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International Journal of Multiphase Flow 28 (2002) 93–104

International Journal of Multiphase Flow

www.elsevier.com/locate/ijmulflow

Dripping phenomena of water droplets impacted on horizontal wire screens

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Received 20 March 1999; received in revised form 15 August 2001

Abstract

The dripping phenomena of water droplets impacted on horizontal wire screens at isothermal condition were studied. Uniform droplet streams of about 350 μm in diameters with a velocity of 2.8 m/s were produced using a piezo-electric droplet generator. The wire diameter of the screens ranged from a coarse screen of 1.6 mm with 2×2 meshes per linear inch to a fine screen of 0.14 mm with 100×100 meshes.

For droplets impinging on the coarse wire screens, they wet the wires and form thin liquid clusters. As these clusters of water accumulate around the wires, dripping drops are produced on the bottom side of the wires as well as at the corners of the meshes. The phenomena are very similar to the dripping drops formed beneath single wires. For screens with medium size opening, the dripping drops are mostly formed at the mesh stitch apertures surrounded by the wires. For fine mesh screens, the liquid films on the top surface pass through the fine mesh openings and form liquid ligaments at the bottom side of the screen. This resembles the situation of drops dripping from a ceiling. In all cases, the drops gradually evolve into a pendent shape under the influence of surface tension and gravity. Eventually, the weight of the pendent drop exceeds the surface tension and the drop falls off from the bottom of the screen. Non-dimensional parameters have been used to identify the dripping characteristics and to quantify the size of the dripping drops. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Mono-size droplets; Impaction; Wire screens; Dripping phenomena

1. Introduction

The impacting process of droplets on wire screens can be found in a variety of industrial applications. For example, woven wire screens are used extensively during distillation for separating

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PII: S0301-9322(01)00061-1

the liquid droplets from gaseous streams. They can also be utilized in typical process plants for size classification, product separation, impurity removal, particle filtration, and mist elimination (Muldoon, 1984; Capps, 1994). Fine water sprays have also been proposed as a fire suppressant specially targeted for certain type of fire situations occurring inside electronic or equipment compartments (Jones and Nolan, 1995; Ramsen, 1996). However, these sprays must be able to reach the fire inside through the compartment openings. A mist spray contains a spectrum of different drop sizes. The smaller droplets may follow the gas streams closely and penetrate through the openings while the larger droplets may impinge on the openings directly. Since the intercepting processes are strongly influenced by the geometry and configuration of the openings which could be in the form of a ventilating screen, it is important to understand the impingement of droplets on the screen structures.

A typical mesh screen is made up of wires of a particular diameter interweaving together to form a perforated planar structure with a desirable mesh opening size. Depending on the applications, the wire sizes and mesh openings of a screen may vary typically from micrometers to millimeters. The woven structure of the wire screen may be as soft and flexible as a silk cloth or as rigid and durable as a solid steel plate (Soar, 1991).

Even though the screens may appear to be planar in many practical applications, their characteristics with respect to droplet impaction are quite complicated. Thin liquid films may build up on the screens during the droplets' impingement and subsequently they block a portion of the meshes. Hence, the penetration processes are strongly influenced by the droplet size, the flow condition, the configuration of the screens, and the behavior of the liquid films subsequent to the impaction process.

Much of the available literature on the droplet impacting phenomena is only applicable to the flat solid surfaces (Chandra and Avedisian, 1991; Cohen, 1991; Fukai et al., 1995). The information of droplets impacting on wire screens remains relatively limited. Apart from the results of the penetration of sub-micron range ultrafine particles through fine screens (Wang, 1996; Ichitsubo et al., 1996), not much information is available for larger droplets impinging on screens with interweaving wires of comparable sizes.

