Experimental Investigation of Heat Transfer Coefficient in Vertical Tube Rising Film Evaporator

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ABSTRACT

This paper reports the experimental evaluation of the heat transfer coefficient (U) in a VRF (Vertical Tube Rising Film Evaporator). The aim is to describe the variation of U against different process parameters. Experiments were carried out for laminar flow conditions. The experimental unit is a floor standing tubular framework for a rising film evaporation system. There are many parameters affecting heat transfer coefficient in evaporators, but it was not possible to consider all of them, so parameters including, Reynolds Number (N_{Re}), Temperature Difference (ΔT), Feed Temperature (T_f) and Re-circulation Ratio (R) were investigated while other factors were kept constant. The experimental results obtained showed that heat transfer coefficient increased with the increase in Reynolds number, feed temperature and temperature difference. The increase in re-circulation ratio also increased the heat transfer coefficient but up to the value of 0.85 and after this the heat transfer coefficient started decreasing slowly and then remained almost constant. An experimental correlation has been developed to relate the Nusselt number and the parameters investigated during the research work.

Key Words: **Evaporation, Vertical Tube Evaporator, Rising Film Evaporator, Heat Transfer Coefficient.**

1. INTRODUCTION

Evaporation is one of the most energy intensive processes used in the dairy, food and chemical industries. It is a unit operation that is used extensively in processing foods, chemicals, pharmaceuticals, fruit juices, sugar industries, desalination, dairy products, paper and pulp, and both malt and grain beverages. Evaporation process starts with a liquid product and ends up with a more concentrated product from the process. In some special cases, the evaporated, volatile component is the main product [1].

Evaporators are used to concentrate a solution through evaporation. During the evaporators operation two main points are always considered, suitability of the equipment for its best duty and efficient and economical use of the equipment. Therefore, many types of evaporators and many variations in processing techniques have been developed to take into account different product characteristics and operating parameters. The different types of evaporators are, forced circulation evaporators, natural circulation evaporators, rising film tubular evaporators, falling film tubular evaporators, Rising/falling

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film tubular evaporators, plate evaporators and multiple effect evaporators. Multiple effect evaporators are used to achieve heat economy by recovering heat from vapors, which can be further utilized in other effects operating at lower boiling temperature [1-3].

Since the main objective of all types of evaporators operations is to improve the efficiency and effectiveness of the process through efficient utilization of heat and energy. Therefore reliability of evaporation processes like thermal desalination, processing of sugar juice etc, strongly depends on the calculation of heat transfer coefficient. Heat transfer coefficient is also mainly estimated during the designing of an evaporator.

2. LITERATURE REVIEW

Heat transfer coefficient is one of the most important factors in flow boiling and a lot of research has been carried out on accurately investigating heat transfer coefficient over the last few decades [2-3]. Knowledge of these coefficients and their parametric behavior is important because this can reduce the cost and keep away from drastic results due to under design or over design of evaporators, boilers and other two phase process equipments [2-4].

Heat transfer coefficient depends on different factors of process conditions and liquid properties. Among liquid properties include, dynamic viscosity of liquid, liquid density, surface tension, etc. and important process conditions are, heat flux or temperature difference, boiling temperature or pressure, specific flow rate, nature and geometry of the heating surface etc. The boiling heat transfer coefficient also depends on the type and configuration of evaporator for example, rising or falling film evaporators, etc. [3-5].

Liquids with high viscosities give low heat transfer coefficient. Therefore different methods like increasing boiling temperature of the liquid or decreasing concentration of the feed liquid are used to improve the heat transfer coefficient. Decreasing concentration of liquid or increasing boiling temperature of the liquid actually decreases viscosity of the liquid and so heat transfer coefficient increases [3,6-7].

