

Experimental Analysis of Heat Transfer with Dropwise and Filmwise Condensation on Inclined Double Tubes Heat Exchanger

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ABSTRACT

Dropwise condensation provides larger heat transfer coefficients compared to filmwise condensation, as discovered in the year 1930 by Schmid et al. Dropwise condensation can be described as a phenomenon of the incomplete wettability of a surface.

The wettability of the surface is responsible for the formation of the respective type of condensation and has a very strong effect on the performance of the heat transfer process. Likewise, the wettability of the surface has a very strong effect on the subcooling of the condensate, for constant cooling performance.

Although the conditions necessary for promoting dropwise condensation are well known since several decades, and experiments with coatings as promoters have been carried out successfully, at least in part, the application of dropwise condensation is still today in a testing phase.

The main problems in the realization of dropwise condensation are the insufficiency of the theoretical description of working boundary surface phenomena, such as complete or incomplete wettability and their strong dependence on influences caused in the practical operation by contamination, oxidation of the surface, adsorption layers, and gas enclosures.

Keywords: chromium coating, ceramic coating, polished surface, condensation, dropwise, Filmwise, inclined surface.

تحليل عملي للانتقال الحراري بالتكثيف التقطيري والغشائي لمبادل حراري مائل
مزدوج الأنابيب

الخلاصة

يوفر التكثيف التقطيري معاملات انتقال للحرارة أكبر مقارنة بالتكثيف الغشائي، كما اشار الى ذلك Schmid في العام 1930 وآخرون . ويمكن وصف بلل السطح بأنه نوع من التكثيف الغير مكتمل. أن قابلية ترطب السطح هي المسؤولة عن تحديد نوع التكثيف ، ولها تأثير قوي جدا على أداء عملية انتقال الحرارة . وبالمثل، فإن قابلية ترطب السطح لديها تأثير قوي جدا على حالة subcooling في المكثفات، للحصول على أداء تبريد مستمر. على الرغم من أن الظروف اللازمة لتعزيز التكثيف التقطيري معروفة منذ عدة عقود، اذ أجريت التجارب باستخدام الطلاء (coating) لتسريع عملية التكثيف بنجاح ، لا يزال الى يومنا هذا في مرحلة الاختبار وأن المشاكل الرئيسية في التكثيف التقطيري هي قصور في الوصف النظري لهذه الحالة. وأن التكثيف التقطيري عملياً يتأثر بعدة عوامل منها التلوث، وأكسدة السطح، و طبقات الامتزاز، ومرفقات الغاز.

Nomenclatures

- A_o External heat transfer surface area m^2
 A_i Internal heat transfer surface area m^2
 d_h Hydraulic diameter of condenser m
 d_o Outlet diameter of condenser m
 d_i Inlet diameter of condenser m
 h_i Internal Heat transfer coefficient $W/m^2 \cdot ^\circ C$
 h_o External Heat transfer coefficient $W/m^2 \cdot ^\circ C$
 h_{fg}^* Modified latent heat of vaporization J/kg
 L Effective length m
 \dot{m}_w Mass flow rate of cooling water L/hr
 q Heat flux kW/m^2
 Q_o Amount of heat supplied to the cooling water W
 R_w Wall resistance $m^2 \cdot ^\circ C /W$
 R_c Resistance due to liquid condensate $m^2 \cdot ^\circ C /W$
 R_i Resistance due to flowing coolant $m^2 \cdot ^\circ C /W$
 T_w Wall temperature $^\circ C$
 u Cooling water velocity m/s
 U_o Overall heat transfer coefficient $W/m^2 \cdot ^\circ C$
 T_{w_o} Outlet cooling water temperature $^\circ C$
 T_{w_i} Inlet cooling water temperature $^\circ C$
 T_s Saturated steam temperature $^\circ C$
 θ Angle of inclination degree

INTRODUCTION

The use of steam both for power production and to convey heat has a long history, and its use in these fields is likely to continue into the foreseeable future. In all applications, the steam must be condensed as it transfers heat to a cooling medium. This could be the cold water in the condensers of a generating station, the hot water in a heating clarifier, a sugar solution in a sugar refinery.

During condensation, very high heat fluxes are possible and provided, the heat can be quickly transferred from the condensing surface into the cooling medium, and steam using heat exchangers can be compact and effective.

Steam may condense on a surface in two modes, known as filmwise and dropwise. For the same temperature difference between the steam and the surface, dropwise condensation is several times more effective than filmwise, and for this reason the

former is desirable although in practical plants it seldom occurs for prolonged periods [1, 2, and 3].

By specially treating the condensing surface, the surface becomes "non-wettable" and as the steam condenses, a large number of generally spherical beads form on its surface. These beads become larger coalesce, and then trickle downwards. The moving bead gathers all the static beads along its downward path, becomes larger, accelerates and leaves a virtually bare surface.

