Heat Transfer Characteristics and Temperature Distribution of Falling Film over Horizontal Hot Tube Arrays

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Abstract Falling film heat exchanger is widely used in the industry, because of its high heat transfer coefficient, low liquid quantity and lower fouling factor. The heat exchanger considered here is a falling film one. It consists of a unique feeding tube, supply liquid such as pure water over seven parallel horizontal tubes which are heated internally. Convection heat transfer takes place outside the tubes surface and it is experimentally investigated. The falling film over the test tubes may be in the form of a droplet, jet or sheet. A combination of these forms is also possible. The tested tubes are made of copper and have 28.5 mm outer diameter and 300 mm length, each. They are arranged in series so that heated water enters each tube with the same flow rate, from bottom to top. The temperatures at the entrance and exit of the hot water flow and the falling film liquid are recorded. Also, the average surface temperature at one test tube is measured using five impeded thermocouples. An infrared camera is used to show the temperature distribution on the test tubes surfaces. The flow rates of each liquid path are controlled and monitored. The effects of different falling film forms and hot water flow rate, on the heat transfer coefficient are studied. Initial results show that changing the falling film forms and internal flow rate has a significant effect on the heat transfer coefficient. They also show that jet mode falling film has the best heat transfer coefficient.

Key words Falling Film, Forced Convection, Heat Exchanger

Nomenclature

A	=	outside area of the tube
C_p	=	specific heat, J.kg^{-1}.K^{-1}
d	=	diameter
h	=	heat transfer coefficient, Wm^{-2}K^{-1}
k	=	thermal conductivity, Wm^{-1}K^{-1}
L	=	length of the test tube, m
$\dot{m}$	=	mass flow rate, kg.s^{-1}
Nu	=	Nusselt number
Q	=	heat transfer rate, W.m^{-2}
Re	=	Reynolds number
ρ	=	fluid density, kg.m^{-3}
T	=	temperature, ^{o}C
U	=	overall heat transfer coefficient, Wm^{-2}K^{-1}
Γ	=	mass flow rate per unite length, kgs^{-1}m^{-1}
$\boldsymbol{\sigma}$	=	Gas/ liquid surface tension, N/m
μ	=	Liquid dynamic viscosity, N.s/m^2

I. Introduction

Falling film heat exchangers with horizontal tubes are widely used in the industry because of their high heat transfer coefficient and small liquid inventory. They are used in chemical, petroleum, refrigeration and desalination applications. Several issues like safety, cost and maintenance make the design of heat exchanger more challenging. Common challenges in designing such heat exchanger are falling film distribution, tube diameter, spacing between the tubes and tubes arrangement. Several works have been done to investigate the characteristics of the falling film heat exchanger on horizontal tubes.

Several authors, [1]-[5] investigated the behavior of the falling film modes like droplet, jet and sheet modes. They also studied the transitional mode between droplet-jet and jet-sheet modes. The flow behavior has a significant impact on heat transfer. The ability to predict the falling film mode would allow a better data correlation and improve the modeling and analysis of heat transfer and fluid flow. From previous works,[6]-[8] it is clear that the falling film Reynolds number (or the flow rate) plays an important role in mode transition. However, the effects of geometric and thermo physical property effects are not well understood.

The flow behavior of liquid falling film on a horizontal rotating tube was studied by Mohamed A.,[9]. The study is concerned with the effect of the rotation speed of the tube on the falling film mode transitions, film thickness and dimensionless wavelength. Experiments have indicated that, when a liquid falling film falls on a horizontal rotating tube, the transition starts at a low Reynolds number. The value of the film thickness is slightly decreased by increasing the rotation speed. A clear reduction of the dimensionless wavelength occurs due to the increase of the rotating speed of the tube for high viscosity fluids.

Binglue Ruan, et. al ,[10] studied the effects of a countercurrent gas flow on falling-film mode transitions between horizontal tubes. They developed a correlation to predict the countercurrent gas flow effects on falling-film mode transitions. Also, they found that the transition hysteresis was reduced with an increase of gas velocity. Also, the liquid feeding length can affect the mode transitions in quiescent surroundings when a countercurrent gas flow imposed.