Previous experiments from the droplets impacting on single wires (Hung and Yao, 1999) revealed that both the finer disintegrated droplets and larger dripping drops could be generated. The outcome of the impaction was dependent upon the droplet incoming velocity, the droplet size, and the wire diameter. Initially, the velocity of the drop played a critical role because it affected the magnitude of impact onto the wire. When the wire was wetted with water films, a larger drop was forming underneath gradually. The detachment of hanging drop was under the influence of both the gravitational effect and the surface tension. In addition, the wetting of the surface would affect the interfacial contact phenomenon. Also, the contact angle between the solid surface and the droplet would subsequently influence the size of the dripping drops. This is because when the surface wettability is lowered, the interfacial contact angle between the wire and the liquid film is increased and the net effect of the surface tension is reduced. The liquid film has a much less tendency to stick or wet the surface. However, due to the scope of this investigation, the measure of interfacial contact angle is not included in the current investigation. Furthermore, the effect of viscosity in terms of Reynolds number is also not considered.

The objective of this experimental study is to extend the previous work on the impaction of droplets on simple wires to more complicated wire screen structures. Fig. 1 displays the schematic

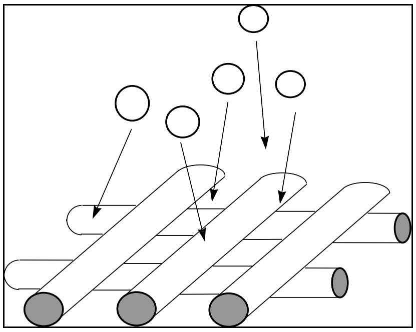


Fig. 1. Schematic of the droplets impacting on a horizontal screen.

diagram of the impacting process. Since a wire screen is composed of a multitude of interweaving wires, the fundamental understanding of droplet impingement on more complex wire screen structures may be built upon the results from the impaction process on single wires. Non-dimensional parameters such as the Bond number and screen parameter were used to characterize the impaction regime and to quantify the dripping drop size.

2. Experimentation

2.1. Description of the wire mesh screens

Muldoon (1984) reviewed some common types and general specifications of wire screens. A plain square weave type of wire screen was chosen for the current investigation. The square meshes are formed by passing wires over and under other successive warp wires in an orthogonal orientation. The term 'mesh' refers to the number of openings per linear inch. The distance is the length between the two centers of the adjacent parallel wires, which is simply the inverse of the mesh number. The clear width of mesh opening is the distance minus the diameter of the wire. For example, a 5×5 mesh screen with a wire diameter of 1.59 mm has five square openings per inch on each side, a distance of 5.08 mm between the diameters of the two wires, and a clear width of mesh opening of 3.48 mm.

It must be noted that even though, in theory, any wire screen configuration with a specific wire size and a mesh opening dimension can be made, not all of them are commercially available. It is because the screens with small wire diameter and large mesh opening are impractical to be manufactured and could be of limited value to industrial applications. Therefore, within the scope of this investigation, 20 plain-weave stainless steel screen samples covering a wide range of different wire sizes and mesh openings were mindfully selected for the experiments. All of them were available commercially from several wire cloth manufacturers (F.P. Smith Wire Cloth Co., Cleveland Wire Cloth & Mfg. Co., Fenway Wire Cloth Co, and Newark Wire Cloth Co.). The wire diameter of the screens varied from a coarse screen of 1.6 mm with 2×2 meshes to a fine screen of 0.14 mm with 100×100 meshes.

2.2. Experimental set-up and conditions

Fig. 2 displays the overall schematic diagram of the experimental set-up. The mono-size water droplet stream was generated using the modified design of the Impulsed Liquid Spray Generator developed by Ashgrizzadeh and Yao (1983). The operation of this generator is based on the Rayleigh-type breakup of liquid jet which has been well documented. This droplet generator was able to produce a uniform water droplet stream of 350 μm in diameter with velocities of 2.8 and 7 m/s, respectively. Each wire screen with the dimensions of 5 cm long × 2 cm wide was positioned horizontally at a distance of 10 cm below the nozzle tip. Two small opposing air jets were located half way between the nozzle tip and the screen. They were used to disperse the droplet stream, ensuring that the droplets were able to spread randomly over the screen before the impingement occurred. Close observation was made to ascertain that no droplets would impinge on the screen at the exact same location over repeatedly. The volumetric flux, measured at the location where the screen was positioned, was about 17.6 cc/ min /cm^2, and it was maintained for all the experiments. This value was selected primarily to match the same experimental condition previously tested for the single wire cases. At the end of each experiment, the wire screens were cleaned with alcohol to ensure that the surface of the screens was wettable.