The "bare" surface offers little resistance to the transfer of heat, and very high heat fluxes are therefore possible. Unfortunately, as stated earlier, due to the nature of the materials normally used in the construction of condensing heat exchangers, filmwise condensation is normal, but the desirability of dropwise condensation has led to many investigations into methods which will promote and maintain it in practical plants.

During condensation, the latent heat of vaporization must be released, and the amount of the heat is the same as that absorbed during vaporization at the same fluid pressure.

Literature Review

Vemuri, (2005), [4] studied two different types of hydrophobic coating and analyzed experimentally their ability to promote dropwise condensation (DWC). For any technique used for promoting dropwise condensation, the longevity of the coating is critical if it is to be used in any further applications. Experiments were carried out using self-assembled monolayers for more than 2600 h of experimentation, and it showed good dropwise phenomena. Stearic acid solution (SAM-1) and n-octadecyl mercaptan solution (SAM-2) were used to form an ultra-thin organic hydrophobic film on the surface. An oxide layer was initially formed on the substrate surface before coating the surface with monolayers.

Lifetime of maintaining dropwise condensation is greatly dependent on the bonding of SAM coating to the condensing surface. From the experimental investigation, it was evident that n-octadecyl mercaptan showed good DWC due to its covalent bonding with the substrate surface when compared to that of stearic acid which is bonded to the substrate surface by hydrogen bonding. Contact angles were measured for all the SAM coated surfaces before and after experimentation, respectively.

Bonner, (2010), [5] studied experimentally the data from a life test of self-assembled monolayers on copper and gold plated surfaces. In the life test, the surfaces have been continuously exposed to saturated steam at (60°C). Both surfaces have continued to promote dropwise condensation for over 9 months under conditions representative, the test section was then tilted at a (45°) angle and tested. The experimental data for the 45° orientation .

The increasing thermal demand of electronics devices has pushed the limits of current two-phase thermal technologies. The most obvious area for thermal improvement is centered on the high heat flux generating chips including improved evaporators and thermal interfaces.

However, heat fluxes in the sink/condensing regions have also risen as the size of electronics packages has decreased. One way to reduce the thermal resistance associated with condensation is to promote dropwise condensation.

The condensation performance improvement using self-assembled monolayer coated surfaces (to promote hydrophobicity) has been shown. However, the question of the life of the self-assembled monolayer coatings needs to be addressed before the technology is adopted, as this has plagued other dropwise condensation coatings in the past.

Basant, et al. (2011),[6]observed experimentally the dropwise condensation of water vapor on a chemically textured surface of glass and its detailed computer simulation. Experiments were focused on the pendant mode of dropwise condensation on the underside of horizontal and inclined glass substrates.

Major conclusions arrived at in the study are the following. The area of droplet coverage decreases with an increase of the substrate inclination. As the substrate inclination increases, the time instant of commencement of sliding of the droplet is advanced.

Condenser Design

The accuracy of obtaining experimental results depends on the nature of rig design and the infirmities of heat flux on the tube surface. In present investigation, a double pipe heat exchanger type is used. The best design for small double pipe heat exchanger is given by [7]. They concluded that the heat exchanger design can be conducted commonly by the LMTD (logarithmic mean temperature difference) as given by the following relation:

$$LMTD = \frac{T_{w_o} - T_{w_i}}{\ln\left(\frac{T_s - T_{w_i}}{T_s - T_{w_o}}\right)} \quad \dots (1)$$

The amountofheat supplied to the cooling water is calculated from the following equation:

$$Q_o = \dot{m}_w \cdot c_{p_w} \cdot (T_{w_o} - T_{w_i}) \quad \dots (2)$$

The overall heat transfer coefficient is calculated as;

$$U_o = \frac{Q_o}{A_o \times LMTD} \quad \dots (3)$$

The heat balance applied to heat exchanger shown in figure (1), the overall heat transfer coefficient (U_o) of the condenser test rig is calculated from the following equation:

$$U_o = \frac{1}{A_o \left[\frac{1}{h_o \times A_o} + R_w + \frac{1}{h_i \times A_i} \right]} \quad \dots (4)$$

As seen from this equation, there are three resistances to heat flow, a good design of condenser must reduce the resistance as much as possible especially the wall resistance (R_w), obtained as:

$$R_w = \frac{\ln\left(\frac{d_o}{d_i}\right)}{2 \times \pi \times K_{tube} \times l} \quad \dots (5)$$

The outlet diameter of condenser play a main role to determine heat transfer area, in good design of heat exchanger there is an optimum value of the outlet and inlet diameters of condenser tube, according to [8].

Also the selection of material which has high thermal conductivity (copper) is important parameter affecter to reduce the wall resistance as shown in figure (1).