The heat transfer of falling film on horizontal tubes bundles was investigated by Jiri Pospisil, et al, [11]. The study used different tubes geometries, smooth surface tubes, ribbed tubes, and fin tubes. The work focused on water falling film at atmospheric pressure where the film formation was accompanied with phase change. The diameter of the studied tubes is 12 mm and in arrangement with different spacing, namely 15, 20, 25 and 30 mm. The falling film fluid flow rate was tested for values 100, 150, 200 and 300 liter/hour on all arrangements of the tested tube bundles. It is found that the identified heat transfer coefficients varied in the range from 0.75 $kW.m^{-2}K^{-1}$ to 3 $kW.m^{-2}K^{-1}$. In addition, an increase in the falling film flow rate increases the heat transfer coefficient. Although, he judged the highest heat transfer coefficient for certain tube geometry and tubes spacing, but had no reasonable justification.

From all previous literature it appears that further studies are needed to utilize the horizontal falling film heat exchanger. The effect of tube diameter, tube spacing and working fluid, needs to be investigated. Enhancing heat transfer by using different tubes geometry and probably wind tunnel may be an issue.

In this research, the aim will be focused on the enhancement of heat transfer coefficient with different operating parameters. A test rig of horizontal tubes heat exchanger is built. Series tubes arrangement that allow the heating fluid enter from one side is used.

II. Methodology

A test rig has been built to investigate the problem. It consists of the test section, supporting box, control temperature cool path and constant head tank, as shown in Fig. 1.

The test section consisted of feed tubes, test tubes and catching tubes. All the tubes are made of copper, which has a high thermal conductivity. The feed tubes consist of the upper feed tube and lower feed tube. Along a 230 mm length on the bottom of upper feed tube, 2.0-mm-dia holes were drilled 3 mm apart, center to center providing 77 holes. The upper tube has inside and outside diameters of 20 and 22 mm. It receives liquid from the upper constant head tank and supplies it to the below tubes. The lower feed tube which has a diameter of 28.5 mm, was placed 1.5 mm edge to edge from the upper feed tube. Seven in-line test tubes bank configuration with diameter of 28.5 mm are placed at a pitch of 57 mm under the feed tubes. They were all held by the supporting box, which was made of 6 mm transparent Perspex.

The control temperature cool path gave a capability of adjusting the temperature to keep it constant. It was used to supply hot water for inside the tubes. The constant heat tank provides pure water to the outside the test tubes with different flow rate.

Inlet temperature, outlet temperature and flow rate of water, inside and outside the test tubes were recorded. Surface temperature was measured for one tube. Data acquisition was used to collect temperature measurement. Thermal images were captured to explain the behavior of the liquid falling film.

Scope and Limitations of the work

This work aims to analyze the heat transfer characteristics and temperature distribution of specific type of a falling film heat exchanger with horizontal feed tubes. The analysis is limited by the manufacturing and fabricated structures of the test rig. The tubes spacing is fixed and tubes are connected in series. The falling film flow is also limited by the type of the used feeding tube. The low thickness of the tube, make it difficult to embed the thermocouples in the surface. Inlet falling film temperature and flow arte need to have wider range for investigation.

Measuring Techniques

The temperatures of the heated fluid inside the tube and water falling film were measured by using k-type immersed thermocouples. They are fixed in a well through tubes. The flow rate of the heated fluid and the water falling film was measured by using calibrated flow-meters (1.0 -15 Lmin-1 for a Specific gravity =1) and (0.5 - 5 Lmin-1, for a Specific gravity = 1) respectively. A data acquisition system was used to collect temperature readings. Thermal images camera was used to get temperature distribution of the test sections.

III. Experimental Procedure

The control temperature cool path is the main source of the hot water inside the tubes. The supply hot water temperature varied for 60, 70, 80 and 90 °C. Several runs were conducted for each temperature and for different flow rate. The inlet temperatures, outlet temperatures and water flow rate were recorded. The water falling film on the test tubes came from the constant head tank which has a constant temperature. The flow was controlled to supply different falling film modes, like droplet, jet and sheet and transient mode. Several runs were conducted for each mode to ensure accuracy. The experimental ranges for different variables are shown in Table 1.

