

## FLOW MODE CHARACTERISATION OF LIQUID FILMS FALLING ON HORIZONTAL PLAIN CYLINDERS

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### ABSTRACT

The objective of this study is to investigate experimentally and numerically liquid film falling over three cylinders, the axes of which are perpendicular to the flow direction. This work forms part of an experimental and numerical frame-work in which to study the flow field and heat transfer using the power of computational fluid dynamics (CFD) to better design beds of irrigated horticultural produce. The primary objective of the present study is to use numerical predictions, following experimental verification, towards reducing energy and cooling water requirements in cooling horticultural produce.

The effects on the liquid flow field of Reynolds number, cylinder diameter, and the spatial placement of cylinder on droplet mode, have been studied. The Reynolds number is defined in terms of the liquid mass flow rate per unit length of cylinder divided by the dynamic viscosity. The Reynolds number range studied in this research is, 50 to 2000.

The present numerical results show good agreement with the experimental results

The use of a numerical tool has resulted in a detailed investigation of these characteristics, which has not been available in the literature previously.

*Key words:* Falling film, flow modes, cylinders.

### NOMENCLATURE

$D$	cylinder diameter (m)
$g$	acceleration due to gravity ( $\text{m/s}^2$ )
$Ga$	Galileo number, $Ga = \rho\sigma^3 / \mu^4 g$
$k$	thermal conductivity ( $\text{W/m}^\circ\text{C}$ )
$m^*$	mass flow rate ( $\text{kg/s}$ )
$P$	pressure (Pa)
$Re$	film Reynolds number, $Re = 4\Gamma/\mu$
$S$	distance between cylinders (m)

### Greek symbols

$\rho$	density ( $\text{kg/m}^3$ )
$\mu$	Newtonian dynamic viscosity ( $\text{kg/ms}$ )
$\sigma$	surface tension ( $\text{kg/s}^2$ )
$\Gamma$	mass flow rate of the liquid film per unit length of cylinder ( $\text{kg/ms}$ )
$l_c$	characteristic length (m), $l_c = (v^2 / g)^{1/3}$

$\xi$	capillary constant, $\xi = (\sigma/(\rho g))^{0.5}$
$\lambda$	instability wavelength, spacing between neighbouring jets or droplets (m)
$\lambda^*$	dimensionless wavelength, $\lambda^* = \lambda / \xi$
$V$	velocity (m/s)
$u$	velocity in the x direction (m/s)
$v$	velocity in the y direction (m/s)
$X, Y$	coordinates centred on the impingement point

### INTRODUCTION

A liquid film flowing over horizontal cylinders is of great importance as a high rate of heat transfer exists between the falling liquid film and the horizontal cylinders. For this reason falling film is widely used in chemical and food process industries and in refrigeration equipment where high rates of heat transfer are important. The flow field and heat transfer processes that occur in such configurations are generally calculated by means of empirical relationships amongst dimensionless groups.

Three-flow modes can be observed when liquid films flow past horizontal cylinders, namely,

1. Droplet mode,
2. Jet or column mode and
3. Sheet mode.

The flow patterns observed in falling film heat exchangers have been described by Mitrovic (1986) as indicated in Figure 1. Ambruster and Mitrovic (1994) have predicted transitions between the flow modes. Additional work on the flow mode is given by Hu and Jacobi (1996) for the flow characteristics and mode transitions for wide ranges of flow rate and fluid properties.

Experiments carried out by Maron-Moalem *et al.* (1978) indicate that transition from the droplet mode to the jet mode occurs at Reynolds numbers between 150 to 200, while the transition from the jet to the sheet mode occurs in the range 315 to 600.

The distance between two streams of droplets or jets is characterised by the wavelength,  $\lambda$  as shown in Figures 1 and 2. The wavelength is an important key to understanding the behaviour of the falling film as well as its flow mode. The wavelength can be calculated according to Lienhard and Wong (1964) :

$$\lambda = 2\pi \sqrt{\left( \frac{g\Delta\rho}{\sigma} + \frac{2}{D^2} \right)^{-1}} \quad (1)$$

$$\lambda^* = \lambda / \zeta \quad (2)$$

where  $\lambda$  is the wavelength;  $g$  is gravity;  $\rho$  is the density;  $\sigma$  is the surface tension;  $D$  is the cylinder diameter;  $\lambda^*$  is the dimensionless wavelength; and  $\zeta$  is the capillary constant given by  $(\sigma/(\rho g))^{0.5}$ .