Feed temperature is also one of the important technological parameters affecting heat transfer coefficient in a process. With increase in feed temperature viscosity of the liquid decreases and heat transfer coefficient increases. Similarly by entering pre- heated feed in an evaporator, less amount of steam is consumed to bring the entering stream at boiling temperature and more is used for evaporation process, this also helps to increase the heat transfer coefficient. Pre heating of feed also helps in optimizing the size of evaporator tubes [6-8]. Boiling heat transfer coefficient is also affected by mass flow rate of the feed entering the evaporator. Increase in mass flow rate increases turbulence in the stream and causes the heat transfer coefficient to increase [3,7].

Developing a general flow boiling correlation can satisfy the requirements for designing of evaporators and also it can help in studying the effects of different parameters leading to a better understanding of flow boiling phenomena [2-4,9]. Brief study of some of the heat transfer correlations developed recently in the field of evaporation processes by different researchers is shown below:

Sadaf, et al. [10], studied heat transfer to boiling liquids under natural convective flow in a single tube vertical thermosiphon reboiler. They used distilled water, various concentrations of propan-2-ol in water and their azeotrope to investigate the effect of heat flux and submergence on circulation rates and developed the following correlations:

For Water

$$Re=5.78(Pe_B)^{1.2312}(K_{sub})^{-0.1324}(S)^{0.2341}(X_{tt})^{0.7432} \quad (1)$$

For Propan-2-ol water azeotrope

$$Re=9.5194(Pe_B)^{1.0622}(K_{sub})^{0.0204}(S)^{0.0036}(X_{tt})^{0.8945} \quad (2)$$

For Propan-2-ol water mixture

$$Re=9.9709(Pe_B)^{0.8051} (K_{sub})^{-0.0089} (S)^{0.4031} (X_{tt})^{1.0314} \quad (3)$$

Where Re is Reynolds number, Pe is Peclet number, K_{sub} is sub-cooling number and X_{tt} is Lockhart-Martinelli parameter. The circulation rate in thermosiphon reboilers depends on heat flux, liquid submergence (S), inlet liquid sub-cooling and the vapor fraction for pure liquids, binary mixtures and the azeotropes [10].

Adib, et al. [3], described the laws of variation of boiling heat transfer coefficient (h) against the main process parameters like, the dry matter concentration XDM (or Brix for sugar solution), the evaporating temperature (θ_L) or pressure (P) taking into account the BPE (Boiling Point Elevation), the heat flux (Φ) or the temperature difference between the heated surface and boiling liquid temperature ($\Delta\theta$) and the specific mass flow rate per unit of perimeter length (Γ). They used a pilot scale falling film evaporator using pure water and sugar solutions at different concentrations as a model of Newtonian liquid food. They concluded that the boiling heat transfer coefficient decreases sharply with increase in the concentration of a solution because by increasing the concentration of a solution, the viscosity increases and so the heat transfer coefficient decreases, in both non-nucleate and nucleate boiling regimes. Similarly, the boiling heat transfer coefficient increases with an increase in boiling liquid temperature, because the viscosity of the solution decreases with the increase in boiling temperature. The following two correlations were developed for which the best results were obtained for linear model.

Logarithmic Model (A)

$$h = 30.37\ \Phi^{0.19}\ X_{DM}^{-0.29}\ \Gamma^{0.17}\ \theta_L^{1.14} \quad (R^2 = 0.76) \quad (4)$$

Linear Model (B)

$$h = 218 + 24\ \Phi - 37\ XDM + 1090\ \Gamma + 32\ \theta_L \quad (R^2 = 0.92) \quad (5)$$

In vertical tube evaporators two boiling regimes are present, non nucleate and nucleate. Non nucleate regime takes place at low temperature differences, while nucleate regime takes place when the heat flux or temperature difference increases. In nucleate regime, increasing the heat flux or temperature difference increases the heat transfer coefficient [3,5,7].

