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Citation
Liu, Tianshu et al. "Deposition of Micron Liquid Droplets on Wall in Impinging Turbulent Air Jet." Experiments in Fluids 48.6 (2009) : 1037-1057.

As Published
http://dx.doi.org/10.1007/s00348-009-0790-7

Publisher
Springer Science + Business Media B.V.

Version
Author’s final manuscript

Citable link
http://hdl.handle.net/1721.1/65392

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Deposition of Micron Liquid Droplets on Wall in Impinging Turbulent Air Jet

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Revision submitted to Experiments in Fluids for consideration of publication

(11/4/2009)

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Abstract

The fluid mechanics of deposition of micron liquid (olive oil) droplets on a glass wall in an impinging turbulent air jet is studied experimentally. The spatial patterns of droplets deposited on a wall are measured by using luminescent oil visualization technique, and the statistical data of deposited droplets are obtained through microscopic imagery. Two distinct rings of droplets deposited on a wall are found, and the mechanisms of the formation of the inner and outer rings are investigated based on global diagnostics of velocity and skin friction fields. In particular, the intriguing effects of turbulence, including large-scale coherent vortices and small-scale random turbulence, on micron droplet deposition on a wall and coalescence in the air are explored.

1. Introduction

Considerable studies have been made on interactions between liquid droplets and solid walls in still air due to the relevance to engineering applications like spray cooling, spray coating and fuel injection. Focus has been on the deformation and breakup process of a droplet impacting onto a wall. The time evolution of deformation of a droplet impacting onto a wall has been extensively studied (Fukai et al. 1995, Mundo et al. 1995, 1997, Range & Feuillebois 1998, Lee & Hanratty 1988, Rioboo et al. 2000, 2001, 2002, Sikalo et al. 2002, Kalantari & Tropea 2007, Andreassi et al. 2007). The parameters that have been identified to have significant effects on the impact process of a droplet include wettability, surface roughness, impact speed, viscosity, surface tension and droplet size. At this stage, a considerable understanding has been gained into spray and droplet-wall interactions for droplets larger than 20 µm in still air. However, few studies have been conducted on deposition of droplets of about 1 µm on a wall since it is very difficult in experiments to image the time evolution of such a small droplet.
impacting onto a wall. Furthermore, for micron droplets, interactions between the droplets and air flow transporting them, particularly the effects of turbulence, become important in deposition of the droplets on a wall. There is a lack of investigations on this aspect.

In this paper, an impinging turbulent air jet is used as a canonical flow in the study of deposition of micron droplets on a solid wall. Impinging jets have been extensively studied mainly for enhancement of heat and mass transfer on a surface in many engineering applications (Jambunathan et al. 1992, Viskanta 1993). Considerable efforts have been made to explore the relationship between flow structures and heat transfer by using various optical diagnostic techniques (Cooper et al. 1992, Fairweather & Hargrave 2002a, 2002b, Birch et al. 2005). Direct numerical and large-eddy simulations have been performed to examine detailed flow structures (Tsubokura et al. 2003, Hadziabdi & Hanjalic 2008). However, the relationship between flow structures and deposition of micron droplets on a wall in an impinging turbulent air jet has not been explored.

When a droplet impacts onto a dry solid wall in still air, the deposition-splashing process occurs for relatively large droplets (0.1-4 mm diameters). Mundo et al. (1995) proposed a deposition-splashing model and gave a velocity-diameter relation for possible deposition

\[ d_0 < \frac{\sigma \alpha_1}{\rho_0} \left( 1 + \frac{4.5 \beta_{max} \mu w_0}{\alpha_1 \sigma} \right) \frac{1}{w_0^2}, \]

where \( \alpha_1 = 3 \beta_{max}^2 (1 - \cos \theta) - 12 \), \( \beta_{max} = d_{max} / d_0 \), \( d_{max} \) is the maximum diameter of a circular liquid disk formed after impacting and before receding, \( d_0 \) is the initial droplet diameter, \( \theta \) is the static contact angle, \( w_0 \) is the initial normal velocity of droplet, \( \rho_0 \) is the liquid density, \( \mu \) is the liquid viscosity, and \( \sigma \) is the liquid surface tension on the liquid-air interface. To illustrate the deposition and splashing regimes, a diameter-velocity diagram is shown in figure 1.
for an olive oil droplet, where \( \rho_0 = 920 \text{ kg/m}^3 \), \( \sigma = 3.2 \times 10^{-2} \text{ N/m} \), \( \mu = 8.1 \times 10^{-2} \text{ Ns/m}^2 \), \( \beta_{\text{max}} = \beta_r = 2.3 \), and \( \theta = 70 \text{ deg} \) (this value is somewhat arbitrary only for the purpose of illustration and the contact angle may change during an impact process). The boundary between deposition and splashing given by Mundo et al. (1995) in figure 1 is valid only for some impact cases. It is noticed that splashing and rebound might occur at low impacting velocities in other cases, depending mostly on the wettability (Rioboo et al. 2006, 2008). This study focuses on the marked area in figure 1 indicating the regime of deposition of spherical olive oil droplets of 1-10 \( \mu \text{m} \). The physical phenomena in this regime are not well understood due to technological difficulties to directly observe the impact process of such a small droplet onto a wall.