Video images were used to record the dripping phenomena using a Javelin Newvichip CCD camera equipped with a Nikon SMZ-10 high power magnification stereo-microscopic lens. To enhance the viewing directions, the CCD camera was positioned at three different angles towards the screen from the top, front, and bottom viewing directions. This illumination was provided by

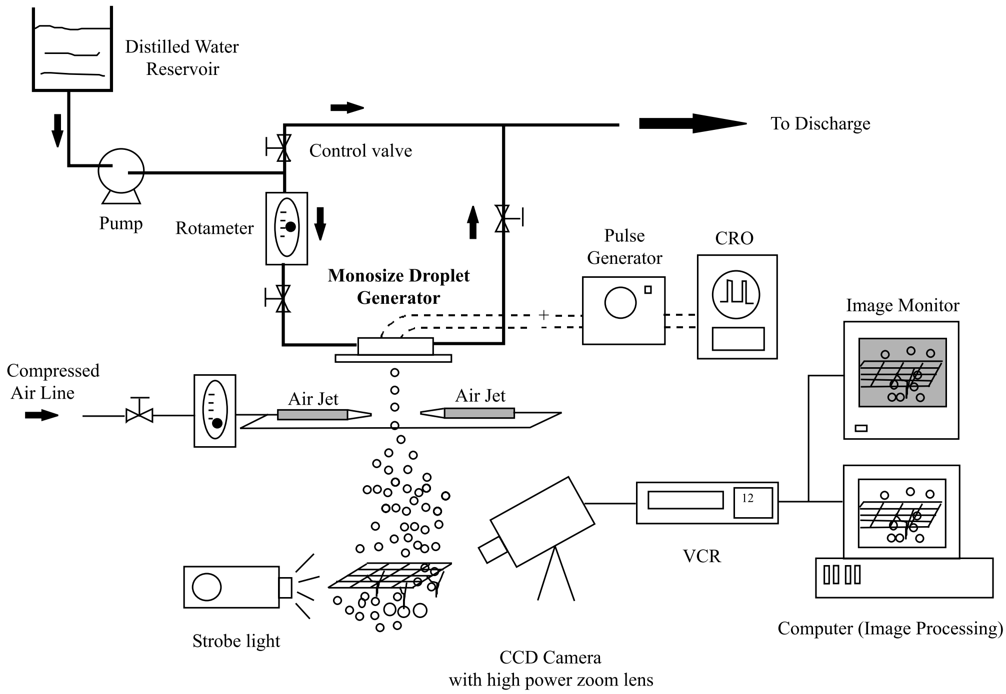


Fig. 2. Schematic diagram of the overall experimental set-up.

a background strobe light (Strobotac, 1531-A) of about 10 ms pulse duration. For each screen configuration, at least three representative images were captured into a computer using a frame grabber and were analyzed via a digital image processing technique with the Optimas™ analysis software. The digitized images were mainly used to reveal different kinds of dripping phenomena and to extract the size of the drops dripping off from the screens.

3. Results and discussions

3.1. General dripping phenomena

Experimental results show that some droplets pass through the mesh openings of the coarser screens without hitting the interwoven wires. As the screens become finer, droplets either impinge upon the wire meshes or not. These droplets tend to wet the wires and thus create thin liquid films (Padday, 1957). Fig. 3 summarizes the general behavior of the droplets dripping from a horizontal screen.

For all the screens being studied, the major outcome of the drops following the impaction is dripping with an incoming velocity of 2.8 m/s. The higher droplet velocity of about 7 m/s did not show any different outcome on the overall dripping phenomena. It is because the specific dripping characteristics depend more on the physical geometry of the wire meshes such as wire diameter of the screen and the size of the mesh opening and relatively less on the droplet incoming velocity. Only one condition of the liquid volumetric flux was tested. This was to match the same condition previously tested for the wire cases. It is believed that the dripping process would become more dynamic as the volumetric flux increased and the dripping drops would be formed more frequently. If the incoming liquid flux is less than the rate the drop is dripping, the basic observation of the dripping phenomena would remain essentially unchanged.

