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Falling Film Transition and Heat Transfer on Horizontal Circular Cylinders

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Abstract

In this paper, an investigation of liquid film falling over three horizontal cylinders is presented. A numerical investigation verified with experimental results is carried out using a computational fluid dynamics (CFD) code, FLUENT, for 2D and 3D configurations towards better design of beds of irrigated horticultural produce.

The primary objective of the present study is to use numerical predictions to study the effects of liquid flow rate, cylinder diameter and the heat flux towards reducing energy and water requirements in cooling horticultural produce.

The present numerical results show good agreement with the experimental results. The use of a numerical tool has resulted in a detailed investigation of flow and heat transfer characteristics which have not been available in the literature previously.

Key words: horizontal tube, interface, CFD simulations, falling liquid film, FLUENT, GAMBIT.

List of Symbols

g	acceleration due to gravity, m/s^2
Ga	Galileo number, Ga = $\rho\ \sigma^3/(\mu_L{}^4 g)$
h_ϕ	local heat transfer coefficient, W/(m^{2}K)
$\bar{h}$	average heat transfer coefficient, W/(m^{2}K)
k	thermal conductivity, W/(mK)
Nu	local Nusselt number, $Nu = (\nu^2/g)^{1/3} h_\phi / k$
$\overline{Nu}$	average Nusselt number, $\overline{Nu} = (\nu^2/g)^{1/3} \bar{h} / k$
q''	heat flux, W/m^2
Re	film Reynolds number, Re = $4\Gamma/\mu_L$
Γ	liquid film flow rate per unit length of tube flowing over one side of horizontal tube, kg/(ms)
λ	instability wavelength, spacing between neighbouring jet or droplets, m
μ_L	liquid Newtonian dynamic viscosity, kg/(ms)
ρ_L	liquid density, 998.2 kg/m^3 for water
σ	surface tension, 0.073 kg/s^2 for water

Introduction

The rate of heat transfer that exists between falling liquid film and a horizontal cylinder is generally high. For this reason, falling liquid film is widely used in refrigeration, petroleum refining, chemical and desalinization devices and utilized in food and dairy industries.

Three flow modes can be observed when liquid films flow over horizontal cylinders, namely, droplet, jet or column and sheet modes. These flow patterns are described by Mitrovic [9]. Armbruster & Mitrovic [1] predicted transitions between flow modes. Additional work of flow modes is given by Hu & Jacobi [5] as they described the flow characteristics and mode transitions for wide ranges of flow rate and fluid properties. They proposed a flow mode transition map of film Reynolds number, *Re*, against the Galileo number, *Ga*. Here, Re = $4\Gamma/\mu_L$ and Ga = $\sigma^3/(\mu_L{}^4 g)$, where Γ is the liquid flow rate per unit length, ρ_L and μ_L are the liquid density and dynamic viscosity, respectively, and σ is the surface tension.

Studies of flow transition of the falling film modes have attracted the attention of many researchers. Yung et al. [11] have investigated the jet-droplet transition. Their correlation can be written as,

$$\Gamma = 0.81\frac{\rho_L}{\lambda}\frac{\pi d_p^3}{6}\left(\frac{2\pi\sigma}{\rho_L\lambda^3}\right)^{0.5} \qquad (1)$$

where λ is the stability wavelength on horizontal tubes, and d_p is the diameter of primary drops which can be written as,

$$d_p = C_L\sqrt{\frac{\sigma}{\rho_L g}} \qquad (2)$$

where C_L is an empirical constant equal to 3 for water. The horizontal distance between two neighbouring drops or jets is defined as the wavelength λ of the falling film.

Many researchers have studied the parameters which affect heat transfer between liquids and horizontal tubes. Parken [10] reported that the heat transfer coefficient increases with the liquid flow rate. Fletcher et al. [2] reported that the Nusselt number increases with flow rate and heat flux. Ganic & Roppo [3] have experimentally studied the effect of liquid flow rate over heated horizontal tubes on the flow regimes. They found that there are two types of flow modes associated with liquid films. The first is the droplet mode, which is related to lower flow rates, and the second is the jet mode which manifests at higher flow rates. They have also found that the heat transfer coefficient increases with liquid flow rate and tube spacing. Sensible heat transfer under different film modes has been investigated by Hu & Jacobi [6]. They found that the heat transfer coefficient in the sheet mode shows large circumferential variations related to flow.

They reported that average Nusselt number increases with Reynolds number and decreases with tube diameter.