The objective of this work is to provide insight into how flow structures affect deposition of micron liquid droplets on a wall in an impinging turbulent air jet. The spatial distributions (patterns) of deposited droplets on a glass wall and their temporal evolution are first measured by using luminescent oil visualization technique, where the glass wall is considered as a smooth dry wall. The spatial distributions of droplets deposited on a wall exhibit two distinct rings (the inner and outer rings) where deposition of droplets is significantly higher than their neighborhoods. Further, the statistics of the droplets deposited on a wall is studied based on microscopic imagery. The connection between the rings and flow structures are explored based on global diagnostics of velocity and skin friction fields by using optical-flow-based particle image velocimetry (PIV) and global luminescent oil-film skin friction meter. The physical mechanisms of the formation of the rings of deposited droplets are revealed. In particular, the effects of turbulence on the formation of the outer ring in the wall-jet region are studied, where large-scale vortices and small-scale turbulence play significant but different roles in deposition.
of droplets. In addition, the effects of the nozzle-to-plate distance and wire-generated turbulence are examined to further confirm the effects of turbulence on deposition of droplets on a wall.

2. Experimental apparatus and measuring techniques

2.1. Jet setup

A diagram of the air-oil jet facility is shown in figure 2. The facility consists of an oil particle generator (atomizer), two pressure chambers and a solid plate (e.g. glass plate). Air from a compressed air line (160 psi) enters a TSI particle generator (Model 9307) at a regulated air pressure of 25 psi that has been specified by TSI to provide an aerosol flow rate of 30 l/min. For luminescent oil visualization, a mixture of olive oil and UV luminescent dye was made for the atomizer. The UV dye was a standard oil based dye (Dye-Lite All-In-One Leak Detection Dye from Tracerline) used for automotive leak detection applications. A relatively small amount of dye to the quantity of olive oil (1:100) allows the assumption that the dye does not change the physical properties of olive oil. Droplets generated from the atomizer have a distribution with a mean diameter of about 1 µm (a description of measurements of droplet sizes is given in subsection 3.1).

Leaving the atomizer, the air-oil flow moves into the first pressure chamber (mixing chamber) through a 9.5 mm clear vinyl tube where it is then mixed with regulated compressed air. Adding regulated compressed air allows the jet velocity to be controlled with changing the pressure inside of the mixing chamber. The mixing chamber is a 445 mm long capped tube with a 100 mm diameter. The mixed flow exits the top of the mixing chamber and enters the top of the second pressure chamber traveling through a 3/8” clear vinyl tube. Oil film creation inside of the pressure chambers and connecting vinyl tubing often lead to oil pooling and once a critical
point is reached; a large droplet detaches and is swept along the flow and into the jet. To deal with this problem, two features were added into the second pressure chamber, as shown in Fig. 2(b). As the air-oil flow enters the top of the chamber, a set of two baffle plates cause the entering air to make several rapid turns, changing the flow direction rapidly. The larger oil droplet’s inertia is large such that they no longer follow the flow and deposit upon the baffle plates and chamber walls. Exiting the baffle plates, the flow proceeds to the bottom of the chamber and the oil collection pool. Instead of the chamber walls sloping gently into the impinging jet nozzle to reduce internal pressure loss, the jet nozzle is a tubular pipe with an inner diameter of 9.5 mm that extrudes upwards into the pressure chamber for 50 mm. With a diameter of 50 mm for the second chamber, a pooling area is created at the bottom of the chamber for collection of any oil. A small tube protrudes into the middle of the chamber allowing measurement of the differential pressure between the chamber and atmosphere with a digital manometer. The continuous jet impinges upon a rigid wall represented by a glass plate positioned parallel to the ground. Before each test, the glass surface was cleaned by using acetone. The glass surface is assumed to be a dry wall although the wettability of the olive oil/glass system is not determined.

2.2. Optical-flow-based global velocity diagnostics

To measure velocity fields, the axisymmetrical plane of the impinging jet was illuminated by a 2-mm thick laser sheet generated by a Big Sky laser (CFR190) at 15 Hz, and the interval between two pulses generated by two synchronized laser units was 20 $\mu$s for optical flow calculations to reconstruct velocity fields. The measured area, including the central impinging jet region and wall-jet region after the flow turns to the horizontal direction, was imaged by a 14
bit PIV camera (LaVision Imager Pro X) with a 60-mm lens. The image size is 2000×2000 pixels, and a CCD sensor size is 9×9 µm. In our camera setup, 1 pixel in an image corresponds to 0.03 mm on the laser sheet in the object space. The wall-jet thickness was approximately 3 mm. This thickness corresponds to about 100 pixels in PIV images that cover about a range of 3 jet diameters in the radial direction in the object space, where the jet diameter is 9.5 mm. For such images, the conventional correlation-based method could provide only 6 data points across the wall jet at most. Such a low spatial resolution is not satisfactory to resolve the detailed flow structures in the wall jet. If the camera was zoomed into the wall jet to increase the spatial resolution in the normal direction, we could lose a wide view covering a sufficiently large area in the horizontal direction in images (or the radial direction in the object space). Therefore, instead of using the correlation-based method, a physics-based optical flow method was applied to high-density PIV images to obtain high-resolution velocity fields (one vector per pixel) particularly in the wall-jet region. The physics-based optical flow equations for PIV images and other flow visualization images have been derived by Liu & Shen (2008) based on projection of the relevant transport equations in the 3D object space onto the image plane. For PIV images, the optical flow is proportional to the path-averaged velocity of particles weighted in the particle concentration across a laser sheet. For ideal particles whose image intensity distributions are the Dirac-delta functions, the velocity of a particle in the image plane equals to the path-averaged velocity at the location of that particle. The optical flow is calculated by an algorithm based on a variational formulation with the first-order smoothness constraint for regularization (Liu & Shen 2008).
2.3. Luminescent oil visualization and global skin friction diagnostics

To measure the oil droplet concentration or oil film thickness in the impinging jet, the luminescent oil was used. Two UV lamps were used to excite the luminescent oil. Since the luminescent intensity is proportional to the oil thickness on a wall when oil is sufficiently thin, the oil concentration or thickness measurement can be converted to luminescence measurement by using a CCD camera with a 580-nm-long-pass optical filter (Liu & Sullivan 1998).

