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Experimental Analysis for Estimating Steam Condensation Heat Transfer Coefficient of a Mini Diameter Tube

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ABSTRACT: Heat exchanger is a common part of technological systems and tubular heat exchanger is the most widely applied variant. Tubular heat exchanger uses latent heat of condensation to undergo phase change from vapor to liquid. This paper focuses on experimental analysis for estimating the condensation heat transfer coefficient of a vertical copper tube of length 1000mm, inner diameter 2mm and wall thickness 0.5mm. Condensation experiments were performed using steam as a heating medium that flows inside the copper tube while water was used as base fluid flowing from outer side of the copper tube. The mass flow rates of steam and cooling water are variable. Condensation heat transfer coefficient on inner surface of tube is calculated by thermal resistance method and is compared with theoretical correlation for prediction of condensation heat transfer coefficient and also corroborated using Wilson plot method. It was found that the increase in condensation heat transfer coefficient is more significant at higher saturation temperature. Also Nusselt equation does not take into account the effects of waves on the condensate surface. The waves that are formed on the condensate surface because of the flow of steam inside the tube, increase the condensation heat transfer coefficient. New correlation which takes into account the wave effect and the steam pressure was developed.

KEYWORDS: Condensation; Condensation heat transfer coefficient; Vertical tube; Wave effect.

I. INTRODUCTION

Condensers are used in a range of chemical, petroleum, processing and power facilities for distillation, for refrigeration and for power generation. Most condensers used in the chemical process industries are water-cooled, shell-and-tube exchangers and air-cooled tube or plate exchangers. Shell-and-tube condensers, which are used for condensing processed vapours, are classified according to orientation (horizontal and vertical) and according to the placement of the condensing vapour (shell-side and tube-side). This paper deals with vertical shell-and-tube condensers with tube-side condensation. Many industrial systems use vertical tube condensers and industrial practice has indicated that, often, much higher coefficients of heat transfer are obtained when vapours are condensed inside tubes rather than outside. The Nusselt's condensation model, which is often recommended for calculating the condensing side HTC, is derived for conditions which need not be satisfied in real operation.

Nusselt [1] published the first article about laminar film condensation. Later Bromley [2] introduced the effect of sub-cooling condensate on wall surface and Rohsenow [3] studied non-linear temperature distribution in film condensate. Flowing steam in tube causes waves on condensate surface and these waves improve condensation heat transfer. The wave effect was studied by Kapitza [4] in 1948 and later McAdams [5] recommended that the Nusselt equation should be multiplied by the wave factor 1.2 as a discrepancy correction between experimental results and theoretical Nusselt solution. Whitham [6] considered the wave effect on condensation heat transfer coefficient and found that the HTC obtained using Nusselt equation is increased by 20%. The next theoretically determined equation which includes the wave effect is published by Hobler [7]. Later Kutateladze [8] developed relation for the average condensation heat transfer coefficient in wavy laminar condensate flow for $30 < R < 1800$. Wilson plot method [9] used to

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calculate the condensation heat transfer coefficient graphically which is more reliable than thermal resistance method and inaccuracy is eliminated by linear regress function and least square method. The Grober's [10] method is commonly used for calculating the shell-side heat transfer coefficient.

Steam condensation is continuously studied in many literatures in different experimental or theoretical ways. In past literature the condensation heat transfer coefficient for L/Di ratio up to 300 was available. Very few literatures are present on the L/Di ratio above 300. The purpose of this paper is to study condensation inside the vertical tube with L/Di=500. Impact of mass flow rate of steam, variable inlet temperature and variable mass flow rate of cooling water in shell side on condensation heat transfer coefficient is also studied. The main objective of this study is to perform the experimental analysis for estimating the condensation heat transfer coefficient in small diameter tube and compare it with the theoretical Nusselt's condensation heat transfer coefficient and also with four other equations given by different researchers.

II. EXPERIMENTAL MODEL

The experimental investigation is conducted on vertically oriented copper tube with a length of 1000mm, 2.0mm inner diameter and 0.5mm wall thickness. The bundle of 18 tubes is surrounded by outer chlorinated polyvinyl chloride tube of diameter 200mm.

