Collision of water drops with a thin cylinder

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Abstract. The collision of water drops with a thin cylinder is studied. The droplet flight trajectory and the cylinder axis are mutually perpendicular. In the experiments, the drop diameter is 3 mm, and the diameter of horizontal stainless-steel cylinders is 0.4 and 0.8 mm. The drops are formed by a liquid slowly pumped through a vertical stainless-steel capillary with an outer diameter of 0.8 mm, from which droplets are periodically separated under the action of gravity. The droplet velocity before collision is defined by the distance between the capillary cut and the target (cylinder); in experiments, this distance is approximately 5, 10, and 20 mm. The drop velocities before the impact are estimated in the range of 0.2–0.5 m/s. The collision process is monitored by high-speed video recording methods with a frame rate of 240 and 960 Hz. The test liquids are water. Experiments and numerical simulation show that, depending on the drop impact height (droplets velocity) different scenarios of a drop collision with a thin cylinder are possible: a short-term recoil of a drop from an obstacle, a drop flowing around a cylindrical obstacle while maintaining the continuity of the drop, the breakup of a drop into two secondary drops, one of which can continue flight and the other one is captured by the cylinder, or both secondary droplets continue to fly, and the drop can be also captured by the cylinder, until the impact of the next drop(s) forces the accumulated drop to detach from the cylinder. Numerical modeling satisfactorily reproduces the phenomena observed in the experiment.

1. Introduction

Protection against infections transmitted by airborne droplets is carried out through the use of medical masks and filters that either inhibit or retard the movement of droplets, possible carriers of infections. Pathogenic droplets are formed by breathing, talking, coughing, sneezing of a sick person and enter the body of a healthy person with inhaled air containing such droplets. The work is aimed at studying the mechanisms of collision of liquid droplets with the material of the masks and filters. An elementary act of such an interaction is simulated experimentally, namely, the fall of a drop onto the lateral surface of a thin cylinder imitating the fibrous component of the mask. The collision of Newtonian fluid droplets with a thin fiber is studied in [1]. The results of rheological tests of fluids corresponding to real oral and bronchial fluids are presented in [2, 3]. A comparison of Newtonian and non-Newtonian fluids in the collision of a drop with a thin cylinder is shown in [4].

2. Experimental method

The schematic of the experiment and experimental setup are shown in Fig. 1. A drop of liquid was formed at the end of a capillary, the function of which was performed by an injection needle with an outer diameter of $d_c = 0.8$ mm. The liquid slowly filled the drop using a SINO SN-50C6 infusion pump. Upon reaching a certain weight, the drop was separated from the capillary [2]. Then the drop
collided with a transverse cylindrical obstacle. Another injection needle with a diameter of $d_t = 0.4$ or 0.8 mm was used as an obstacle. The distilled water was used as tested liquid. All tests were carried out at a room temperature (21–22°C).

To increase the contrast and remove foreign objects from the field of photography, the needle was bent approximately at a right angle, so that only the drop and the tip of the needle were visible in the frames (Fig. 2). In the experiments, the distance from the cut of the upper needle to the lateral surface of the lower one was $h_0 \approx 5$, 10, and 20 mm. The collision process was monitored using video recording with a frame rate of $f = 240$ Hz. For these purposes the smartphone iPhone6 was used in the regular mode (frame rate $f = 240$ Hz and resolution 720p HD 1280×720 pixels). The processing of video frames served to determine the diameter $d_i \approx 3$ mm and estimate the velocity $v_i \approx 0.2$–0.5 m/s of the droplet before its contact with the obstacle, as well as to trace all the phases of the collision shown in Fig. 3–8.

3. Numerical model

Mathematical problem statement. In this part of the paper, we consider a mathematical model of the problem of the transverse central collision a water drop with a diameter $d_i = 0.5$ mm on a thin cylinder (thread) with a diameter $d_t = 0.1$ mm. In this model, gravity is excluded from consideration. The computational domain is a rectangle with sides of 2 mm and 5 mm. In the center of the computational domain there is a thread with cylindrical cross section (Fig. 2). At the initial moment, the drop is located at the distance of its radius from the surface of the thread and has a velocity $u(t_0) = u_i$. It is assumed that the “water-air” interface is intentionally slightly blurred at the initial moment (Fig. 2). The considered range of initial velocities of the drop $v_i$ is from 0.1 to 10 m/s. The drop is located in an airstream moving at a speed of 0.1 m/s in the direction of the horizontal x-axis. The following boundary conditions are set: constant velocity at the input of the calculated area ($x=-2.5$ mm), pressure at the output ($x=2.5$ mm), and flow symmetry conditions at the horizontal boundaries ($y=\pm 0.5$ mm). On the interface of the gas-liquid interface, the condition of equilibrium of surface forces and pressure is set. The wetting angle on the thread is set to 90°.
The mathematical model is based on solving the system of two-dimensional Navier-Stokes equations for a two-phase gas-liquid system in the approximation of the “mixture” model [5] can be written in the form:

\[
\frac{\partial u_1}{\partial x} + \frac{\partial u_2}{\partial y} = 0
\]  