Further, a global luminescent oil film skin friction meter developed by Liu et al. (2008, 2009) was used for diagnostics of skin friction fields. When the oil film thickness is transformed to the image intensity, the thin oil-film equation can be projected onto the image plane to provide a relationship between skin friction and the temporal and spatial derivatives of the image intensity. The projected thin oil-film equation can be written as the same mathematical form as the physics-based optical flow equation (Liu & Shen 2008). Therefore, this technique is an extension of the physics-based optical flow method, and the same variational formulation for optical flow computation can be used to obtain a snap-shot solution for a skin friction field. Then, a complete relative skin friction field is reconstructed through fusion of a time-sequence of snap shot solutions (Liu et al. 2008). Without a priori calibration, this method is able to give a normalized, time-averaged skin friction field. In the present experiments, the luminescent oil used for mapping skin friction fields was silicone oil doped with a UV luminescent dye [high visibility UV powders (UVHiVisOR) produced by LDP LLC (www.MaxMax.com)]. A luminescent oil film (typically 20 µm thick) was pre-coated in an interested region on a wall, and the development of the luminescent emission of the oil film was detected by a CCD camera with a 580-nm long-pass filter under excitation by two UV lamps.
3. Flow structures and deposition of droplets

3.1. Free jet characteristics

To provide an understanding of the exit conditions of an impinging jet, the flow characteristics of the corresponding free jet were measured by using a hot-wire probe. Figure 3(a) shows the mean velocity profiles normalized by the local maximum velocity at different streamwise locations for the jet exit velocity of 30 m/s. The Reynolds number based on the exit diameter is $Re_D = 19,300$. Figure 3(b) shows the corresponding turbulence intensity normalized by the jet exit velocity at the center. The mean profiles near the centerline were relatively flat between the shear layers of the jet. However, as indicated in figure 3, the turbulence intensity normalized by the jet exit velocity at the centerline near the exit is about 5%, and therefore the freestream turbulent fluctuation is considerably high even at centerline. This is because the baffle plates existed in the relatively small chamber and a non-contoured nozzle was used. The turbulent intensity in the shear layer is 14-16%, and the power spectra in the shear layer are continuous that do not show any distinct peaks. This indicates that the exit shear layer is fully turbulent. As indicated in figure 3, the jet was not completely symmetrical due to the imperfect setup.

The size distribution of droplets directly generated from the TSI oil particle generator was measured by inserting a glass plate into a stream of droplets for sampling. The size statistics of the deposited droplets on the glass plate was determined from microscopic images. Here an underlying assumption is that intrusiveness of the sampling glass plate to the flow does not change the statistics of droplets. Figures 4(a) and 4(b) show a typical microscopic image and a histogram of the disk diameters of the deposited droplets from the TSI particle generator on the glass plate. The mean disk diameter of the deposit droplets is about 2 µm. The sphere diameter
$d_o$ of a droplet in the 3D space is related to the disk diameter $d$ on a wall by a proportional relation. In general, this relation depends on the wettability of the system. For a dry wall, $d_o \approx d / 2.3$ according to Mundo et al. (1995), and therefore the estimated mean diameter of sphere droplets generated from the TSI particle generator is about 1 $\mu$m. The histogram in figure 4(b) indicates the existence of a small number of large deposited droplets of 5-20 $\mu$m. The volume fraction of oil droplets in air at the jet exit was determined by taking a ratio between the measured consumption of the oil in the generator and the total volume of outgoing air through the nozzle in a given time period (for example 2 hours). The volume fraction in the normal operational condition of the generator (25 psi) is $\alpha_\nu = 1.02 \times 10^{-5}$. Therefore, when droplets in a space are considered as spheres with the diameter of $d_o = 1 \mu m$, the estimated concentration of particles at the jet exit is $n_p = N_p / V = 6 \alpha_\nu / \pi d_o^3 = 1.94 \times 10^{13} m^{-3}$, where $N_p$ is the number of particles in a volume $V$. This data will be used later to estimate the rate of droplet collisions in turbulence.

3.2. Global patterns of deposited droplets

To measure the process of deposition of droplets with increasing time at an early stage of $t = 10-45$ s, luminescent oil visualizations were conducted by using the olive oil doped with a small amount of a UV dye. When the oil thickness is optically thin, the luminescent emission projected onto a camera is proportional to the concentration of deposited droplets when the droplets are not connected, or the oil film thickness when the droplets are connected to form a continuous film (Liu & Sullivan 1998, Liu et al. 2008). For simplicity of expression, in this paper, the term “oil film thickness” also represents “concentration of deposited droplets” when
deposited droplets are discretely distributed in luminescence measurements. When a pattern of deposited droplets was formed on a wall at a given instant after starting the jet, its luminescent emission intensity image under excitation by two UV lamps was immediately detected by a CCD camera. In this section, a typical case was investigated in detail, in which the nozzle-to-plate distance (H) was 10 mm and H/D was 1.05, where D is the inner diameter of the nozzle. The jet exit velocity was 30 m/s and the Reynolds number is \( \text{Re}_D = 19,300 \). Figure 5 shows the luminescent intensity images of droplets deposited on the wall at different times after starting the jet in a period of \( t = 10-45 \) s. Clearly, there are two distinct rings where the luminescent intensity is considerably higher than that in their neighborhoods, indicating more droplets deposited in these regions. The inner and outer rings are approximately located at \( r/D = 0.7 \) and \( 1.7 \) from the stagnation point, respectively. Figure 6 shows the normalized distributions of the thickness/concentration of deposited droplets at different times, where the reference value at the stagnation point at \( t = 10 \) s is used for normalization. The thickness/concentration of deposited droplets at the stagnation point increases with time, as indicated in figure 7. The relative error in measurements of the thickness/concentration of deposited droplets is less than 10%. When the distributions of the thickness/concentration of deposited droplets are normalized by the value at the stagnation point at that time, all the profiles are collapsed, as indicated in figure 8. This indicates that the evolution of the distribution of the thickness/concentration of deposited droplets is self-similar in a period of \( t = 10-60 \) s.