The experimental setup can be divided into two loops, one of steam and other of cooling water (Fig. 1). Loop of steam starts from steam generator, where water steam is produced with known temperature T_{vi} and pressure P_{vi} . After that water steam enters into measured bundle of 18 copper tubes, where the condensation process is realized. Volume flow rate of condensate V_c and temperature of condensate T_{co} is measured on outflow from the bundle before collection tank. The interspaced of bundle is counter-flow cooled by loop from source of cold water. Cold water is pass by using water pump from bottom of the shell to out let of the water is at top of the shell. Inlet temperature T_{wi} and volume flow rate V_w of cooling water is monitored on enter to the bundle of tubes by using measuring flow. Outlet temperature T_{wo} of cooling water is measured on outflow from the bundle of tubes. The steam condensate is measured by collecting the condensate from bundle of tube into the measuring flask V_c .

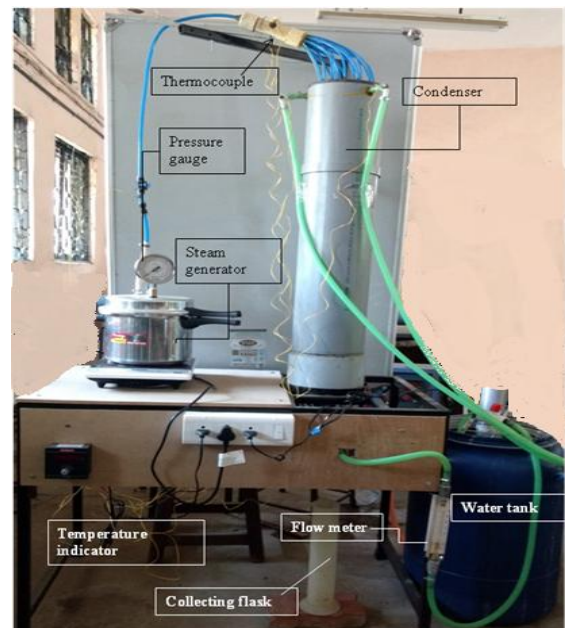


Fig.1. Experimental setup for condensation of steam inside the vertical tube

III. DATA REDUCTION

In the present work, the transferred condensation heat Q_v [W] between water steam and cooling water is calculated from Eq.(1).

$$Q_v = m_v \times (h_{v,in} - h_{v,out}) \quad \dots(1)$$

Logarithmic mean temperature difference is calculated by

$$\Delta T = \frac{(T_{v,in} - T_{w,out}) - (T_{v,out} - T_{w,in})}{\log \left(\frac{T_{v,in} - T_{w,out}}{T_{v,out} - T_{w,in}} \right)} \quad \dots(2)$$

$$U = \frac{Q_v}{\eta T \times \pi \times D_i \times L \times \Delta T} \quad \dots(3)$$

The overall heat transfer coefficient U of cylindrical wall includes inverted sum of Thermal resistance of solid tube wall R_T , Thermal resistances on internal R_v and external surface R_w of tube, see Eq. (4). The external Thermal

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resistance R_w of tube on cooling water site can be estimated by average heat transfer coefficient h_w from Eq. (7). Subsequently the condensation heat transfer coefficient h_v on inner surface of tube can be obtained from Eq. (4).

$$\frac{1}{U} = \frac{1}{\pi \times D_i \times k_v} + \frac{\ln(D_o/D_i)}{2 \times \pi \times k_t} + \frac{1}{\pi \times D_o \times k_w} \quad \dots(4)$$

Calculation of Nusselt's number and heat transfer coefficient for water in shell side by using Grober's equation is

$$Nu_w = 1.86 (Re_w \times Pr_w \times \frac{D_o}{L})^{0.33} \quad \dots(5)$$

Reynold's number calculation for water in shell side is given by

$$Re_w = \frac{V \times D_o}{\nu} \quad \dots(6)$$

Prandtl's number for water at mean film temperature is taken from heat transfer data book.

Heat transfer coefficient for water in shell side is given by

$$h_w = \frac{Nu_w \times k_w}{D_o} \quad \dots(7)$$

By using this Grober's correlation the heat transfer coefficient for the water on shell side is calculated.