Thin liquid films accumulate over the screen surface in a random manner. As the liquid films build up, they wrap around the wires, gradually causing drops to be formed on the bottom side of

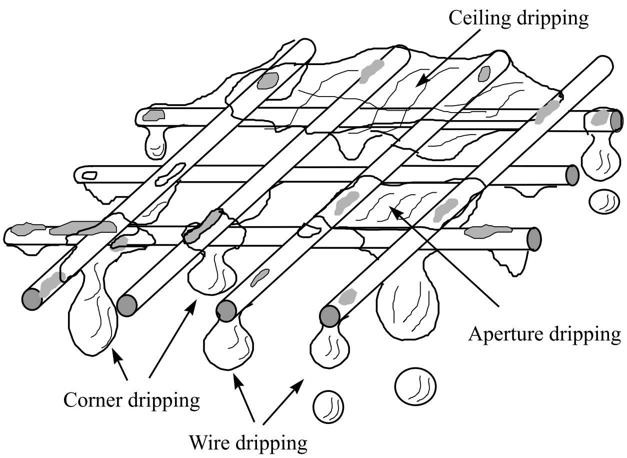


Fig. 3. General dripping phenomena of droplets impacted on a horizontal screen.

the screen. Typically, larger dripping drops may be found at different locations across the screen, for example, at the bottom side of a single wire, at the corners of the meshes, and even at the mesh stitch apertures surrounded by the wires. If the screen is very fine, the accumulation of droplets would first form a thin film on top. It then gradually permeates to the bottom side, resulting in a gradual pendent drop formation. The pendent drops resemble the situation of drops dripping from a ceiling top. Based on the resemblance and screen geometry from which the dripping drops are formed, the general dripping observation can be approximately classified into four types of phenomena. It is noted that multiple dripping phenomena could also be observed simultaneously for a given screen configuration.

3.1.1. Wire dripping

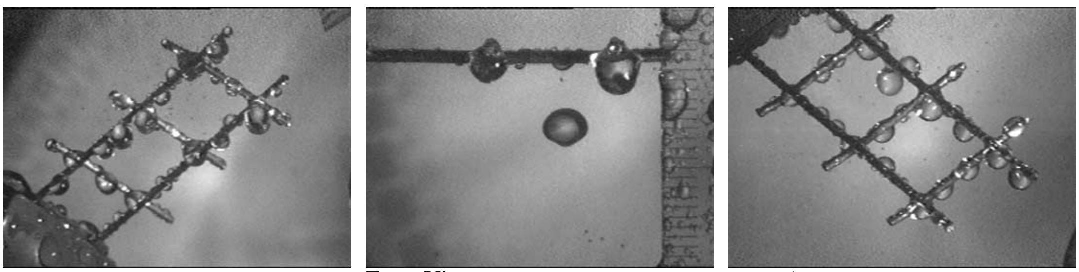
Fig. 4 displays the top, front, and bottom view of the situations where the droplets impinged on a coarse screen of 2×2 mesh. This wire screen is made up of wire with a diameter of 1.19 mm and a clear width of mesh opening of 11.51 mm. In general, when the droplets impinge on such a coarse screen, water films wet the wire surface and stick onto the wire at the locations of the impingement. The liquid films gradually wrap around the wires as more droplets accumulate. As seen in these pictures, some drops are hanging under the bottom side of the wires. The films gradually evolve into a pendent drop profile. The weight of each drop becomes large enough to overcome the surface tension force at the contact and the drop detaches from the wire eventually. This dripping phenomenon resembles the situation of that for a single wire condition (Hung and Yao, 1999).

3.1.2. Corner dripping

In addition, dripping drops also occur at the corners of the meshes formed between two crossing wires. This type of dripping drops is generally larger than the ones formed at the bottom side of single wires. This is because the interfacial contact surface area between the liquid and wire at the corner locations is larger than that at the bottom side of a single wire. The fluid adheres onto a bigger contact surface area, thus creating a larger surface tension force.

