Thermal Modelling and Productivity Analysis of a Double Slope Wick-Type Solar Still

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Abstract

In this paper Thermal Modeling and productivity analysis of the flow rate of saline water in a double slope wick-type solar still is presented The work analyses the influence of water flow rate on the tilted-wick surfaces of a double slope wick-type solar still on the internal heat and mass transfer. The internal heat and mass transfer coefficients were determined using the experimental data and compared with the results obtained by using Dunkle's relation. Experiments have been carried out with the proposed still in Coimbatore, TamilNadu, India and the results have shown a decrease in the internal heat and mass transfer coefficients for increased saline water flow rate on the tilted-wick surfaces due to large thermal capacity. The daily productivity was found to be 5.39 kg/m^{2}day and 4.175kg/m^{2}day for minimum and maximum flow rates respectively.

Keywords: Thermal Modelling, Wick-type solar still, Water flow rate, Heat and Mass transfer, Radiative Heat Transfer Coefficient Productivity, Intensity of Solar Radiation Ambient Air Temperature, Distillate yield, Dunkle's Model.

1. Introduction

One of the oldest and successful techniques for the production of fresh water from brackish/saline water is solar distillation. The design, performance and limitations of the technology have been documented by various researchers in the world. Two modes of heat transfer are taking place in solar stills viz., internal and external heat transfer mode. The basic difference between the two modes is the mass transfer which occurs inside the still along with r adiative and convective heat transfer from evaporating to condensing surface, whereas only convective and radiative heat transfer occurs outside the still

.Many of the researchers working on solar stills have used the expressions for internal heat transfer coefficients developed by (Dunkle 1961) under simulated conditions. It has been confirmed that, Dunkle's expression is not valid for large inclinations of condensing surface and distance between condensing and evaporating surfaces. Kumar and Tiwari (2009) have determined the values of heat transfer coefficients hcw and hew by using the model developed, based on regression analysis of the experimental data obtained from the still. The model proposed by Kumar and Tiwari (2009) has been used by Tiwari (2006) and Tiwari (2005) for the determination of internal heat transfer coefficients. It has been inferred that the model has given more realistic values of convective and evaporative heat transfer coefficients of the solar still. Further Tripathi and Tiwari (2005) have analyzed the effect of water depth on internal heat transfer of active solar still during winter days. Transient theory for a double basin solar still has been proposed by Tiwari, Sumegha and Yadav (1991) and the effect of water depth on the productivity has been discussed. Further Sanjay Kumar and Tiwari (1996) have developed a thermal model for the determination of convective mass transfer for different Grashof number range in solar distillation process (both active and passive). The proposed model has shown an accuracy of 12% for the evaluation of convective heat transfer coefficient. Suneja and Tiwari (1999)have carried out a transient analysis of a double basin solar still and inferred that the increase in water depth in the lower basin for given water mass in the upper basin has produced more distillate yield. . Shukla and Sorayan(2005) have developed expressions for water and glass temperatures, yield and efficiency for single and double slope multi-wick distillation systems. Also, internal heat transfer coefficients have been modified based on inner glass cover temperature instead of outer glass cover temperature. It has been proved that the modified internal heat transfer coefficients based on inner glass cover temperature have shown a fair agreement between theoretical and experimental results. The annual as well as seasonal performance analysis for different water depths in a single slope passive solar still has been carried out by Tiwari and Tiwari [2006 and 2009] from June 2004 to May 2005 at IIT, Delhi. It has been reported that for least water depth, the distillate yield is more and for higher water depths, the yield becomes almost constant. Phadatare and Verma (2007) have designed a single basin single slope plastic solar still using the sheet of plexiglass and studied the effect of water depth on internal heat and mass transfer in the still. It has been concluded that the increase in water depth decreases the productivity. Kumar and Tiwari (2009) have estimated the internal heat transfer coefficients of a deep basin hybrid (PV/T) active solar still using the thermal models developed by various researchers and inferred that Kumar and Tiwari model has shown better validation of the results than the other models.

Dwivedi and Tiwari (2009) have made an attempt to evaluate the internal heat transfer coefficient of single and double slope passive solar stills in summer and winter climatic conditions in New Delhi for three different water depths by using various thermal models. It has been concluded that Dunkle's model has shown better agreement between theoretical and experimental results in both seasons. Rajamanickam and Ragupathy (2012) have studied the effect of water depth (0.01m, 0.025m, 0.05m and 0.075m) on internal heat and mass transfer in a single and double slope solar still. In double slope solar still, maximum distillate yield of 3.07 L/m^{2}day has been obtained for the water depth of 0.01m in the basin. Al-Sulttani, Ahsan, Rahman, Daud, and Idrus (2017) have used rubber scrappers in double slope solar still to transmit large amount of solar radiation with small slope of the condensing cover. Results of the experiment have shown enhanced productivity and total heat transfer of the still. Sarray, Hidouri, Mchirgui and Brahim (2017) have determined water vapor partial pressure, humid air temperature, humidity ratio, molecular diffusivity and thermal diffusivity in a solar still and found that productivity increased with increase of water vapor partial pressure and humid air temperature. Jani and Modi (2018) have made a review regarding the enhancement of heat transfer rate in different types of solar still by various method and reported. Mohamed, Hegazi, Sultan, and El-Said (2019) have used basalt stones (1cm, 1.5cm, and 2cm) as porous absorbers in the basin of solar still and analyzed. It has been found that the exergy efficiency increased by 65%, 104.4% and 123% compared to conventional solar still for 1cm, 1.5cm, and 2cm basalt stones.

In the present study, an attempt has been made to find the optimum flow rate of saline water over the tilted-wick surface to get maximum distillate yield. The internal heat and mass transfer coefficients is found using the experimental data and compared with the coefficients determined by using Dunkle's expression. The results of one of the typical summer days corresponding to each flow rate have been considered for discussion

2. **Experimental Methods**

The schematic sectional view and photographs of the proposed still have been shown in the Figs. 1 and 2. In the proposed still, the blackened jute wick is spread along with 30˚ double slope tilted portion and the remaining part of the wick is immersed in the water reservoir. The thermo coal insulation of thickness 6 cm is introduced to the sidewalls and bottom side of the tilted portion to minimize the heat losses from the evaporating wick surfaces. The water level in the reservoir is maintained so as not to overflow into the tilted portion and always to be 0.5 cm below the tilted portion. Due to the raised water level in the reservoir, the tilted wick surfaces were always wet. The excess hot water from the tilted surfaces was fed to the reservoir during late and early working hours of the still.