The condensation heat transfer coefficient h_v can be predicted by equation obtained theoretical or experimental way. The first chosen equation is theoretically determined by Nusselt. The Nusselt's equation is express as

$$h_v = 0.9428 \left[\frac{g \times \rho_c \times h_{fg} \times k_c^3}{\theta_c \times (T_{sat} - T_s) \times L} \right]^{0.25}$$

The second chosen equation is Rohsenow's equation which consider the sub-cooling the condensate

$$h_{fg}^* = h_{fg} + 0.68 c_{pl} (T_{sat} - T_s)$$

$$h_v = 0.9428 \left[\frac{g \times \rho_c \times h_{fg}^* \times k_c^3}{\theta_c \times (T_{sat} - T_s) \times L} \right]^{0.25}$$

The next equation for calculating the condensation heat transfer coefficient and include wave effect in laminar range is Witham's equation

$$h_v = 1.137 \left[\frac{g \times \rho_c \times h_{fg} \times k_c^3}{\theta_c \times (T_{sat} - T_s) \times L} \right]^{0.25}$$

The Kutatateledza's represents the condensation heat transfer coefficient in the form of Reynold number, which relates the heat transfer coefficient in wavy laminar flow to that in wave-free laminar flow.

$$h_v = 0.8 Re^{0.11} h_{c,smooth}$$

The next chosen equation is Hobler equation, which is valid for many kind of fluids with pressure $0.07 < P_v [\text{MPa}] < 17$.

$$h_v = 0.00252 \times \left(\frac{\rho_v \times h_{fg}^* \cdot \rho_c}{\rho_c - \rho_v \cdot \sigma_c} \right)^{0.33} \times \frac{k_c^{0.8} q_v^{0.7}}{\mu_c^{0.5} \times c_e^{0.167} \times T_v^{0.37}} \times p_v^{\frac{10}{T_v - 273.15}}$$

The last chosen equation for comparison of condensation heat transfer coefficient is Wilson plot equation, which is in exponential form

$$h_v = c \times q_v^{0.8}$$

$$\frac{1}{U} = \frac{q_v^{-0.8}}{c} + \frac{D_i \ln(D_o/D_i)}{2 \times k_t} + \frac{D_i}{D_o \times h_w}$$

IV. RESULTS AND DISCUSSION

The experimental measurement is performed on bundle of 18 vertical copper tubes of length of 1000 mm with inner diameter 2.0 mm and 0.5 mm wall thickness. The ratio of tube length to inner diameter is $L/D = 500$. The inlet temperature of steam $T_{v,in}$ [oC] and mass flow rate m_v [kg/s] of water steam. The pressure of steam is changed in 5

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steps during the experimental measurement. The mass flow rate m_w [kg/s] and inlet temperature $T_{w,in}$ [°C] of cooling water is kept almost on constant values.

4.1 Influence of saturation temperature on condensation heat transfer coefficient

Saturation temperature of steam in range $T_{v,in} = 101$ °C to $T_{v,in} = 113$ °C. The impact of inlet steam temperature on condensation heat transfer coefficient is shown in figure 2. the condensation heat transfer coefficient is increased by 14% as saturation temperature of steam is increase. Hence, the effect Saturation temperature of steam on condensation heat transfer coefficient is significant.

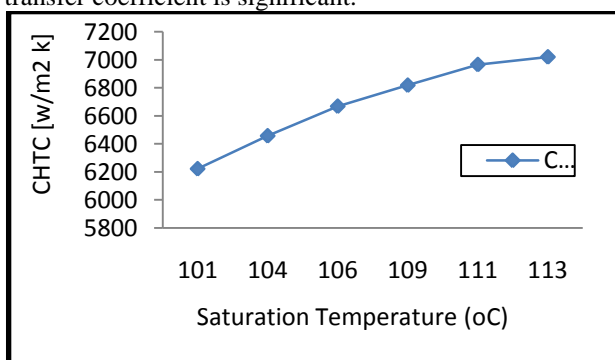


Figure 2: Plot of CHTC Vs saturation temperature of steam.

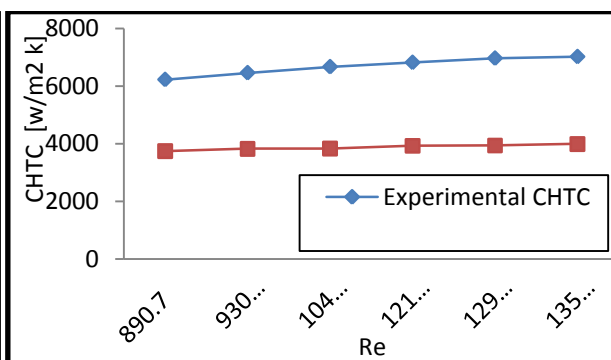


Figure 3: Plot of CHTC Vs Reynold's number, compare for experimental and theoretical CHTC.

