A new empirical model for water production in a double slope tilted-wick type solar still

R. Rajanarthini, B. Janarthanan

Department of Physics, Karpagam University, Eachanari Post, Coimbatore - 641021, Tamilnadu, India.

Tel: +91-422-2611082 Fax: +91-422-2611043

E-mail: rajaguru_1991@rediff.com and bjanarthanan2002@yahoo.co.in

Abstract - **An attempt has been made to propose a new empirical model for water production through the energy balance equation of the brine water in double slope tilted-wick type solar still. Various modes of heat transfer in the collector have been analyzed to develop the model. Experiments have been carried out in typical summer days and it is found that the thermal efficiency of the proposed still is always less than 50%. The empirical equation is obtained for distilled water production in terms of input heat flux and length of the tilted-wick portion.**

Keywords: Water Purification, Renewable Energy, Empirical Model, Wick Type Solar Still, mass production rate, renewable energy, heat transfer

1 Introduction

Fresh water is essential for human beings and it is very fortunate that portable water is a major problem in many countries. In this scenario, use of solar energy is recommended for purifying salty or brackish water. Solar stills operated with solar energy can be used to produce fresh water because of its low initial and maintenance cost, simple construction and operation, high fresh water productivity.

Many researchers have designed different designs of solar stills and studied the performance. Among the designs, wick-type solar still shows better performance for the production of fresh water. In wick-type solar still many parameters affect the productivities of the still which include climatic, operational and design parameters. The productivities of solar still has been influenced by solar intensity, wind velocity, ambient temperature, water-glass temperature difference, free surface area of water, absorber plate area, temperature of inlet water, glass angle and depth of water [1-3]. Though the parameters influences the thermal performance of solar still, it is necessary to consider the heat fluxes i.e., evaporation, convection and radiation from brine to condensing surface separately. Narjes setoodeh *et al.*,[4] have modeled and determined the heat transfer coefficient in a basin type solar still using computational fluid dynamics [CFD]. It has been concluded that the CFD is a powerful tool for design, parameter analysis and diagnostic purpose of solar still. A mathematical model based on system of energy and mass conservation differential equations have been developed for multi-stage solar water desalination still by Shatat and Mahkamor [5] for simulation of stills operation. The developed model has provided an acceptable level of accuracy in the prediction of the performance of the system and can be used for the determination of rational design parameters of the multi-stage basin for a given aperture area of the collector. Kalidasa murugavel *et al.*,[6] have proposed a thermal model for the determination of water and glass temperatures and production rate of single basin double slope solar still by incorporating the variations in solar incidence angle and transmittance of the glass cover. It has been inferred that the theoretical maximum values of production rate, water and glass temperatures are varying inversely with heat capacity of basin water and other materials used in the basin. Moreover the experimental values have higher deviation with theoretical values due to non inclusion of higher proportion of water vapor in the air inside the still, effect of change in evaporation area and absorptivity of materials used in the basin. A new radiation model has been proposed for single slope solar still incorporating the effect of all walls of the still on the amount of

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incident solar radiation on the water surface and each wall by Feilizadeh *et al.*,[7]. The result has shown that the effect of accuracy of thermal radiation analysis of the still.

Amimul Ahsan and Teruyuki Fukuhara [8] have proposed a new mass and heat transfer model of a tubular solar still by incorporating the properties of humid air inside the still. The proposed model has paved the way to calculate the diurnal variations of the temperature, water vapor density and relative humidity of the humid air and hourly condensation flux precisely. The influence of water flow rate on the internal heat and mass transfer and daily productivity of weir-type cascade solar still has been studied by Farshed Farshehi Tabrizi *et al.*,[9]. The result has shown that the internal heat and mass transfer rates as well as daily productivity decreased with the increased water flow rate. Kalidasa Murugavel and Srithar [10] have fabricated and tested a basin type double slope solar still with minimum mass of water and different wick materials like light cotton cloth, sponge sheet, coir mate and waste cotton pieces in the basin.