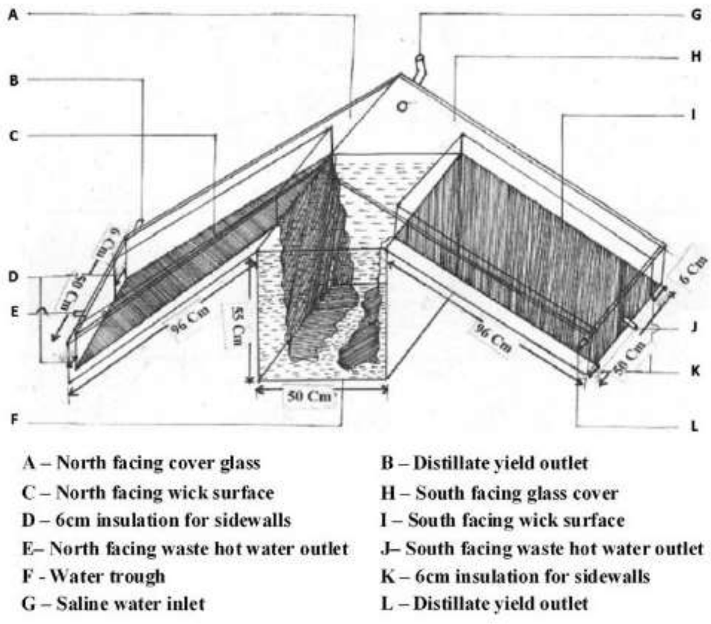


Fig. 1 Schematic sectional view of the proposed still

Fig. 2 Photograph of the proposed still

Brine water from the tank flows through North-South facing tilted-wick type portion due to capillary action. The brine water flowing through the tilted wick is heated by the total flux inside the still transmitted through the condensing glass cover. The water evaporates and condenses in to water drops, which flow along the condensation surface and are collected in the distilled water tank. The remaining hot water is fed in to the tank. Distilled water from both sides is measured with a measuring jar.

The proposed double slope wick-type solar still has been tested from March 2018 to March 2019 in Coimbatore, TamilNadu, India. The still has been oriented in North-South direction during the experimental days to receive large amount of solar radiation. Three different flow rates of saline water along the tilted-wick portion namely 0.050 (10.03.2018), 0.10 (15.03.2018) and 0.20 (17.03.2019) kg/min has been maintained for different days in the year and corresponding hourly daily productivity are measured

3. Methodology

During the working hours of the proposed still, the driving force is the temperature difference between the evaporating wick and condensing glass cover surface. This led to the convective, radiative and evaporative heat transfer between the two surfaces. The dimensionless Nusselt number is related with the convective heat transfer coefficient by

$$Nu = \frac{h_{cw} d}{k} = C(Gr^*, Pr)^n \quad (1)$$

Where h_{cw} is the convective heat transfer coefficient, Gr^* *and* Pr are the modified Grashof and Prandtl numbers. The expression for Gr^* *and* Pr based on the physical properties of vapor presented by Farshchi Tabrizi*et al*. [16] has been utilized in the study. The unknown values *C* and *n* by Dunkle's [1] for convective heat transfer coefficient is given as

$$h_{cw} = 0.884 \times \left[(T_w - T_g) + \frac{(P_w - P_g)(T_w + 273)}{268.9 \times 10^3 - P_w} \right]^{1/3} \quad (2)$$

And

$$q_{cw} = h_{cw}(T_w - T_g) \quad (3)$$

The evaporative heat transfer coefficient is given by

$$h_{ew} = 0.01623\, h_{cw} \frac{P_w - P_g}{T_w - T_g} \quad \text{(Dunkle [1])} \tag{4}$$

Substituting for h_{cw} in Eq. (4) from (1), we get

$$h_{ew} = 0.01623 \frac{k}{d}\, C(Gr^*, Pr)^n \frac{P_w - P_g}{T_w - T_g} \tag{5}$$

With the help of Eq. (5), the mass transfer M_{ew} is given by

$$M_{ew} = \frac{0.01623}{L} \frac{k}{d} A_w \left(P_w - P_g\right) C(Gr^*, Pr)^n\, t \tag{6}$$

Eq. (6) can be written as

$$\frac{M_{ew}}{Z} = C(Gr^*, Pr)^n \tag{7}$$

Where

$$Z = \frac{0.01623}{L} \frac{k}{d} A_w \left(P_w - P_g\right)\, t$$

Taking log on both sides of Eq. (7), we get

$$\ln\left(\frac{M_{ew}}{Z}\right) = \ln C + n \ln(Gr^*, Pr) \tag{8}$$

Taking

$$Y = \ln\left(\frac{M_{ew}}{Z}\right) \ \text{and} X = ln(Gr^*, Pr)$$

We get

$$Y = nX + \ln C \tag{9}$$

The values of C and n can be calculated by linear regression using the expression similar to the that of FarshchiTabrizi*et al*. [16]. The radiative heat transfer coefficient is found by using the expression

$$h_{rw} = \varepsilon\sigma\left[(T_w + 273)^2 + \left(T_g + 273\right)^2\right]\left(T_w + T_g + 546\right)$$

Therefore the total internal heat transfer coefficient is calculated by

$$h = h_{cw} + h_{rw} + h_{ew}$$

The thermal efficiency of the proposed still is expressed as

$$\eta_{passive}(\%) = \frac{\Sigma M_g\, L}{A \int I(t)dt}\ X\ 100 \tag{10}$$

4. Results and Discussion

The proposed still has been tested with three different flow rates (0.050, 0.10 & 0.20 kg/min) throughout the year from March 2018 to March 2019. The variations of intensity of solar radiation for three typical days for three different flow rates have been depicted in the Figs. 3 and 4. From the figures, it is understood that the instantaneous variation of solar radiation intensity and ambient temperature for the days considered have same trend and considered to be typical days as they were clear sunny days. Also, the solar radiation gradually increases during morning hours up to 13hrs and started decreasing in the afternoon hours.

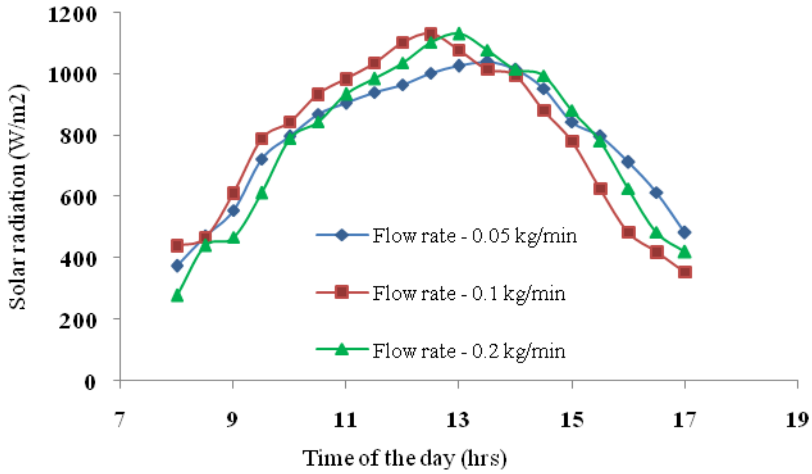


Fig.3 Variation of intensity of solar radiation on 10.03.2018, 15.03.2018 and 17.03.2019