Prost, et. al. [9], investigated the heat transfer parameters in a single effect falling film evaporator under different operating conditions and then extrapolated them for multiple effect evaporators. The experimental values obtained were used to develop a correlation for heat transfer coefficient analysis. Correlation developed was the function of Reynolds and Prandtl numbers and also a correlation was developed in terms of Reynolds number only for their experimental setup.

$$h^+ = 1.6636 Re_L^{-0.2648}\ Pr_L^{0.1592} \quad (6)$$

$$Pr_L = 1878\ Re_L^{-0.8204} \quad (7)$$

$$h^+ = 5.5236\ Re_L^{-0.3854} \quad (8)$$

Pacheco, et. al. [6], studied the evaporation of sugar juice in a single effect climbing/falling film plate evaporator and observed the variation in overall heat transfer coefficient related to juice concentration. The results obtained through experiments showed that a 15-40% increase in concentration results in a decrease in the overall heat transfer coefficient to about 60%. Such variation promotes an increase in the heat-transfer area for a specified evaporation duty in the higher concentration effects. The authors also concluded that, the climbing/falling, flat plate evaporator requires a preliminary test or a simulation before sizing because there is no correlation yet available for boiling.

Uche, et. al. [11], compared different heat transfer coefficient correlations for thermal desalination units. They concluded that the performance of the thermal desalination units strongly depends on the calculation of the heat transfer coefficients used to model the heat transfer phenomena in the desalting process. The authors used different correlations for calculating heat transfer coefficient in three types of evaporators, HFF (Horizontal Falling Film) evaporators, VFF (Vertical Falling Film) evaporators and VRF evaporator. Comparison of about six or seven correlations were made for the water and for vapor side of the evaporator/condenser included in the thermal desalination unit. After examining the results from different correlations, the authors selected some correlations which were considered the best alternative to include in the models describing the performance of MSF (Multi-Stage Flushing), VC (Vapor Compression) and TVC (Thermal Vapor Compression) plants.

Al-Hawaj, [12] studied different types of evaporators which include climbing film, falling film, rotating surface, wiped film, deflecting liquid jet and flash evaporators and after the experiments he concluded that the plate coil type evaporator is better than other types of evaporator for future MED (Multi-Effect Distillation) plants because of its acceptable size and high production capacity. The author concluded that plate-coil evaporator can produce 65% more distillate per unit volume than conventional horizontal-tube evaporators, because the heat transfer coefficient is high due to turbulence, while an increase in the vapor pressure drop amounts to 50% more than in conventional horizontal-tube evaporators.

Cvangros, et. al., [13], investigated the temperature of a liquid entering the evaporating cylinder of a molecular evaporator and said that it is one of the important technological parameters that determine an evaporator's operation. The authors observed the effect of feed temperature on the film surface temperature on the evaporating cylinder for various liquid loads and for various differences between evaporation surface temperatures and feed temperatures. The length of the evaporating cylinder measured from the top, increases with decrease in feed temperature and with rising the liquid load and evaporator cylinder temperature. Along this length, which may reach up to several hundred millimeters, evaporation occurs at a reduced rate which corresponds to the real temperature on the film surface. Therefore, it is useful to gently preheat the feed before it enters the evaporator in appropriate heat exchangers to a temperature close to the asymptotic temperature.

The study and the literature review showed that main emphasis is given on improving the heat transfer coefficient and developing correlations for different process conditions in evaporation processes. VRF was selected for this research project to investigate the effect of different parameters on U and to develop a correlation for laminar flow conditions.

VRF Evaporator operates on a "thermo-siphon" principle. Feed enters the vertical tubes at the bottom of the heat exchanger and steam condensing on the outside of the vertical tubes causes the brine feed to boil. A film of feed establishes during the process on the tube wall and causes the vapor to form as it moves in the upward direction. The vapor liquid mixture then enters in to the separator where the separation of both phases vapor and liquid takes place. VRF evaporators are important for handling the viscous fluids and the fluids that tend to foam.

The paper deals with the experimental investigation of heat transfer coefficient in a VRF Evaporator. The effect of different variables like NR_e, ΔT, T_f and re-circulation ratio (R) on Heat transfer coefficient (U) are studied and a correlation has been developed between Nusselt Number (Nu) and the factors affecting the heat transfer coefficient in VRF.

