IN-FLIGHT COLLISION BEHAVIOUR OF DROPLETS ON A SPHERICAL PARTICLE FALLING UNDER GRAVITY


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ABSTRACT

Droplet-particle interaction is critical in design of many industrial processes. In the current work, a systematic experimental study of the impact of water droplets on a moving glass particle falling under gravity at NTP was investigated by a high speed imaging technique. The droplet and particle impact velocities were varied in the experiment independently to observe the effect on the collision outcome. In the entire operating range, the droplets were observed to undergo inelastic collision resulting into complete deposition onto the particle surface forming a thin film. Significant deflection in the particle trajectory during collision was observed at higher droplet Weber number however this deflection was observed to decrease when particle velocity was increased. Two dimensional CFD simulations were also carried out using the Volume of Fluid method in conjunction with the dynamic meshing technique resulting in qualitative agreement with the experimental observations.

Keywords: Droplet-particle collision, CFD modelling, VOF method, Dynamic mesh, Image processing

1. INTRODUCTION

Critical understanding of droplet-particle collision phenomenon is crucial to successful design of many significant industrial applications like fluidized catalytic cracking (FCC), spouted bed coating and bitumen upgrading coking process. In all such applications, feed droplets undergo direct contact with the moving solid particles. These droplet-particle collisions influences the heat and mass transfer processes significantly. In typical FCC environment, rapid impact occurs between feed droplets and particles involving very short contact time. It is thus obvious that a droplet undergoes several random collisions with particles around it before complete vaporization. Undoubtedly, the evaporation phenomenon involves fairly complex hydrodynamics and heat transfer. With the droplets and particles of different sizes having different momentum at contact, the collision of the particles and the droplets may experience different contact modes. Ge and Fan (2007) [8] suggested four different possibilities of such probabilistic nature of the collision process. Smaller droplets may rebound from the surface of a larger particle upon impact because of the nature of the non-wetting contact (Mode 1). A smaller particle may penetrate or be retained inside the larger droplet (Mode 3). Droplets may splash during the impact (Mode 2) or remain attached to the particle surface after the collision, thereby intensifying particle aggregation (Mode 4). While a significant number of studies [1,2,3,5,6,8] have been devoted to the understanding of the droplet impingement on a stationary surface, very less studies are actually reported [7] on in-flight collision behaviour of a droplet onto a moving particle. Dubrovsky et al. (1992) [7] carried out extensive experimental studies on the interaction of drops with solid particles of different sizes at moderate and high velocities. Their research shows that every collision between and droplet and particle results into droplet breakup with poydisperse fragments. Due to complex nature of droplet-particle interactions, more understanding is required in this area. To address this requirement, in this work, the in-flight droplet-particle collision process under cold condition has been studied both experimentally and numerically at different droplet and particle velocities. In particular, collision between droplets with particles was studied with the aid of high speed imaging in the droplet Weber number range of 3.1–24.4 and particle Reynolds number range of 17-45. Liquid film growth over the particle surface and deflection in the particle trajectory during collision were calculated by carrying out image analysis using an in-house MATLAB code. Numerically, a two-phase CFD model was developed using an interface tracking volume of fluid (VOF) approach implementing dynamic meshing technique to model the collision phenomena and compared with the experimental observations.

2. EXPERIMENT

2.1 Scope of experimental investigation:

In this work, experiments were carried out to investigate collision behaviour between water droplets and a particle both in motion. Specifically, in-flight droplet particle interaction characteristics were studied at different impact velocity of the droplet at room temperature operating conditions. A liquid water jet consisting of droplets in the size range of 300-500 microns diameter was sprayed onto a particle falling under gravity. The impact velocity, and hence Weber number, of the droplets was changed in the experiment by varying the impinging liquid jet flow rate. Glass ballotini particles, with average diameter of 1.17 mm, were used in the experiment. The collision phenomena between the droplets and the particle were captured by a high speed digital camera.
2.2 Experimental setup

An experimental setup (Fig. 1) with arrangement for dispensing droplets at different angles and a particle release mechanism was used. The particle release mechanism consisted of a nozzle made of Swagelok 1/16” male connector fitted with 1/16” OD tube and connected to a vacuum pump with a solenoid valve in between. The nozzle position varying mechanism (k) consisting of adjustable roller having millimetric precision was used which could be moved both horizontally and vertically. This mechanism attributed to the suitable positioning of the nozzle and different particle velocity by varying the nozzle (h) height vertically.