A theoretical model has been proposed by considering the variation in transmittance of the glass cover. Theoretical values obtained for water and glass temperatures and production rate using the proposed model have close agreement with the experimental observations. Performance study of an inverted absorber solar still with different depth of water and total dissolved solid has been presented by Rahul Der *et al.*,[11] and also a thermal model has been developed. It has been inferred that the optimum water is less than 7 i.e., acidic in nature and has low electrical conductance due to low values of TSD in the distilled water. Aboul Jabbar N-Khalifa [12] has cited the relation between the cover tilt angle and productivity of simple solar still in various seasons and latitude. It has been inferred that that tilt angle should be close to the latitude and larger in winter and smaller in summer seasons.

The existing heat and mass transfer models are not favorable for brine flowing through the wick surface due to the varying temperature of the brine to predict distilled water production. In the present work, a simple empirical method has been proposed to evaluate the distilled water production of brine flowing through wick type solar still by utilizing the energy balance equation.

2 Design of double slope single wick solar still

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.

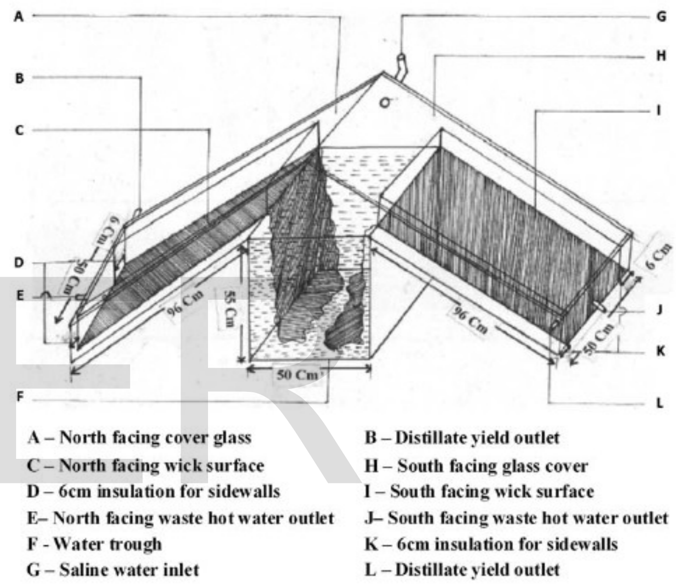

Fig. 1 Schematic sectional view of the proposed still

Fig. 2 Photograph of the proposed still

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The experiments have been conducted with the proposed still in the month of March 2012 (summer days) at Karpagam University, Coimbatore, Tamilnadu, India. 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 are measured with a measuring jar.

3 Empirical model

The figure.3 shows the flowing brine water through South-North tilted-wick surface accompanied by evaporation, convection and radiation to the condensing surface. It is assumed that the convection, evaporation and radiation heat fluxes are homogeneous along the water flow direction. Also the temperature of the brine water is equivalent along x-axis.

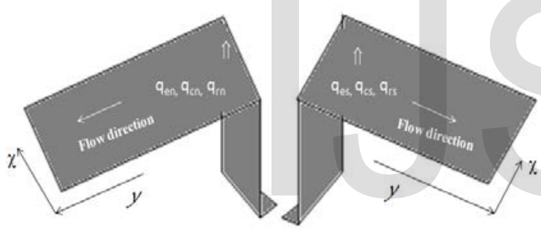

Fig.3. flowing brine water through South-North tilted-wick surface accompanied by evaporation, convection and radiation to the condensing surface

Based on the assumption, a steady state equation of energy balance for North and South facing tilted-wick portion have been written as.

North-facing

$$Q\,dl = m_n C\,dt + (q_{en} + q_{cn} + q_{rn})dl \quad 1$$

South-facing

$$Q\,dl = m_s C\,dt + (q_{es} + q_{cs} + q_{rs})dl \quad 2$$

Eqs. 1 and 2 can be rewritten as

$$\frac{[1 - \frac{(q_{en}+q_{cn}+q_{rn})}{Q}]dl}{\frac{m_n C}{Q}} \quad 3$$

$$\frac{[1 - \frac{(q_{es}+q_{cs}+q_{rs})}{Q}]dl}{\frac{m_s C}{Q}} = dt \quad 4$$

Where Q is the total input heat flux and $q_{en} + q_{cn} + q_{rn}$, $q_{es} + q_{cs} + q_{rs}$ are the evaporative, convective and Radiative heat flux for North and South facing tilted-wick portion. m_n and m_s are the brine water mass flow rate kg/ms and C is the specific heat capacity of water.