### 3.3. Statistics of deposited droplets

Although the luminescent intensity images show the continuous patterns of deposited droplets, the droplets in microscopic images are in fact discretely distributed on a wall in a
period of t = 10-45 s. A Nikon optical microscope was used to analyze the statistics of droplets deposited on a glass wall. Images taken with a digital camera at an optical magnification of 400X provided a spatial resolution of 0.5 µm/pixel. Figure 9 shows the characteristic regions in a luminescent image of deposited droplets at t = 10 s. A series of microscopic images in figure 9 taken along the horizontal axis (the radial axis r/D) across the impingement point on the wall was analyzed with a Matlab image processing program to determine the statistics of deposited droplets in each microscopic image. The statistical data from each microscopic image describe the characteristics of deposited droplets at different locations from the stagnation point (r/D = 0). Figure 10(a) shows a typical microscopic image of deposited droplets at r/D = 0 over an area of 320×240 µm² at t = 10 s. In image processing for computing the droplet sizes, the droplet boundary is detected by setting a suitable intensity threshold and then the closed boundary is filled with a given intensity value to form white blobs. The effective diameter of a droplet blob is determined as a diameter of an equivalent circle that has the same area as the blob. Here, the measured diameter is the disk diameter of a droplet deposited on a wall rather than the sphere diameter in the 3D space. Figure 10(b) is a histogram of the diameters of deposited droplets, $N(d)$, at the stagnation point (r/D = 0), where $N(d)$ is estimated as the number of deposited droplets in a microscopic image (320×240 µm²). Figure 10(c) shows the oil coverage area by droplets with a disk diameter $d$ that is estimated by using a relation $N(d)\pi d^2 / 4$. The histogram shows a bi-mode distribution at the stagnation point, in which a sharp and high peak is at 1-2 µm and a broader but much lower peak is at 6-10 µm. This histogram is similar to figure 4(b) for the droplets directly from the TSI particle generator. As indicated in figure 10(c), although the sizes of most deposited droplets are 1-2 µm, the oil area is mainly covered by the deposited droplets of 5-16 µm.
The histogram at $r/D = 0.7$ (the inner ring) in figure 11(b) has a distinct bi-mode distribution, indicating one sharp peak at 1-2 $\mu$m and another peak at about 8 $\mu$m in a broader range of 6-15 $\mu$m. At the inner ring, in contrast to the stagnation point, there are more large deposited droplets of 6-15 $\mu$m than those of 1-2 $\mu$m. The large droplets of 5-25 $\mu$m diameters cover most of the total area in an observed microscopic image, as indicated in figure 11(c). As shown in figure 12, at $r/D = 1.3$ between the inner and outer rings, the histogram is still a bi-mode distribution. However, the total number and size of deposited droplets are much smaller than those at the stagnation point and the inner ring, and the oil area is mainly covered by deposited droplets of 5-10 $\mu$m diameters. At the outer ring at $r/D = 1.7$, the histogram in figure 13(b) is a broad distribution in a range of 1-20 $\mu$m, and the oil area is covered by the deposited droplets ranging from 5 to 25 $\mu$m [see figure 13(c)].

Figure 14(a) shows a distribution of the mean diameters of deposited droplets over a microscopic image along a horizontal line across the stagnation point. It can be seen that the mean sizes of deposited droplets are larger at the inner ring ($r/D = 0.7$) and outer ring ($r/D = 1.7$) than those at the stagnation point and between the two rings. This is consistent with the histograms of the sizes of deposited droplets at these locations. A ratio between the oil area and the total area in a microscopic image along a horizontal line across the stagnation point has a similar distribution, as shown in figure 14(b). The peaks of the droplet-covered area correspond to the inner and outer rings observed in luminescent oil visualizations. The above results indicate that the deposition of droplets in the inner and outer rings is mainly contributed by the deposited droplets of 5-25 $\mu$m although a large number of smaller deposited droplets of 1-6 $\mu$m also exist. From these observations, two main problems need to be answered. The first question is how the distributions of sizes of deposited droplets in the inner and outer rings are developed.
from the original distribution at the jet exit. The evolution of the statistical distribution of droplets is obviously related to the development of flow structures in the impinging jet. Another relevant question is why more large deposited droplets are observed in the inner and outer rings than other regions.

3.4. Flow structures and formation of rings of deposited droplets

To explore the physical mechanisms of the formation of the inner and outer rings in deposited droplets, PIV measurements were conducted under the same test conditions as for luminescent oil visualizations. The physics-based optical flow method was applied to high-density PIV images to obtain high-resolution velocity fields particularly in the wall jet (Liu & Shen 2008). Figure 15(a) shows typical snap-shot velocity and vorticity fields in the wall-jet region. Strong large-scale coherent vortices have been observed in the wall jet, which are developed due to the Kelvin-Helmholtz instability in the shear layer of the jet. To estimate the entrainment of droplets by these vortices toward the wall, the probabilities of the relative normal velocity magnitude that is greater than several thresholds of the normalized velocity \( |V|/V_{\text{ref}} \) are obtained by using conditional sampling, where the reference velocity \( V_{\text{ref}} = 30 \) m/s is the jet exit velocity at the center. Figure 15(b) shows the conditionally-sampled normal velocities induced by large-scale vortices in the wall jet in one realization. The peaks of the normal velocity at several locations correspond to the large-scale vortices shown in figure 15(a).