The heat transfer coefficient (h_o) of dropwise condenser calculated as:

$$h_o = \frac{1}{\frac{1}{U_o} - \left[\frac{A_o}{A_i} \left(\frac{1}{h_i} \right) + A_o \times R_w \right]} \quad \dots (6)$$

Therefore (d_o, d_i, L, k) are the main parameters affect on determination of heat transfer coefficient (h_o) of dropwise condenser calculation.

Equation (7) was developed for vertical plates, but it can also be used for laminar film condensation on the upper surfaces of plates that are inclined by an angle (θ) from the vertical. By replacing g in that equation by $g (\cos\theta)$. This approximation gives satisfactory results especially for ($\theta = 45^\circ$), [9].

Note that the condensation heat transfer coefficients on vertical and inclined plates are related to each other by

$$h_{includ} = h_{vert} (\cos \theta)^{1/4} \text{Laminar} \quad \dots (7)$$

Experimental setup and procedure

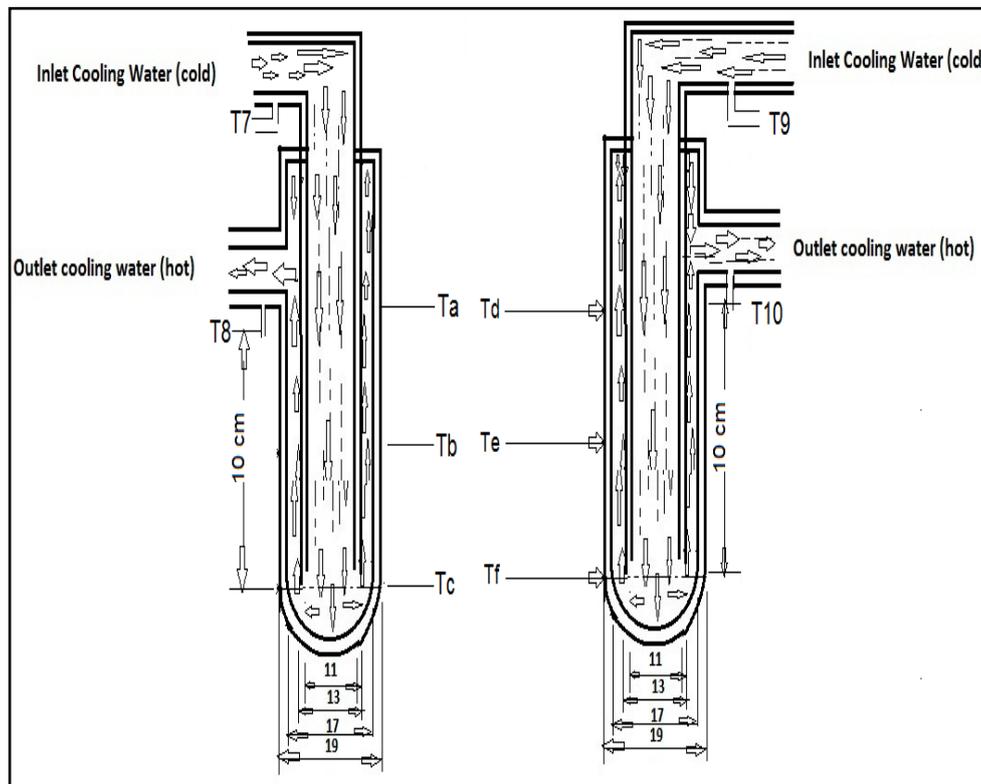
The experimental test rig consist the following main parts:

-Cooling water supply equipment.

-The steam chamber: Steam chamber is composed of the following parts: Glass cylinder with outer and inner diameters of (165 and 160 mm), respectively and 400 mm length. Iron plate with circular grooves for closing the lower end of glass with (14 mm) thickness and (210 mm) diameter with the following accessories: Electrical coiled element of (3 kW) for steam generating supplied by two electrical poles. Charging and drain valve. Thermostat. Aluminum plate for closing the upper end of glass cylinder with (210 mm) diameter and (12 mm) thickness with the following accessories, vent valve, pressure relief valve, air extraction valve, pressure gage, and two condensers (heat exchanger) for dropwise and filmwise. Coiled electric heating element (3 kW) with thermal protection heater control is used to manually vary the heat rate by of approximately (0.4 to 3.0) kW, it is made of (Cr-Ni) metal, the heating element is fixed on the lower cover. Figure (1) shows the schematic diagram of the test rig assembly.