The investigation in this paper is part of an experimental and numerical exploration of heat transfer of falling film modes. Different parameters such as liquid flow rate or Reynolds number, cylinder diameters and heat flux are investigated. The ultimate aim of this research is to reassess the empirical correlations that govern the performance of trickle bed reactors and other porous media that involve two fluid phases with more detailed computer simulations. In this paper, the numerical predictions are obtained using the power of a computational fluid dynamics (CFD) code FLUENT for 2D and 3D configurations of three horizontal plain cylinders. The mathematical approach is based on the volume of fluid (VOF) method where the primary phase is represented by air and the secondary phase by the liquid. The VOF technique has been employed to mark a point occupied by liquid as 1 and 0 if occupied by air. The values between one and zero indicate a free surface. The volume of fluid method was established by Hirt & Nichols [4], when they traced the fluid regions through an Eulerian mesh of stationary cells.

Experimental Setup

A schematic diagram of the experimental test rig is shown in Figure 1. The test rig was designed after considering several schemes described in the literature. Further experimental details are given by Jafar et al. [7, 8].

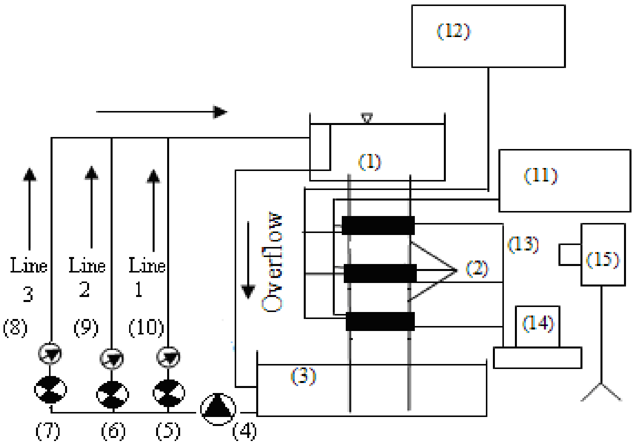

Figure 1. Schematic diagram of heat transfer setup. 1) water tank, 2) cylinders, 3) reservoir, 4) water pump, 5), 6), 7) valves, 8) low flow rate flow meter, 9) high flow rate flow meter, 10) bypass line, 11) digital voltmeter, 12) electric power meter, 13) thermocouples, 14) computer and data acquisition system, 15) digital camera.

Numerical Model

The system investigated in this paper consists of a column of cylinders, the axes of which are parallel and located one above the other as indicated in Figures 2 and 3 for the 2D and 3D configurations, respectively. Water, with a uniform velocity, is introduced onto the array of cylinders through a slot nozzle located above the top cylinder. Three phases, liquid (water), gas (air) and solid (the cylinders) were modelled numerically. Numerical simulations have been performed at liquid mass flow rates of 0.0125, 0.025, 0.0625, 0.125, 0.2, 0.325, 0.5 and 0.75 kg/(ms), to achieve Reynolds numbers of 50, 100, 250, 500, 800, 1,300, 2,000 and 3,000, respectively. A commercial finite-volume CFD code, FLUENT has been used for the simulations. The grid has been generated in GAMBIT. Half of the domain has been modelled in order to obtain faster solutions. The boundary conditions imposed are shown in Figures 2 and 3.

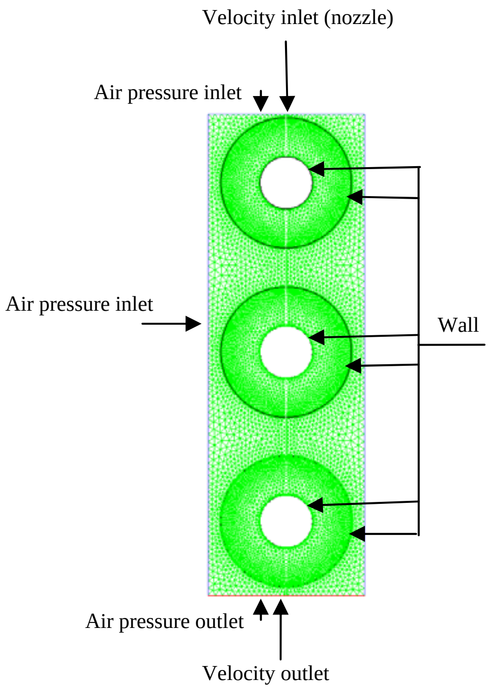

Figure 2. Physical configuration of the 2D model.

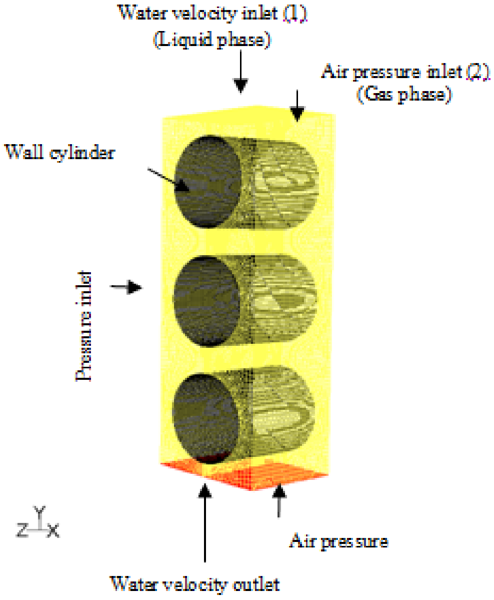

Figure 3. Physical configuration of the 3D model.