4.2 Comparison of experimental condensation heat transfer coefficient with Nusselt equation:

Experimental result is compare with Nusselt's condensation heat transfer coefficient. In figure 3, Nusselt's condensation heat transfer coefficient is $h_v = 3868.5 \pm 125.5$ [w/m² k] showing the very small increasing in condensation heat transfer coefficient. Nusselt assume that velocity of the steam is negligible so that effect of Re number on condensation heat transfer coefficient is very less. Hence, Nusselt's equation shows straight line.

In experimental calculation the value of condensation heat transfer coefficient is $h_v = 6710 \pm 510$ [w/m² k] which increases with increasing the Reynold's number. As the vapour velocity increased, the shear stress on the condensate film became stronger and made the film thinner. Finally the thermal resistance decreased and the condensation heat transfer coefficient increased. It could be seen that, the heat transfer coefficient increased with the increase in steam velocity and Reynold's number is function of velocity.

4.3 Comparison of experimental condensation heat transfer coefficient with various correlation:

The first chosen correlation for prediction of condensation heat transfer coefficient is theoretical Nusselt's equation and predicted $h_v = 3868.5 \pm 125.5$ [w/m² k]. The second tested equation is published by Rohsenow's equation and predicts $h_v = 3951 \pm 133$ [W/m²k] which is 2% more than the Nusselt's predict value because Rohsenow's consider the sub-cooling of condensate. The third tested equation is publish by Witham's equation and predict $h_v = 4765 \pm 160$ [W/m² k] which is 23% higher than the Nusselt's predicted value because Witham,s consider the wave effect and say increasing the condensation heat transfer coefficient is 23% than the Nusselt's prediction.

The fourth tested equation is publish by Hobler's equation and predict $h_v = 5334 \pm 350$ [W/m²k] which is 38% higher than the Nusselt's predicted value because Hobler's study the effect of pressure on the condensation heat transfer coefficient. The fifth tested equation is publish by Kutatededza's, in which condensation heat transfer coefficient $h_v = 6692.5 \pm 370$ [w/m²k] which is 72% higher than the Nusselt's predicted value. Kutatededza's develop a condensation heat transfer coefficient correlation for the steam flowing through the tube in laminar range. In experiment the range of Reynold's number is laminar so that the deviation between the experimental and Kutatededza's correlation condensation heat transfer coefficient is very less.

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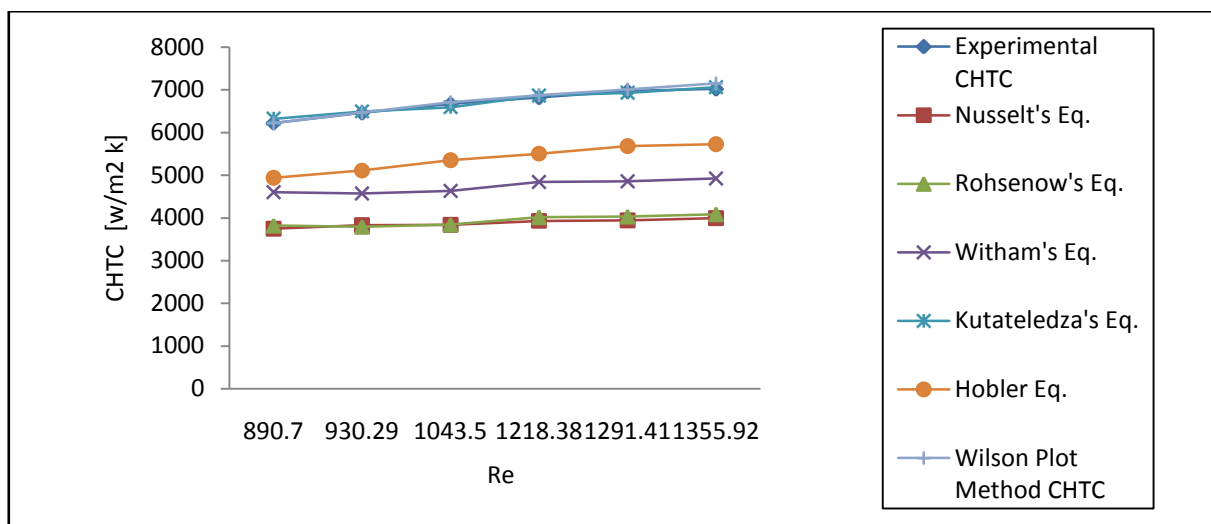