Considering X_1 and X_2 as the rates of total heat flux including evaporation, convection and radiation to the input heat flux for both North and South facing tilted-wick portion, it can be written as

$$X_1 = \frac{(q_{en}+q_{cn}+q_{rn})\,[Q>0]}{Q} \quad 5$$

$$X_2 = \frac{(q_{es}+q_{cs}+q_{rs})\,[Q>0]}{Q} \quad 6$$

The temperature increase of the brine water per unit length X_3 and X_4 along y-axis for north and south facing sides can be written as

$$X_3 = \frac{Q}{m_n C}\ (m_n > 0) \quad 7$$

$$X_4 = \frac{Q}{m_s C}\ (m_s > 0) \quad 8$$

Integrating the eqs.3 and 4, and using eqs.5, 6, 7 and 8

The equation can be written as

$$X_3 l - (T_{on} - T_{in}) = X_1 X_3 l \quad 9$$

$$X_4 l - (T_{os} - T_{is}) = X_2 X_4 \quad 10$$

where

T_{on}- Outlet temperature of North facing tilted-wick portion

T_{in}- Inlet temperature of North facing tilted-wick portion

T_{os}- Outlet temperature of South facing tilted-wick portion

T_{is}- Inlet temperature of South facing tilted-wick portion

l- Length of north and south facing tilted-wick portion

4 Result and discussion

With $X_3 l - (T_{on} - T_{in})$ and $X_4 l - (T_{os} - T_{is})$ as ordinate, experimental data has been plotted and a linear equation fit is done for North and South facing tilted-wick portion, $X_1 X_3 l$ and $X_2 X_4 l$ are plotted against $X_3 l$ and $X_4 l$ respectively and represented in Figs 4 and 5.

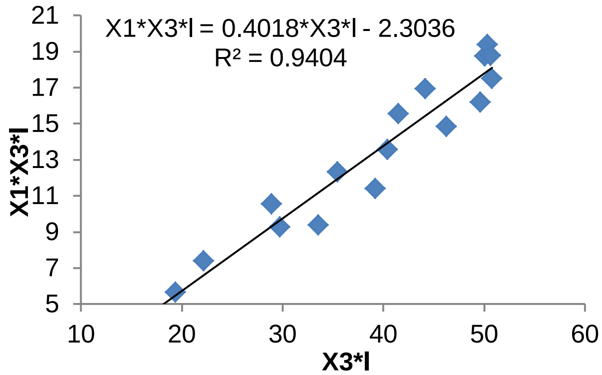

Fig.4. Function of X_1X_3l-$(T_{on} - T_{in})$ vs X_3l

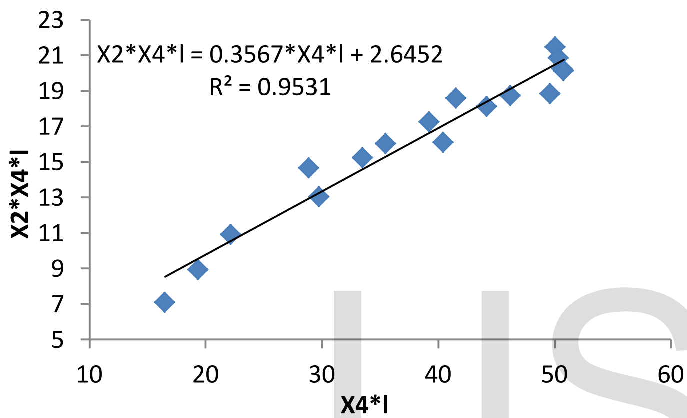

Fig.5. Function of X_2X_4l-$(T_{os} - T_{is})$ vs X_4l

The experimental feed water flow rate has been fixed as 4.85 kg/hm on both tilted-wick portions. From the graph, the equation for linear fit has been found as