3. EXPERIMENTAL SETUP

The main purpose of this experimental work was to measure U as a function of the system operating parameters in a VRF. A laboratory scale evaporation unit having model No. UOP 20 X STM was used for the experimental work. The full experimental setup is shown in Fig. 1.

The experimental unit is a floor standing tubular framework for a rising film evaporation system. The setup is provided with a vapor glass cyclone liquid separator. This separator is used to separate the vapor liquid mixture from the evaporated steam. The evaporator column contains a stainless steel evaporation tube of 1m length, within an insulated heated jacket for the hot water or steam. The setup consists of two peristaltic pumps, one is used as a feed pump and the second is as a recirculation pump. Thermocouples are provided at twelve different points to measure the temperatures of the product and heating fluid.

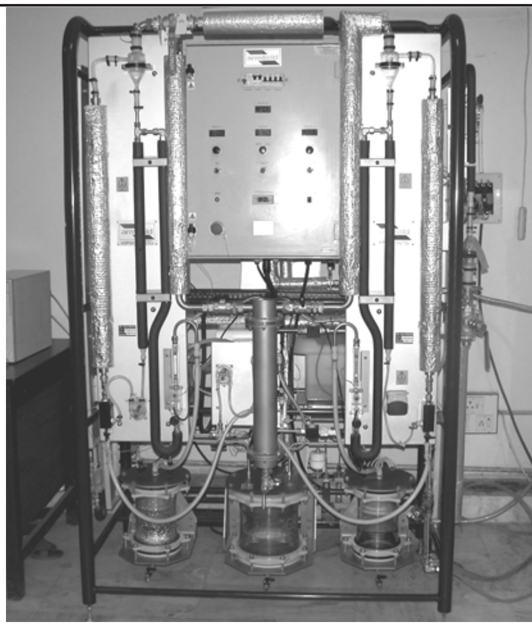

FIG. 1. EXPERIMENTAL UNIT

The unit also comprises of a vacuum pump, condenser, condensate vessel, temperature controlled feed pre-heater of 2KW and collection tanks. For controlling the evaporation process manual control console and an integral USB interface for computer data logging and control with full set of instrumentation is provided. A laboratory scale boiler is provided with the evaporation system for steam generation named as UOP 10 Laboratory Steam Generator. The generator comprises a main feed header tank with level control, a heavy duty and high pressure feed pump. The boiler can generate steam up to 3 bar. Fig. 2 shows the schematic diagram of the rising film operation.

