Calculating liquid droplets settling on a cylinder in gas–liquid spray flow

M. Pawlowski* and B. Siwoń*†

Adding atomized liquid to air flowing around a cylinder gives an appreciable increase in heat transfer by forming a liquid film on the cylinder surface. The heat transfer coefficient depends upon the amount of liquid forming the film, which is limited by two phenomena: droplet deflection from the liquid film on the surface and droplets not striking the cylinder. This paper presents a method of calculating the quantity of liquid droplets settling on a cylinder surface in a gas–liquid spray flow. A coefficient $\bar{k}$, the volume ratio of the liquid entering the film to the amount of liquid directed at the cylinder, is introduced. $\bar{k}$ values were calculated by means of numerical computation and the theory verified experimentally. The calculation method permits estimation of the dependence of the amount of liquid settling on a cylinder on the droplet diameter distribution parameters and on the linear gas velocity

Keywords: *heat transfer, spray flow, liquid droplets*

Heat transfer between a gas–liquid spray and a cylinder has been the subject of many theoretical and experimental studies. In experimental studies, a gas–liquid spray is directed perpendicularly at a horizontal or vertical cylinder. Liquid film forms on the surface of the cylinder, covering approximately half the surface. This film flows on the cylinder surface from the stagnation point to the separation point (Fig 1), where the liquid drops off vertical cylinders under gravity or is torn off horizontal cylinders in the shape of droplets and carried away by the stream.

The results of these experimental investigations have been used to verify conclusions drawn from theoretical considerations. There are a few papers dealing with the theoretical aspect of heat transfer between a liquid mist flow and a cylinder[2,3,7,10,12]. The mathematical models presented there include equations of continuity, momentum and energy for the liquid film on the front surface of the cylinder. The quantity of liquid droplets captured by the cylinder was not considered. In most of those papers it was assumed that the droplet trajectories were straight and all droplets which reached the film surface were entrapped in the film. These assumptions are correct for large values of the gas velocity and quite large droplet diameters. For smaller gas velocity the droplets, which are of small diameter, can pass around the cylinder or bounce from the liquid film surface. Agreement between the experimental and theoretical data reported in an earlier paper was a result of the large linear gas velocities used in those experiments. It has been stated, however, that the main parameter determining the heat transfer coefficient is the mass flow rate of the liquid attached to the cylinder, while the linear velocity of the gas has a minor influence[6,9].

* Department of Chemical Engineering and Physical Chemistry, Technical University of Szczecin, Poland

† Contact: Bogdan Siwoń, 72010 Police, ul. Mieszka 1 8c/44, Poland

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From a practical point of view, therefore, one can suppose that small linear gas velocities should be used. In that case, the main criteria for the choice of the linear gas velocity will be the occurrence of droplet deflection and droplet avoidance of the cylinder.

Goldstein, Wen-Jei Yang and Clark[2] introduced a method of calculating heat transfer coefficients between the cylinder and gas–liquid spray flow assuming curved droplet trajectories. Their analysis employed the results obtained using the Tribus[11] and Langmuir and Blodget[4] investigations. The calculation was performed assuming that the droplet diameters are similar. In practice, gas–liquid spray flow droplet diameters vary and, therefore, using the mean droplet diameter in the calculations will give poor results as the phenomena of droplet deflection and avoidance of the cylinder are mainly associated with the small droplets. The values of the heat transfer coefficients calculated using a mean diameter may be greater than those actually present.

Wilson and Jones[12] described a theoretical investigation of the heat transfer between a circular cylinder and gas–liquid spray flow. They compared the results of their own calculations and the experimental results of the Hodgson, Saterbak and Sunderland[3] investigation and obtained a fair measure of agreement. Droplet trajectory analysis was performed and it was stated that, for the typical range of droplet diameters and linear velocity of gas, curved droplet trajectories have a minor influence on the heat transfer coefficient. Since the authors did not obtain the droplet diameter distribution in the gas–liquid stream, they made calculations for droplet diameter $d_d = 250\ \mu m$. Some of the equations published by Wilson and Jones are used in this paper.