-Measuring devices: The type of thermocouple and the method of fixing it on the surface effect the accuracy of obtaining results. Thus multi point (12 channels recorder) electronic analogue thermometer type "BTM-4208SD" is used to indicate the required temperatures. Paperless Real time data logger saves the measuring data along the time information. Data along with time information can be saved and down load to the extra software, such as Excel. Temperature measurement sensor type: (Type K) thermocouple is used to measure the saturated steam temperature inside the

steam chamber. A digital clamp meter (type M9805m G) is used to measure the electrical current (2-20A) of the heating element in order to calculate input power. Bourdon Gage (-1 to 5 bars) is used to measure the steam pressure in the system, and to measure the atmospheric pressure during the experiment carrying out. Glass flow meter is used to measure the flow rate of cooling water with range of (60 - 260) lit/hr. Figure (2) shows schematic diagram of experimental test rig assembly, and figure shows (3) photo of the experimental test rig.



**Figure (1) (a) Schematic of dropwise heat exchanger
(b) Schematic of filmwise heat exchanger**

-Condenser tubes surfaces: the polish surface of the condenser is prepared by using smoothing superfine paper softness. Ceramic coating of low thermal conductivity ($40 \text{ w/m} \cdot ^\circ\text{C}$), with small thickness is used in which there is an advantage when use small thickness ceramic coating to promote dropwise condensation. Glasses ceramic (Al_2O_3) is used to coat the condenser tube with ceramic coating thickness of $170\mu\text{m}$. Finally chromium coating, made like a mirror-finish, is used third condenser tube. The three heat exchanger dropwise tubes used in the experimental are shown in

Figure (4). Rough copper tube (matt surface) is used for filmwise condensation model.

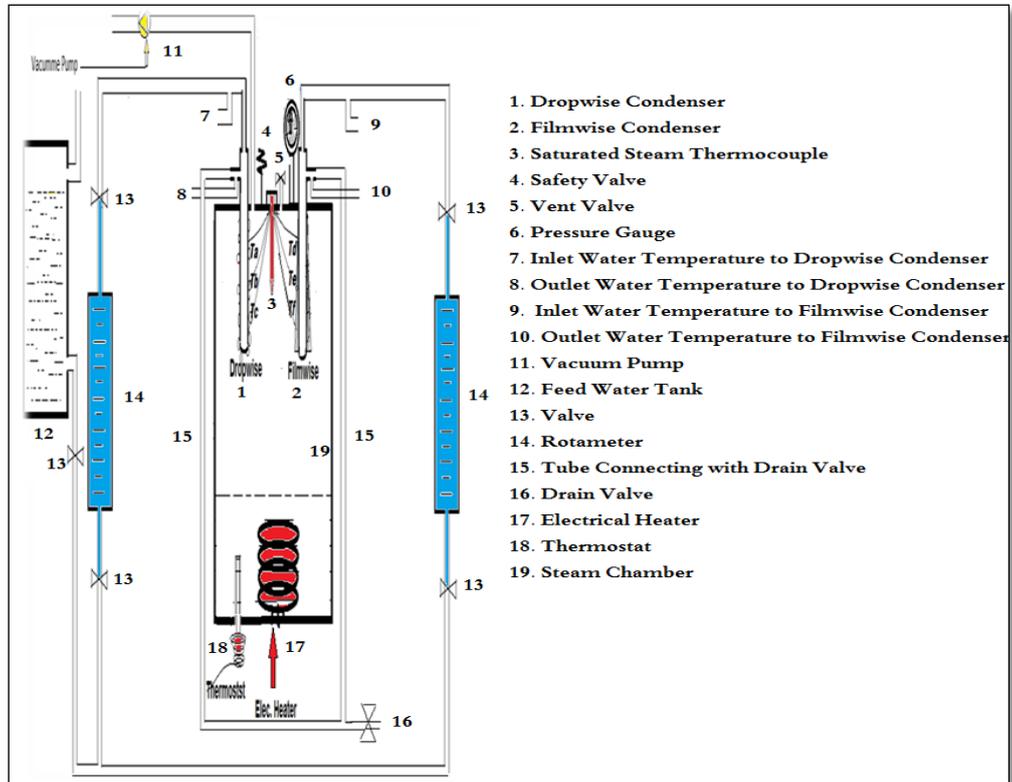


Figure (2) Schematic Diagram of Experimental Test Rig Assembly



Figure (3) Photo of the Experimental Test Rig.