The effect of liquid flow rate,  $\Gamma$ , cylinder separation or the distance between cylinders,  $S$ , and cylinder diameter,  $D$ , on the wavelength are experimentally investigated by Hu and Jacobi (1996). They found that the wavelength depends on flow rate and decreases with an increase in film Reynolds number. They also found a weak dependency of the wavelength on cylinder diameter and cylinder spacing. They suggested that the droplet, droplet-jet and an unsteady jet modes are characterized by stability in the location of the jet departure site, jet-sheet and sheet modes.

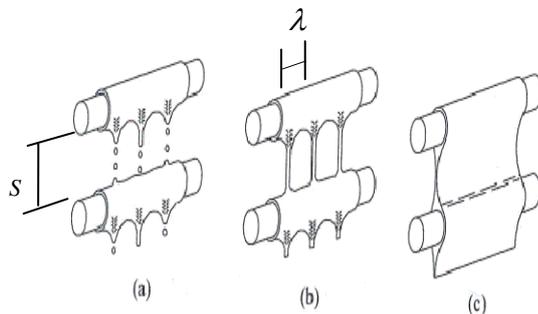
The falling film flow mode transitions have been experimentally studied by Mohamed (2007). He obtained the following correlation between the Reynolds number,  $Re$ , and Galileo number,  $Ga$ :

$$Re = a Ga^b \quad (3)$$

where  $a$  and  $b$  are the empirical constants given in Table 1.

	Droplet/ droplet-jet	Droplet-jet /jet	Jet/jet- sheet	Jet- sheet/sheet
$a$	0.0785	0.0978	1.5031	1.491
$b$	0.2965	0.2998	0.2273	0.2353

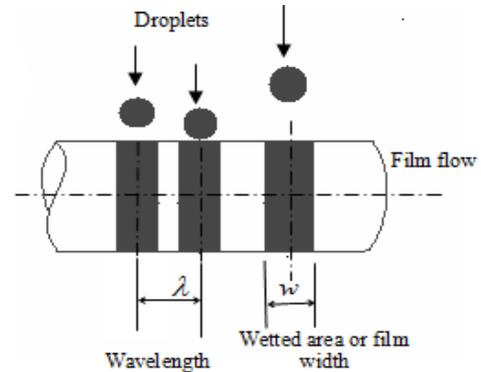
**Table 1:** Constants in Mohamed's (2007) correlation for the change in the flow mode of a falling film over a cylinder.



**Figure 1:** Schematic of the three main flow modes; a) droplet mode, b) column or jet mode and c) sheet mode from Mitrovic (1986a).

Armrueter and Mitrovic (1994) studied the mode transition hysteresis (mode transition at distinct  $\Gamma$  for increasing and decreasing flow rates). They noted that hysteresis occurs only for the transition from jet to sheet

mode, and that the transition depends only on the liquid flow rate.



**Figure 2:** Visualisation of falling film flow with partial wetting.

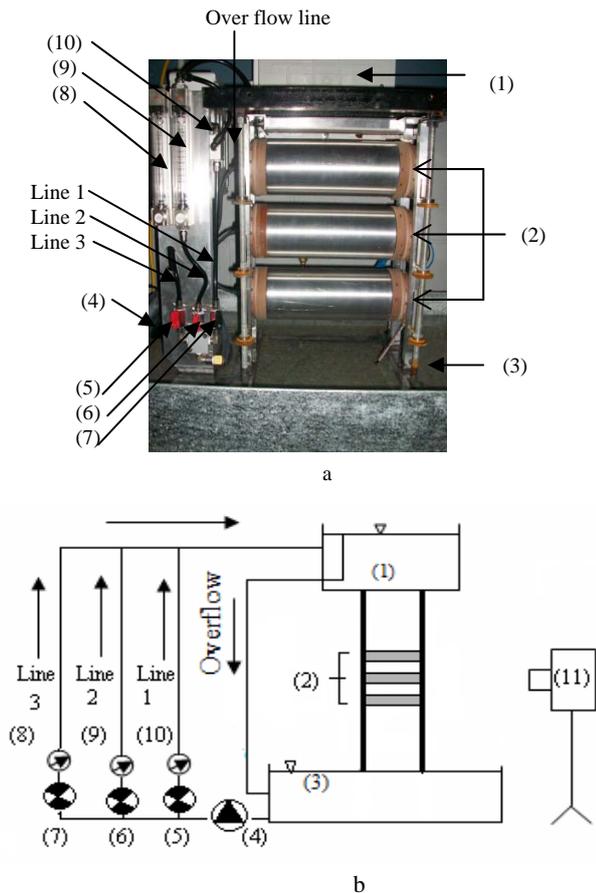
Fujita and Tsutsui (1994, 1995) defined the two flow modes as follows. A distinct droplet mode occurs when the liquid originally falls as a jet, and then, it disintegrates into droplets. As the falling velocity increases, a disturbed jet mode—characterized by the collapse of neighbouring jets, results in the sheet mode, followed by splitting. They noted that the transition between the droplet and droplet-jet modes occurred at Reynolds numbers around 100, independent of the feeding method.