In an experimental investigation on the droplet deflection from a film surface, Gagliardi[1,8] observed the behaviour of the droplets striking a flat surface covered with the liquid film using a high-speed camera. It was found that some droplets bounced from the liquid film surface and Gagliardi accepted the assumption that the

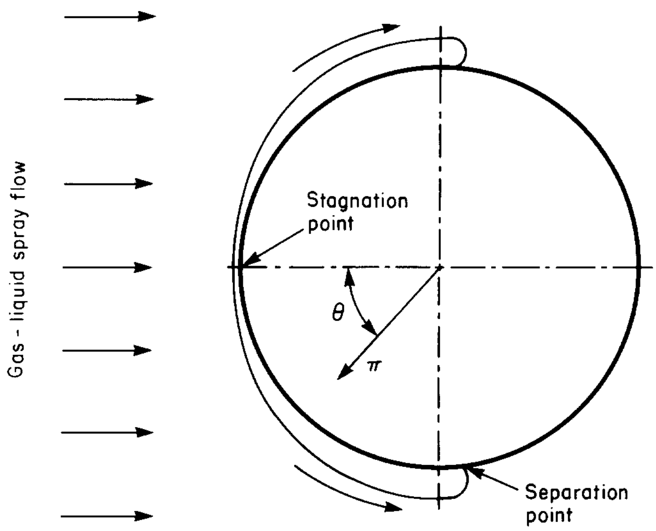

Fig 1 Behaviour of the film on a cylinder surface in a gas–liquid spray flow

droplet behaviour depends on the droplet momentum. He found that on the basis of the results of his experimental investigation, droplets possessing momentum $m_d w_d > 2.67 \times 10^{-8}$ Ns passed into the film; if $m_d w_d < 1.65 \times 10^{-8}$ Ns the droplet bounced from the liquid film surface and in the range $1.65 \times 10^{-8} < m_d w_d < 2.67 \times 10^{-8}$ Ns both phenomena took place. Gagliardi performed his experiments in a narrow range of temperatures so droplet deflection did not depend on liquid surface tension in this investigation.

In this paper droplet behaviour, for a gas–liquid spray passing perpendicular to the cylinder surface, is considered. The purpose of this study was to develop a method of calculating the volume ratio of the liquid, $\bar{k}$, entering the film to the amount of liquid directed at the cylinder. The theoretical approach was verified experimentally.

On the basis of the calculations, a condition has been found in which $\bar{k}$ is almost equal to 1. Fulfilling this condition one can obtain a better heat transfer process. The method presented here can be used in designing heat exchangers and other apparatus with a liquid droplet–gas flow.

Theoretical considerations

We wish to predict the droplet behaviour for a mist flow striking the cylinder surface. The principal assumptions are:

1. The droplets are uniformly distributed throughout the gas stream;
2. The gas and droplets have the same velocity;
3. The droplet diameter distribution is described by the Rosin–Rammler function;
4. After deflection from the liquid film surface, droplets are not in contact with the film.

Consider a cylinder set perpendicular to the gas–liquid spray flow (Fig 1), where the droplets do not bounce from the liquid surface and their trajectories are straight. The liquid quantity settling on the front half of the cylinder in unit time can be expressed as:

$$G_1 = g_1 D h \tag{1}$$

If droplets bounce or if curved droplet trajectory phenomena are observed, Eq (1) overestimates the liquid quantity G_1, which also depends on the cylindrical coordinate θ. In this case Eq (1) can be written as:

$$G_1(\theta) = k(\theta) g_1 D h \tag{2}$$

Notation

- D Cylinder diameter, m
- d_d Droplet diameter, m
- $d_{d,1}$ Droplet diameter below which droplets bounce from the liquid film surface, m
- $d_{d,2}$ Droplet diameter below which the droplets pass round the cylinder, m
- d_m Median droplet diameter, m
- E_d Kinetic energy of the liquid droplet, J
- E_{cr} Critical kinetic energy of droplet below which droplets bounce from the liquid film surface, J
- g_1 Mass velocity of liquid in a gas–liquid spray stream, kg/m^2 s
- G_1 Liquid quantity settling on the cylinder, kg/s
- $G_1(\theta)$ Local liquid quantity settling on the cylinder, kg/s
- h Height of cylinder, m
- $k(\theta)$ Local volume ratio of liquid entering film to amount of liquid directed at the cylinder in gas–liquid spray flow
- $\bar{k}$ Average volume ratio of liquid entering film to amount of liquid directed at the cylinder in gas–liquid spray flow
- $k_1(\theta)$ Volume ratio of liquid entering film to amount of liquid directed at the cylinder as a result of the deflection of droplets from the liquid film surface
- $k_2(\theta)$ Volume ratio of liquid entering film to amount of liquid directed at the cylinder as a result of the droplets' trajectories
- m_d Mass of droplet, kg
- R Radius of cylinder, m
- r_d Radius of droplet, m
- s Reciprocal of the Stokes number
- Stk Stokes number (Eq(13))
- $U(\theta)$ Liquid film velocity, m/s
- w_d Droplet velocity, m/s
- $w_{d,x}$ Droplet velocity in x-direction, m/s
- w_g gas velocity, m/s
- x, y Cartesian coordinates
- y_∞ Droplet coordinate at infinity
- β Angle between the straight droplet trajectory and x-coordinate, radians
- δ Liquid film thickness, m
- η_g Gas dynamic viscosity, kg/ms
- θ Cylindrical coordinate
- χ Distribution parameter of Rosin–Rammler function
- ρ_l Density of liquid, kg/m^3
- σ Liquid surface tension, N/m
- σ_X Surface tension component in X-direction, N/m

For the whole cylinder of height, h:

$$G_1 = \bar{k} g_1 D h \tag{3}$$

where $\bar{k}$ is calculated for the front half of the cylinder.

The volume ratio of liquid entering film to the amount of liquid directed at the cylinder $k(\theta)$ depends on droplet deflection from the liquid film surface and the curve of the droplet trajectories. We can assume that these phenomena are independent of each other. Then $k(\theta)$ will depend on two parameters: $k_1(\theta)$, the volume ratio of liquid entering the film to the amount of liquid directed at the cylinder in the gas–liquid spray flow resulting from deflection of the droplets from the liquid surface; and $k_2(\theta)$, the volume ratio of liquid entering the film to the amount of liquid directed at the cylinder in the gas–liquid spray flow resulting from the curvature of the droplet trajectories.

Calculating $k_1(\theta)$

Explaining droplet deflection from the liquid film surface is not easy. A liquid droplet coming into contact with the liquid film surface should pass into the film due to the cohesion force pulling liquid molecules into the film. If the droplet striking the film surface has a small diameter, one can assume that surface tension on the curved droplet surface causes the droplet to preserve its shape during contact with the approximately flat liquid film surface. Often the droplets have a lower temperature than the liquid film (as a result of cooling of the cylinder surface by the two-phase flow) so that the surface tension of the droplet is greater than the surface tension of the film.

To determine the conditions under which the droplet deflects from the film surface, it is assumed that the droplet preserves its shape after striking the film. The droplet will be deflected if it possesses too little energy to surmount the liquid film surface tension.

Consider a spherical liquid droplet striking the liquid film surface (Fig 2). β is the angle between the straight droplet trajectory and the X-coordinate which is

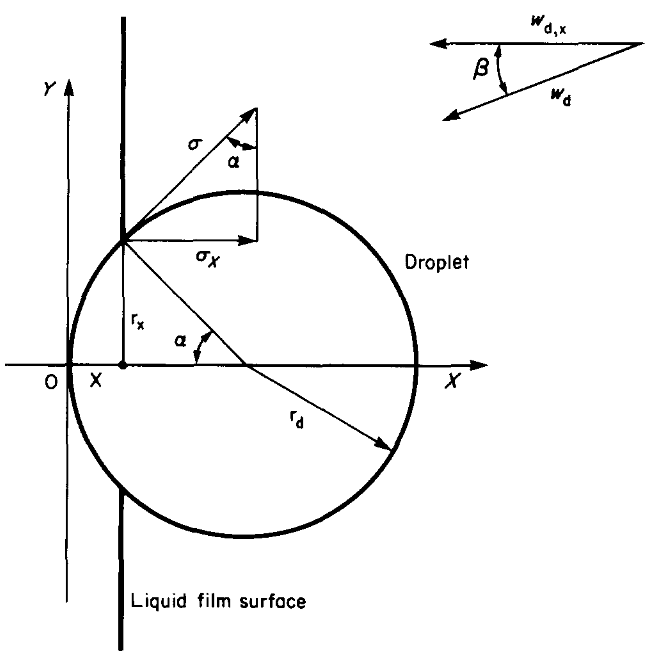

Fig 2 Droplet striking the film surface

perpendicular to the film surface. The change in droplet energy is equal to work done against forces of the film surface tension:

$$-m_d w_{d,x} \mathrm{d}w_{d,x} = \sigma_x 2\pi r_x \mathrm{d}x \tag{4}$$

Using the geometrical relationship from Fig 2 one obtains:

$$-m_d w_{d,x} \mathrm{d}w_{d,x} = 2\pi\sigma\left(2x - \frac{x^2}{r_d}\right)\mathrm{d}x \tag{5}$$

Assuming that the droplet preserves its shape until it is submerged in the liquid film, the droplet energy necessary to surmount surface tension can be calculated by integrating Eq (5):

$$\int_{w_{d,x}}^{0} -m_d w_{d,x} \mathrm{d}w_{d,x} = 2\pi\sigma \int_0^{2r_d} \left(2x - \frac{x^2}{r_d}\right)\mathrm{d}x \tag{6}$$

Integration gives:

$$E_{cr} = \tfrac{1}{2} m_d w_{d,x}^2 = \tfrac{8}{3}\pi\sigma r_d^2 \tag{7}$$

If the droplet strikes the liquid surface at an angle β (Fig 2) Eq (7) can be rewritten:

$$\tfrac{1}{2} m_d w_d^2 \cos^2\beta = \tfrac{8}{3}\pi\sigma r_d^2 \tag{8}$$

The mass of the droplet, m_d, can be expressed as a function of droplet diameter, d_d, and liquid density ρ_l. We can then obtain the range of droplet diameters which get inside the film:

$$d_{d,1} \geqslant \frac{8\sigma}{\rho_l w_d^2 \cos^2\beta} \tag{9}$$

The droplet diameter distribution in a liquid spray stream can be expressed by the Rosin–Rammler function which gives the volume ratio of droplets with diameter greater than d_d as:

$$1 - \phi_3(d_d) = \exp\left[-0.693\left(\frac{d_d}{d_m}\right)^{\chi}\right] \tag{10}$$

$k_1(\theta)$ can be written as:

$$k_1(\theta) = \exp\left[-0.693\left(\frac{8\sigma}{\rho_l w_d^2 d_m \cos^2\theta}\right)^{\chi}\right] \tag{11}$$

In Eq (11) σ is the surface tension of the liquid film, which is evaluated at the film surface temperature.

Calculating $k_2(\theta)$

Consider the droplet trajectory in a gas stream flowing in the direction of the side surface of the cylinder (Fig 3). A long distance from the cylinder the only force acting on the droplets is in the X-direction. In the neighbourhood of the cylinder a force component in the y-direction results from the changing flow direction of the gas. If the inertia force of the droplet is much higher than a force component in the Y-direction, the droplet trajectory will be approximately straight. If the forces are of the same order, a distinct curve in the droplet trajectory takes place. If the droplet deviation is not large, it still reaches the cylinder but at a location different than that projected for a straight droplet trajectory. In the case of large deviation, the droplet will pass around the cylinder.

Wilson and Jones[12] presented a droplet trajectory equation in the following form for gas–liquid spray flow:

$$y = y_\infty + s\left[\frac{\pi}{2} - \arctan\left(\frac{x}{y_\infty}\right)\right] \tag{12}$$