Figure 16 shows the mean fields of the velocity, vorticity and turbulent kinetic energy \( k = (u^2)^{1/2} + (v^2)^{1/2} / 2 \) in the wall jet, where \( u = U - \langle U \rangle \) and \( v = V - \langle V \rangle \) are the radial and normal fluctuating velocity components, respectively, and \( \langle \rangle \) denotes the ensemble
average. Note that the azimuthal velocity component in the kinetic energy is not included since it cannot be measured by using a planar PIV. The velocity vector turns sharply from the normal impingement direction to the horizontal direction at \( r/D = 0.7 \) where the inner ring of deposited droplets forms. This velocity change at \( r/D = 0.7 \) is also evidenced by the conditionally-sampled normal velocities, as shown in figure 15(b). The rapid directional change of the flow velocity at \( r/D = 0.7 \) is directly responsible for the formation of the inner ring because larger droplets cannot follow the sharply turning flow due to their larger inertia. As a result, the large droplets impact and deposit to the wall. This explanation is supported by microscopic measurements. Indeed, the dominant presence of large deposited droplets of 6-15 \( \mu \)m at the inner ring is shown in figure 11. It will be indicated later that the large droplets are mainly formed by collisions and coalescences between smaller neighboring droplets due to the effect of small-scale turbulence in the jet shear layer before the rapid directional change of flow. Therefore, the formation of the inner ring is also influenced by the effect of small-scale turbulence.

Further, a time-averaged skin friction field was obtained by using a global luminescent oil film skin friction meter. As shown in figure 17, the distribution of the mean skin friction magnitude in the impinging jet exhibits a single ring. The ring of the maximum skin friction magnitude at \( r/D = 0.75 \) basically corresponds to the inner ring of deposited droplets. Therefore, the rapid directional change of the mean flow is a plausible mechanism for the formation of the inner ring. However, it will be pointed out that this mechanism is not suitable for explaining the formation of the outer ring in the wall jet.

Interestingly, the mean skin friction field does not show any significant signature at \( r/D = 1.5-2.0 \) where the outer ring is located. The mean flow properties are further examined. Figure 18 shows the normalized local maximum radial velocity \( U_m / V_{ref} \) in the wall jet and the half
width $\delta_{1/2}/D$, where $\delta_{1/2}$ is defined as a distance from a wall at which the mean radial velocity is $U_m/2$ in the wall jet, and the reference velocity $V_{ref}$ is the jet exit velocity at the center. In the development of the wall jet, $U_m$ decreases in a near-linear fashion while $\delta_{1/2}$ increases as $r/D$ increases. Figure 19 shows the profiles of the normalized radial and normal velocities and turbulent stress. The profiles of the normalized radial velocity are basically collapsed, and they approach a certain self-similarity. However, unlike the results reported by Birch et al. (2005) for a larger region, no negative mean radial velocity is found in $r/D = 1-2$. In contrast to the radial velocity, the normalized normal velocity and turbulent stress fail to collapse, and therefore the wall jet is not completely self-similar for all the properties. These mean profiles do not provide any clues for the formation of the outer ring of deposited droplets in the wall jet.

An implication of the above discussions is that the outer ring is not directly related to the mean flow properties, and the mechanism for the formation of the outer ring may be related to turbulent motions in the wall jet. As shown in figure 15, there are intermittent but strong normal velocity components induced by large-scale vortices near $r/D = 1.7$. Furthermore, as shown in figure 16(b), the turbulent kinetic energy is considerably higher in $r/D = 1.6-2.0$, which implies that the formation of the outer ring could be related to active turbulent motions. Higher turbulent kinetic energy in $r/D = 1.5-2.0$ was found in large-eddy simulation (LES) of a turbulent impinging jet for $H/D = 2$ and $Re_D = 20,000$ (Hadziabdic & Hanjalic 2008), showing a pattern similar to that in figure 16(b). Hot-wire measurements in an impinging jet for $H/D = 2$, 4 and 6 and $Re_D = 23,000$ also showed the higher turbulent intensity at $r/D = 1.5-2.0$ that corresponds to the maximum heat transfer near $r/D = 2$ (Cooper et al. 1993). Liu & Sullivan (1996) found two rings in the Nusselt number distributions in an excited impinging jet for $H/D = 1.1$ and $Re_D =$
12,300, where the inner and outer rings were at r/D = 0.7 and 1.6, respectively. The locations of the heat transfer rings coincide to the rings in deposited droplets. The outer ring in heat transfer was sensitive to external excitation, and the peak of the Nusselt number was associated with high turbulent intensity. Apparently, there is a phenomenological analogy between the rings in heat transfer and deposited droplets in the approximately corresponding locations in the wall jet.