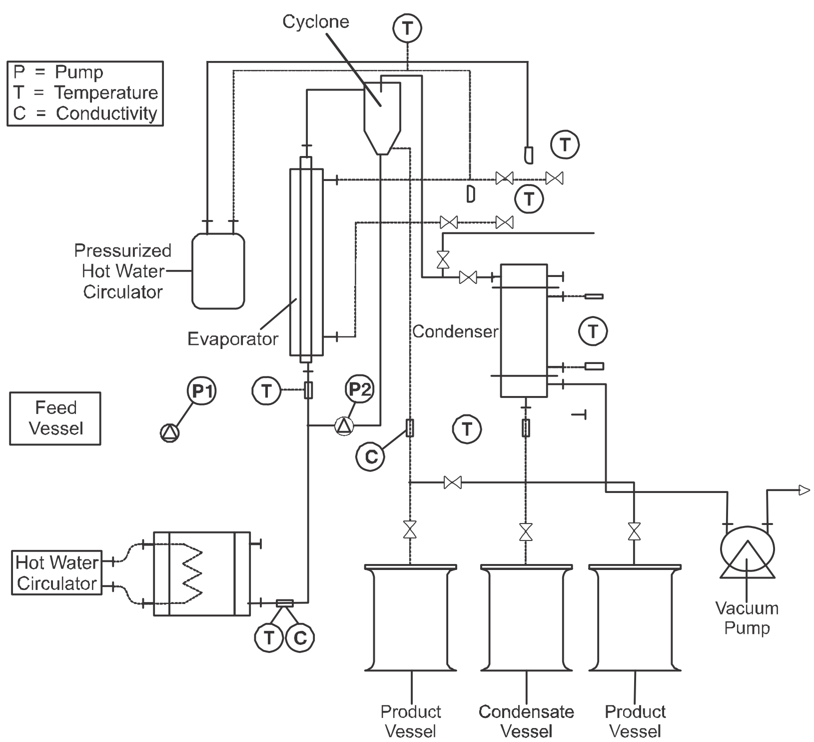

FIG. 2. SCHEMATIC DIAGRAM OF SINGLE EFFECT VERTICAL TUBE RISING FILM EVAPORATOR

4. OPERATING PROCEDURE

Before starting the experimental work, the setup was hydraulically tested for leaks. It was flushed with distilled water for thorough cleaning. The connections to power supply thermocouple and various measuring instruments were made and caliberated for ensuring satisfactory performance. Distilled water was used for the generation of experimental data. All the data has been generated at atmospheric pressure prevailing in Peshawar. The liquid entered the evaporator through inner tube at its bottom end, got heated and rose upwards with subsequent boiling. Steam at 0.4 bar was allowed from laboratory steam generator in the shell side of the evaporator. As the liquid moved in upward direction vapors were formed due to boiling. The vapor liquid mixture came out from the top of the evaporator and entered the cyclone separator. In the separator vapor liquid separation took place and vapors then moved towards the condenser for total condensation. Cold water was supplied continuously to the condenser as a cooling medium. The concentrate or thick liquor was collected in the tank. The temperature of concentrate was measured from the thermocouple. The condensed liquid was collected in the condensate tank through a vertical tube fitted with a liquid level indicator. A thermocouple is also available in this tube to measure the condensate temperature. Table 1 shows the operating variables for Vertical Tube Rising Film Evaporator.

TABLE 1. OPERATING VARIABLE FOR VERTICAL TUBE RISING FILM EVAPORATOR

Operating variables	Range
Feed Inlet Temperature (°C)	20-70
Boiling Water Outlet Temperature (°C)	60-88
Cooling Water Inlet Temperature (°C)	18 - 20
Mass Flow Rate of Water (kg/sec)	1.33×10^{-3}-2.83×10^{-3}
Mass Flow Rate of Cooling Water (kg/sec)	0.00831-0.0332
Steam Pressure (bars)	0.1-0.4
Steam Temperature (°C)	100-110
Re-Circulation Ratio	0.2-1.0

5. RESULTS AND DISCUSSION

The heat transfer coefficient depends upon the fluid properties such as surface tension, flow viscosity, temperature difference, geometry of the system and surface roughness in which heat transfer occurs. It also depends on the operating conditions such as density, thermal conductivity and vicosity. It was not possible to consider all the factors but some main factors such as Reynolds number, feed temperature, temperature difference and re-circulation ratio were taken into account. The re-circulation ratio is the ratio of speed of re-circulating pump to the speed of feed pump. The results were calculated for the laminar flow conditions having Reynolds number ranging from 590-1265.

The following equations were used in calculating the amount of heat gained by water during its flow inside the evaporator [9-10,13].

Balance on Water

$$Q = m^0 Cp (T_{out}-T_{in}) + m^0_v \lambda \tag{9}$$

Heat Removed from the Condenser

$$Q = m_c^0 Cp (T_{out,c}-T_{in,c}) \tag{10}$$

The steam was available at 0.4 bar and 110°C.

The data was accepted only when the differences in the "Q" evaluated is less than 10% of the absolute value.

The Overall heat transfer coefficient (U) in the evaporator was calculated from the equation:

$$Q = UA \Delta T_{LMTD} \tag{11}$$

Viscosity and Specific heat values were taken at film temperature (T_{film}).

$$T_{film} = (T_s+T_m)/2 \tag{12}$$

$$T_m = (T_{in}+T_{out})/2 \tag{13}$$

A = Surface area = $0.256 m^2$.