In this study, the flow mode characteristics of liquid films falling over horizontal cylinders have been studied. Numerical predictions have been used to study the details of the flow field and resulting heat transfer characteristics which could not be observed experimentally in similar detail. Numerical predictions have been verified with present experimental results and those available from the literature. Following verification with limited experimental results, the numerical results will enhance effective cooling of fresh horticultural produce.

In this paper, flow field results are given. Numerically, 2D and 3D configurations of axially aligned cylinders irrigated with water have been investigated. The system comprising of three phases (gas, liquid and solid) has been numerically investigated using FLUENT<sup>®</sup>. The governing equations are as discussed by Jafar *et al.* (2009).

## EXPERIMENTAL SETUP

For the verification of some of the numerical results, an experimental rig has been designed. A photograph and schematic diagram of the apparatus are shown in Figures 3a and 3b, respectively.



**Figure 3:** a) Photograph and b) schematic diagram of the apparatus; 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) high flow rate flow meter; 11) digital camera.

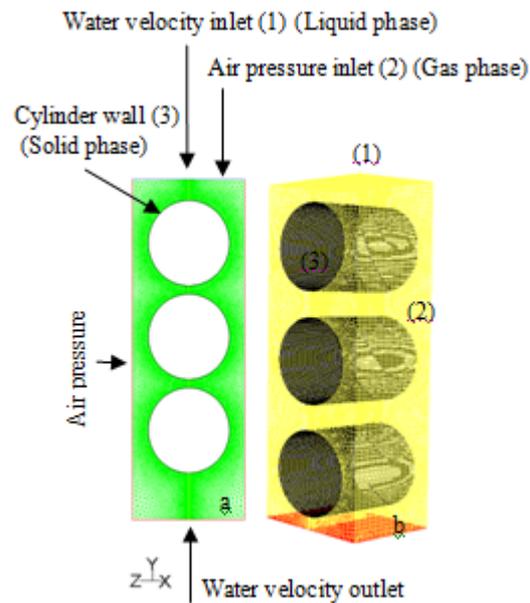
### Numerical model

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 Figure 4a for the 2D and Figure 4b for the 3D configurations. 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, 0.0375, 0.0625, 0.125, 0.2, 0.325, and 0.5 kg/ms, to achieve Reynolds numbers of 50, 100, 150, 250, 500, 800, 1300, and 2000, respectively. A finite-volume finite difference CFD code, FLUENT<sup>®</sup> was used for the simulations. The VOF (volume of fluid) technique has been employed to mark a point occupied by fluid as unity and zero if occupied by air. The values between zero and one indicate a free surface. The volume of fluid method was established by Hirt and Nichols (1981), when they traced the fluid regions through an Eulerian mesh of stationary cells.

2D and 3D simulations were implemented with similar characteristics of mesh generation and the solver setup for laminar flow. The upper and lower surfaces were modelled as air pressure inlet and outlet respectively. The

base radius of the cylinders was 0.05 m. This value was varied to study the effect of the cylinder diameter.

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.* (2007)



**Figure 4:** Numerical model; a) 2D configuration and b) geometry of 3D. (1), (2), and (3) represented liquid, gas, and solid phase respectively.

## RESULTS AND DISCUSSION

### Effect of Flow Rate on Droplet Mode

The experiments were carried out with Reynolds numbers in the range 20 to 150. It can be seen from Figure 5 that the number of large drops increased relatively slowly as the Reynolds number was increased to about 80, and the frequency of the large drops remained about constant as the Reynolds number increased further. In contrast, the frequency of the small droplets increased sharply by a factor of about 4 as the Reynolds number increased from 20 to about 50.

