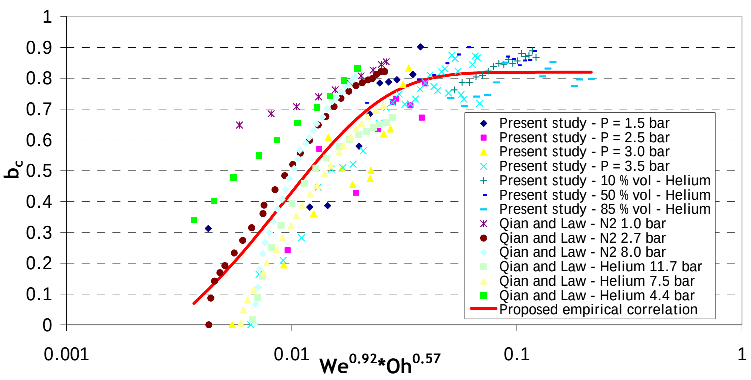

Figure 10: Proposed empirical correlation for the bouncing regime transition curve

This correlation should be strictly used in the range of parameters corresponding to the present investigation: water droplet with sizes of around 200-300 µm, droplet velocities between 1-5 m/s, pressure from 1 to 12 bar and air, nitrogen, and air-helium gas mixture conditions (from 0%vol to 100%vol of helium in air), i.e. valid for $0.1 < We < 2.8$ and $0.001 < Oh < 0.01$.

Conclusion

The existing database of experiments of water droplet collision under various gas conditions is extended to the range of pressures of 1 to 3.5 bar and helium-air mixtures gas compositions that are representative models of nuclear applications. The results have confirmed the former observations of Qian and Law [3] regarding the dependency of the bouncing transition curve on gas mixture parameters, even for pressures that are smaller than in their case.

For the point of view of theoretical understanding of the bouncing process, this study shows the difficulty of providing a simple model for the bouncing transition curve depending on some gas parameters. Knudsen and Ohnesorge numbers seem to be a good starting point for the analysis, but more investigations are needed.

As for the concerned industrial application, i.e. nuclear reactor application, the new results obtained here are important since they show that under the conditions typical of a hypothetical nuclear reactor accident the bouncing regime clearly appears, which is in favour of minimizing coalescence. These results are interpreted here in terms of an empirical correlation for the transition to bouncing that can be used in spray modelling including collision calculations.

Another outlook would be to extend the experimental database for various droplet size ratios, under ambient gas conditions as considered here.

Nomenclature

b non dimensional impact parameter
b_c critical non dimensional impact parameter
d droplet diameter
Kn Knudsen number
Oh Ohnesorge number
P_{abs} absolute pressure
U droplets relative velocity
x dimensional impact parameter
We_s Weber number based on the smaller droplet size
We symmetric Weber number [8]
σ surface tension
ρ density
Δ droplet diameter ratio
g: gas, liq: liquid, s: small, l: large

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