A tri-pave mesh has been generated for the fluid and solid domains using a boundary layer technique, where the boundary layer around the cylinder is relatively small. This boundary layer thickness has been found to accurately capture phenomena that occur in the liquid adjacent to the cylinder walls. A size function technique has been employed to smoothly control the growth in the mesh size over a particular region of the geometry starting from a source or origin. It can also be used for smooth transition from a fine mesh needed to resolve flow physics with curved geometries and to model flows in thin gaps.

The simulations were allowed to continue to quasi-steady state. Both 2D and 3D simulations have been verified to be grid and time step independent. Further details are given by Jafar et al. [8]. The differential equations that govern heat and momentum transfer have been presented by Jafar et al. [7].

Flow Mode Visualization

To understand the falling film modes and transitions, a horizontal cylinder can be considered with a smooth thin liquid film around it. The hanging or suspended drops separate from the lowest cylinder position. Some drops might break away from the film and fall under the effect of gravity prior to this position. This is the beginning of the droplet mode from a falling liquid film. The axial distance between the neighbouring droplets is determined primarily by the wavelength of the most unstable free surface.

At low liquid flow rates, liquid droplets fall with a low frequency from the bottom of the top horizontal cylinder to the one below. The droplet formation frequency increases with an increasing liquid flow rate. With a further increase of the liquid flow rate, the liquid leaves the cylinder at the same location in a continuous column. This event is the transition from the droplet to droplet-jet mode. With a further of increase of the liquid flow rate, a transition from the droplet-jet to the jet mode occurs. As the flow rate increases further, the liquid leaves the surface in a continuous column in the jet mode, where the diameter of the liquid jet increases with the flow rate. When the flow rate increases even further, the jet becomes unstable and an additional column appears, resulting in the jet-sheet to sheet mode transition. The liquid jets are unsteady in location for a short time. Then, the sheet thickness becomes thin, and the sheet becomes stable at a closer spacing to produce a full sheet mode. Liquid film modes have been observed from the present experimental and numerical flow visualization results. A brief summary is presented in Figures 4 and 5, respectively.

Effect of Falling Film Modes and Reynolds Number on Heat Transfer Characteristics

Nusselt number shows a strong dependence on the Reynolds number, as illustrated from the experimental and numerical results in Figure 6. The effect of heat transfer coefficient on Reynolds number in the droplet mode is due to the increase of droplet frequency with increasing Reynolds number. In the jet mode, the average heat transfer coefficient increases with the Reynolds number, but the dependence is less pronounced than for the droplet mode. The effect of heat transfer coefficient on Reynolds number in the jet mode is due to the increase of heat transfer coefficient in the impingement region more than what occurs in the droplet mode. For falling film in the sheet mode, the Nusselt number still exhibits a Reynolds number dependence. In this mode, the heat transfer coefficient in the impingement region is higher than in the jet and droplet modes, due to greater heat removal. The numerical results differ from the experimental ones by about 2.4% at the droplet mode, Re = 250. This difference is 1.5% or less at jet mode, Re = 800, and 0.7% at sheet mode, Re = 3,000. The closer agreement at higher Reynolds numbers is attributed to the better control of the higher liquid volume flow rates during the experiments.

Effect of Cylinder Diameter on the Heat Transfer

Cylinder diameter has a significant effect on the heat transfer coefficient as demonstrated by the results shown in Figure 7.

Figure 4. Experimental visualization of flow modes: a) droplet, b) droplet-jet, c) inline jet, d) staggered jet, e) jet-sheet and f) sheet modes.

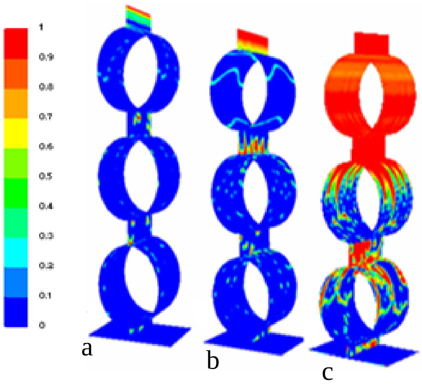

Figure 5. Contours of volume fraction. The numerical flow visualization of 3D falling liquid film modes: a) droplet, b) jet and c) sheet modes. Red is volume fraction of 1 for water. Blue signifies volume fraction of 0 for air.