The results presented in Figure 6 were obtained with monotonically increasing and decreasing flow rates. When the flow rate was progressively decreased from its high value, it was observed that the general relationship between droplet frequency and Reynolds number was similar to that obtained when the flow rate was increased. However, the frequency at which the droplets detach decreased somewhat more rapidly when the flow rate decreased. The system stabilized at different frequencies and sites at the same flow rate, depending on whether the desired flow rates were reached by positive or negative increments, as shown in Figure 6. For instance, in a Reynolds number range of 80–150, the frequency of the small drops is 14.3/s for positive and 15.5/s for negative changes in the flow rate, and the corresponding

dimensionless wavelengths are 4.1 and 4.8, as illustrated in Figure 6.

In Figure 7, the dependence of the distance between active sites (the wavelength) on the Reynolds number can be seen. For  $Re > 80$ , the horizontal spacing between two streams of droplets remains constant. The distance between simultaneously active sites seem to be large at low Reynolds number. As the film flow rate increases, more sites become simultaneously active and complete wettability of the cylinder is obtained at  $100 < Re < 150$ .

### Effect of Spatial Placement of Cylinder on Droplet Mode

In many practical applications, the cylinders that may form part of a heat transfer system are axially aligned one above the other. One might surmise that the flow mode of water around a lower cylinder will be influenced by the flow around the cylinder immediately above it. To examine such effects, the data are taken from each horizontal cylinder in the vertical column in this study.

The horizontal distance between the active sites decreases, with a corresponding change in the frequency of the drops, as the vertical distance of the cylinder from the feeder increases. The large drops decrease in size and fall at lower frequencies. The drop producing sites are distributed closer at the bottom of the cylinder and drop size becomes more uniform as the water falls down, as shown in Figure 8.

In Figure 9, the dependence is presented of the wavelength on the Reynolds number for the three cylinders, the top, middle and the bottom cylinders. The wavelength is large for the top cylinder, and then, it decreases for the middle and the bottom cylinders. As the film flow rate increases, more sites become simultaneously active. The distance between active sites seem to be large at low Reynolds numbers for the top, middle and bottom cylinders.

The agreement between the numerical results and the experimental ones for the diameter of 0.1 m is worse for low Reynolds number. The discrepancy for the numerical and experimental work for the top cylinder is in the range of 0.25% to 15%. For the middle cylinder the inconsistency is between 0.26% and 15%. For the bottom cylinder it varies between 0.26% and 1.3%. The reason for the discrepancy is the difficulty of controlling the liquid flow rates experimentally at low Reynolds number. This difficulty results in reduced the wetting the bottom cylinder

### Effect of Cylinder Diameter

The effect of cylinder diameter on the frequency of droplet detachment was studied by changing the diameter of the bottom cylinder. Diameters of 0.02, 0.05 and 0.1 m were studied. Drop detachment from smaller cylinders stabilized at lower frequencies, as shown in Figure 10. The wavelength decreases with increasing the cylinder size, as shown in Figure 11. The discrepancy between the numerical and experimental results for the cylinder diameter of 0.1m ranges from 1% to 13.7%. The inconsistencies are lower in the cases of the 0.05 m and 0.02 m diameter cylinders, i.e. in the ranges 1% to 4.5% and 1% to 2% respectively. The reason is as described in Figure 9.

### Visualizations of Flow Pattern

In Figure 12, the effect is shown of increasing the liquid flow rate or Reynolds number on the flow pattern where Figure 12a is for a droplet mode and 12b for a jet mode and 12 c is for a sheet mode.

Flow mode transitions are also determined experimentally and numerically. These results are compared with the literature in Figure 13. It can be seen that the droplet mode occurs at a low Reynolds number, and at a higher Reynolds number of 120, the flow exhibits features of the jet mode. Further increases in the Reynolds number results in the sheet mode. Low pattern visualization in 2D is shown in Figure 14.