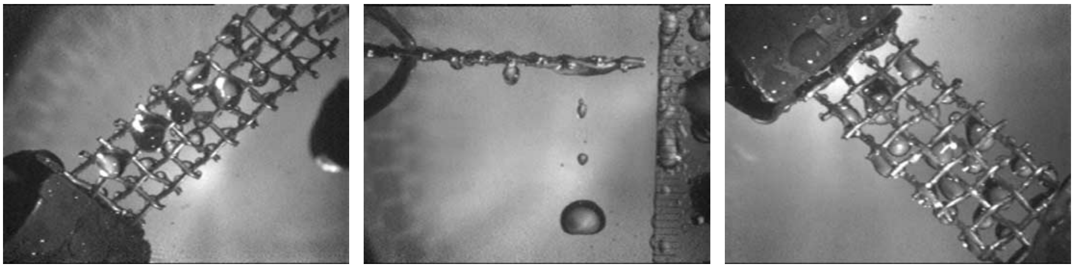
3.1.3. Aperture dripping

Dripping also occurs under single mesh aperture surrounded by the wires, as demonstrated in Fig. 5 for a medium-sized screen of 6×6 meshes with a wire diameter of 0.89 mm and a clear width of mesh opening of 3.35 mm. This screen is finer than the previous one. In accordance with



Bottom View Front View Top View

Fig. 4. 2×2 mesh screen with wire diameter of 1.19 mm.



Bottom View Front View Top View

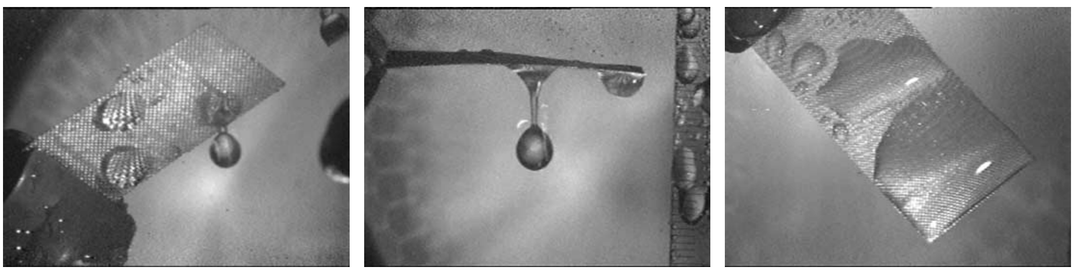
Fig. 5. 6 × 6 mesh screen with wire diameter of 0.89 mm.

the observation by Padday (1957), the droplets that coalesce on the wires will reach a critical volume when spreading to form a film over the surface. The film is then drained toward the 'cross-over' points of wire in the basic interweaving structure. These are the locations where the effective pore apertures are smallest (Feord et al., 1993). As displayed in the figures, instead of dripping directly under the wires as in the previous situation, pendent drops are formed mostly under the mesh stitch apertures. In addition to the main dripping drops, smaller satellite droplets are occasionally formed after the primary drops detach from the screen.

The size of the pendent drops can be determined by the physical dimensions of the aperture which is dependent on the stitch geometry of the woven screen. Generally, the dripping drops in this condition are larger than the ones in the previous two cases.

3.1.4. Ceiling dripping

Fig. 6 displays another situation of droplets dripping from a very fine screen. This screen has 100 × 100 meshes with a wire diameter of 0.14 mm and a 0.14 mm clear width of mesh opening. This fine screen resembles a perforated flat sheet with tiny mesh openings. This type of dripping is similar to the aperture dripping case, except that the dripping drops mostly originate from multiple mesh apertures rather than from a singular one. Since the stainless steel wire is hydrophilic, therefore when the droplets impinge on a fine screen, a thin water film usually builds up on the top of the screen. This film becomes thicker as more droplets impinge on it. The top surface of the wire is wetted which allows the liquid to soak through the tiny meshes. The liquid film gradually permeates to the bottom side through these mesh openings. This film continues to grow