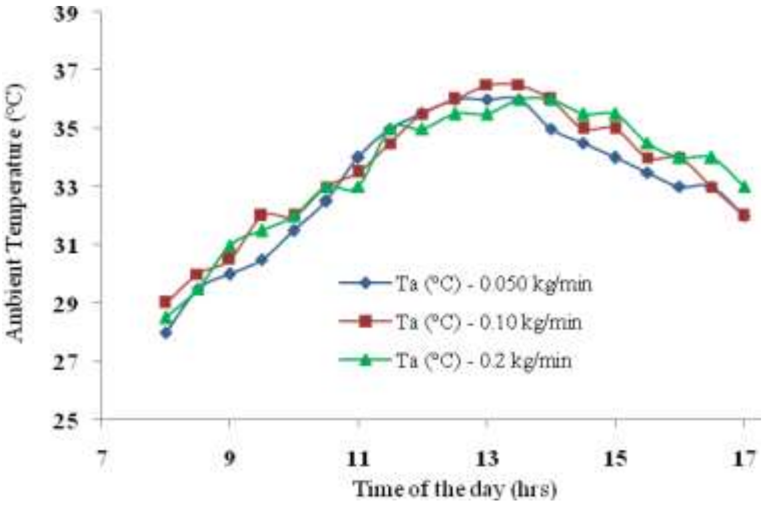


Fig. 4 Variation of ambient temperature on 10.03.2018, 15.03.2018 and 17.03.2019

The values of h_{cw} and h_{ew}has been found by using the expressions developed in the study (Present model) and it has been compared with the results obtained by using Dunkle's[1] expression for both North and South facing wick surfaces for the flow rate of 0.050 kg/min and depicted in Figs. (5-8). It has been seen that the Dunkle's expression underestimate the convective and evaporative heat transfer coefficients from the evaporating wick surface to the condensing glass cover surface. This is due to the fact that the Dunkle's model is based on the temperature difference between the evaporating and condensing surface and the limitation of no temperature gradient across the length of the tilted wick surfaces. In the double slope wick-type solar still, the temperature gradient across the length of the both North and south facing tilted-wick surfaces plays a vital role and giving the values of the coefficients greater than the Dunkle's model. Therefore the total heat transfer coefficient has shown significant increase throughout the working hours of the still for both the surfaces. The radiative heat transfer coefficient and total heat transfer coefficient for the saline water flow rate of 0.050 kg/min for both the North and South facing tilted-wick surfaces have been depicted in the Figs. (9-12).

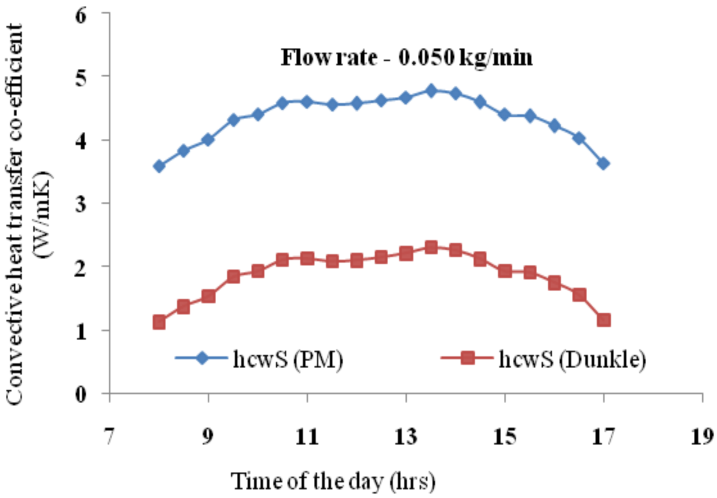


Fig .5 Variation of convective heat transfer coefficient of South facing wick surface

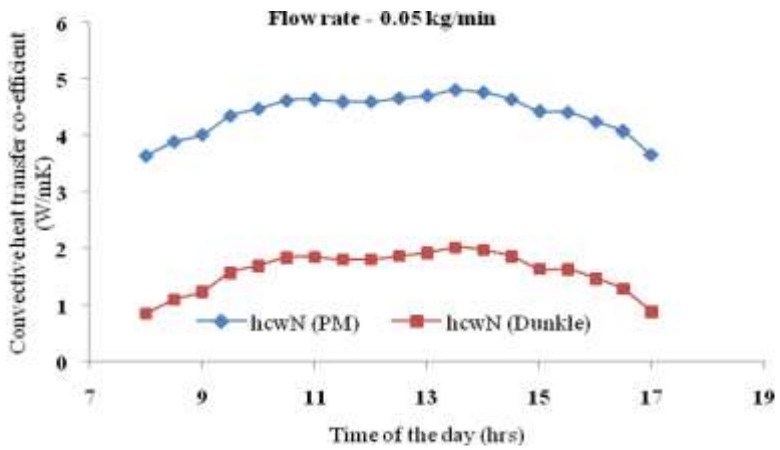


Fig .6 Variation of convective heat transfer coefficient of North facing wick surface

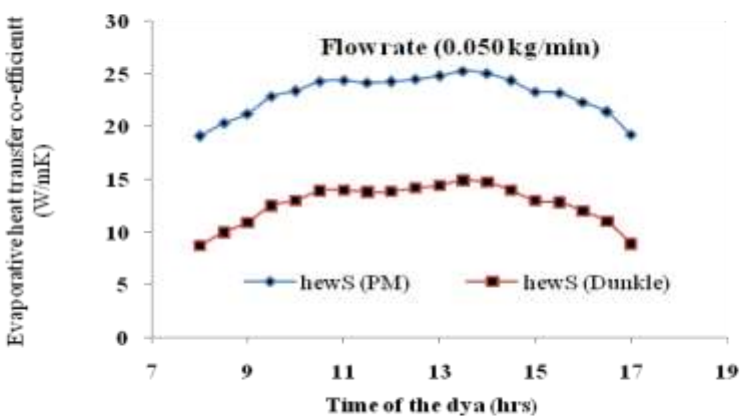


Fig .7 Variation of evaporative heat transfer coefficient of south facing wick surface

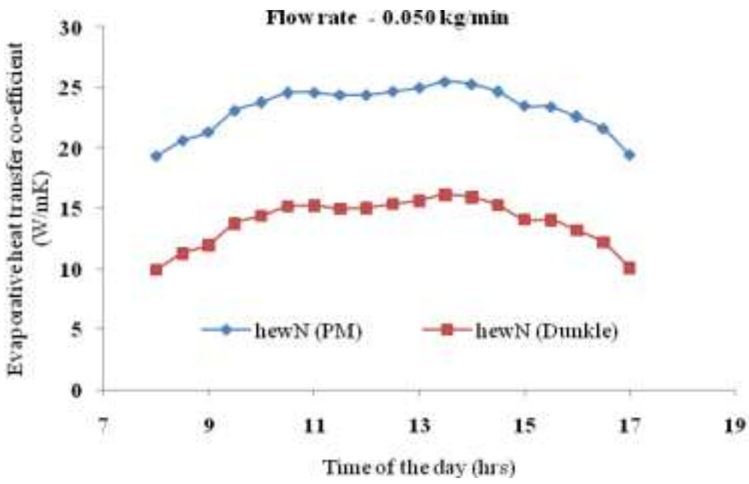


Fig .8 Variation of evaporative heat transfer coefficient of North facing wick surface