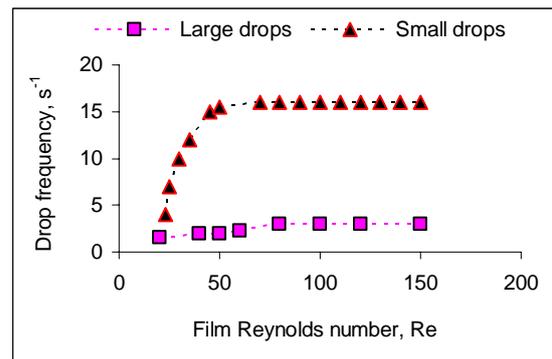


Figure 5: Effect of film Reynolds number on the frequency of droplet detachment for middle cylinder.

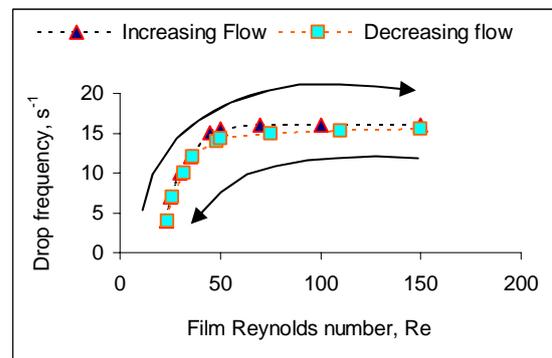


Figure 6: Effect of direction of film flow rate variation on the frequency of small droplet detachment for middle cylinder.

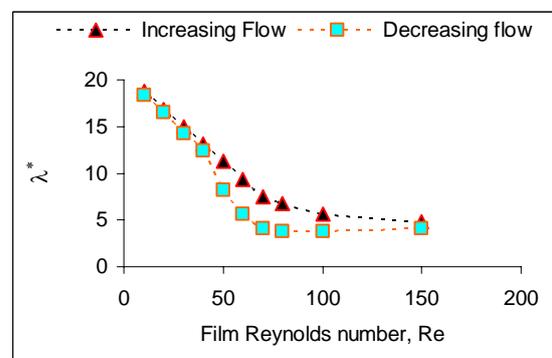
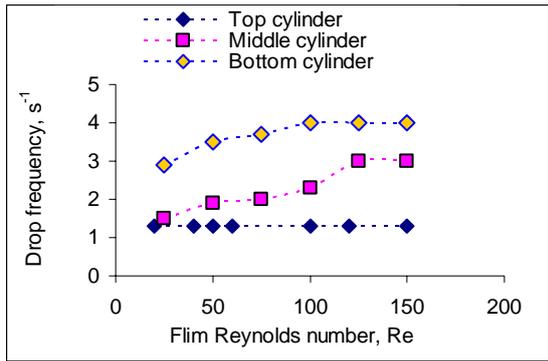
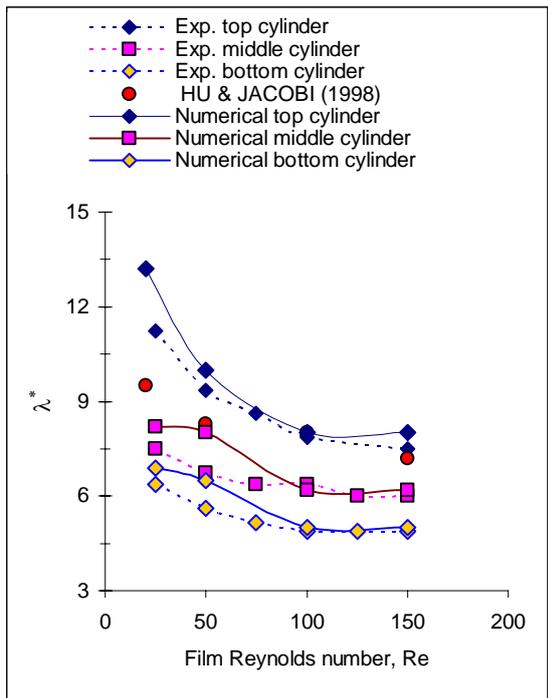


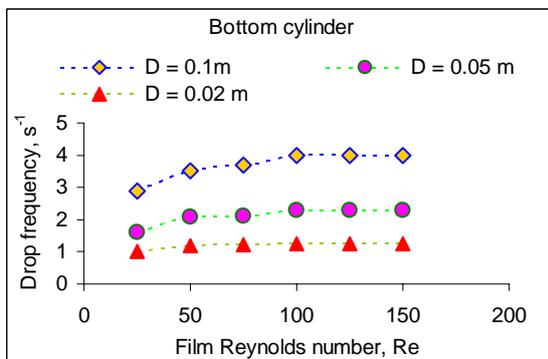
Figure 7: Effect of direction of film flow rate variation on distance between small droplet producing sites for the middle cylinder.