A digitally flow controlled syringe pump (Adelab Scientific) with arrangement for dispensing droplets at different angles was used. A fixed needle of size 30G (ID: 0.16 mm) was used to produce the droplets. The Weber number of the impinging droplets was varied by changing the flow rate of the syringe pump. The needle fitted to a 1 ml syringe was connected to the syringe pump by a soft silicone rubber tube and placed on a holder duly positioned on an X-Y optical traverse capable of producing micrometric precision movement in both directions horizontally.

![Fig. 1 Experimental set up – a) syringe pump with flow controller b) needle holding stand with droplet injection angle control mechanism c) collection container d) computer e) high speed CCD camera f) diffuser screen g) light source h) particle release nozzle i) solenoid valve j) vacuum pump k) particle release nozzle position varying mechanism l) X-Y optical traverse with height elevation jack](image1)

The impinging angle of the droplet could be varied by suitably positioning the holder by an adjustable screw and setting the angle with the protractor also positioned on the same axis of the holder. The particle position during the experiment was held constant at one end of the tube under vacuum, and released when required by turning off the solenoid valve hence breaking the vacuum allowing the particle to fall under gravity. For high contrast imaging, a high speed digital camera (Phantom v311, Vision Research) was deployed with a diffuser screen being placed between the test section and the light source. All liquid and the particle were collected in the tray kept at bottom.

2.3 Experimental methodology

The positioning of the droplet injection needle and the particle releasing mechanism was carefully conducted ensuring their proper alignment. The angle of impingement with respect to vertical plane was held constant at 52 degrees. The particle release mechanism was activated by switching on the solenoid valve and the vacuum pump respectively. The particle was held carefully with a pair of tweezers and positioned at the tube end. To ensure the particle fall was consistent, a separate experiment was carried out by dropping the particle several times from the same position. Each time the particle fall was captured by the camera and images were analysed by an in-house MATLAB code. Fig. 2 presents the normal distribution of the lateral displacement (non-dimensionalized with respect to the image width) of the particle in flight having standard deviation of +/-0.0054 which ensured consistency of the particle release process.

![Fig. 2 Uncertainty analysis of lateral displacement of the particle from a sample size of 10 follows a normal distribution pattern with average mean of 0.587 and average standard deviation of +/- 0.0054.](image2)
liquid droplets was collected in the collection tray below. A clean, dry particle was used for each experiment. The Shadowgraphy technique was used to capture high contrast images (1953 - 4069 fps, 50 – 100 µs exposure time) of droplet-particle collision process in a field of view of 512 pixels X 800 to 512 pixels X 384 pixels. An in-house image processing MATLAB code was used to mark the droplet and particle boundaries and centroid for all further analyses.

3. NUMERICAL MODELLING:

A two-phase CFD model using interface tracking volume of fluid (VOF) approach was adopted in the finite volume method based commercial solver ANSYS Fluent (version: 14). 2D models in Cartesian coordinates comprising of continuity, and momentum equations were solved as follows,

\[
\frac{\partial \rho_i}{\partial t} + \nabla \cdot (\rho_i \mathbf{u}_i) = 0 \quad (1)
\]

\[
\frac{\partial \rho_i \mathbf{u}_i}{\partial t} + \nabla \cdot (\rho_i \mathbf{u}_i \mathbf{u}_i) = -\nabla P + \nabla \cdot \left( \tau + \rho_i g \right) + F_s \quad (2)
\]

The mixture density (\(\rho_{\text{mix}}\)) and viscosity (\(\mu_{\text{mix}}\)) were calculated based on the individual phase fractions (\(\alpha\)) where,

\[
\rho_{\text{mix}} = \rho_1 \alpha_1 + \rho_g (1 - \alpha_1) \quad (3)
\]

\[
\mu_{\text{mix}} = \mu_1 \alpha_1 + \mu_g (1 - \alpha_1) \quad (4)
\]