Bottom View Front View Top View

Fig. 6. 100 × 100 mesh screen with wire diameter of 0.14 mm.

underneath in the form of a pendent drop as a result of the gravity effect and the drop detaches from the wire eventually. However, if the surface is non-wettable (hydrophobic), the liquid film will not be able to build up on the screen. Overall, the ceiling dripping phenomenon exhibits a form of instability process. Due to the limited size of the wire screen sample, it was not possible to detect the wavelength of the droplet separation. This situation resembles the breakaway of a drop from a flat horizontal wetted surface (Tamada and Shiback, 1966). Eventually when the weight of the pendent drop is large enough to overcome the surface tension force associated with the contact area of the screen, the drops break away by detaching from the screen. As shown in the bottom view of Fig. 6, a single large drop has been formed and it is about to detach from the bottom side of the screen while two other drops are forming gradually.

3.2. Non-dimensional parameters

Non-dimensional parameters and correlations are used to characterize the results of the dripping phenomena.The controlling parameters in this study are surface tension and density of the droplet (σ, ρ_L), the wire size in the screen (D), and the clear width of mesh opening (L). Two important non-dimensional parameters which can be used for this analysis are the wire Bond number (B_w) and mesh Bond number (B_m), with the following definitions:

$$B_\mathrm{w} = \frac{D}{\sqrt{(\sigma/g\rho_L)}}, \tag{1}$$

$$B_\mathrm{m} = \frac{L}{\sqrt{(\sigma/g\rho_L)}}. \tag{2}$$

The Bond number represents the ratio of the gravitational force to surface tension. This Bond number is a key parameter in the analysis when both the effects of gravity and surface tension are considered during the dripping process. In addition, a screen parameter (S) is often used to characterize a screen with the following definition (Cheng and Yeh, 1980):

$$S = \frac{4\alpha h}{\pi(1-\alpha)D}. \tag{3}$$

In our screen selection, the wire diameter (D) and the screen thickness (h) are assumed to be of the same size. The term α is the screen's solid fraction when the flow is perpendicular to the screen. It is a function of both L and D. The screen parameter represents a measure of mesh fineness of the screens. In general, a finer screen has a higher S value.

Fig. 7 displays a regime map for four types of dripping by plotting all 20 screens based on the wire Bond number verses the mesh Bond number. It identifies how each type of dripping occurs in relation to the screen geometry characteristics. Wire dripping (square symbols) represents the dripping drops formed at the bottom side of a single wire and corner dripping (circle symbols) is designated for those formed at the corners of the meshes. Typically, dripping drops formed for these two types are associated with coarser screens (larger wire and mesh sizes). As the meshes are smaller, aperture dripping (diamond symbols) from multiple mesh openings is likely to occur. This is because the interfacial contact surface for the dripping drops to be formed is larger under the stitch mesh apertures. For very small mesh openings, as indicated by the small mesh Bond

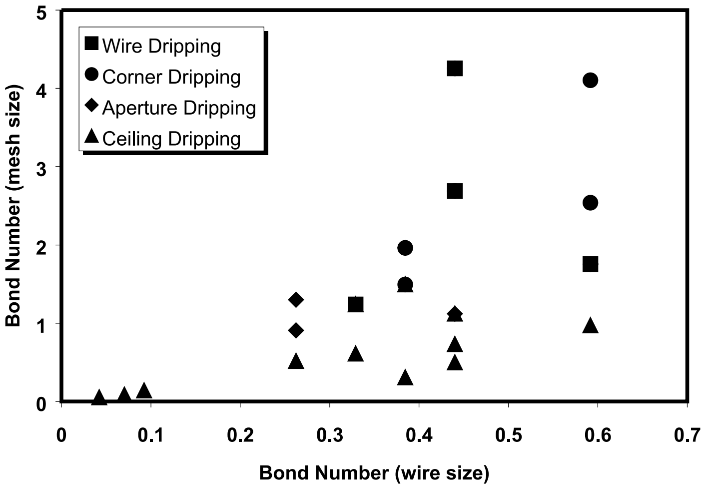


Fig. 7. Regime map for the phenomena of dripping drops from screens.

number, ceiling dripping (triangle symbols) resembles the situation of drops dripping off from a flat horizontal surface.