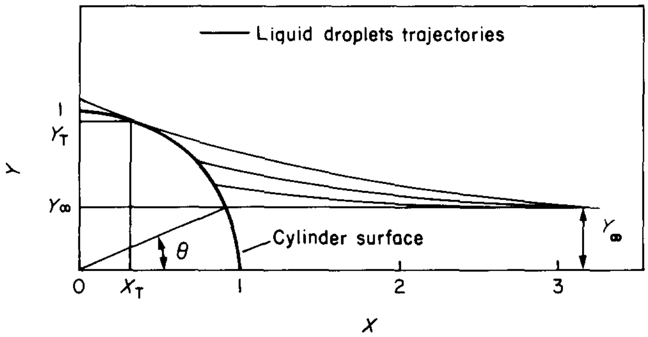

Fig 3 Behaviour of the droplets near the cylinder surface

where s is the reciprocal of Stokes number:

$$\frac{1}{s}=Stk=\frac{\rho_l w_g d_d^2}{18\eta_g R} \tag{13}$$

It has been assumed that the droplets reach the cylinder surface if the droplet trajectory intersects a circumference which is a cross-section of the cylinder in the X,Y-plane or the droplet trajectory is tangential to this circumference (Fig 3). The droplet trajectory deviates more when the droplet diameter is small (Eqs (12) and (13)). For a specified value of y_∞ we can calculate the diameter of the droplet whose trajectory is tangential to the cylinder cross section. Smaller droplets will pass round the cylinder. Differentiating Eq (12) we obtain:

$$\frac{dy}{dx}=\frac{-s\sin\theta}{\sin^2\theta+x^2} \tag{14}$$

where $\sin\theta=y_\infty$ (Fig 3). This is an equation of the directional coefficient of the tangent to the droplet trajectory. At the tangent point of the droplet trajectory and circumference (Fig 3) the directional coefficient of the tangent of the droplet trajectory and the circumference are equal to each other:

$$\frac{x}{\sqrt{1-x^2}}=\frac{s\sin\theta}{\sin^2\theta+x^2} \tag{15}$$

At the tangent point one can write:

$$\sqrt{1-x^2}=\sin\theta+s\left[\frac{\pi}{2}-\arctan\left(\frac{x}{\sin\theta}\right)\right] \tag{16}$$

Solving Eqs (13), (15) and (16), one can obtain a value for the droplet diameter $d_{d,2}$. Droplets with diameters less than $d_{d,2}$ will pass round the cylinder. In this case $k_2(\theta)$ can be represented by:

$$k_2(\theta)=\exp\left[-0.693\left(\frac{d_{d,2}}{d_m}\right)^{\chi}\right] \tag{17}$$

The value of $k_2(\theta)$ from Eq (17) is approximate because it does not take into account the droplets which, after bending of the trajectory, reach the cylinder surface. Determination of $k_2(\theta)$ included the assumption that the trajectory of droplets which reach the cylinder surface was straight. This causes minor errors in the value of $k_2(\theta)$ calculated but it does not significantly change the $\bar{k}$ calculation. A more detailed description of $k_2(\theta)$ is given elsewhere[5].

Calculating k(θ)

Assuming that droplets which bounce from the film surface never reach the cylinder, $k(\theta)$ can be calculated on the basis of $k_1(\theta)$ and $k_2(\theta)$ using the following reasoning. If in the defined conditions droplets with diameters smaller than $d_{d,1}$ bounce from the liquid film surface and the droplets with diameter smaller than $d_{d,2}$ pass round the cylinder, then:

—if $d_{d,2}>d_{d,1}$, no deflection of the droplets will take place because those droplets which would bounce do not reach the film surface; thus $k(\theta)=k_2(\theta)$;

—if $d_{d,2}\leqslant d_{d,1}$, the droplets with diameters less than $d_{d,2}$ pass round the cylinder and the droplets of diameter $d_{d,2}<d_d\leqslant d_{d,1}$ bounce from the film surface; droplets with diameter larger than $d_{d,1}$ reach the cylinder and $k(\theta)=k_1(\theta)$.

On the basis of this reasoning it appears that in calculating $k(\theta)$ one should use the larger value of $d_{d,1}$ or $d_{d,2}$, thus $k(\theta)$ is equal to the smaller value of $k_1(\theta)$ or $k_2(\theta)$. The average value of $\bar{k}$ on the front half of the cylinder can be calculated by integrating $k(\theta)$ in the range $0\leqslant\theta\leqslant\pi/2$.

Experimental verification of the model

The model has been verified on the basis of our own experiments and Gagliardi's investigation.

The Gagliardi experiments were used to prove the method of calculating the droplet bounce. Although Gagliardi employed as a bounce criterion the momentum of the liquid droplet, this does not prevent comparison of the experimental results with the energy criterion.