Table 1. Experimental ranges for different variables

Physical Parameter	Symbol	Experimental Range	Units
Falling film Mass flow rate	$\dot{m}$	Up to 0.075	Kg/s
Liquid thermal conductivity	k	0.6-0.633	W/m.K
Liquid specific heat	*Cp*	4170-4175	J/kg.K
Liquid dynamic viscosity	μ	$7.975*10^{-4}$-$8.5*10^{-4}$	$N.s/m^2$
Mass density of the liquid	ρ	996.5-997.5	Kg/m^3
Gas/ liquid surface tension	σ	$7.12*10^{-2}$-$7.2*10^{-2}$	N/m
Tube diameter	D	285	mm
Inlet falling film temperature	T	25-33	°C

IV. Results and Discussion:

A. Falling Film Behavior

In Fig. 2, the falling film on the tubes shows clearly the different modes, i.e. droplet, jet and sheet and transient mode. Table 2 shows the falling film flow rate that contributes to the different modes. Sometimes multi modes appeared at the set of the tubes when the flow rate increases. For low flow rates of less than 0.0125 kg/s, the droplet mode clearly covers all seven test tubes. The tubes are all wet and no backsplash appears. When the flow increases above 0.013 kg/s, the jet mode appeared in conjunction with the droplet mode in the upper two tubes. Flow rates between 0.0125 and 0.013 kg/s show un-stability between droplet and droplet-jet. As the falling film flow rate increases more than 0.0233 kg/s the jet mode appeared clearly on the upper two tubes. The Jet-Sheet mode appeared on the upper two tubes as the flow rate is further increased above 0.0333 kg/s, while the rest of the bottom tubes are covered by the jet mode. The backsplash increases toward downstream tubes. The sheet mode can be only shown completely on the first test tubes when the flow rate increases to 0.0633 kg/s, while the rest of the tubes are covered by the jet-sheet and jet modes. A large quantity of falling film water falls out of the test tubes due to backsplash.

Table 2. Range of falling film modes

Mode	Flow rate			
	From		To	
	Kg/s	Re	Kg/s	Re
Droplet	0.0000	0	0.0125	165.191
Uncertain	0.0125	165.191	0.0130	171.7986
Droplet-	0.0130	171.7986	0.0217	286.331
Uncertain	0.0217	286.331	0.0233	308.3565
jet	0.0233	308.3565	0.0300	396.4583
Uncertain	0.0300	396.4583	0.0333	440.5092
Jet-sheet	0.0333	440.5092	0.0600	792.9166
Uncertain	0.0600	792.9166	0.0633	836.9675
Sheet	0.0633	836.9675	0.0750	991.1458

B. Temperature Distribution analysis

The heating fluid enters the test section from the bottom of the test tube. Since the test tube is concentric, the liquid flows internally from the left end to the right end of the tube. After it exits from the right end inner tube , it turns back to the left to flow between the inner and outer tube. The maximum fluid temperature is expected to enter the test section from the left bottom inner tube. The fluid is then subjected to heat transfer to the liquid flow in concentric region. According to Fig. 3, the maximum temperature appears to the right and to left of all test tubes, except the middle one, in which there is a change in geometry. The middle tube has about 50% grooves, which reduce the wall thickness and increase the exposed surface.

While starting the falling film, the behavior of the temperature distribution is changed. The maximum temperature appears at the right ends for all tubes. The maximum temperature appears at the bottom two tubes while the lowest temperature distribution appears at the top tube, Fig. 4a. The middle tube, which has grooves, has a temperature distribution in between. Fig. 4b shows the maximum temperature for each tube at three location right, middle and left. It suggests that maximum temperature always occurs at the right end of the tube, while the lowest temperature occurs always to the left side of all test tubes. It also shows the highest temperature occurs at the bottom tubes while the lowest temperature occurs at the top tubes. It can also be verified that the temperature change within the tube is larger in the top tubes than the bottom tubes. This s possibly explained by the fact that the temperature of the falling film at the upper tubes is so low comparing to the temperature of the falling film liquid covers the bottom tubes.