It can be seen that the wire screens with small wire Bond number and large mesh Bond number do not exist in Fig. 7 because they represented the screens made with the combination of very small wire and large mesh opening, which were not available commercially. If the droplets were to impinge on such screens, their impingement and dripping characteristics would be quite similar to the situation of those single wire cases.

3.3. Determination of the size of the dripping drops

The sizes of the dripping drops were determined from the digitized images. From the photographs shown in Figs. 4–6, it can be observed that some of the dripping drops are not spherical. After detachment, they appear to be like prolate spheroids with a major axis L_1 and a minor axis L_2. An equivalent drop diameter of a prolate spheroid can be found by equating its volume using the following formulation:

$$\frac{4}{3}\pi\left(\frac{L_1}{2}\right)\left(\frac{L_2}{2}\right)^2 = \frac{1}{6}\pi(D')^3. \tag{4}$$

Therefore, the equivalent diameter of a dripping drop can be found by measuring both L_1 and L_2 with the following equation:

$$D' = \sqrt[3]{L_1 L_2^2}. \tag{5}$$

This formulation is used for deducing the data from the non-spherical dripping drops.

Fig. 8 shows the relationship between the equivalent diameter of the dripping drops and the screen parameter. The typical dripping drops range from 3.5 mm to about 6 mm in our studies. Larger dripping drops are associated with the ceiling dripping case while smaller ones occur in the wire or corner dripping cases.

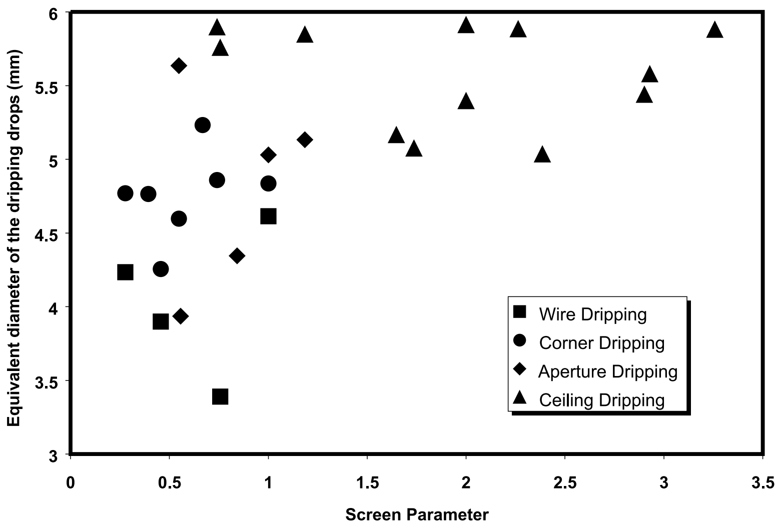


Fig. 8. Size measurement of the dripping drops from horizontal screens.

Smaller dripping drops are associated with the coarser screens. For these cases, it appears that the size of the dripping drop depends on the wire diameter and the geometry of the liquid–solid interfacial contact on the wires. However, due to the complex three-dimensional nature of the pendant drop attaching under the screen, an exact analysis to determine a detailed measure of the liquid–solid contact at the interface will be very difficult. Therefore, a simple two-dimensional force balance can be established to predict the dripping size when the drop is about to detach from the wire. If it is assumed that the dripping drop for the wire dripping mode attaches onto the wire over a length of D on both sizes, then the balance between the attachment force and the weight of the drop can be given as

$$\sigma 2D = \frac{\pi D'^3}{6}\rho_L g. \tag{6}$$

Rearranging Eq. (6) yields the following relationship of the size of a dripping drop:

$$D' = \left[\frac{12\sigma}{\pi\rho_L g}D\right]^{1/3}. \tag{7}$$

In general, if the width of the mesh opening is wide enough so that only dripping drops from the wires are encountered, the dripping size decreases as the wire size decreases. Similar analysis can be established for the cases of corner dripping and aperture dripping which are dependent on the stitch geometry of the woven screen.