For 79 experimental results obtained by Gagliardi, the energy criterion from Eq (7) was calculated. In 66 cases the behaviour of the droplets agreed with our analysis. Of the remaining 13 experiments, in 9 cases the droplet behaviour did not agree with the analysis, but the difference between the droplet energy and critical energy was less than 30%. This can be explained as an experimental error. In only 4 cases where the droplet behaviour did not agree with the analysis was the difference $|E_d-E_{cr}|$ more than 30%.

Experimental evaluation of k used apparatus described in detail elsewhere[6]. In a wind tunnel an air–water spray was produced. Into this two-phase flow a circular, 0.045 m diameter cylinder was introduced and the water which settled on the cylinder collected in a burette. Measurement of the quantity of water collected in unit time allowed $\bar{k}$ to be calculated, because liquid mass flow rate in the wind tunnel was measured. During the experiments water covered the front half of the cylinder while the rear half was dry.

The droplet diameter distribution in the water spray stream was estimated by catching the droplets on a flat plate covered with oil and introduced, for a moment, into the air–water stream. The plate was photographed and a slide was made which was projected onto the screen so that the droplets could be measured and counted.

In the measurement of $\bar{k}$, the linear air velocity was in the range of 5 to 15 m/s and the water flow ratio in the range of 0.2 to 0.4 kg/m^2 s. The temperature of the air and water changed from 15°C to 25°C. Droplet distribution was regulated through the alteration of the compressed air flow ratio to the pneumatic atomizer. The $\bar{k}$ measurements were executed for three droplets size distributions characterized by the following distribution parameters:

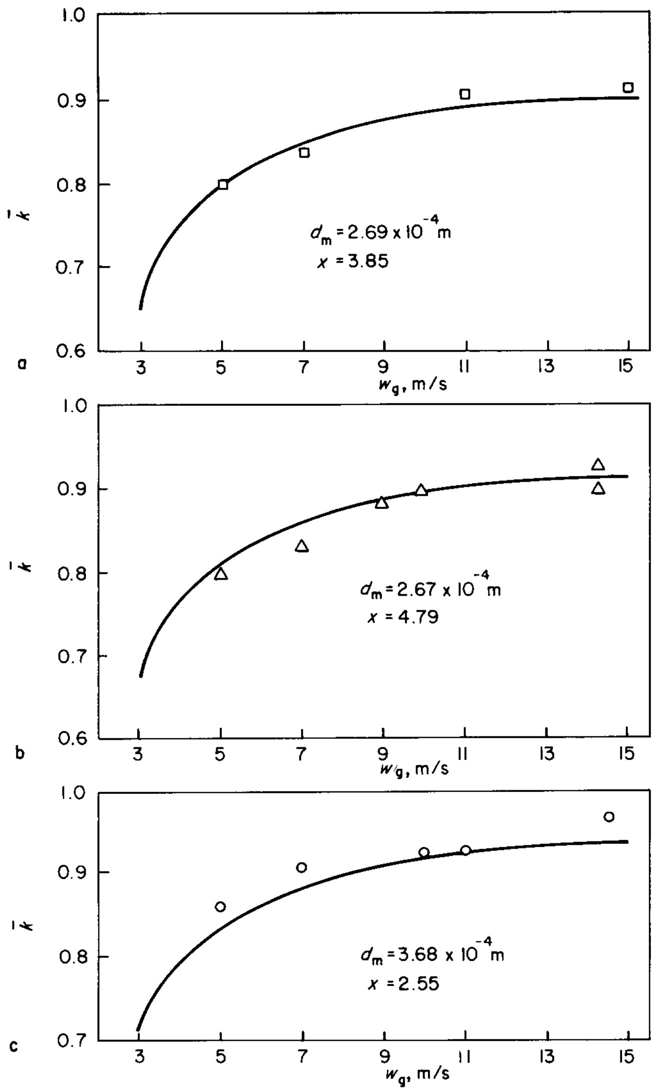

Fig 4 Dependence of $\bar{k}$ *on gas linear velocity (curves obtained from the numerical calculations)*

$d_m = 3.68 \times 10^{-4}$ m	and	$\chi = 2.55$
$d_m = 2.67 \times 10^{-4}$ m	and	$\chi = 4.79$
$d_m = 2.69 \times 10^{-4}$ m	and	$\chi = 3.85$

Comparison of calculations and experimental data is given in Fig 4. The curves on the figure were obtained on the basis of numerical calculations. The $\bar{k}$ values were calculated for the front half of the cylinder ($0 \leqslant \theta < 90°$).