The effect of each mode on the temperature distribution of the test tubes was also captured. Fig. 5 shows that as the falling film increases, it cools the test tubes faster and reduces the high temperature at the bottom tubes from about 66.3^{o}C to52.2^{o}C. The exit temperature of the falling film also decreases from 57^{o}C to about 42^{o}C. This implies that increasing the falling film flow rate is not beneficial to the system, since it ends up to decrease the exit temperature of the falling film.

The inlet and outlet temperature of both heating liquid inside the tubes and falling film liquid are registered By using k-type thermocouples and a data acquisition system. Note that a temperature drop for the falling film can reach up to 45oC for the jet-droplet mode. The falling film temperature drop for sheet-jet mode is lower than that of the jet-droplet mode. The temperature drop inside the hot liquid varies between 11-12.5^{o}C.

The total rate heat transfer can be calculated from

$$\dot{Q}_{hf} = \dot{m}_{hf} C_{p,hf} \Delta T_{hf} \qquad (1)$$

Where $\dot{m}_{hf}$ is the hot fluid mass flow rate, and ΔT_{hf} is the temperature difference between inlet and outlet temperature of the hot fluid. They were all measured and recorded.

Then, the overall heat transfer coefficient U can be calculated by using the following equation,

$$U = \frac{\dot{Q}_{hf}}{A_s \Delta T_{lm}} \qquad (2)$$

Where $A_s$is the total surface area given by

$$A_s = n\pi DL \qquad (3)$$

n is number of tubes , D is the outside diameter of the tube and L is the effective length of each test tube. Nusselt number is then can be calculated using

$$Nu = \frac{UD}{k} \qquad (4)$$

Reynolds number for falling film can be given by

$$Re = \frac{2\Gamma}{\mu} \qquad (5)$$

Where Γ is mass flow rate per unite length of the tube, kg/s.m.

Error analysis:

Relative error in the overall heat transfer coefficient, h_{ov} is:

$$\frac{\Delta h_{ov}}{h_{ov}} = \frac{\Delta Q_{h,f}}{Q_{h,f}} + \frac{\Delta T_f + \Delta T_h}{T_f + T_h} \qquad (6)$$

The relative error in the absorbed heat from the falling film is:

$$\frac{\Delta Q_{h,f}}{Q_{h,f}} = \frac{\Delta m_f}{m_f} + \frac{\Delta C_p}{C_p} + \frac{\Delta T_{fi} + \Delta T_{fo}}{T_{fi} + T_{fo}} \qquad (7)$$

The Δm_f can be taken as 0.020 as well as ΔT_f and ΔT_h =0.02, while $\Delta C_p \approx 0$

$$\Delta T_h = \frac{\Delta T_{hi} + \Delta T_{hoi}}{2} \qquad (8)$$

And the same for ΔT_f

$$\Delta T_f = \frac{\Delta T_{fi} + \Delta T_{fo}}{2} \qquad (9)$$

So, the error in the absorbed heat from the falling film can be calculated and the relative error is: $\Delta Q_{hf}/Q_{hf}$.

This leads to the relative error in the experimental overall heat transfer coefficient, which is given by: $\Delta h_{ov}/h_{ov}$. These values are calculated for all runs and found to not exceeding 20% , which is acceptable for this kind of experimental studies.

Fig.6 shows the variation of the average Nusselt number with the outside Reynolds number. It shows that the Nusselt number increases while the Reynolds number increases, and it reaches to 158 at Re=300. After that the Nusselt number stays the same for a while and then shows a sudden drop at Re=420 and reaches to a value of 140 at Re=580. It then has a little increase to a value of 143 at Re=600. To relate the phenomenon of Fig. 6 to the temperature behavior distributions shown in Fig. 5; increasing the falling film flow rate causes the increase of Reynolds number and the decrease in the exit temperature of the falling film. The falling film flow stays stable for the droplet and jet modes. In which the film thickness is very small and can get sufficient heat to lead to high temperature increase at the falling film flow exit. In the sheet mode, the film thickness increases and the high velocity of the flow reduces the chance of some layers of the fluid to be indirect contact with the hot tube surface and thus did not get enough heat, as for the case of small film thickness. The low exit temperature of the high falling film flow rate leads to a decrease in the Nusselt number as can be shown in Fig. 7. The increase of the backsplash leads to high quantity of water falls outside the test tubes, which also leads to the low Nusselt number. When the falling film velocity increases, it causes a high attack to the tube surface. This attack causes some falling liquid to withdraw out of the system and to fall out of the test tubes and prevent the outlet temperature of the falling film from further increase.