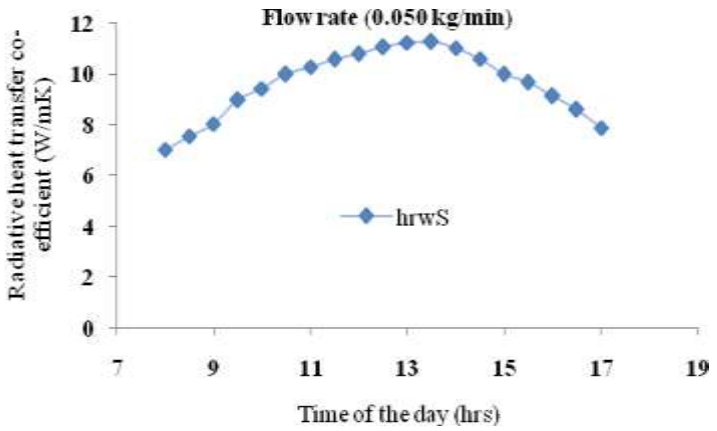


Fig. 9 Variation of Radiative heat transfer coefficient of South facing wick surface

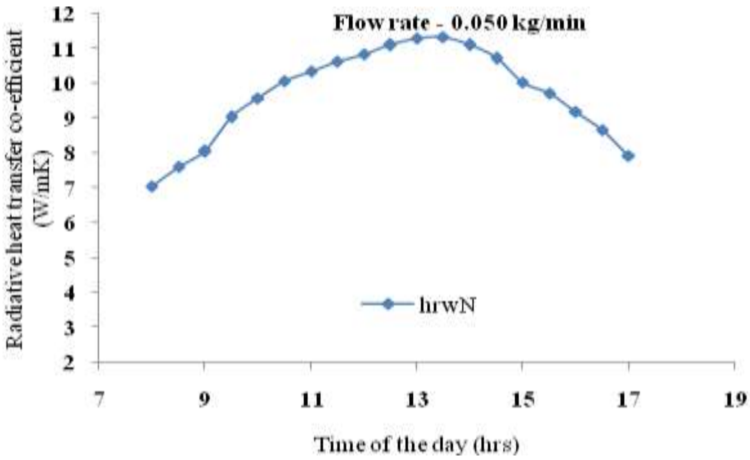


Fig .10 Variation of radiative heat transfer coefficient of North facing wick surface

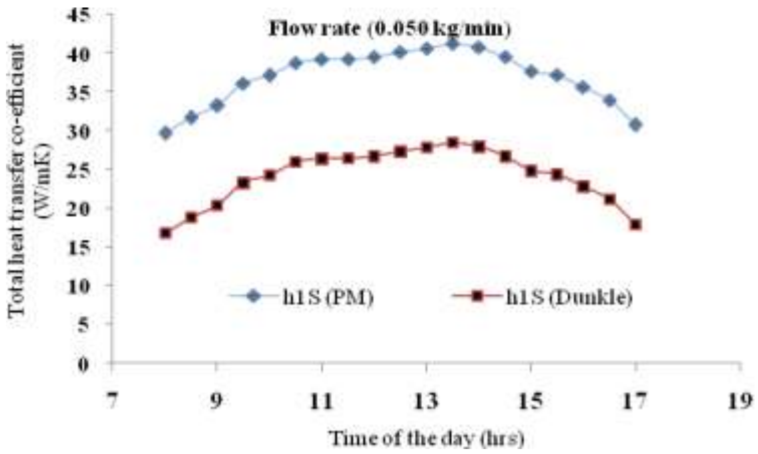


Fig. 11 Variation of total heat transfer coefficient of South facing wick surface

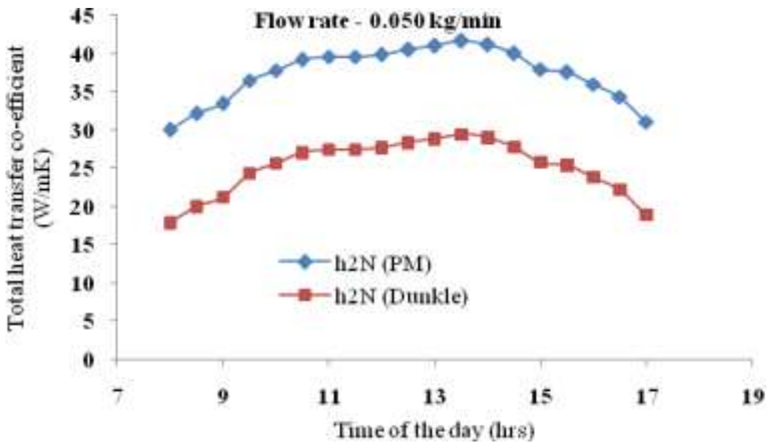


Fig .12 Variation of total transfer coefficient of North facing wick surface

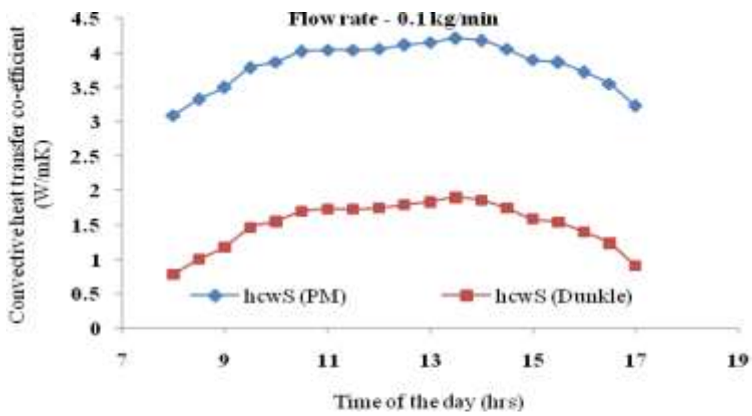


Fig .13 Variation of convective heat transfer coefficient of South facing wick surface

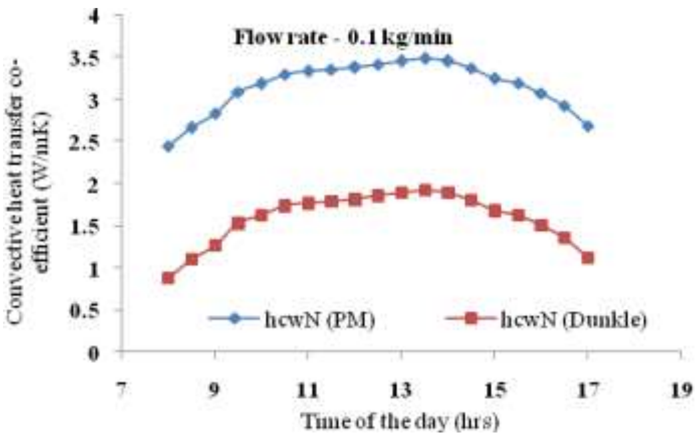


Fig. 14 Variation of convective heat transfer coefficient of North facing wick surface