(1)

\[
\frac{d(\rho u_1)}{dt} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( \mu \frac{\partial u_1}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu \frac{\partial u_1}{\partial y} \right) + F_1
\]  

(2)

\[
\frac{d(\rho u_2)}{dt} = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left( \mu \frac{\partial u_2}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu \frac{\partial u_2}{\partial y} \right) + F_2
\]  

(3)

where \( df / dt = \partial f / \partial t + u_1 \partial f / \partial x + u_2 \partial f / \partial y \) is the substantial derivative; \( x, y \) are the Cartesian coordinates; \( u_1, u_2 \) are the components of velocity vector \( \mathbf{u}(u_1, u_2) \), \( t \) is the time, \( p \) is the pressure; \( \rho \) is the density; \( \mu \) is the dynamic viscosity coefficients; and \( F_1, F_2 \) are the components of external force \( \mathbf{F}(F_1, F_2) \), operating in a narrow zone along the air-liquid interface [6].

To describe the two-phase air-liquid system, we used the system of equations (1-3) with one equation for momentum transfer under the assumption of a “mixture” model [5] with averaged velocities \( \mathbf{u} = \varepsilon \mathbf{u}_{\text{air}} + (1-\varepsilon)\mathbf{u}_{\text{liquid}} \), density \( \rho = \varepsilon \rho_{\text{air}} + (1-\varepsilon)\rho_{\text{liquid}} \), and viscosity \( \mu = \varepsilon \mu_{\text{air}} + (1-\varepsilon)\mu_{\text{liquid}} \), where the values with the index air refer to air, and with the index liquid refer to liquid. The volume fraction of liquid \( \varepsilon \) (\( 0 < \varepsilon < 1 \)) was determined from the solution of the transfer equation:

\[
\frac{\partial \varepsilon}{\partial t} + \varepsilon \frac{\partial \mathbf{u}}{\partial x} = 0
\]

(4)

The boundary conditions at the air-liquid interface were determined from the equilibrium condition of surface forces and pressure [5]:

\[
(p_1 - p_2 + \sigma k)n_i = (\tau_{ij} - \tau_{2ij})n_j + \sigma \frac{\partial \mathbf{c}}{\partial x_i}
\]

(4)

where \( \tau_{ij} = \mu_{\alpha} \left( \frac{\partial \mathbf{u}_{\alpha}}{\partial x_j} + \frac{\partial \mathbf{u}_{\beta}}{\partial x_i} \right) \) is the viscous stress tensor \((i=1,2; j=1,2; x_1 = x, x_2 = y)\); index \( \alpha \) denotes: \( \alpha = 1 - \text{liquid}, \alpha = 2 - \text{air} \); \( \sigma \) is the surface tension coefficient, which depends on the properties of the liquids, the wetting angle, and in common case can be a function of temperature, impurity concentration, and coordinates; \( p_1, p_2 \) are the fluid and air pressures; \( k = 1/R_1 + 1/R_2 \) is the surface curvature where \( R_1, R_2 \) are the radii of curvature for liquid and air; and \( \mathbf{n}(n_1, n_2) \) is the unit normal vector directed into the second fluid.

For numerical solution of the system of equations (1–3), the conservative method of control volumes with the approximation of spatial derivatives of the second order and first order in time was used [7].
accuracy of defining the interface is limited by the size of the grid cells and the solution methods, so a
detailed dynamic grid was used on both sides of the interface. The additional details, validation results of
the mathematical model and the examples of its using are given in papers [4, 8–10].