5.1 Effect of Reynolds Number on Heat Transfer Coefficient

Fig. 3 shows the relationships between the U and the Reynolds number for laminar flow conditions in VRF. The Reynolds number ranged from 590-1265, and it was observed that U increases with increase in Reynolds number. With the increase in Reynolds number the turbulence increases which in turns increases the U. In this experiment, the evaporation of water took place inside the tube of rising film evaporator and the heat was transferred through the rising film by conduction. The Reynolds number was increased by increasing the feed rate while keeping the re-circulation ratio constant.

5.2 Effect of Re-Circulation Ratio on Heat Transfer Coefficient

This particular service unit is provided with a re-circulating pump whose effect on U and on the performance of the evaporator can not be neglected. The re-circulating pump is used to circulate the thick liquor again in the evaporator by combining it with entering feed stream at the bottom inlet. This heated thick liquor, as a result increases the temperature of the entering feed. The effect of re-circulation on U is shown in Fig. 4. The readings were carried out at different values of re-circulation ratio while keeping the Reynolds number constant. The speed of re-circulating pump was increased continuously while the speed of feed pump was kept constant. The results obtained depict that by increasing the speed of re-circulation pump the U increases first because by re-circulation the inlet temperature of the feed increases and so less amount of steam is consumed to bring the entering stream at boiling temperature. The graph also shows that the U increases first but after some time it starts decreasing slightly and then remains almost constant. The readings for this experiment were taken for re-circulation ratio ranging from 0.2-1.0, and it is seen that after R=0.85 the U started decreasing.

5.3 Effect of Temperature Difference on Heat Transfer Coefficient

Fig. 5 shows the effect of ΔT on U. ΔT is the difference between the surface temperature and boiling temperature of the feed. The U increases with the increase in ΔT, because as the temperature difference increases the driving force for heat transfer increases resulting in high U.

5.4 Effect of Feed Temperature on Heat Transfer Coefficient

The temperature of the feed entering the evaporator is an important operational parameter. Fig. 6, shows that with increase in feed temperature U also increases. When feed enters the evaporator a part of steam is used to bring its