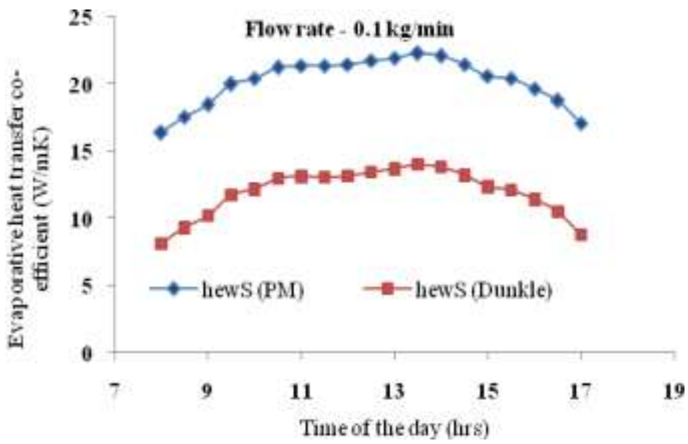


Fig. 15 Variation of evaporative heat transfer coefficient of South facing wick surface

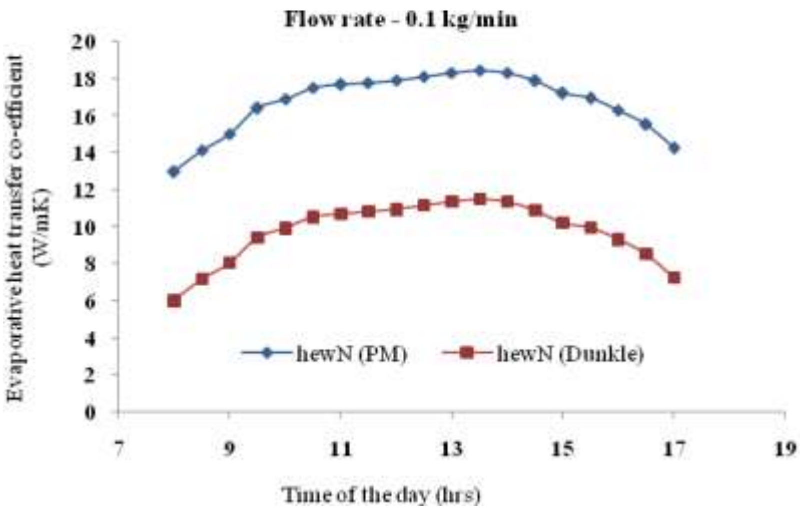


Fig.16 Variation of evaporative heat transfer coefficient of North facing wick surface

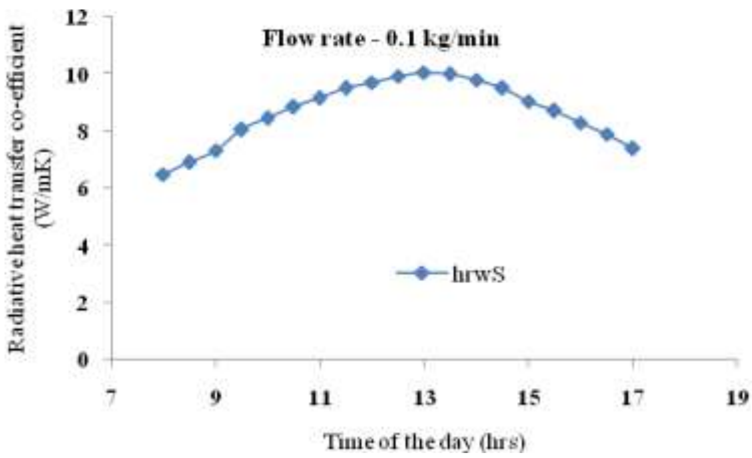


Fig.17 Variation of Radiative heat transfer coefficient of South facing wick surface

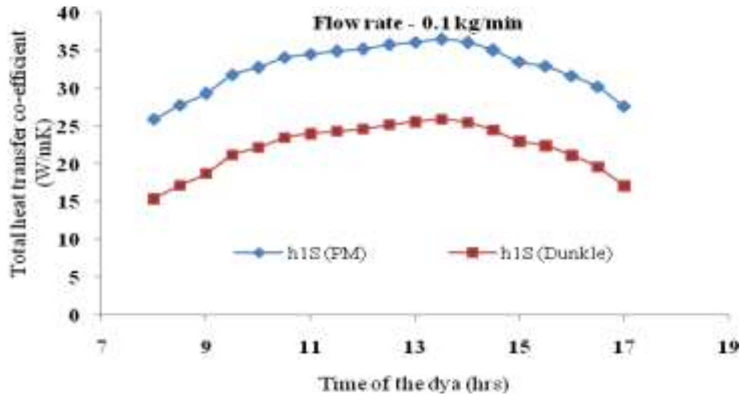


Fig.18 Variation of Radiative heat transfer coefficient of North facing wick surface