The comparison of measurement points and theoretical curves allows us to conclude that the prediction model is in good agreement with the observed droplet behaviour for a gas–liquid spray mixture at the cylinder surface at right angles.

Calculated results

Our mathematical model can be used to calculate $\bar{k}$ as a function of the droplet distribution parameters d_m and χ, the gas linear velocity w_g and the physical properties of the atomized liquid. The dependence $\bar{k} = f(w_g)$ is shown in Fig 4. From the correlation curves, with increasing linear velocity of gas the value of $\bar{k}$ approaches 1. Let us assume a value of $\bar{k}$ below which the heat transfer process, performed by cooling of the cylinder surface by means of gas–liquid spray flow, will not be intensive. Then we can estimate for a definite droplet diameter distribution, the minimal linear gas velocity below which the process is unprofitable. The optimum conditions would be for $\bar{k} = 1$.

In Fig 5 the distribution coefficients $k_1(\theta)$ and $k_2(\theta)$ on the cylinder surface obtained by the numerical calculation are shown. The thick line represents the $k(\theta)$ value which is the smaller of $k_1(\theta)$ and $k_2(\theta)$ values. In Fig 5(a) the $k(\theta)$ distribution on the cylinder surface for the smaller value of the linear gas velocity ($w_g = 3$ m/s) is shown. Clearly, droplet bounce is the principal influence on $k(\theta)$. Also, the droplets get into the film in the angle coordinate range $0 \leqslant \theta < 67°$. Thus, omitting $k(\theta)$ from the theoretical model would cause considerable errors. In Fig 5(b) the dependence $k(\theta) = f(\theta)$ for the gas velocity $w_g = 9$ m/s is shown. Note that in this case the curve of the droplet trajectories is the principal influence on $k(\theta)$ ($k(\theta) = k_2(\theta)$ for $0 < \theta < 80°$); in the narrow range of θ, however, droplet bounce is significant ($k(\theta) = k_1(\theta)$ for $80° < \theta < 85°$). From the graph one can state that the droplets are entrapped in the film in the angle coordinate range $0 < \theta < 80°$. Therefore the omission of $k(\theta)$ in the mathematical model causes insignificant errors and may be neglected.

In the process of directing the gas–liquid spray at the cylinder surface, the choice of the atomizer is a fundamental problem. It is important to use droplets of suitable sizes. Fig 6 shows four dependences $\bar{k} = f(\theta)$ for the different median droplet diameters in the two-phase flow (with χ constant). From the graph one can see distinctly the influence of droplet size on the $\bar{k}$ value. For droplets of median diameter $d_m = 100$ μm, for the given range of w_g, only from 40 to 80% of the liquid directed at the cylinder surface passes inside the film. For droplets of median diameter $d_m = 800$ μm ($3 \leqslant w_g \leqslant 20$ m/s), from 90 to 100% of liquid passes into the film. One notes that using of