Volume fraction of each dispersed phase was solved by the following advection equation,

\[
\frac{\partial \alpha_i}{\partial t} + \nabla \cdot (\alpha_i \mathbf{u}_i) = 0 \quad (5)
\]

while the phase fraction of the continuous phase was calculated using the following conservation equation,

\[
\sum_{i=1}^{n} \alpha_i = 1 \quad (6)
\]

The momentum equation, in addition to pressure, gravity and viscous stress, included a surface force (\(F_s\)) where

\[
F_s = \sigma \frac{\partial \alpha_i}{\partial s} \quad (7)
\]

The curvature of the interface (\(\kappa\)) used in Eq.(7) was expressed in terms of surface normal i.e.

\[
\kappa = \frac{1}{|n|} \left( \nabla \times \frac{n}{|n|} \right) \cdot n = \nabla \cdot n \quad (8)
\]

The surface normal in the VOF approach is expressed as a gradient of phase volume fraction at the interface and can be written as

\[
n = \nabla \alpha \quad (9)
\]

Wall adhesion is significant for fluids with non-zero contact angle on the surface. This effect was incorporated in the model expressing unit normal at the wall boundary in terms of unit vectors \(\mathbf{n}_w\) for fluid and \(\mathbf{f}_w\) for wall and the contact angle (\(\theta_w\)) i.e.

\[
f = \mathbf{n}_w \cos(\theta_w) + \mathbf{f}_w \sin(\theta_w) \quad (10)
\]

A 7.5 × 5.5 mm unstructured grid containing 34176 cells was used for simulation using the GAMBIT meshing tool. Domain dimensions of the mesh were determined based on the field view of the experimental images. A contact angle (\(\theta_w = 55^\circ\) for water on glass surface) boundary condition was applied on the particle surface. Pressure outlet boundary condition was applied on all the surrounding faces. A second order upwind scheme was used for discretization of the momentum equation while the volume fraction parameter and pressure were discretized using Geo-Reconstruct and Presto scheme respectively. Pressure-velocity coupling was obtained by Coupled scheme. A residual of 10\(^{-4}\) was set for convergence of continuity, momentum and volume fraction. All simulations were performed using a time step of 10\(^{-5}\) s with 40 iterations per time step. A first order implicit time stepping was used in all the simulations. To model the solid particle motion, a dynamic meshing technique was used involving smoothing and remeshing scheme on the adjacent cells of the particle boundary within the specified limits as it moved with time. The particle motion was obtained by implementing a user defined function (UDF) based on the six degree of freedom solver. The rotational motion of the particle was however not simulated in the present work.

4. RESULTS AND DISCUSSION

In the present study, the effect of droplet Weber number (\(W_e_d\)) on the dynamics of droplet collision with an accelerating particle falling under gravity was investigated. Using the height adjustment facility of the setup, the particle Reynolds number (\(Re_p = D_p u_{dp}/\mu_g\)), where \(D_p\) is particle diameter, \(u_{dp}\) is particle velocity and \(\mu_g\) are air density and viscosity respectively, before collision was varied in the range of 17 to 45. In all the experiments, the droplet Weber number expressed as ratio of inertial force to surface tension force (\(W_e_d = D_u^2 u_{dp}/\sigma\)) where \(D_u\) is droplet density, \(u_d\) is droplet velocity, \(D_d\) is the droplet diameter and \(\sigma\) is surface tension of the liquid, was varied by using the liquid jet flow rate in the range of 1.8 to 3.0 mL/min. This range of flow rates corresponded to \(W_e_d\) in the range of 3.1 to 24.4.