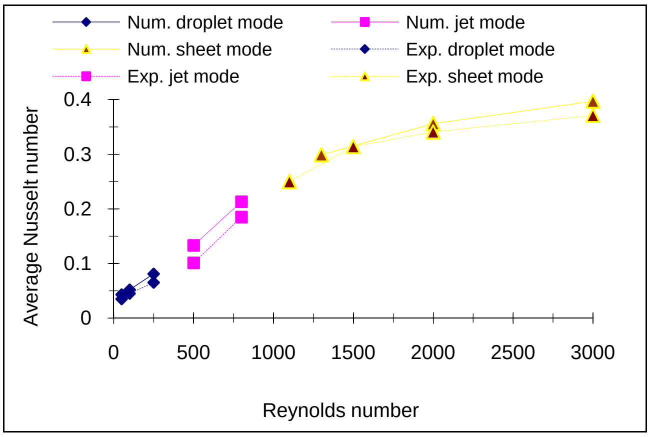

Figure 6. Average Nusselt number for droplet, jet and sheet modes at different Reynolds numbers, present experimental (Exp) and numerical (Num) results.

The heat transfer coefficient is larger for a smaller diameter cylinder over the whole range of liquid flow rates or Reynolds numbers covering the droplet, jet and sheet modes. The effect of tube diameter on the heat transfer coefficient can be explained in terms of the boundary layer development. The film thickness is larger on a smaller diameter cylinder, keeping all other parameters constant, due to its smaller surface area. Therefore, the average heat transfer coefficient is also greater for a smaller diameter cylinder. It is expected, based on the results presented so far, that the largest contribution to the high average heat transfer coefficient on a smaller diameter cylinder must come from its impingement region.

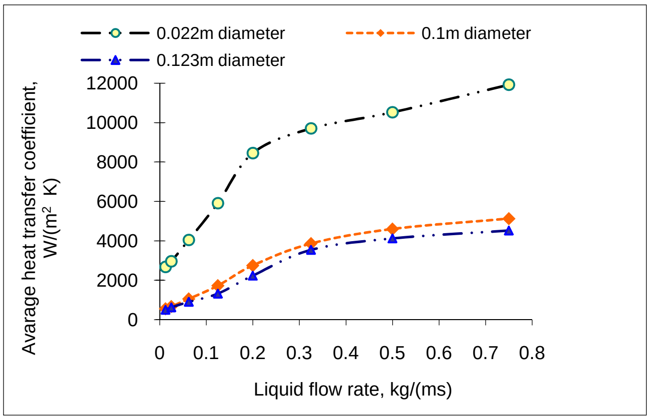

Figure 7. Effect of cylinder diameter on average heat transfer coefficient, present experimental results.

Effect of Heat Flux on the Heat Transfer

The experimental and numerical results indicate that for completely wetted surfaces, the heat flux has no significant impact on the heat transfer coefficient as shown in Figure 8. In this figure, the variation of the average Nusselt number is presented with heat flux. Both experimental and numerical results are given, and the numerical results are verified with the experimental ones. In the experiments and the numerical simulations, the cylinder diameter is 0.1 m, and the Reynolds number is 800. The heat flux on the cylinder surface is the range of 50 to 171.368 kW/m^2. While the surface temperatures vary significantly, there is no significant change in the heat transfer coefficient.

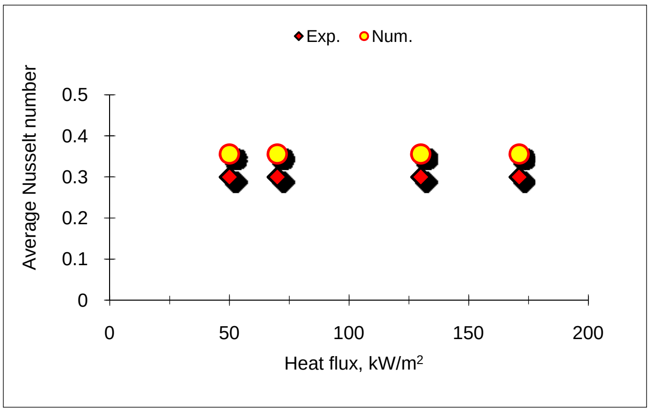

Figure 8. Effect of heat flux on average heat transfer coefficient.

Conclusions

Experimental work and numerical simulations with a commercial finite volume CFD code, FLUENT, have been used to study heat transfer to falling liquid film and the effect on the heat transfer of different parameters such as liquid flow rate or Reynolds number, the cylinder diameter and heat flux.

From the experimental and numerical results, the following can be concluded:

- Increasing the liquid flow rate (and hence, Reynolds number) results in an increase in the heat transfer coefficient.
- Decreasing the cylinder diameter results in an increase in the heat transfer coefficient.
- For the completely wetted surfaces, the heat flux has no significant impact on the heat transfer coefficient.

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