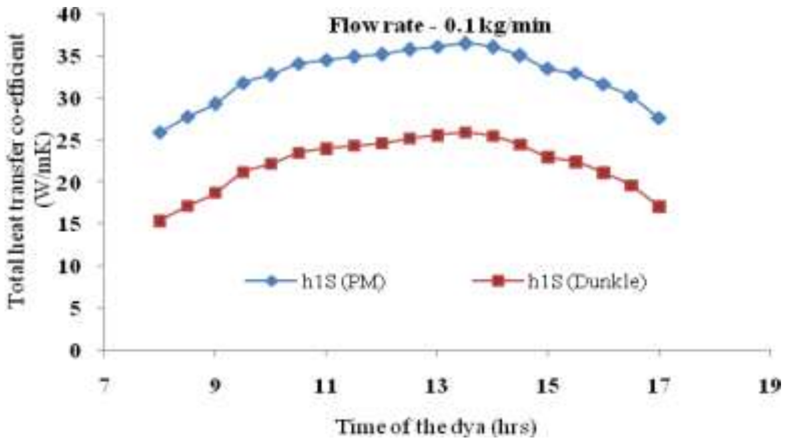


Fig.19 Variation of total heat transfer coefficient of South facing wick surface

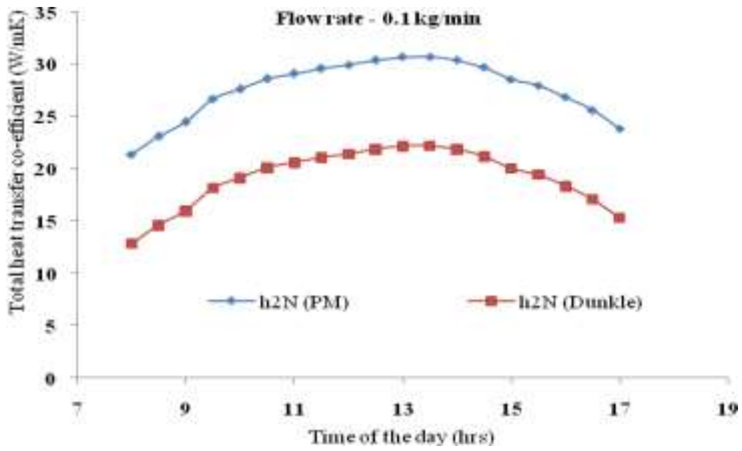


Fig.20 Variation of total heat transfer Coefficient of North facing wick surface

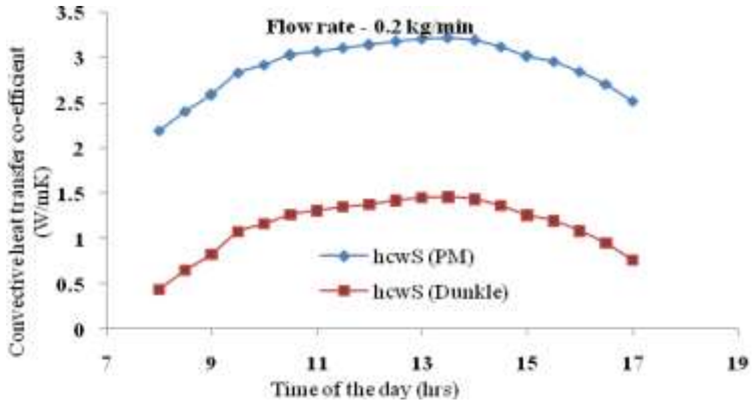


Fig.21.Variation of convective heat transfer coefficient of South facing wick surface

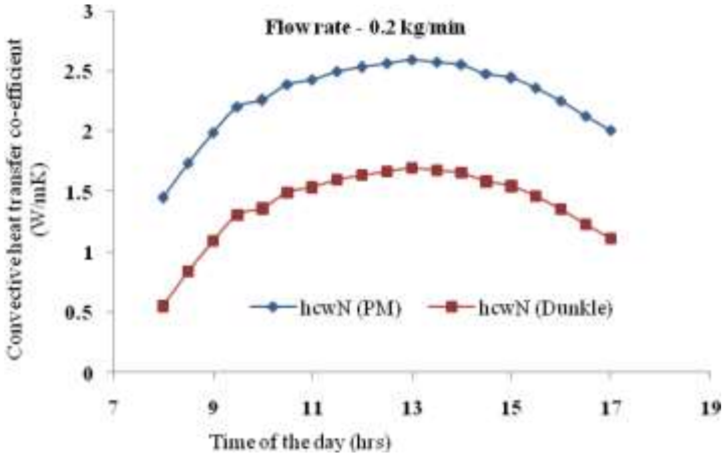


Fig.22 Variation of convective heat transfer coefficient of North facing wick surface

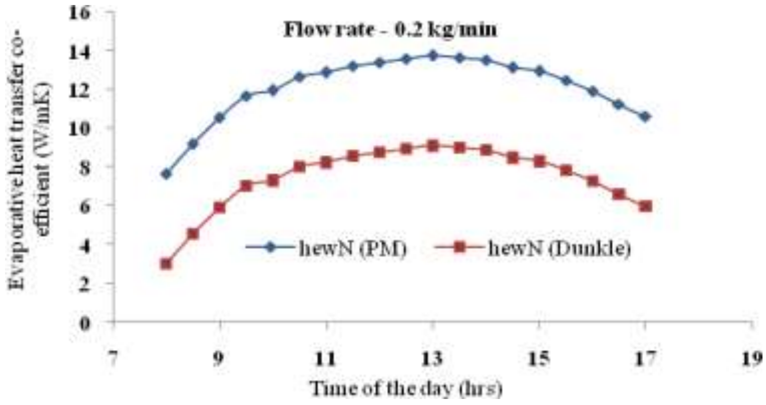


Fig.23 Variation of evaporative heat transfer coefficient of South facing wick surface

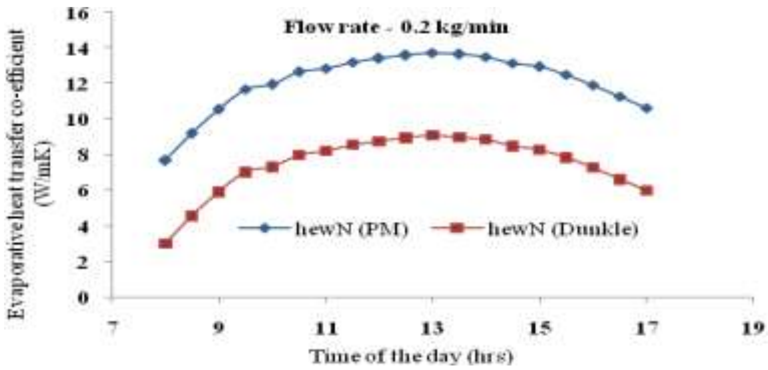


Fig.24 Variation of evaporative heat transfer coefficient of North facing wick surface

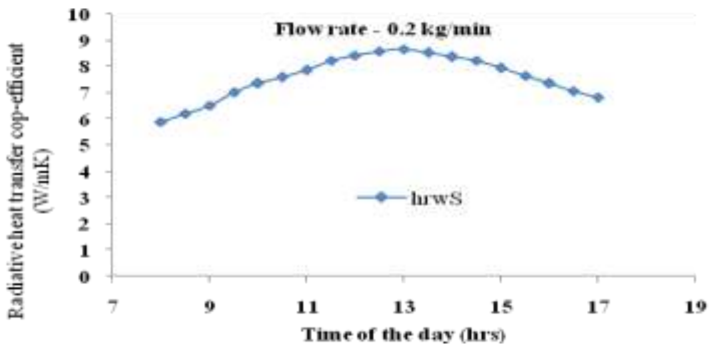


Fig.25 Variation of Radiative heat transfer coefficient of South facing wick surface

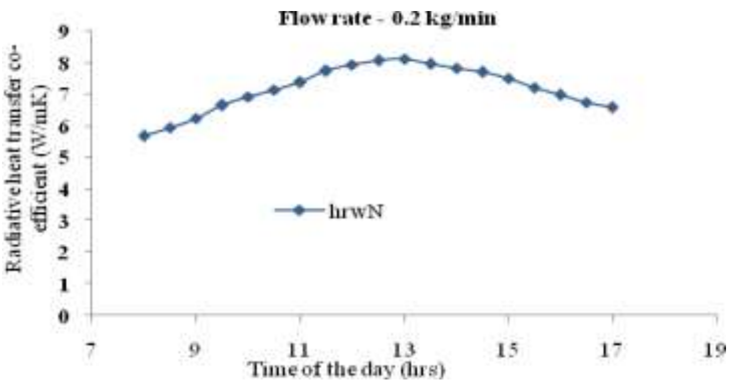


Fig.26 Variation of Radiative heat transfer coefficient of North facing wick surface