4.1 Single droplet-particle interaction:

At lower flow rates, the fewer large size droplets were produced with larger spacing between two successive droplets after jet breakup. After the jet breaks up, the newly produced droplets possess both kinetic and surface energy. The kinetic energy during the flight gets partly converted into surface energy due to the periodic expansion and contraction of the droplet shape and partly into viscous dissipation due to the internal motion. The droplet after impinging on the particle surface undergoes an oscillatory motion with gradually reducing amplitude. In the first oscillatory cycle, the droplet spreads until it impact kinetic energy is completely diminished [5]. This spreading/wetting behaviour largely depends on the characteristics of the particle surface. After reaching a maximum
spreading state, the droplet starts recoiling under the influence of the surface tension force. This pattern however greatly depends on the collision pattern. Fig.3 presents transient behaviour of droplet spreading ratio (spread on the surface/initial droplet diameter) of two droplets colliding at different locations on the particle surface. The top droplet collides in the direction of normal to the surface and undergoes normal oscillatory motion due to symmetric radial flow. However the droplet at the bottom collides with the particle tangentially and therefore partly dissipates its momentum on the solid surface and mostly within leading to an asymmetric flow pattern which leads to larger relatively spreading and weak recoiling on the particle surface.

Fig. 3 Droplet deformation behaviour at different locations of particle surface (injection flow rate 1.8 mL/min, We of 3.1)

The motion of the particle exerts a drag force on the droplet at the bottom location which attributes to the spreading of droplet further by the shearing action on the free surface

4.2 CFD modelling:
An accelerating particle during free fall experiences buoyancy, drag and added mass force resisting its motion. The velocity of the particle gradually increases during the fall and eventually reaches to the terminal settling velocity without any further increase. Under the operating conditions deployed in the experiment, the particle never reaches the terminal settling velocity. Including all these above forces, the velocity of the particle can be calculated solving the following 1D force balance model,

\[
\frac{d u_p}{dt} = m_p g \left( 1 - \frac{\rho_s}{\rho_p} \right) - \frac{1}{8} \pi d_p^2 \rho_s C_d u_p^2 - \frac{1}{12} \pi d_p^3 \rho_s \nu \frac{du_p}{dt} \]

(11)

Experimentally, by image processing, the velocity of the particle was calculated by determining the difference of the y-centroid with time. The CFD model of the particle fall was first validated against both the 1D force balance model and the experimental data. Fig. 4 compares the CFD simulation results of the particle velocity with position which clearly is in very good agreement with both the experimental data and the 1D model.

Fig. 4 Comparison of particle velocity with position obtained from CFD simulation, 1D model and experimental images.

Fig. 5 presents the volume fraction contour of the droplets obtained in the CFD simulations of the collision process using operating conditions of 1.8 mL/min. A number of droplets were introduced into the system to study the collision behaviour. The simulation captures the motion of the droplets and particle and qualitatively predicts the spreading phase of the droplet deformation process upon collision on the particle surface.

Fig. 5 CFD simulation shows volume fraction contour of droplets indicating both particle movement and droplet deformation during collision with the particle at different time instances a) 0.1ms b) 10ms c) 20 ms d) 21.2 ms, e) 21.4 ms f) 21.6 ms

4.3 Droplet-particle interaction outcome:
When the liquid jet flow rate was kept low - less numbers of larger size droplets were produced. At higher flow rate - more numbers of smaller sized droplets were produced along with a reduction in the clearance between two successive droplets. Due to periodic elongation and contraction of the droplets at this operating condition, when the clearance between two droplets reaches a critical value, the attractive Van der Waals force leads to coalescence. These droplets after collision on the particle surface, forms a thin liquid film over it. Fig. 6 presents
droplet-particle collision outcomes when the flow rate is gradually increased. At lower flow rates (Fig. 6a-b) larger size droplets deposit on the particle surface and coalescence begins. At higher flow rates (Fig. 6c-d), more numbers of smaller sized droplets are produced which rapidly coalesce on the particle surface and forms a thin liquid film. With more numbers of droplets available at higher flow rates, the liquid film growth over the particle surface thus increases.

At higher flow rates (Fig. 6c-d), more numbers of smaller sized droplets deposit on the particle surface and coalescence begins. Gradually increased. At lower flow rates (Fig. 6a-b) larger size droplet-particle collision outcomes when the flow rate is increased. To investigate the effect of reduction in relative velocity between droplet and particle on the liquid film growth, experiments were carried out at different particle Reynolds number over the entire range of liquid jet flow rate. Fig. 5 presents transient liquid film growth at 1.8 mL/min liquid jet flow rate where Re was varied in the range of 17-45.