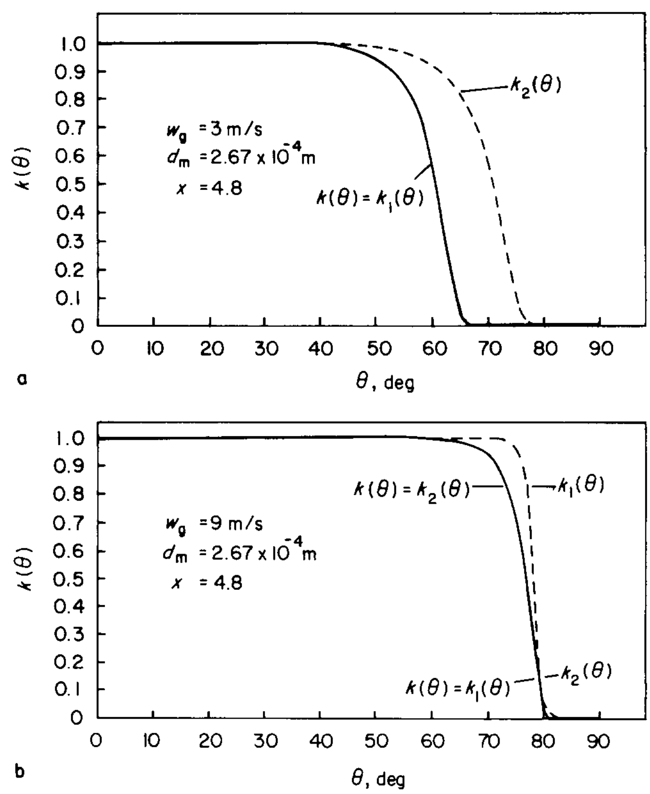

Fig 5 Distribution of k(θ) *on the cylinder surface with* θ

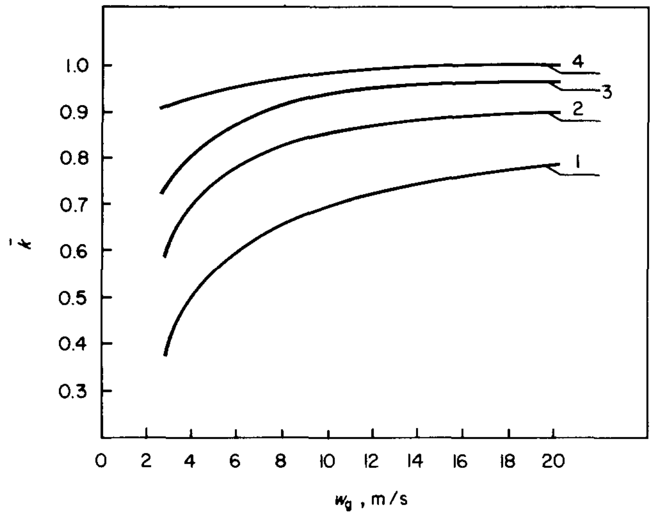

Fig 6 Dependence of $\bar{k}$ *on the median droplets diameter* d_m *and linear gas velocity* w_g. *(1)* $d_m = 10^{-4}$ *m,* $\chi = 4.8$; *(2)* $d_m = 2 \times 10^{-4}$ *m,* $\chi = 4.8$; *(3)* $d_m = 4 \times 10^{-4}$ *m,* $\chi = 4.8$; *(4)* $d_m = 8 \times 10^{-4}$ *m,* $\chi = 4.8$

very large droplets may cause non-uniform film flow on the cylinder surface (waves, splashes) and decreases the heat transfer process.

Conclusions

One can conclude from the theoretical and experimental investigation described here that in definite ranges of the process parameters (w_g,d_m) an appreciable part of the liquid directed at a cylinder surface is not entrapped by the film. In some cases the quantity of liquid captured by the film will be non-uniform (with greater amounts entering near the stagnation point). The omission of this phenomena in previous analyses[3,7,10] caused the differences between the results obtained apparently at the same conditions. One ought to use the coefficient $k(\theta)$ in the continuity, momentum and energy equation. For example, the continuity equation can be written as:

$$\frac{d}{d\theta}\int_R^{R+\delta} U(\theta,r)dr = \frac{g_1 k(\theta)}{\rho_1} R\cos\theta \qquad (18)$$

Solution of Eq (18) can cause difficulties on account of the occurrence of the coefficient $k(\theta)$. Therefore, in the less accurate calculations one can omit $k(\theta)$ when selecting the process conditions to get $\bar{k}=1$. If the choice of these conditions is impossible, one can assume that for $\bar{k}$ near 1, $k(\theta)=\bar{k}$. Then the solution of Eq (18) is simple if the film velocity distribution $U(\theta,r)=f(r)$ is known.

$\bar{k}$ values are important in practical calculation and for selection of the process parameters of the heat exchangers. The basic parameters important for the optimisation of the heat transfer between a gas–liquid spray and a cylinder are a function of the linear gas velocity and droplet diameter distribution. They should be chosen in such a manner as to have $\bar{k}$ nearly equal to 1.

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