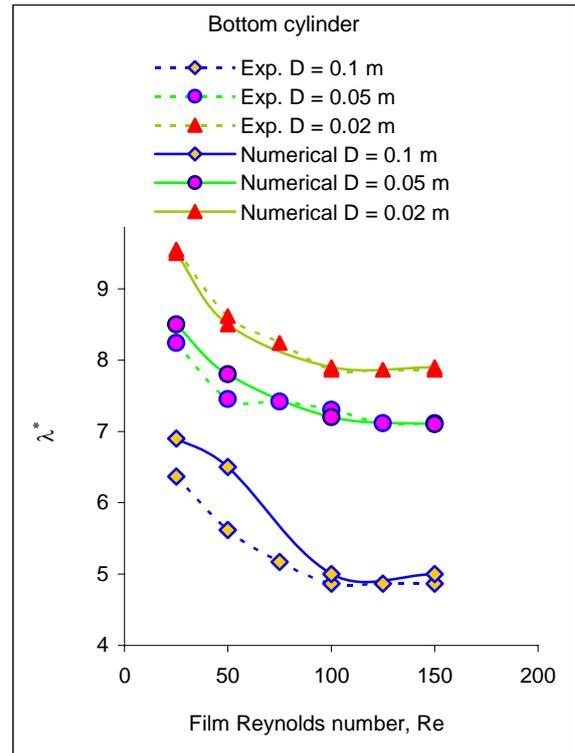
**Figure 8:** Effect of spatial placement of cylinder in the column on the frequency of large droplet detachment.



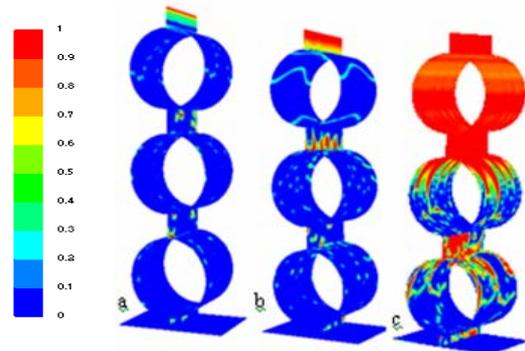
**Figure 9:** Effect of spatial placement of cylinders in the column on the distance between drop producing sites, the present results and those of Hu and Jacobi (1998).



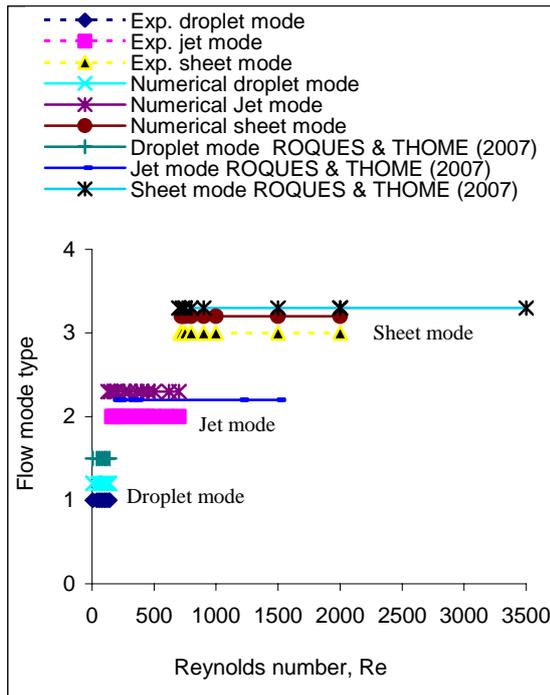
**Figure 10:** Effect of bottom cylinder diameter on the frequency of drop detachment.