Fig. 6 Experimental images of droplet particle collision indicates liquid layer growth on the particle surface at different liquid jet flow rates a) 1.8 L/min, We=3.1 b) 2.1 L/min, We=7.0 c) 2.6 L/min, We=14.6 and d) 3.0 L/min, We=24.4 at the same time instance.

Droplet-particle collision can result either splashing, sticking or deposition and rebounding depending on the impingement hydrodynamics and surface properties. Based on the extensive range of experimental data of an impinging droplet on the solid surface, the following empirical correlation of Mundo et al. (1995) [1] was used to check the splashing and deposition occurrence.

\[ K = \text{Oh}_{sys} \times \text{Re}_{sys}^{1.25} \] (12)

where \( \text{Re}_{sys} = \frac{D_d \vert u_d \vert \rho_d \mu}{\eta} \) is the system Reynolds number, system Ohnesorge number is \( \text{Oh}_{sys} = \sqrt{\text{We}_{sys}/\text{Re}_{sys}} \) and system Weber number is \( \text{We}_{sys} = \frac{D_d \vert u_d \vert \rho_d \sigma}{\eta} \). The definitions of Reynolds number and Weber number are suitably modified to include the effect of particle motion. As per Eq.(12), when the parameter \( K \) < 57.7, complete deposition of the droplet on the surface occurs while splashing occurs when value of \( K \) exceeds 57.7. Using this criterion, values of \( K \) have been calculated for the flow range (1.8 to 3.0 mL/min) investigated and \( \text{Re}_{sys} \) in the range of 17-45, the values of \( K \) was found to lie in the range of 0.5 < \( K \) < 23 implying droplets deposition on the particle without splashing which supports the experimental observation.

The rebounding criterion for impinging droplet was developed by Mao et al. (1997) [7] by carrying out an energy balance analysis at each stage of the deformation process during droplet collision on a flat surface: a) before impact, b) during maximum spread, c) maximum recoil/rebound and finally d) equilibrium or sessile state when excess energy is completely dissipated through periodic spreading and recoiling phase with temporal gradually dampening oscillations. Another fictitious stage (stage - r) was introduced in their analysis to account for excess surface energy that remained in the droplet after achieving the maximum spread stage. Based on the difference of energy at stage - c and stage - r duly normalized by the energy at stage – r, the following expression was suggested to determine excess energy for rebounding (\( E_{exr} \)).

\[ E_{exr} = \frac{1}{4} \left( \frac{d_{max}}{d_0} \right)^2 (1 - \cos \theta_w) - 0.12 \left( \frac{d_{max}}{d_0} \right)^{2.3} (1 - \cos \theta_w)^{0.63} + \frac{2}{3} \left( \frac{d_0}{d_{max}} \right) - 1 \] (13)

where \( d_{max} \) is the maximum droplet spread after impact and \( \theta_w \) is static contact angle. For a droplet to rebound after collision, the excess rebound energy should be positive i.e. \( E_{exr} > 0 \).

Several models are reported [4],[6] in the literature to determine the maximum spreading ratio \( d_{max}/d_0 \). In the present work, to evaluate \( E_{exr} \), the maximum spread ratio \( (d_{max}/d_0) \) was calculated using the following expression suggested by Chandra and Avedisian (1991) [6].

\[ \frac{3 \text{We}}{2 \text{Re}} \left( \frac{d_{max}}{d_0} \right)^4 + (1 - \cos \theta_w) \left( \frac{d_{max}}{d_0} \right) - \left( \frac{d_0}{d_{max}} \right) = 0 \] (14)

\( E_{exr} \) was calculated for all the flow rates and found to be negative in each case indicating occurrence of no droplet rebound which agreed with the experimental observation.