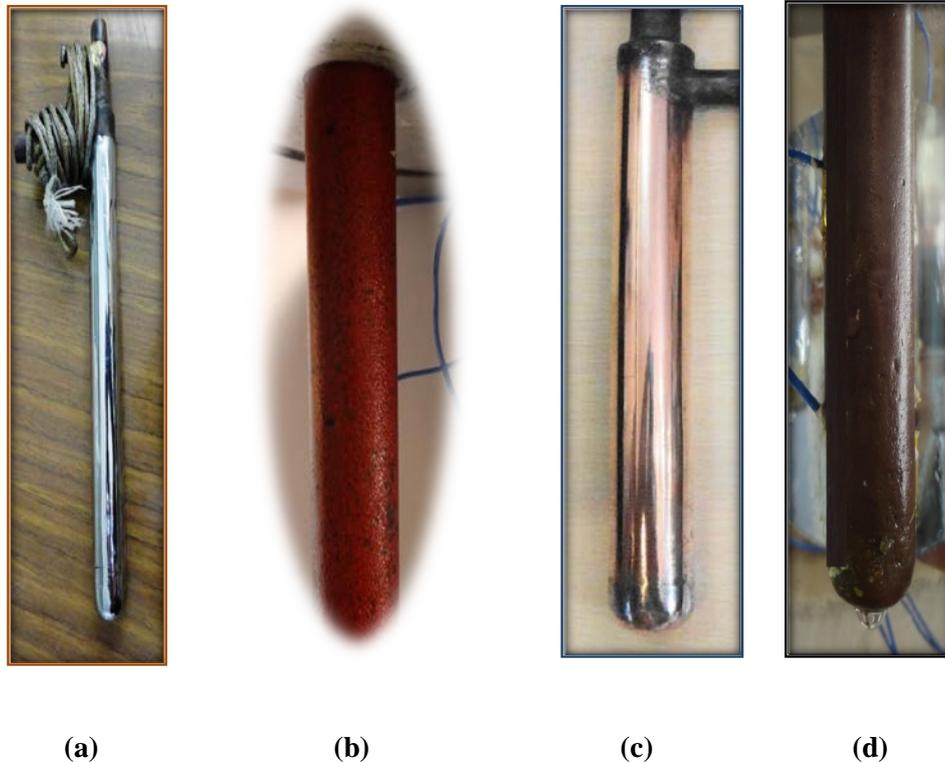


Figure (4) Dropwise heat exchanger tubes, (a) Chromium Coated Tube
(b) Ceramic Coated Tube, and (c) Polished Tube, (d) Matt Surface

Experimental Test Procedure

To carry out the experiments, the following procedure was followed:

- Fill the steam chamber with sufficient distilled water ensuring that the electrical heater is submerged with distilled water.
- Ensure that filling and draining valve is closed.
- Switch on the electric power.
- Increase the voltage gradually by using voltage regulator (variac).
- Open cooling water valve.
- Fix the mass flow rates of cooling water on the required value (60, 80,100,120,140 and 160l/h).
- Record tubes surface temperature (T_a, T_b, T_c) for the dropwise condenser and (T_d, T_e, T_f) for filmwise condensation and get the average of these reading for each tube.
- Record inlet cooling water temperature for the dropwise condenser and for filmwise condensation.

-Record outlet cooling water temperature for the dropwise condenser *and* for filmwise condensation.

-Record (voltage, current) at all tests.

-Remove the air from steam chamber by opening the vent valve.

Results Errors

There is no doubt, the maximum portion of error in calculation referred to essentially to the error in the measured quantities. Hence to calculate the error in the obtained results Kline and Mc clintock method is used in this field.

Results and Discussion

The details of calculating output results obtained by using equations (1 to 7) for six flow rates quantities.

Inclined Orientation –Chromium Coating

Figure (5) shows the relation between the heat transfer coefficient and the velocity of cooling water presented by Reynolds number, (h_o) decrease with increasing Re. number. Figure (6) depicts the variation of the heat transfer coefficients with Re. number, in vertical orientation for chromium coating, it is clearly that the heat transfer coefficient at inclined case is approximately half value comparing with the heat transfer coefficient of vertical case for all ranges of Reynolds number due to the effect of gravity increase the wettable area then increased the resistance to heat transfer from the saturated steam to the cooling water.

Figures (7,8) shows the comparison of variation of (h_o) and (q) with Re. for chromium coated and matt surface (filmwise condensation), the heat transfer coefficient of chromium coating surface proportion to heat transfer coefficient of filmwise condensation (matt surface) was from (4.4 to 1.5) times the heat transfer coefficient of filmwise condensation at inclined orientation $^{\circ}45$.

It is seen that (h_o) in dropwise condensation gave a higher value for vertical orientation than the inclined orientation while for filmwise condensation (matt surface) there is a slight effect on (h_o) for all ranges of Re number. (h_o) for vertical orientation of matt surface is 1.2 greater than (h_o) for inclination matt surface.

Inclined Orientation – Ceramic Coating

Figures (9) and (10) show the variation of (h_o) and (q) with Re number for ceramic coating (vertical and inclined cases), as seen from these two figures (h_o , q) behaves at the same manner exists in figures (7, 8) but with the lowest values of (h_o , q) with Re., respectively due to the difference in wettability for the two surfaces. Ceramic coating was wettable surface more than chromium coating therefore the resistance to heat transfer was more than chromium coating, so the value of (h_o) decreased. The heat transfer coefficient (h_o) in figure (9) for inclined orientation was half the value of (h_o) at vertical orientation for ceramic coating, but the heat transfer coefficient of ceramic coating at inclined orientation still greater than filmwise condensation about (2.7 – 1.34) times the heat transfer coefficient of filmwise condensation, at inclined orientation $^{\circ}45$.