C. Effect of inside flow rate

The internal flow rate that flows inside the hot tubes was measured and its inner and outer temperatures were recorded. The temperature difference between inner and outer temperature from the test tubes are highly affected by the changing the inner flow rate. As the mass flow rate increases the temperature difference decreases, and the rate of the heat transfer increases as shown in Fig.8.

V. Conclusion

A falling film heat exchanger was built. The liquid falling film fell into seven test tubes arranged horizontally. Three main falling film modes (droplet, jet and jet-sheet) were noticed during the experiments. Transitional modes also appeared. Temperature distributions were captured by thermal images camera. The maximum temperature appeared at the entrance of each tube. The falling film liquid can be heated by 45^{o}C instantaneously. The droplet and jet modes were very stable and the jet mode shows the highest Nusselt number. These results are preliminary and more experiments are needed to analyze the heat transfer coefficient and the Nusselt number. Parametric equations need to be developed and other types of falling film liquid need to be investigated.

The anticipated results will help in understanding the characteristics of the falling film behavior, and its effect on the heat transfer for the indicated heat exchanger. The results will also help the interested investigators and researchers to build advanced models of falling film heat exchangers. Manufacturers of such type will also consider the results in designing new heat exchangers.

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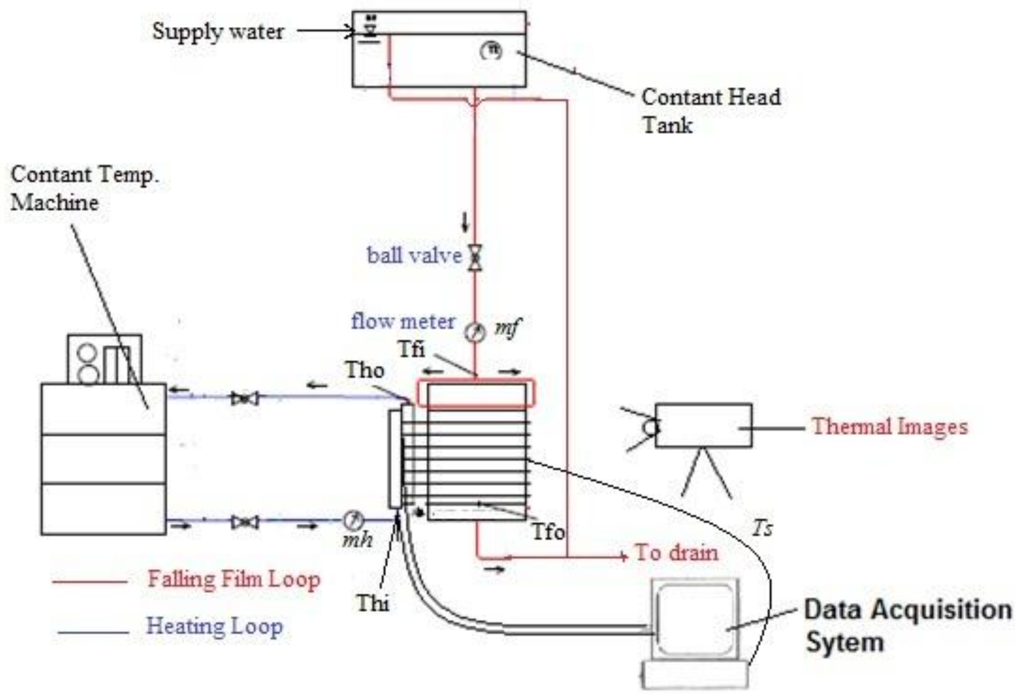