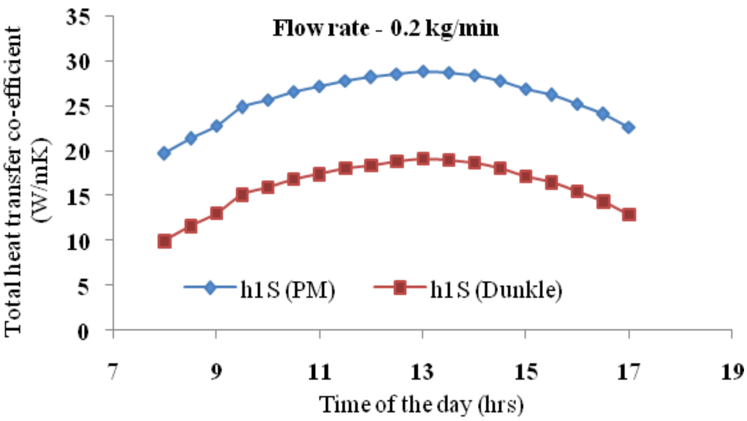


Fig .27 Variation of total heat transfer coefficient of South facing wick surface

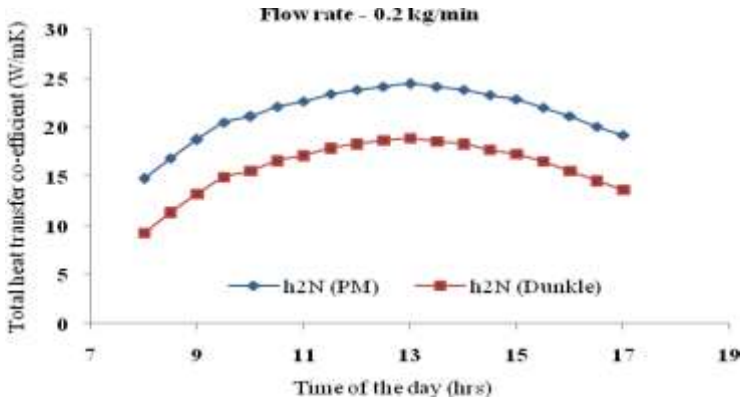


Fig .28 Variation of total heat transfer coefficient of North facing wick surface