Inclined Orientation – Polished surface

Figures (11) illustrates comparison of variation of (h_o) with Re. for polish surface and matt surface for vertical and inclined surfaces for all ranges of Re., polished surface behave similar to those for (chromium and ceramic coatings) but with the lowest value of (h_o) for all ranges of Re number. Figures (12) shows comparison of variation of (q) with Re for polish surface and matt surface for vertical and the inclined surfaces for all ranges of Re number, the behavior of heat flux at inclination polished surface is similar to those dropwise surfaces (chromium an ceramic coatings), but with the lowest value of heat flux for all ranges of Re number, The heat transfer coefficient of polished surface proportion to heat transfer coefficient of filmwise condensation (matt surface) was from (2.2 to 1.2) times the heat transfer coefficient of filmwise condensation orientation of the Reynolds number range from (1079.8 to 2879) at inclined orientation $^{\circ}45$.

Inclined Orientation – Matt Surface

Figure (13) manifests the variation of heat transfer coefficients (experimentally according to approach 1) of filmwise condensation (matt surface) with Re. number, for vertical and inclined cases experimentally, there were a slight effect of inclination at matt surface comparing with dropwise condensation (chromium coating, ceramic coating and polished surface). Figure (14) show the variation of heat flux with Re. number for vertical and inclined cases, there were a small affect of inclination on heat flux of matt surface.

CONCLUSION

The effects of surface processing conditions on the condensation heat transfer characteristics were investigated experimentally. Excellent dropwise condensation was obtained on one of the chromium coating surfaces at atmospheric pressure then for ceramic coating and finally polished surface:

- The heat transfer coefficient of chromium coating surface proportion to heat transfer coefficient of filmwise condensation (matt surface) was from (8 to 2.5) times the heat transfer coefficient of filmwise condensation at vertical orientation at the Reynolds number range from (1079.8 to 2879).
- The heat transfer coefficient of ceramic coating surface proportion to heat transfer coefficient of filmwise condensation (matt surface) was from (5.4 to 2) times the heat transfer coefficient of filmwise condensation at vertical orientation at the Reynolds number range from (1079.8 to 2879).
- The heat transfer coefficient of polished surface proportion to heat transfer coefficient of filmwise condensation (matt surface) was from (4 to 1.6) times the heat transfer coefficient of filmwise condensation at vertical orientation at the Reynolds number range from (1079.8 to 2879).

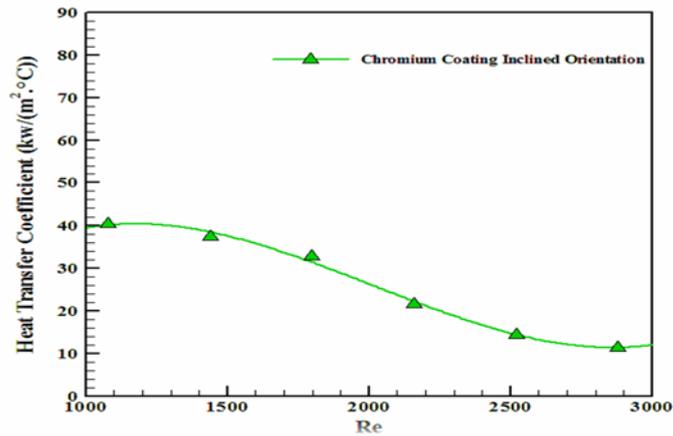


Figure (5) Variation of Heat Transfer Coefficient with Re.

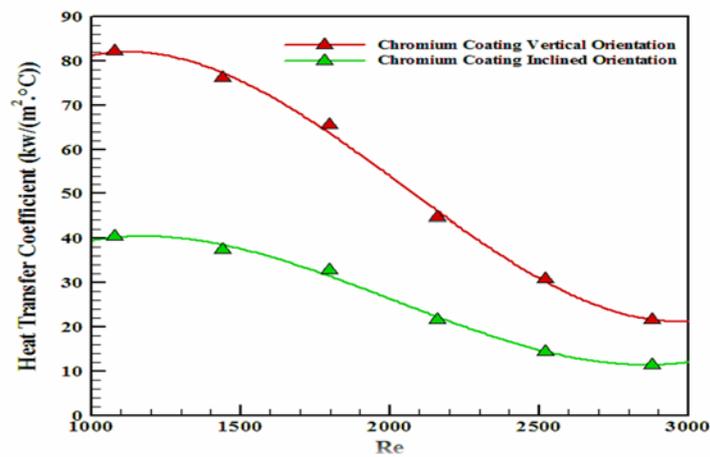


Figure (6) Variation of Heat Transfer Coefficients with Re.