4.4 Formation of liquid film:

It has been discussed in the previous section that, droplet-particle interaction results into two possible outcomes – droplet may stick to the particle or it separates or rebounds. Also, part of the droplet may stick to the particle surface while the rest separates [2]. The latter phenomenon is more prominent at the higher velocity cases. The ratio at which this droplet mass splitting occurs is obtained primarily by the empirical correlations involving hydrodynamic parameters. Dubrovsky et al. (1992) [7] obtained general formulation of the fraction of droplet mass carried away by the particle during droplet-particle collisions. Based on their work, they suggested correlations based on Reynolds number, Laplace number and size ratio of droplet and particle. An analytical model was proposed by Petela & Zajdel (1980) [4] based on the balance between drag force and surface tension force, to calculate maximum film growth over the particle surface in a flowing gas stream. Their model however is not suitable to predict film thickness over particle when drag force acting on the droplet is very low similar to the operating conditions used in the present study. In absence of any suitable model to predict the liquid film growth over the particle surface, image processing technique was applied. At higher liquid jet flowrates, multiple droplets interacted with the particle followed by coalescence which gradually developed the thin liquid film on the particle surface. To investigate the effect of reduction in relative velocity between droplet and particle on the liquid film growth, experiments were carried out at different particle Reynolds number over the entire range of liquid jet flow rate. Fig. 5 presents transient liquid film growth at 1.8 mL/min liquid jet flow rate where Re was varied in the range of 17-45.
The 2D projection of the liquid film area was obtained by image processing subtracting the original surface area of the dry particle from all subsequent liquid laden images. The film thickness obtained from these areas was found to vary in the range of 0.019-0.183mm. The film area was observed to increase in general at all Re indicating interaction between the dry particle and droplets however at higher Re, this liquid film area reduces indicating lesser interaction time between the droplets and particle. Fig. 6 shows similar comparison of liquid film growth at the higher liquid jet flow rate of 3.0 mL/min. Comparing Figures 5 and 6, it can be seen that at the higher liquid jet flow rate, due to presence of more smaller droplets to interact with the particle, the liquid film growth at all particle Reynolds numbers was nearly uniform contrary to the lower flow rate case where liquid film growth varied significantly at the same particle Reynolds numbers. In both these figures, it can be seen that liquid film area reduces after reaching a peak. It was also observed that there was no droplet separation after impact on the particle surface in the all operating cases investigated which could be attributed to the reduction of the film area. The image analysis indicates that particle undergoes rotational motion during the collision and contributed to the the apparent reduction in the film area because of out-of-plane orientation of the liquid laden particle. This rotational motion is more prominent at higher liquid jet velocities which explains the phenomenon of sharp film area reduction at 3.0 mL/min liquid jet flow rate case (Fig. 6). The rotation of the particle is presented in Fig.7 for better visualization. Particle rotation is more at 3.0 mL/min case compared to 1.8 mL/min due to higher momentum transfer. This resulted in a lower reported film area at 3.0 mL/min due to out-of-plane orientation.

Determining liquid mass accumulation on the particle surface is of importance in many industrial applications such as spouted bed coating process. Direct measurement of liquid mass deposition is tedious because of precision involved in careful collection of the wet particle without loss of deposited liquid and weight measurement. In absence of direct measurement of liquid film mass, an image analysis based method was utilized in the present study. Consider an interaction region (Fig. 8) of diameter \( (D_p + D_d) \) around the particle of size \( D_p \) where collision with surrounding droplets of diameter \( D_d \) will always occur. The rectangular region with area \( (l_{X} \times l_{Y}) \) inscribing the droplet-particle system represents the field of view (FOV) of the camera. A depth equal to the droplet diameter \( D_d \) is considered to determine the volume of the field of view \( (V_{FOV}) \). When both droplets and particle are in motion, then the interaction swept volume per unit time can be expressed as the interaction region area times the relative velocity between the droplet and particle. To obtain the rate collision between the droplet and particle per unit volume, the number density of droplets is required in the field of view which can be readily calculated from the image processing. The duration of collision can be determined by the
time taken by the particle to traverse the diameter of interaction region.