Figure 4: Plot of CHTC Vs Reynold's number comparison of various theoretical equations.

4.4 Influence of mass flow rate of water in shell side on condensation heat transfer coefficient:

The mass flow rate of water on shell side change during the experiment measurement in the range of $m_w=0.022 \text{ Kg/s}$ to $m_w=0.027 \text{ Kg/s}$ at atmospheric pressure shown on figure 5. Experimental reading is taken at steady state condition i.e. heat gain by water in shell side is equal to the heat loss by steam in tube side. The mass flow rate of water in shell side is increases the Reynold's number of water is increases which increases the Nusselt's number and due to this the heat transfer coefficient is increases on shell side for water. Heat transfer is same at steady state condition, as mass flow rate of water is increases which increases the heat transfer coefficient but reduces the temperature difference. In tube side the temperature difference is increases and condensation heat transfer coefficient is decreases at steady state condition.

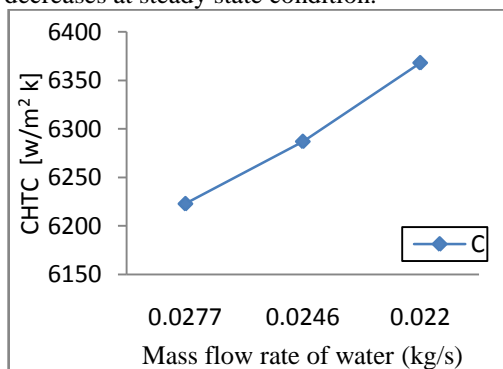


Figure 5: Plot of CHTC Vs mass flow rate of water

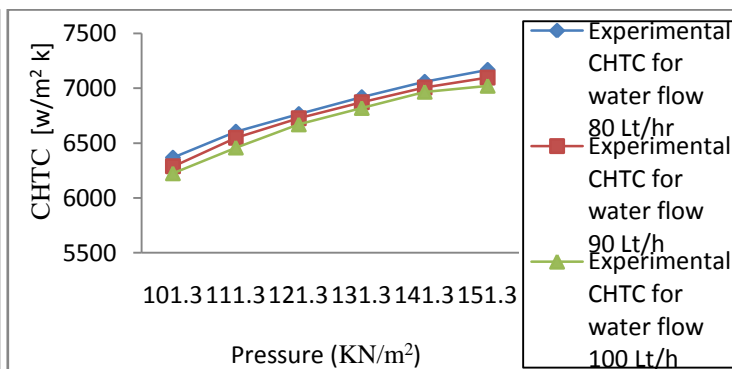


Figure 6: Plot of CHTC Vs pressure of steam and for different mass flow rate of water

The impact of mass flow rate of water in shell side on condensation heat transfer coefficient in tube side is not significant i.e about only 2% increase in condensation heat transfer coefficient in tube side.