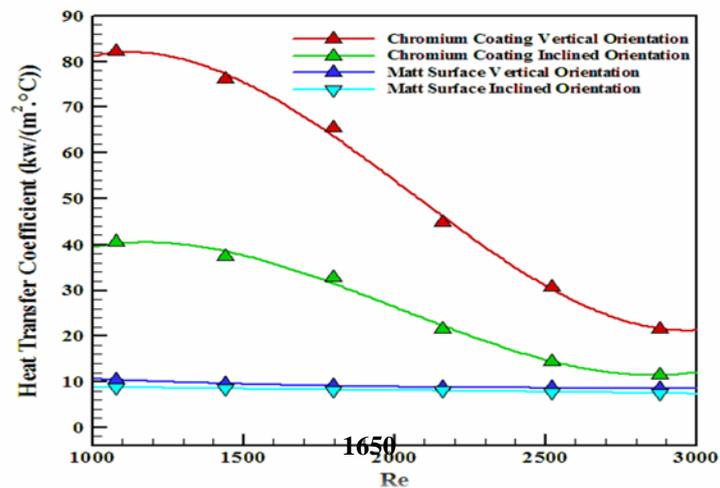


Figure (7) Variation of Heat Transfer Coefficient with Re.

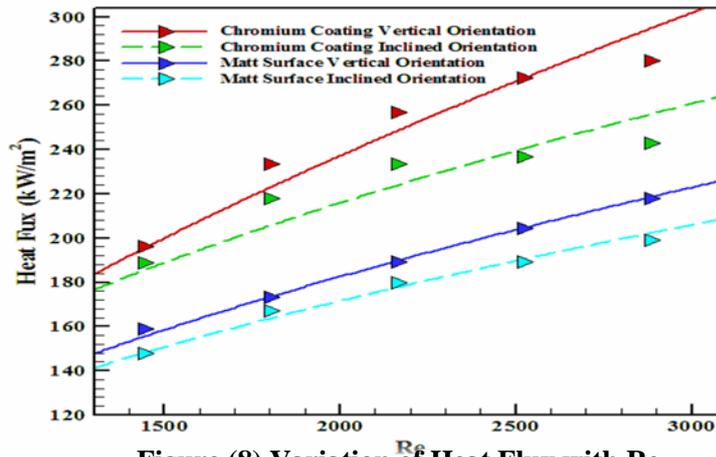


Figure (8) Variation of Heat Flux with Re.

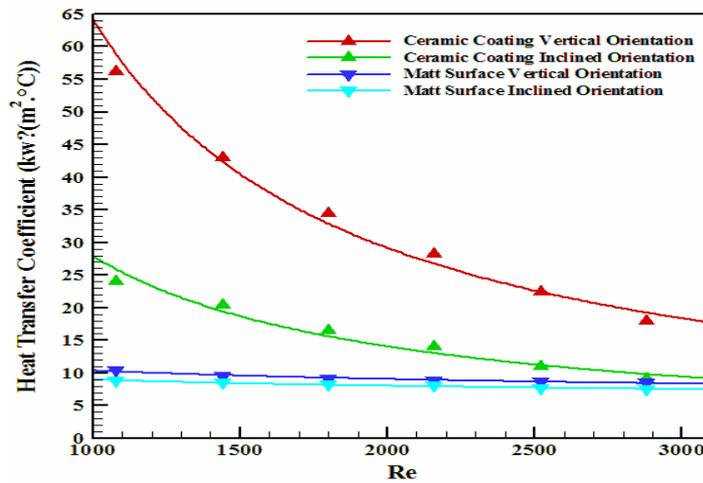


Figure (9) Variation of Heat Transfer Coefficient with Re.

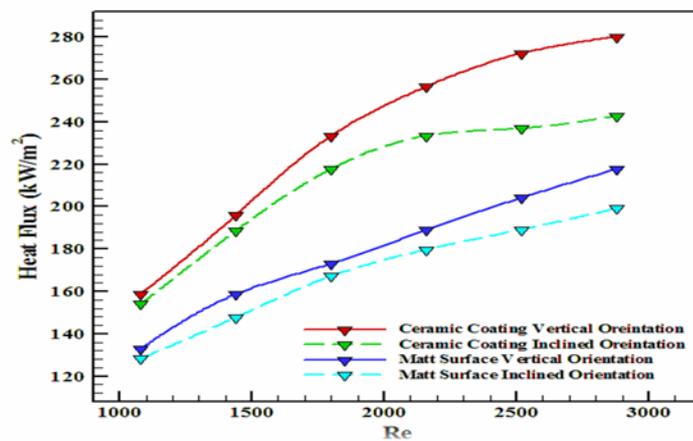


Figure (10) Variation of Heat Flux with Re.