Turbulent flow in the wall jet contains both large-scale coherent vortices and small-scale random turbulence. The evident role of large-scale vortices in deposition of droplets is to intermittently induce large normal velocity and entrain droplets toward a wall. From the histograms in figure 13, it is found that the oil coverage is mainly contributed by large deposited droplets ranging from 5 to 25 \( \mu \text{m} \). The further question is where these large deposited droplets in the outer ring come from. One obvious possibility is that some of them come from a small group of the original large droplets directly from the TSI particle generator in the tail of the distribution of the initial droplet sizes shown in figure 4(b). This explanation implies that the statistics of droplet sizes remains invariant in flow. This is probably true in a uniform laminar flow, but it cannot be true in a turbulent shear flow. Another possibility is that some large droplets are generated by collisions and coalescences of small droplets in the turbulent flow. Small-scale turbulence induces random fluctuations of small droplets around their trajectories in the mean flow. It is argued that the probability of collisions between neighboring droplets is increased by small-scale turbulence, which leads to coalescence into large droplets. Since collisions between small droplets in turbulence cannot be directly observed in experiments, indirect evidences should be sought to support this explanation.
4. Effect of nozzle-to-plate distance

The effect of the nozzle-to-plate distance (H) on the pattern of deposited droplets is studied to further examine the relationship between turbulent structures and deposition of droplets. Experiments were conducted for several relative distances from H/D = 0.53 to H/D = 2.63. The jet was maintained at an exit velocity of 30 m/s and the Reynolds number of 19,300. Figure 20 shows the luminescent intensity distributions for H/D = 0.53, 1.58 and 2.63 at t = 45 s, which are normalized by the reference intensity value at the stagnation point for H/D = 0.5. Clearly, deposition of droplets in the outer ring considerably decreases with increasing H, and in contrast the global oil patterns near the stagnation point and the inner ring approximately remain basically unchanged. In the radial oil thickness/concentration distributions normalized by the reference value at the stagnation point, as indicated in figure 21, a significant decrease of the peak of deposition of droplets in the outer ring is found. Also, the location of the outer ring moves outward from r/D = 1.5 to r/D = 1.8.

The statistics of sizes of deposited droplets is obtained from microscopic image measurements. Figure 22 shows the histograms of sizes of deposited droplets at the outer ring (r/D = 1.7) at t = 45 s for H/D = 0.53, 1.58, and 2.63. The histograms at the outer ring have a single mode. The total number of deposited droplets decreases as H/D increases from 0.53 to 2.63, which is consistent with luminescent oil visualizations (see figure 20). It is also observed that the mean diameter of deposited droplets is about 5 μm at H/D = 0.53, and then it decreases to about 2 μm as H/D increases to 2.63. Figure 23 shows the turbulent kinetic energy in the wall jet for H/D = 0.53, 1.58 and 2.63, indicating that the turbulent motion at the outer ring decays as H/D increases. This supports the previous observation that stronger turbulence, including the large-scale structures and small-scale turbulence, causes more droplets deposited on a wall. In
addition, stronger turbulence at \( H/D = 0.53 \) generates deposited droplets twice larger than those at \( H/D = 2.53 \) where turbulence is weaker. This shift in the mean diameter of deposited droplets can be explained by the proposed mechanism that turbulence, particularly small-scale turbulence, induces collisions between neighboring droplets to coalesce into larger droplets. The statistics of deposited droplets on a wall in more controllable wire-generated turbulence will be investigated to further illustrate this mechanism.

5. Effect of wire-generated turbulence

To gain insight into the effect of turbulence on deposition of droplets, an impinging jet is tripped by a thin wire (a small circular cylinder) spanned across the jet exit through the center. Three wires with the diameters of 0.13, 0.35 and 0.65 mm were used for tripping the flow. For the jet exit velocity of 30 m/s, the corresponding Reynolds numbers based on the wire diameter were \( Re_{d_w} = 263, 709 \) and \( 1317 \), respectively, where \( d_w \) denotes the wire diameter. The nozzle-to-plate distance was \( H/D = 1.05 \). Figures 24(a) and 24(b) are the luminescent oil images at \( t = 5 \) s in the impinging jet tripped by a 0.35 mm wire and a 0.65 mm wire, respectively. Clearly, the pattern of deposited droplets is drastically changed, and particularly droplets are much more rapidly and heavily deposited behind a tripping wire due to wire-generated turbulence. There are two peaks in deposition of droplets on a wall around the location directly behind a tripping wire. A larger wire, such as a 0.65 mm wire, generates more effective deposition. The inner ring observed in the natural impinging jet does not appear clearly. The outer ring is still visible, but considerably thinner compared to the pattern of deposited droplets behind a wire.
The statistical data obtained from microscopic images provide more evidences on the favorable effect of wire-generated turbulence on deposition of droplets. Figure 25(a) shows the distributions of the mean diameter of deposited droplets across the y-axis at $t = 1\ s$ for the natural impinging jet and jets tripped by wires with the different diameters. For the wire-tripped jets, the mean diameter of deposited droplets is larger than $6.5\ \mu m$ around a wire, which is much larger than the mean diameter of $2\ \mu m$ of deposited droplets originally from the TSI particle generator. Figure 25(b) shows the relative oil coverage distributions across the y-axis (see figure 24) at $t = 1\ s$ for the natural jet and jets tripped by wires. The relative oil coverage is defined as a ratio between the oil-covered area in a microscopic image and the total area in the image. It is indicated that deposition of droplets is considerably enhanced by wire-generated turbulence near the center. The relative oil coverage reaches to about 40% at $t = 1\ s$ in the impinging jet tripped by a $0.65\ mm$ wire, and then droplets will soon form a continuous film covering the region. There are two dominant peaks in the relative oil coverage around a wire, and the smaller peaks at $r/D = \pm 1.7$ corresponds to the outer ring. The deposition of droplets increases with the wire diameter.