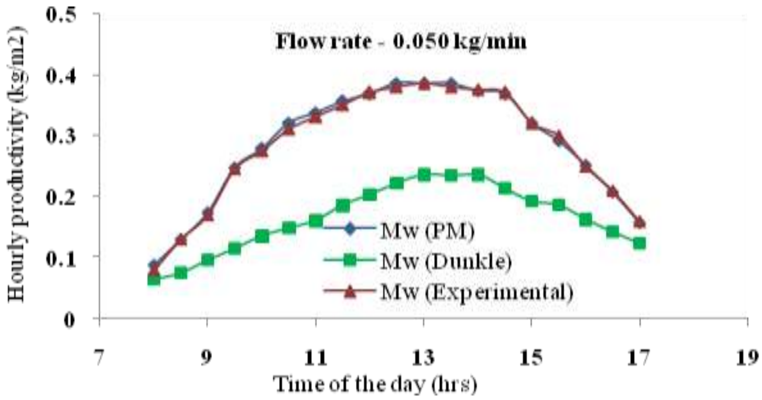


Fig**. 29 Variation to total hourly distillate yield.**

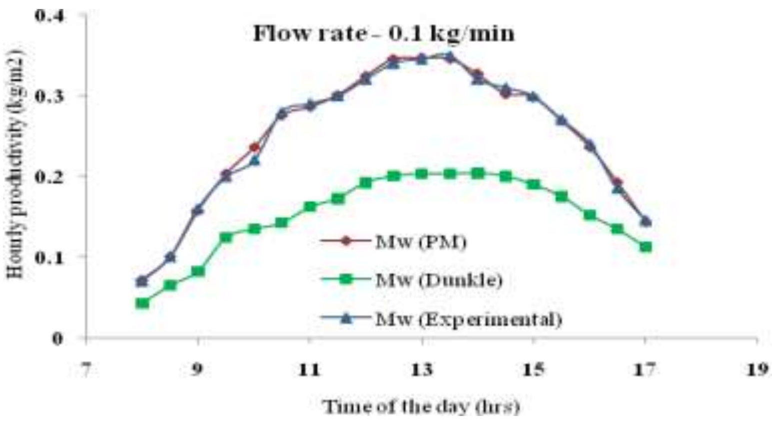


Fig. 30 Variation to total hourly distillate yield

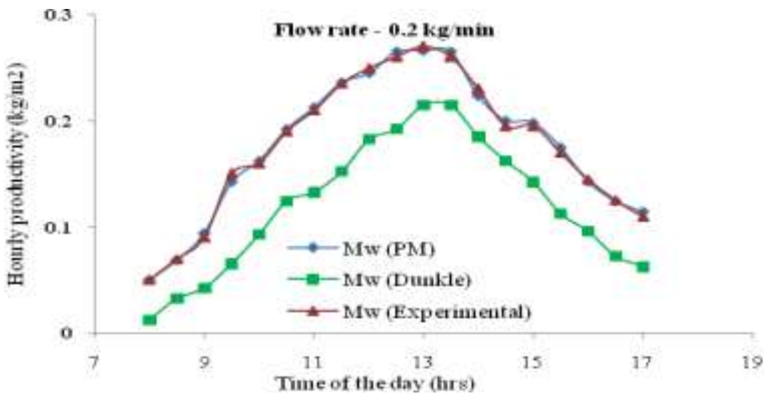


Fig. 31 Variation to total hourly distillate yield

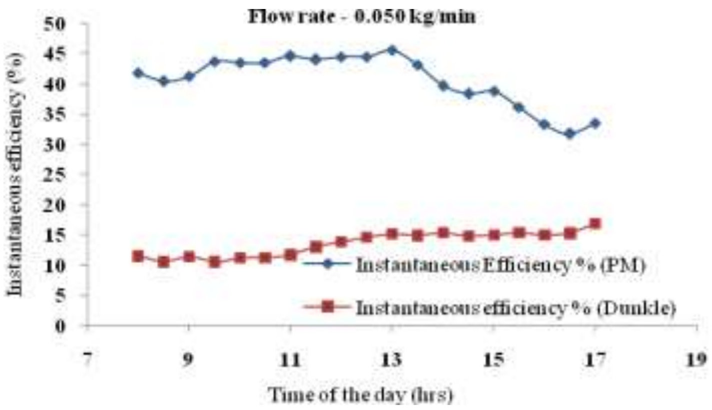


Fig. 32 Variation of instantaneous efficiency

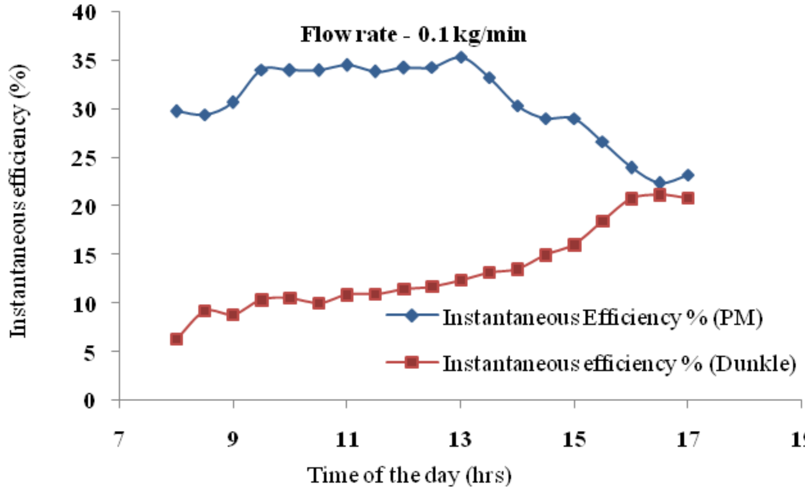


Fig. 33 Variation of instantaneous efficiency

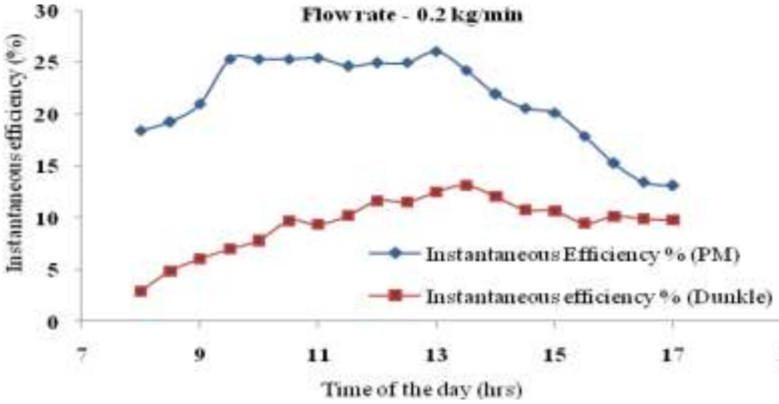
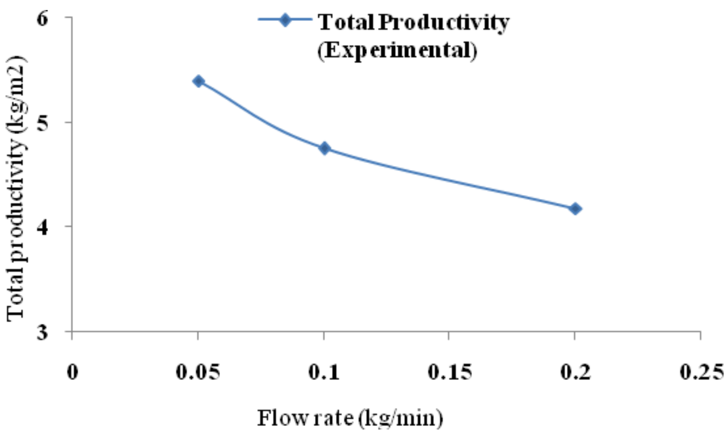


Fig. 34 Variation of instantaneous efficiency



Fig, 35 Total productivity with respect to flow rate

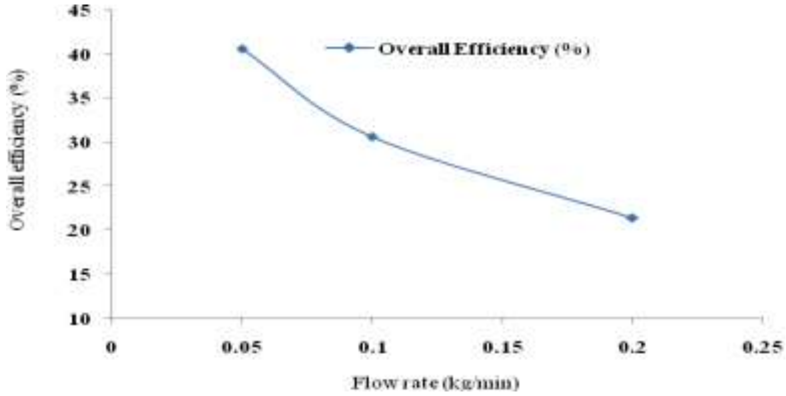


Fig. 36 Overall efficiency with respect to flow rate

Similarly for the flow rates of 0.10 and 0.20 kg/min, the Dunkle's model underestimates the convective, evaporative and total heat transfer coefficients compared to the present model as expected. Graphs have been plotted for the same with radiative heat transfer coefficient and depicted in the Figs. (13-28). It has been confirmed that Dunkle's model has constraints for the prediction of performance of the proposed still with better accuracy. The total hourly distillate yield including the North and South facing surfaces for the three flow rates (0.050, 0.10 and 0.20 kg/min) have been measured experimentally and compared with the results obtained by using present model and Dunkle's model and presented in the Figs. (29-31). It has been shown that for all the flow rates, the results calculated for total hourly distillate yield of the proposed still by using the present model is in close agreement with the experimental observations. Dunkle's model underestimates the total distillate yield for all the flow rates. The instantaneous efficiency of the still has been evaluated by using the present model for the flow rates under study and compared with the results of Dunkle's model and depicted in the Figs. (32-34). From the graphs it is confirmed that Dunkle's model is non-realistic for the prediction of the instantaneous efficiency of the proposed still.

The overall production of distillate yield and efficiency is plotted against the flow rate of saline water in the tilted-wick surfaces has been depicted in the Figs. (35-36). It is observed that the optimum flow rate is 0.050 kg/min for the working hours of the still due to less thermal capacity of the capacity of water flowing through the wick surface due to capillary action. When the flow rate exceeds 0.050 kg/min, the thermal capacity increases and evaporation decreases which led to the excess of waste hot water from the still. Moreover, the flow rate lesser than 0.050 kg/min led to the dryness of the wick surface during peak sunny hours. The calculated daily total distillate yield for the optimum flow rate of 0.050 kg/min is 5.43 kg/m^2 and is in close agreement with the experimental observation i.e. 5.40 kg/m^2. The overall efficiency of the still is found to be 40.58%.

5. Conclusion

The following conclusions have been drawn from the study and summarized as

i. The optimum flow rate of brine water is found to be 0.050 kg/min to produce maximum distillate yield.
ii. The total daily distillate yield of the proposed still is 5.40 kg/m^2day with an average efficiency of 40.5%.

iii. Dunkle's relation for the convective and evaporative heat transfer underestimates for the proposed still.
iv. The internal radiative heat transfer coefficient has no significant impact on the productivity of the still.
v. The mass flow rate of brine through tilted-wick portion influences the internal convective and evaporative heat transfer significantly.

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