Multiplying all these terms, the amount of liquid mass deposited on the particle surface can be obtained from the following expression:

\[ M = \frac{\pi(D_d+D_p)^2u_{rel}N\sqrt{\rho_d\rho_p}}{6V_{FOV}u_p} \]  

(15)

where \( U_{rel} = |U_p - U_d| \), \( N \) is the average number of droplets present in the volume of the field of view at any one time, which is given by:

\[ V_{FOV} = I_H I_W D_d \]  

(16)

Fig. 9 Influence of Re_p on liquid film growth on the particle surface at liquid jet flow rate range 1.8 mL/min to 3.0 mL/min. By processing several images of different operating cases, average number of droplets (N) present in the FOV was obtained and mass of liquid film was calculated based on Eq. (15). Fig. 9 compares the deposition of the liquid film mass as a function of the relative velocity between the droplet and particle. For a given relative velocity the liquid mass increased with increasing liquid flow rate due to a corresponding increase in the rate of generation of droplets to interact. Conversely, at higher particle velocity the interaction time reduces, leading to less deposition of liquid mass on the particle for a given liquid flow.

4.5 Angle of deflection:

The droplet-particle collision process is a pure inelastic collision, where the momentum is conserved although energy is not. Some amount of energy is lost due to viscous dissipation occurring during droplet-particle collision. During collision, transfer of momentum occurs between droplets and particle. When momentum of droplets is higher than the particle, the resultant momentum changes the trajectory of the falling particle. Fig. 10 presents a schematic of such a collision process where a droplet impinges on a particle at an angle (\( \psi \)) with respect to the vertical axis and deflects by an angle (\( \phi \)) during the collision (dashed line indicates the new position of droplet and particle).

For an inelastic collision, the following momentum conservation equations can be written for the droplet-particle system in x and y directions:

\[ N_c m_d u_d \sin(\psi) + m_p u_{px} = M u_{sys} \sin(\phi) \]  

(17)

where \( N_c \) is the number of colliding droplets, \( m_d \), \( m_p \), \( u_d \) and \( u_p \) are droplet and particle mass and velocity respectively and \( U_{sys} \) is the combined velocity of droplet-particle system after collision.

Since, the particle fall is always in vertical direction, it does not have any x-directional velocity component before collision. Consequently, Eq.(17) therefore reduces to:

\[ N_c m_d u_d \sin(\psi) = M u_{sys} \sin(\phi) \]  

(18)

\[ -N_c m_d u_d \cos(\psi) - m_p u_{py} = -M u_{sys} \cos(\phi) \]  

(19)

where the negative sign indicates the opposite direction of vertical velocity component with respect to the coordinate system defined in Fig. 10. The deflection angle (\( \phi \)) is defined as angle between the resultant momentum vector and the vertical
axis and can be obtained from Eq.18 and Eq.19, i.e:
\[
\tan(\phi) = \frac{N_m \sin(\phi)}{N_m \cos(\phi) + \mu \mu_p}
\]
(20)

Particle velocity up before collision can be obtained by solving the force balance equation from Eq. (11). The measured angle of deflection is presented in Fig. 11 as a function of particle velocity and liquid jet flow rate (1.8-3.0 mL/min).

![Fig. 11 Angle of deflection of the particle at different droplet and particle velocities.](image)

At higher liquid jet flow rates, more liquid mass accumulates on the particle surface. This increased momentum transfer leads to higher angle of deflection. In general, this trend is observed in all the cases investigated. When particle velocity is increased, less interaction time is available between the droplet and particle to exchange momentum. Hence, the angle of deflection reduces at higher particle velocity or when the relative velocity between the droplet and particle is reduced.

![Fig. 12 Comparison of angle of deflection – analytical and experimental at different droplet and particle velocities.](image)

5. CONCLUSIONS

In-flight droplet-particle collision behaviour was investigated both experimentally and numerically in the present work. Some significant aspects of the droplet-particle collision process such as liquid film deposition and angle of deflection were addressed. At higher droplet Weber number, both liquid film mass on particle surface and particle deflection angle increases due to higher deposition of mass and momentum transfer. When particle Reynolds number is increased, this in effect reduces the relative velocity between droplet and particle, both liquid film mass and angle of deflection decreases due to less interaction time.

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