Furthermore, Figure 26 shows the histograms of the deposited droplets at $t = 1\ s$ at the stagnation point in the natural impinging jet and the impinging jets tripped by the wires of $d_w = 0.13\ mm$, $0.35\ mm$, and $0.65\ mm$. Compared to the histogram at the stagnation point in the natural impinging jet, not only the total number of deposited droplets is much larger, but also much more deposited droplets are distributed in a range centered at the mean diameter of $5\ \mu m$ in the wire-tripped impinging jets. The single-mode distributions for the wire-tripped impinging jets are qualitatively different from the two-mode shape for the natural impinging jet. Even for tripping by using a tiny wire with a $0.13\ mm$ diameter, an amazing change in the histogram of
deposited droplets can be seen by directly comparing the histogram for the wire-tripped jet in figure 26(b) with that immediately before tripping at the jet exit in figure 4. As indicated in figure 4, deposited droplets around 2 µm are dominant in their number. In contrast, after a tripping wire, the peak of the histogram of deposited droplets is shifted to 5 µm, as shown in figure 26(b). This dramatic statistical change cannot be explained by other rational mechanisms than collisions and coalescences of small droplets into large ones induced by wire-generated turbulence.

Global velocity diagnostics was conducted for the wire-tripped impinging jets. Figure 27 shows snapshot velocity and vorticity fields in the impinging jet tripped by a 0.65 mm wire. Vortex shedding from the wire can be observed. The wake behind the wire contains both large-scale vortices and small-scale random turbulence. Large-scale vortices shed from the wire impinge on a wall to form a pair of vortices around the stagnation point, which intermittently entrain droplets toward the wall to form the two peaks in deposition of droplets around the location directly behind the wire. Figure 28 shows the mean fields of the velocity, vorticity and turbulent kinetic energy in the wire-tripped impinging jet. The turbulent kinetic energy is high near the stagnation point. In contrast to large-scale vortices entraining droplets toward a wall, small-scale turbulence is responsible to particle collisions and coalescences. To quantify the effect of wire-generated turbulence, the relative area-averaged turbulent intensity \( \left\langle k \right\rangle_A^{1/2} / V_{ref} \) is estimated for the wire-tripped impinging jet, where \( \left\langle k \right\rangle_A = A^{-1} \int_A k \, drdz \) and \( A \) is a rectangle area in \(-0.2 \leq r / D \leq 0.2 \) and \( 0 \leq z / D \leq 0.5 \) (see figure 28 for reference). Figure 29 shows an integral of the distribution \( N(d) \) of particle numbers over a range of 4-9 µm as a function of the relative area-averaged turbulent intensity for the wire-tripped impinging jet. This clearly
indicates the dependency of deposition of droplets with the diameters of 4-9 µm on the turbulent intensity.

In the light of the above discussions, the outer ring of deposited droplets is generated by the combined effects of large-scale vortices and small-scale turbulence on the motion of droplets in the wall jet. Strong small-scale turbulence induces collisions and coalescences of small droplets into large ones for more effective deposition. This mechanism is supported by the experimental results obtained in the wire-tripped impinging jet. In contrast, at the inner ring, deposition of relatively large droplets on a wall is mainly caused by a rapid directional change of the mean flow at r/D = 0.7.

6. Probability of droplet collisions in turbulence

The experimental evidences obtained in the natural and wire-tripped impinging turbulent jets indicate that small-scale turbulence enhances the probability of collisions between small droplets to coalesce into large droplets. Here, a brief theoretical account is given to illustrate the probability of droplet collisions in turbulence. The relative motion of small particles (e.g. droplets) around their mean trajectories in a turbulent flow can be considered in the framework of locally homogenous isotropic turbulence. In this section, a droplet is generally referred as to a particle. Separations between particles that are in the order of the Kolmogorov length scale are critical in particle collisions. The probability density function (p.d.f.) of a separation between two inertial particles in turbulence is a key building block in the statistical modeling of particle collisions.

When a separation r between two inertial particles is sufficiently small in homogenous isotropic turbulence, Liu (2009) gives a random differential equation
\[
dr/dt = S(t)r + n(t),
\]
where $S(t)$ is the random particle-strain-rate projected onto the separation vector between the two particles and $n(t)$ is a background noise contributed by all the higher-order spatial derivatives of the particle velocity. Therefore, the random process of a separation $r$ is mainly determined by the random projected particle-strain-rate tensor. An implication is that particle clustering for possible collisions results from the random particle-strain-rate field, and therefore it occurs most probably in regions with high fluctuations of the strain rate. This sheds insight into the experimental findings that large deposited droplets are observed in the regions with high turbulent kinetic energy in the wall jet and the turbulent wake behind a tripping wire.

The Fokker-Planck equation is derived from the random differential equation and a stationary solution for the p.d.f. is sought (Liu 2009). When the correlation between $S(t)$ and $n(t)$ vanishes and the mean noise $\langle n \rangle$ is zero, the asymptotic p.d.f. of a normalized separation $\hat{r} = r / \eta$ by the Kolmogorov length scale $\eta$ for $\hat{r} < 1$ is $p(\hat{r}) = \text{const.} \times (\hat{r}^2 + c_0)^{-(1-c_1)/2}$. The power-law exponent $c_1$ $(0 \leq c_1 \leq 1)$ can be expressed as a non-dimensional quotient of polynomials based on the Stokes number $St = \tau_p / \tau_\eta$, where $\tau_p$ is the particle response time and $\tau_\eta$ is the Kolmogorov timescale. The small constant $c_0$ is related to the strength of the noise $n(t)$. A general power-law behavior $p(\hat{r}) \propto \hat{r}^{-(1-c_1)}$ is exhibited for $\hat{r}^2 >> c_0$ and $\hat{r} < 1$. At $\hat{r} = 0$, $p(\hat{r})$ reaches the maximum value for $St > 0$. Physically speaking, this means that two neighboring inertial particles in turbulence tend to cluster for probable collisions. In other words, clustering between inertial particles in turbulence is a natural trend which leads to particle collisions. Collisions usually happen in a time period of the order of the Kolmogorov timescale. For non-inertial particles where $c_1 = 1$ at $St = 0$, $p(\hat{r}) = \text{const.}$, indicating that no clustering occurs in fluid particles.
In the statistical mechanical modeling and simulation for collisions between inertial particles, the radial distribution function (r.d.f.), which is proportional to the two-particle p.d.f., is usually used (Sundaram & Collins 1999). For a system of \( N_p \) particles in a volume \( V \), the p.d.f. for two specific particles is not physically relevant for in turbulent particle clustering, and the joint distribution function for any pair of \( N_p \) particles is more meaningful (Chandler 1987, Wilde & Singh 1998). Thus, by adopting the classical statistical theory of liquid, the r.d.f.,