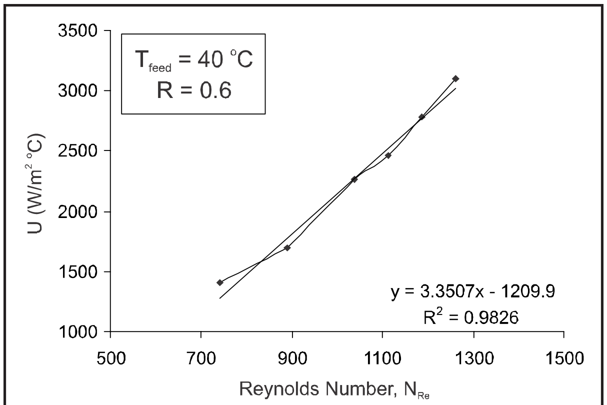

FIG. 3. EFFECT OF REYNOLDS NUMBER ON HEAT TRANSFER COEFFICIENT

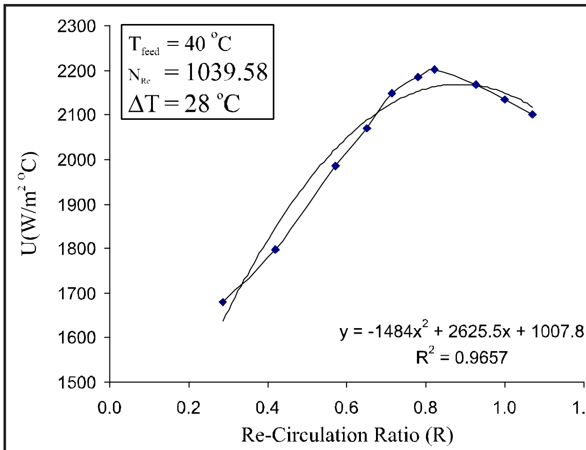

FIG. 4. EFFECT OF RE-CIRCULATION RATIO ON HEAT TRANSFER COEFFICIENT

temperature to boiling temperature and a part of it is used to accomplish evaporation. When feed will enter at higher temperature less amount of heat will be required by steam to bring it to boiling temperature and larger part of steam will be used to accomplish evaporation. This increases the U and also the mass of vapors produce, so the efficiency of the evaporator will increase. When feed enters at boiling temperature then flash evaporation takes place. Also by increasing the feed temperature the viscosity of the feed (liquor) decreases and so it increases U.

5.5 Correlation of Experimental Data for VRF

A correlation has been developed from experimental data for laminar flow in Rising Film Evaporator. The correlation

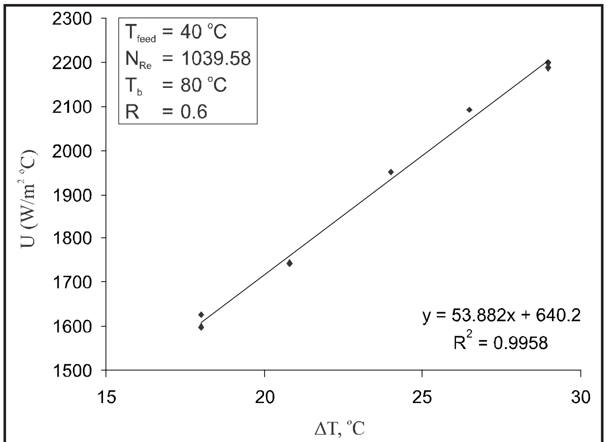

FIG. 5. EFFECT OF TEMPERATURE DIFFERENCE ON HEAT TRANSFER COEFFICIENT

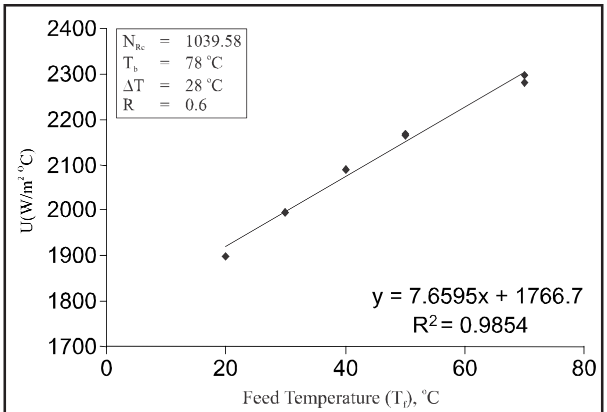

FIG. 6. EFFECT OF FEED TEMPERATURE ON HEAT TRANSFER COEFFICIENT

is developed for the dimensionless groups Nusselt Number (Nu) as a function of process parameters. The values of the dimensionless group Nu were fitted to an equation of the type.

$$Nu = C(NR_e)^a (\Delta T)^b (T_f)^c (R)^d \quad (14)$$

Through regression analysis the following two correlations are then developed, valid for operating ranges given in Table 1.

Logarithmic Model

$$Nu = 0.9054 (NR_e)^{0.386} (\Delta T)^{0.165} (T_f)^{0.038} (R)^{0.051} \quad (R^2=0.9772) \quad (15)$$

Linear Model

$$Nu = 0.00915\, NR_e + 0.1471\, \Delta T + 0.0209\, T_f + 1.615\, R + 10.67 \quad (R^2=0.954) \quad (16)$$

The best results were obtained from the logarithmic model (Equation 15). The comparison between the calculated and measured values of Nu is shown in Fig. 7 for logarithmic model. The values of Nu obtained from the experimental results and through calculations are named "Measured values" and are taken on the y-axis. While the values predicted from the correlation (Equation 15) are termed as "Calculated values from Correlation", and are taken on the x-axis. It is seen that majority of the values lie within maximum error of ±20%. The comparison also shows that the correlation gives best results for the parameters whose ranges are given as:

Reynolds Number = 500 ~ 1188

Recirculation Ratio, R= 0.2 ~ 0.8

Feed Temperature, T_f = 20°C ~ 50°C

Temperature Difference, ΔT = 20°C ~ 28°C

6. CONCLUSION

The thermal performance of rising film evaporator was examined by determining heat transfer coefficient in the evaporator with process variables like flow rates and temperature of the feed. There are other factors on which the heat transfer coefficient and the performance of the evaporators depend. These factors include surface tension, fluid viscosity, temperature difference and geometry of the system, but it was difficult to consider all of them. Therefore, this study concentrated on parameters that include Reynolds Number, Re-circulation Ratio, Temperature Difference and Feed Temperature for laminar flow conditions. It was found from the results and data that Reynolds Number, Temperature Difference and Feed Temperature are directly proportional to heat transfer coefficient. Re-circulation ratio also has a positive effect on U and it was seen that by increasing R the U also increases, but up to the value of R=0.8 ~ 0.85. After this the U start decreasing. The re-circulation pump available in the experimental unit is very advantageous and it can be used to increase the feed inlet temperature without any pre-heating. This can reduce the pre-heating cost. Also by re-circulating the purity of the final product can be increased. Two correlations were developed, relating Nusselt Number and operating parameters for laminar flow conditions. However the logarithmic model gave the best results for Reynolds Number ranging from 500-1188.

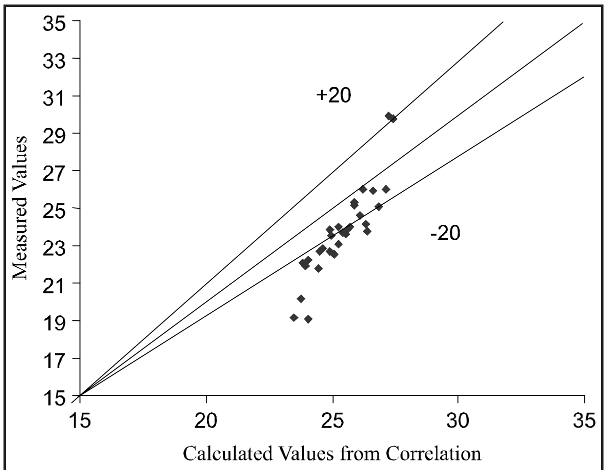

FIG. 7. COMPARISON BETWEEN MEASURED VALUES AND CALCULATED VALUES OF NUSSELT NUMBER USING LOGARITHMIC MODEL

7. NOMENCLATURE

Q	Heat Transfer Rate (Watt)
A	Heat Transfer Area (m^2)
S	Cross-Sectional Area (m^2)
ΔT	Temperature Difference (k)
Cp	Specific Heat of Liquid (J/kg.K)
D	Diameter of the Evaporator Tube (m)
T_{in}	Inlet Temperature (K)
T_{out}	Outlet Temperature (K)
$T_{in,c}$	Cooling Water Inlet Temperature (K)
$T_{out,c}$	Cooling Water Outlet Temperature (K)
ΔT_{LMTD}	Log Mean Temperature Difference (K)
T_s	Surface Temperature (K)
T_m	Mean Temperature (K)
m^o_v	Mass Flow Rate of Condensate (kg/sec)
m_c^o	mass flow rate of cooling water (kg/sec)
T_{film}	Film Temperature (^oC)
K	Thermal Conductivity (W/m.K)
HTC	Heat Transfer Coefficient "U" ($W/m^2.^oC$)

Greek Symbols

ρ	Density (kg/m^3)
μ	Viscosity ($N.s/m^2$)
λ	Heat of Vaporization (KJ/kg)

Dimensionless Groups

NR_e	Reynolds Number
Nu	Nusselt Number
R	Re-Circulation Ratio

Subscripts

in	Inlet
out	Outlet
LMTD	Log Mean Temperature Difference
S	Surface
m	Mean
v	Δapor
f	Film

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