Fig. 1. A schematic of the experimental Apparatus

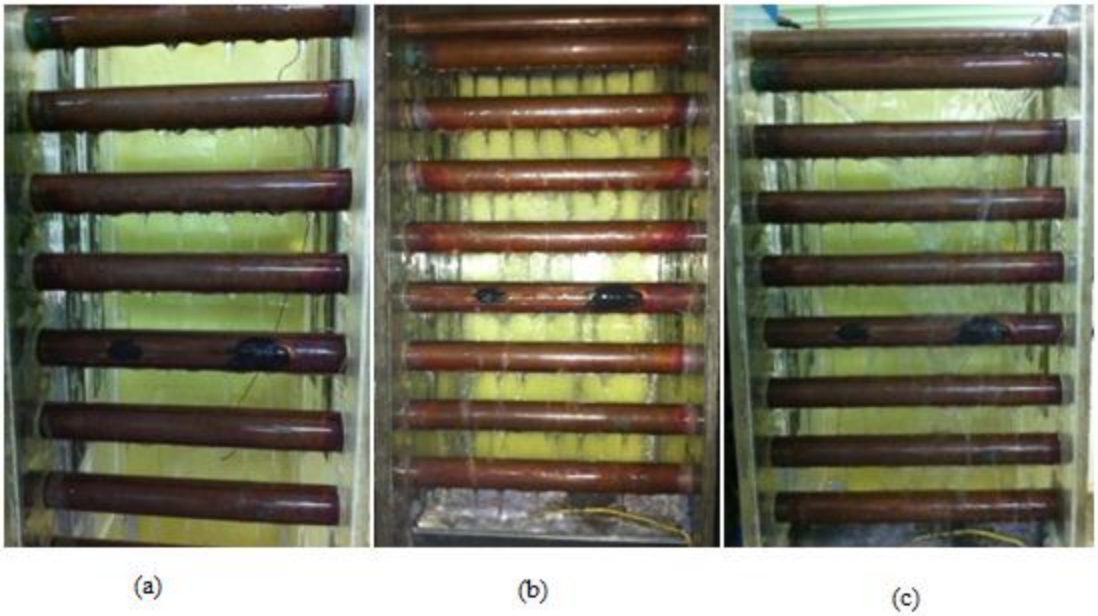


Fig. 2. Falling film modes (a) droplet (b) jet (c) sheet-jet

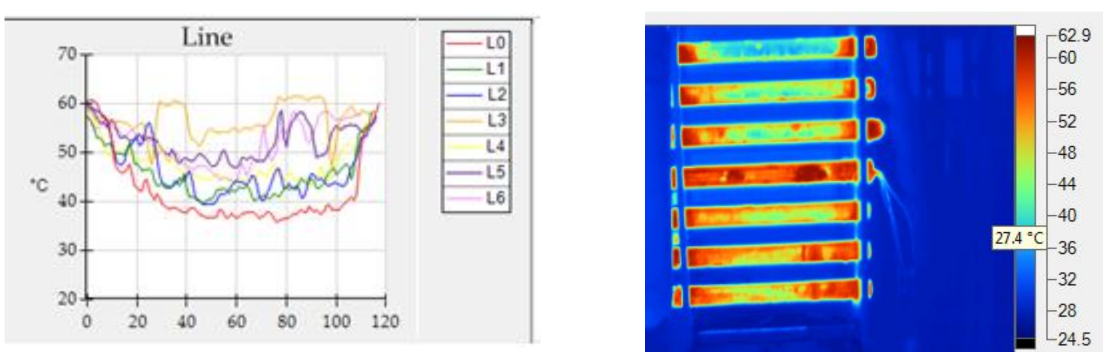
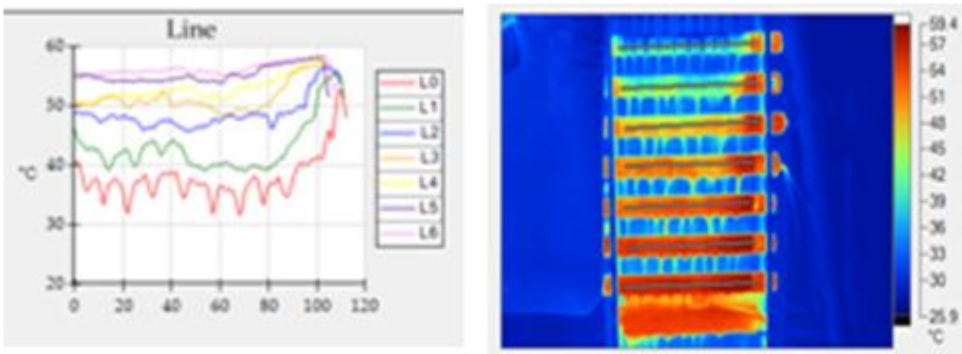
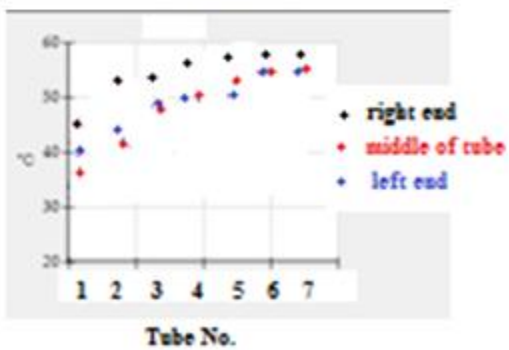