\[
g(\hat{r}) = N_p(N_p - 1)p(\hat{r})/(n_p^2V),
\]

is introduced for particle clustering, where \( p(\hat{r}) \) is the two-particle p.d.f. and \( n_p = N_p/V \) is the concentration of particles. Direct numerical simulation (DNS) of collision statistics of inertial particles in isotropic turbulence has been conducted to understand the physical mechanisms of preferential concentration (Sundaram & Collins 1999, Reade & Collins 2000, Wang, Wexler & Zhou 2000, Wang, Ayala & Kasprzak 2005). DNS indicates that the r.d.f. for inertial particles exhibits a power law of the inverse of a separation over a range of small separations (\( \hat{r} < 5 \)) (Reade & Collins 2000). Analytical models also provided evidences for a power-law behavior of the r.d.f. (Zaichik & Alipchenkov 2003, Chun 2005, Zaichik & Alipchenkov 2007).

Based on the above arguments, the problem of collisions between liquid droplets is directly related to the preferential concentration for inertial particles. In a mono-disperse system consisting of \( N_p \) particles in a volume \( V \), the collision rate per unit volume is given by

\[
N_c = 0.5\pi d_o^5 n_p^2 g(d_o) \langle |w_r| \rangle,
\]

where \( d_o \) is the diameter of a sphere droplet, \( \langle |w_r| \rangle \) is the mean radial component of the relative velocity between two particles, and \( g(d_o) \) is the r.d.f. at contact. Clearly, the collision rate is proportional to \( \langle |w_r| \rangle \) and \( g(d_o) \). DNS has given a ratio

\[
\langle |w_r| \rangle / \langle u^2 \rangle^{1/2}
\]

as a function of the particle inertia characterized by the Stokes number, and an
estimate is \( \langle |w_r| \rangle / \langle u^2 \rangle^{1/2} \approx 0.5 \) for small Stokes number, where \( \langle u^2 \rangle^{1/2} \) is the turbulent intensity (Wang et al. 2000). Clearly, the collision rate of inertial particles is proportional to the turbulent intensity, which sheds light on the enhanced droplet collisions by turbulence for more effective deposition of droplets on a wall in an impinging turbulent jet. As shown in figure 29, the result obtained in the wire-tripped impinging jet is consistent with this theoretical model at least qualitatively.

According to the above theory, the collision rate of droplets can be estimated. Consider a 1-mm cube that travels with the flow toward the wall at \( r/D = 0.4 \) in the jet shear layer. At that location, as shown in figure 3, the mean velocity is 18 m/s, and the turbulent intensity is 0.16. As indicated in §3.1, when droplets in a space are considered as spheres with the diameter of \( d_o = 1 \mu m \), the estimated concentration of particles is \( n_p = 1.94 \times 10^{13} \text{ m}^{-3}. \) The r.d.f. at contact \( g(d_o) \) is a function of the Stokes number. When \( g(d_o) = 1 \) is used for a rough estimate, the collision rate is \( N_c = 1.42 \times 10^{15} \text{ s}^{-1} \text{ m}^{-3}. \) The time for a 1-mm cube to travel a 10 mm distance at 18 m/s in the shear layer from the exit to the wall is \( 5.6 \times 10^{-4} \text{ s}. \) In this case, the number of droplet collisions that take place in the 1-mm cube during this period is 790. This indicates that significant droplet collisions are induced by small-scale turbulence in the jet shear layer.

7. Conclusions

The physical mechanisms of the formation of the two rings of micron liquid (olive oil) droplets deposited on a wall in an impinging turbulent air jet have been studied experimentally. The formation of the inner ring at \( r/D = 0.7 \) is directly caused by a rapid directional change of flow from the normal to horizontal direction such that larger droplets (about 10 \( \mu \text{m} \)) that cannot
follow the sharply turning flow impact to a wall due to their larger inertia. The formation of the outer ring consisting of a broader range of droplets at $r/D = 1.7$ is related to strong turbulence in the wall-jet region, where large-scale coherent vortices and small-scale random turbulence play significant but different roles in deposition. Evidently, large-scale vortices induce large normal velocity and entrain droplets toward a wall for deposition. The effect of small-scale turbulence on deposition of droplets is subtle, and it increases the probability of collisions between neighboring droplets to coalesce into larger droplets that are much easier to deposit on a wall. This observation is confirmed by investigating the effects of the nozzle-to-plate distance and wire-generated turbulence on deposition of droplets. A short theoretical account on the probability density function of the inter-particle separation provides useful insight into collisions and coalescences between neighboring droplets in turbulence. In fact, the formation of the inner ring is also profoundly affected by collision/coalescence to form large droplets in the jet shear layer before the rapid directional change of flow.
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