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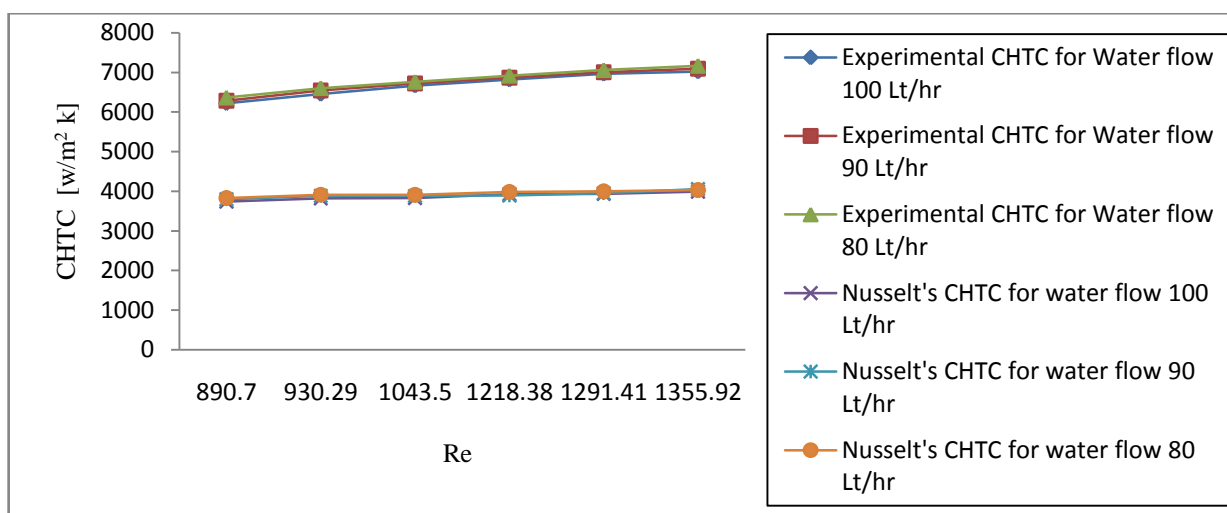


Figure 7: Plot of CHTC Vs Reynold's number and for different mass flow rate of water in shell side and comparing experimental with theoretical Nusselt's correlation

In figure 6 shows, comparison of condensation heat transfer coefficient at different pressure of steam for different mass flow rate of water. In above figure the mass flow rate of water in shell side is decreasing which increases the condensation heat transfer coefficient but impact of mass flow rate of water on condensation heat transfer coefficient is not significant. In figure 8 shows, comparison of condensation heat transfer coefficient with Nusselt's equation at different pressure of steam for different mass flow rate of water on shell side. The impact of mass flow rate of water on the Nusselt's condensation heat transfer coefficient is 0.5% and on experimental condensation heat transfer coefficient is about 2%.

4.5 Development of Correlation

In order to make useful such study by designer and researcher it becomes necessary to develop the correlations for condensation heat transfer coefficient having various parameters investigated. Accordingly, using experimental data correlations for condensation heat transfer coefficient have been developed and discussed as follows.

Correlation for condensation heat transfer coefficient:

Based on the experimental study, the effects of various parameters on condensation heat transfer coefficient have been discussed earlier and are reproduced as follows:

i. Condensation heat transfer coefficient increases monotonically with increasing Reynolds number (Re). Reynold's number introducing the wave effect on condensate.

ii. Nusselt's assume that the velocity of the steam is zero. Therefore, there is need to introduce the wave effect in the theoretical Nusselt's equation of condensation heat transfer coefficient.

The experimental condensation heat transfer coefficient is strongly dependent on Reynold's number and the theoretical condensation heat transfer coefficient. Thus the experimental condensation heat transfer coefficient is express as

$$h_v = f(Re, h_{v, smooth})$$

The data collected from the experimental study for saturation temperature of steam and outlet temperature of water, mass flow rate of steam measure by using the condensate collected to calculate the condensation heat transfer coefficient in tube side. The condensation heat transfer coefficient in tube side is calculated by using thermal resistance method were plotted against theoretical condensation heat transfer coefficient. The regression analysis has been carried out to fit a straight line through the data point, the regression resulted the following:

$$h_v = C_1 h_{v, smooth}^{1.869}$$

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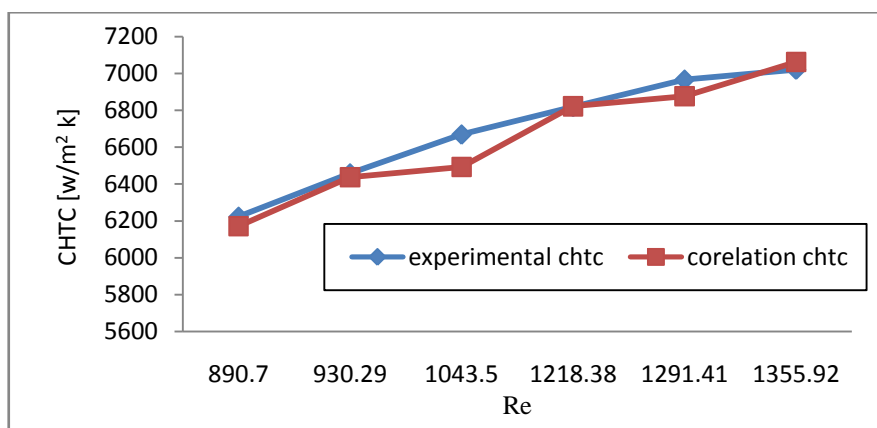


Figure 8: Comparison of experimental and correlation CHTC.