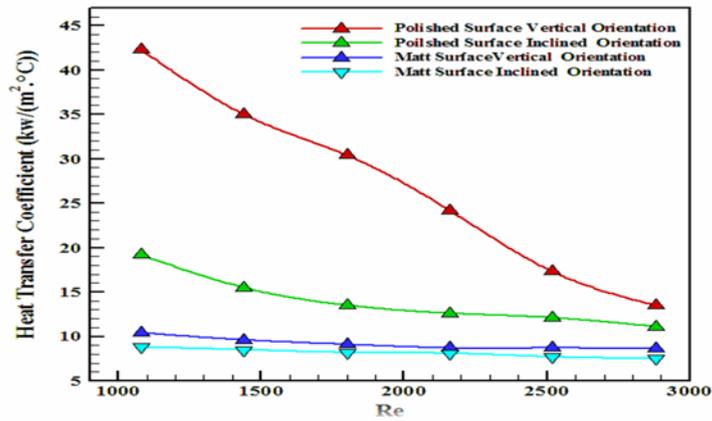
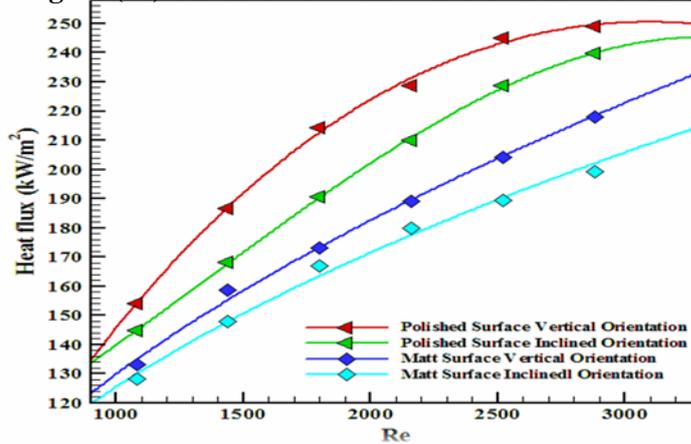


Figure (11) Variation of Heat Transfer Coefficient with Re.



(12) Variation of heat flux with Re.

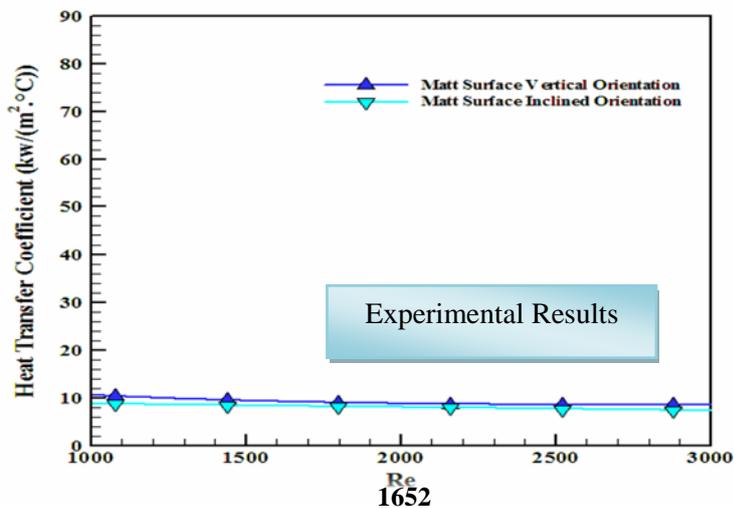


Figure (13) Variation of Heat Transfer Coefficients with Re.

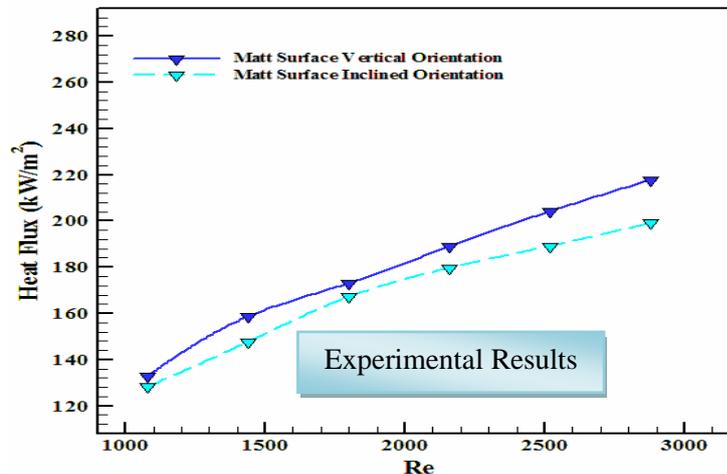


Figure (14) Variation of Heat Flux with Re.

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