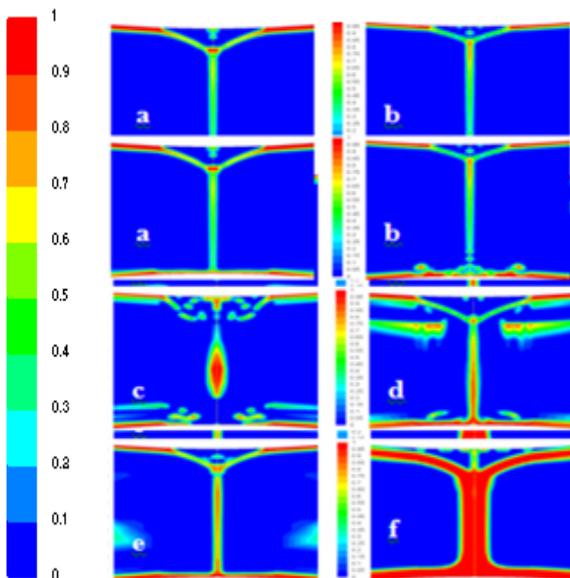
**Figure 11:** Effect of bottom cylinder diameter on the distance between drop producing sites.



**Figure 12:** Contours of volume fraction. The flow visualization of 3D falling liquid film; a) droplet mode; b) jet mode and c) sheet mode. Red colour indicates water which is equal to 1 and blue is air which is equal to 0.



**Figure 13:** The three main flow modes of droplet, jet and sheet mode for present study compared to Roques and Thome (2007).



**Figure 14:** Contours of volume fraction. The flow visualization of 2D falling liquid film between two cylinders a) droplet mode; b) droplet-droplet jet mode; c) jet mode; d) jet-jet sheet mode; e) jet sheet-sheet mode; f) sheet mode. Red colour indicates water which is equal to 1 and blue is air which is equal to 0.

## CONCLUSION

A thorough study of falling film over horizontal cylinders has been conducted. The falling films of droplet, jet and

sheet modes have been illustrated. The dripping between vertically adjacent horizontal cylinders has been studied as a function of the flow rate, cylinder diameter and location.

The numerical results show good agreement with the experimental ones. The droplet frequency increases and the wavelength decreases with Reynolds number. As the bottom cylinder diameter decreases, the wavelength decreases.

## REFERENCES

- ARMBRUSTER, R. and MITROVIC, J., (1994), "Patterns of falling film flow over horizontal smooth tubes", *Proceedings of the Tenth International Heat Transfer Conference*, **3**, 275-280.
- HIRT, C.W. and NICHOLS, B.D., (1981), "Volume of fluid (VOF) method for the dynamics of free boundaries", *J.Comput. Phys*, **39**, 201-225.
- HU, X. and JACOBI, A.M., (1996), "The Intertube Falling Film Part 1 - Flow Characteristics. Mode Transitions and Hysteresis.", *ASME J. Heat Transfer*, **118**, 616 -625.
- HU, X. and JACOBI, A.M., (1998), "Departure-site spacing for liquid droplets and jets falling between horizontal circular tubes.", *Experimental Thermal and Fluid Science*, **16**, 322 -331.
- JAFAR, F., THORPE, G. and TURAN, O.F., (2007), "Liquid Film Falling on Horizontal Circular Cylinders", paper presented to 16th Australasian Fluid Mechanics Conference (AFMC), Gold Coast, Queensland, Australia, 3-7 December.
- JAFAR, F., THORPE, G.R. and TURAN, O.F. (2009), "Toward the detailed simulation of the heat transfer processes in unsaturated porous media.", paper presented to ASME Summer Heat Transfer Conference., San Francisco, USA, July 19-23, 2009.
- LIENHARD, J.H. and WONG, P.T.Y., (1964), "The dominant useable wavelength and minimum heat flux during film boiling on a horizontal cylinder", *ASME Journal of Heat Transfer*, **86**, 220-226.
- MARON-MOALEM, D., SIDEMAN, S. and DUKLER, A.E., (1978), "Dripping characteristics in a horizontal tube film evaporator", *Desalination*, **27**, 117-127.
- MITROVIC, J., (1986), "Influence of tube spacing and flow rate on heat transfer from a horizontal tube to a falling liquid film", *International Heat Transfer Conference San Francisco*, **4**, 1949-1956.
- Mohamed, A.M.I., (2007), "Flow behavior of liquid falling film on a horizontal rotating tube", *Experimental Thermal and Fluid Science*, **31**, 325 - 332.
- Roques, J.F. and Thome, J.R. (2007), "Falling Films on Arrays of Horizontal Tubes with R -134a, Part II: Flow Visualization, Onset of Dryout, and Heat Transfer Predictions", *Heat Transfer Engineering*, **28** no. 5, 415-434.