The constant C1 is dependent of the parameters Reynold's number (Re). The Reynold's number (Re) is incorporated to show the effect of mass flow rate of the steam in tube on experimental condensation heat transfer coefficient. The values of $h_v/h_{v,s1.869}$ are plotted against Reynold's number (Re). The best fit regression yields the following correlation for Nusselt number:

$$h_v = 0.001034 \times Re^{0.033} \times h_{v,smooth}^{1.869}$$

The calculated values of Condensation heat transfer coefficient from developed correlation have been compared with the experimental values as shown in Figure 8. It has been found that these values are reasonably good as maximum deviation found within $\pm 3\%$.

V. CONCLUSION

The experimental analysis is performed on vertical copper tube in length of 1000 mm with 2.0 mm inner diameter and 0.5 mm wall thickness. The impact of variable mass flow rate, inlet temperature of water steam and inlet pressure of the steam on condensation heat transfer coefficient is evaluated on parametric experimental measurement. The obtained results are compared with five chosen equations which predict condensation heat transfer coefficient. The main results of this experimental study can be summarized to following points.

- From the above experimental analysis, the experimental condensation heat transfer coefficient is 72% greater than the Nusselt's condensation heat transfer coefficient equation. Hence, Nusselt's equation is not giving the correct trend for higher L/Di ratio. As the L/Di ratio is more the condenser is compact and which is economically more viable and increases the efficiency of condenser. The heat transfer coefficients increased with the decrease in tube diameter. Nusselt's Equation was not applicable in the case of small diameter tube condensation, and should be corrected.
- Experimental, Wilson plot method and Kutateledza's equation show 97.8% correlation quality.
- The influence of mass flow rate of water in shell side is about 2% on experimental studies and 0.5% on Nusselt's study. The impact of mass flow rate of water in shell side is not significant.
- The condensation heat transfer coefficient increased with the increase in vapour pressure. The heat transfer coefficients at high pressure were obviously larger than 16.2% those at atmospheric pressure. The temperature of the condensate film increases with increasing the vapour pressure. Under the higher vapour pressure, the condensate film became thinner under the effect of gravity, and then the heat transfer was promoted.

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- As the vapour velocity increased, the shear stress on the condensate film became stronger and made the film thinner. Moreover, the disturbance effect also became stronger. Finally the thermal resistance decreased and the heat transfer coefficient increased by 16.2%.
- Based on the experimental values, correlations for condensation heat transfer coefficient have been developed and found to fit the experimental data within $\pm 3\%$ deviation for condensation heat transfer coefficient.

Nomenclature			
CHTC	:Condensation heat transfer coefficient	k	:thermal conductivity [W /m K]
c	:specific thermal capacity [J/ kg K]	μ	:dynamic viscosity [Pa s]
D	:diameter of tube [m]	ν	:kinematic viscosity [m^2 /s]
g	:gravity acceleration [m/s^2]	ρ	:bulk density [kg /m^3]
h	:specific enthalpy [J /kg]	σ	:surface tension [N /m]
U	:overall heat transfer coefficient [W/m K]	Subscripts	
hfg	:latent heat of phase change [J /kg]	c	:condensate
L	:total length of tube [m]	e	:external
m	:mass flow rate [kg /s]	i	:internal
n	:total count of tubes [pcs]	v	:vapour
p	:static pressure [Pa]	w	:water
q	:specific heat flux [W / m^2]	i	:inlet
Q	:total heat flux [W]	o	:outlet
T	:temperature in Kelvin scale [$^{\circ}\text{K}$]	Dimensionless numbers	
ΔT	:logarithmic mean temperature difference [K]	Nu	:Nusselt number
V	:volume flow rate [m^3 / s]	Pr	:Prandtl number
h	:heat transfer coefficient [W / m^2 K]	Re	:Reynolds number

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