An empirical correlation of the dripping drop size as a function of single wire diameters has been formulated experimentally by Hung and Yao (1999):

$$D' = 1.813D\left(\frac{D}{\sqrt{\sigma/\rho_L g}}\right)^{-0.786}. \tag{8}$$

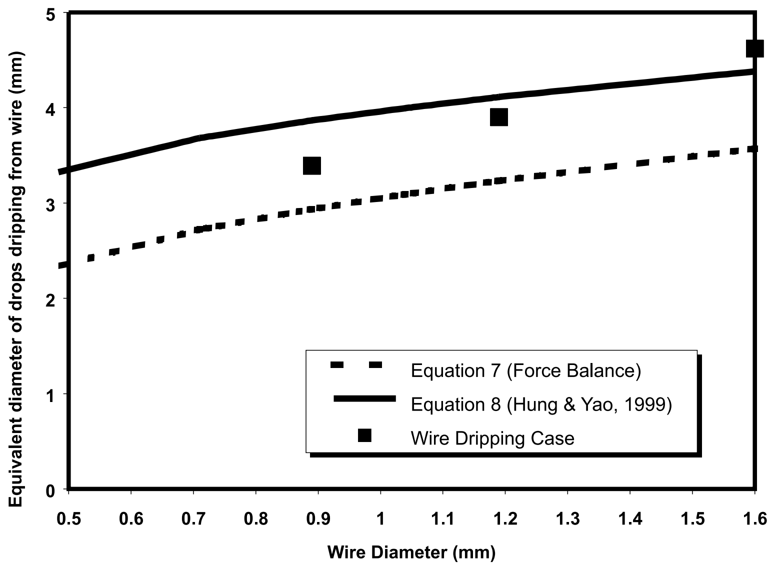


Fig. 9. Drop size comparison: wire dripping and prediction from single wires.

Fig. 9 shows the comparisons between the simplified force balance approach (Eq. (7)), the prediction of drops dripping from single wires experiments (Eq. (8)), and the drops from the screens classified as the wire dripping mode. When the screens are coarse enough such that the dripping drops are formed solely at the bottom side of the wires, then Eq. (8) may be used to predict the dripping drop size reliably within the experimental conditions examined.

From our results displayed in Fig. 8, the largest dripping drops are formed from the fine screen which resemble the situation of dripping from the ceiling. Tamada and Shiback (1966) derived an expression for a drop slowly formed by dripping from a horizontal flat wetted surface, based on a balance between the gravitational and the surface tension forces, as follows:

$$D' = 3.3\left(\frac{\sigma}{\rho_L g}\right)^{0.5}. \tag{9}$$

Therefore, for a water drop dripping off from a flat surface at a very slow flow rate, its diameter would be about 9 mm. Even though a very fine screen may look like a solid flat surface, the dripping mechanism for both cases could be very different. It is because the wetting of water through the tiny wire meshes is different than that on a flat surface. The maximum drop diameter observed from the fine screens in this study is only about 6 mm. Therefore, Eq. (9) may serve as the maximum size limit of a water drop dripping from fine horizontal screens.

4. Conclusions

An experimental investigation of the water droplets dripping from wire mesh screens was conducted. Preliminary results show that when the droplets impinge on the wettable screens directly, the primary outcome is dripping. Within the experimental conditions examined, the dripping characteristics are dependent upon the wire diameter of the screen and the size of the mesh openings and relatively independent on the droplet velocity. For the droplets impinging on coarse screens, the phenomenon resembles the situations of dripping drops from single wires. For medium size screens, the hanging drops may form at the corners of crossing wires or under the mesh stitch apertures. For the droplet impinging on very fine screens, a thin water film is first accumulating on the top of the screen. Then it passes through the tiny mesh openings to the bottom side and gradually forms a dripping drop. This resembles the situation of drops falling off from a ceiling.

Acknowledgements

The authors greatly appreciate the funding for this research supported by the US Department of Commerce, National Institute of Standards and Technology, Building and Fire Research Laboratory, under Grant No. 60NANB5D0093.

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