Fig. 3. Temperature distributions along each the test tube, without subjecting to falling film for m= 0.33kg/s.

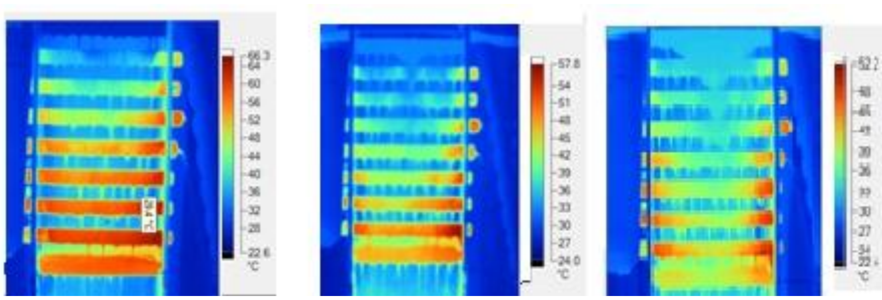


(a)



(b)

Fig. 4. (a)Temperature distributions along each the test tube, subjecting to falling film (b) maximum temperature for each tube, for m_h= 0.16 kg/s. and m_{ff}= 0.022kg/s



(a) (b) (c)

Fig. 5. Temperature distribution for three modes, (a) droplet-jet (b) jet-sheet (c) sheet-jet

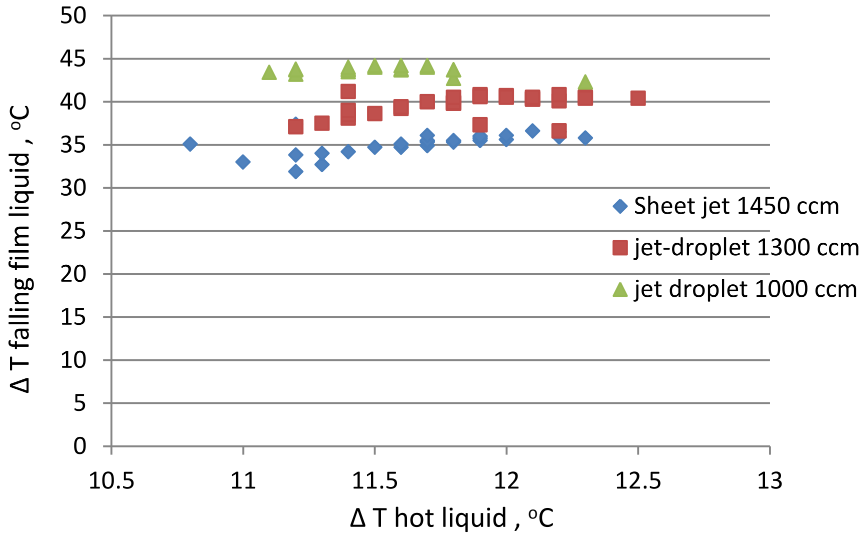


Fig. 6. Relation of the temperature difference for both inner and outer flow rate.