4. Results

4.1. Experimental observations
The observed processes and features of the collision are presented in Table 1.

Table 1. The observed processes and features of the collision drops with thin cylinder.

| $d_c$ | $d_t$ | $h_0$ | Process | Frame |
|-------|-------|-------|---------|-------|
| 0.4 mm | 0.8 mm | ~5 mm | Rebound and fall. | Fig. 3 |
| 0.8 mm | 0.4 mm | ~10 mm | Rebound and fall. | Fig. 6 |
| 2.84 mm | 2.4 mm | ~20 mm | Fall. | Fig. 4 |
| 0.8 mm | 0.4 mm | ~5 mm | Disintegration into two parts, capture of one and separation of the other, as well as separation of the remaining drop by the next drop. | Fig. 7 |
| 0.8 mm | 0.4 mm | ~10 mm | Fall. | Fig. 5 |

Figure 3. An example of rebound and fall of a water drop from an obstacle at $d_c = 0.8$ mm, $d_t = 0.4$ mm, $h_0 = 5$ mm.*

Figure 4. An example of separation of a water drop from an obstacle at $d_c = 0.8$ mm, $d_t = 0.4$ mm, $h_0 = 10$ mm.*
Figure 5. An example of separation of a water drop from an obstacle at \( d_c=0.8 \text{mm}, \ d_t=0.4 \text{mm}, \ h_0\approx20 \text{mm}. \)

Figure 6. An example of a rebound and separation of a water drop from an obstacle when \( d_c=0.8 \text{ mm}, \ d_t=0.8 \text{ mm}, \ h_0\approx5 \text{ mm}. \)

Figure 7. An example of disintegration of a drop of water into two parts, the capture of one by an obstacle and the separation of the other, as well as subsequent separation of the remaining drop from the obstacle after the impact of the next drop at \( d_c=0.8 \text{ mm}, \ d_t=0.8 \text{ mm}, \ h_0\approx10 \text{ mm}. \)
Water
d_c=0.8\,\text{mm}
d_t=0.8\,\text{mm}
h_0\approx20\,\text{mm}
d_i=2.84\,\text{mm}
f=240\,\text{Hz}

Figure 8. An example of breaking a water drop into two parts, coalescence and separation of a water drop from an obstacle at \( d_c=0.8\,\text{mm}, d_t=0.8\,\text{mm}, h_0\approx20\,\text{mm}. \)

4.2. Results of numerical simulations

The results of numerical simulation of the flow around a thread (\( d_t=0.1\,\text{mm} \)) by a water drop (\( d_i=0.5\,\text{mm} \)) has shown that a single thread can delay the penetration of a drop at drop velocities of less than 1 m/s. For example, the drop almost completely passes through the thread at a drop speed equal to 1 m/s, but the tension forces hold it at the thread, and it sticks to the thread making oscillatory movements near the thread (Fig. 9). Under certain conditions, the drop sticking to the thread can make a precessional rotation around the thread. The shapes and positions of the droplet at different consecutive time points are shown in Fig. 9 (\( v_i = 0.1\,\text{m/s} \)) and Fig. 10 (\( v_i = 10\,\text{m/s} \)). When the drop flows around the thread at a speed of more than 1 m/s, it is not delayed by the thread. The drop is broken by the thread into two parts, which are then combined into one drop, which continues to move behind the thread, as shown in Fig. 10.

Figure 9. The shape and position of the drop (\( d_i=0.5\,\text{mm} \)) at different moments of time during the flow around the thread (\( d_t=0.1\,\text{mm} \)), the drop moves from left to right at a rate \( v=1\,\text{m/s} \).

Figure 10. The shape and position of the drop (\( d_i=0.5\,\text{mm} \)) at different moments of time during the flow around the thread (\( d_t=0.1\,\text{mm} \)), the drop moves from left to right at a rate \( v=10\,\text{m/s} \).

Conclusions

Observations have shown that there are various possible scenarios of the interaction of a falling drop with a thin cylinder, which depend on the kinematics of the impact and the rheological properties of the liquid [4]. The elasticity of the liquid, which increases with the concentration of the polymer, is found to promote the capture of droplets by a thin cylinder. The drop separation in this case is provided by additional impacts of the following drops. The experiments also reveal the phenomenon
of droplet rebound from a thin cylinder, which is observed both for water and polymer liquids. Earlier, the rebound of droplets was observed when a droplet collided with a flat surface. In addition, it is experimentally established that under certain circumstances a drop breaks down into two, and their further fate may be different.

The results of numerical simulation have shown the presence of different modes of flow around a thin thread by a water drop, which are in good agreement with the experimental data. At drop rates of less than 1 m/s, the thread (d=0.1 mm) is able to delay the penetration of a water drop (d=0.5 mm), that is, the drop is held near the thread due to surface tension forces.

Acknowledgements
The work was supported by grant RFBR 20-04-60128.

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