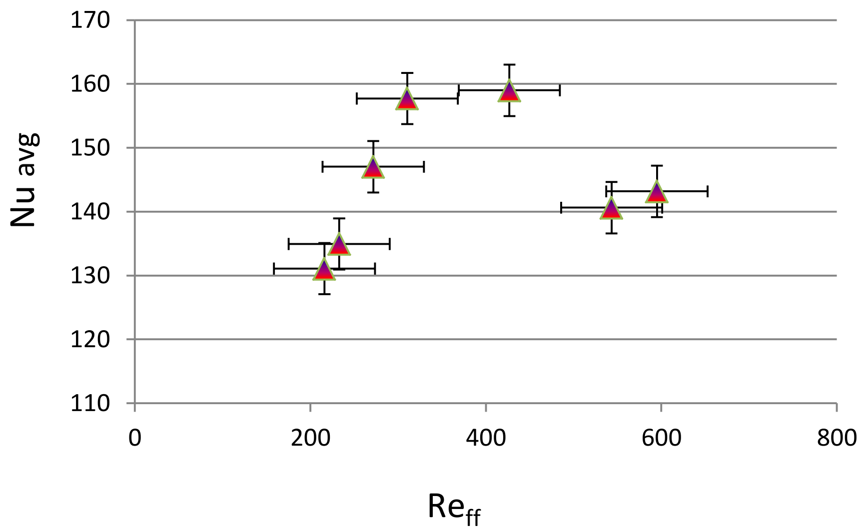


Fig. 7. Effect of changing falling film Reynolds number on the average Nusselt number

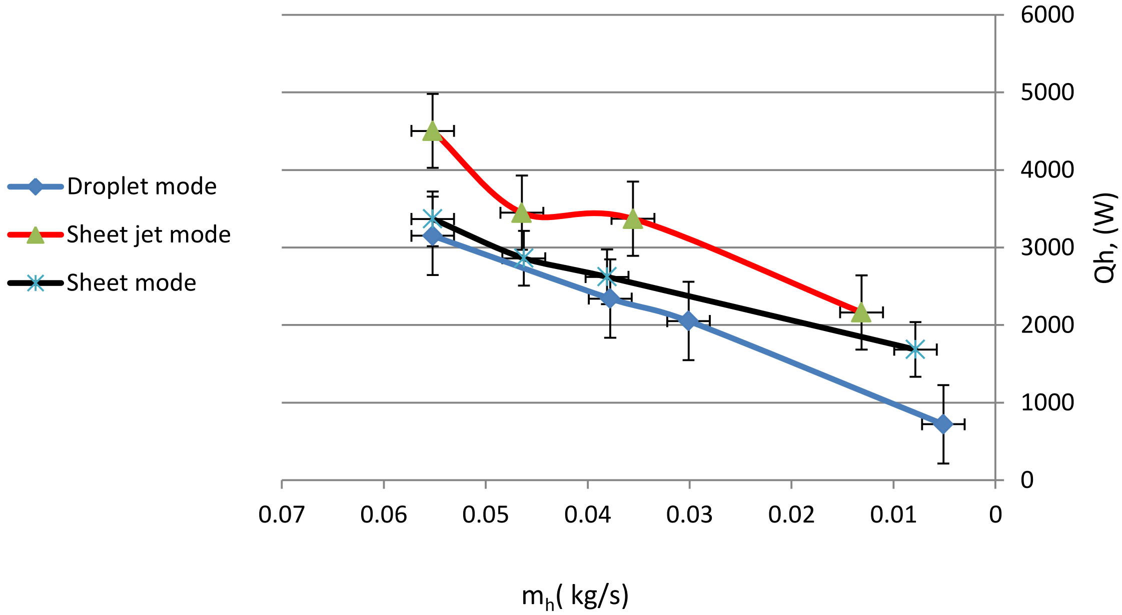


Fig. 8. Effect of the internal flow rate to the heat transfer rate from the test tubes for different falling film modes.