For North facing wick surface

$$X_1X_3l = 0.4018\, X_3l - 2.3036\ [R^2 = 0.9404] \quad 11$$

For South facing wick surface

$$X_2X_4l = 0.3567\, X_4l + 2.6452\ [R^2 = 0.9531] \quad 12$$

Using eqs. 5, 6, 7 and 8, eqs. 11 and 12 can be written as

$$\frac{(q_{en}+q_{cn}+q_{rn})}{Q} = 0.4018 - \frac{2.3036\, m_nC}{Ql}$$
13

$$\frac{(q_{es}+q_{cs}+q_{rs})}{Q} = 0.3567 + \frac{2.6452\, m_sC}{Ql}$$
14

From the equations, it is clear that the thermal efficiency of the proposed still $\eta = \frac{q_{en}}{Q}$ (*North facing*) and $\eta = \frac{q_{es}}{Q}$ (*South facing*) are apparently less than left hand side of the equations 13 and 14 and could exceed 40.18 and 35.67%.

Figs.6 and 7 shows the temperature of the brine water along y-axis for different input heat flux. The temperature difference between the inlet and outlet of North and South facing tilted wick portion in all the cases of input heat flux is approximately varies between 35°C and 40°C. Therefore the existing models for stationary brine water in wick-type solar still are not favorable due to the rapidly increasing temperature of brine water along the flow direction.

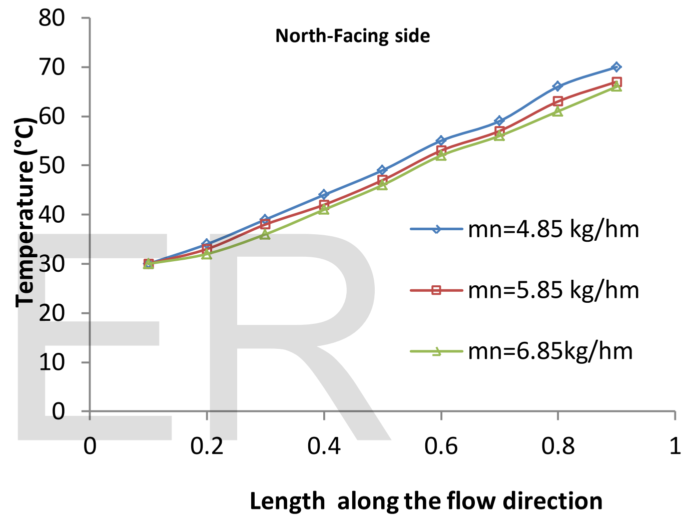

Fig.6.Temperature along y-axis

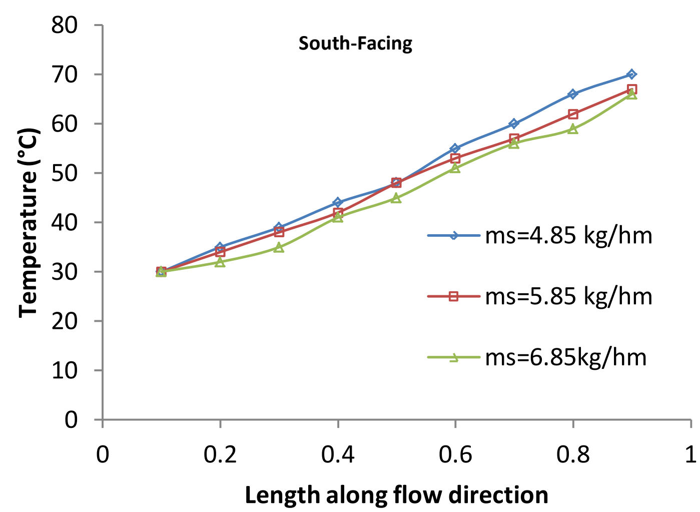

Fig.7.Temperature along y-axis

In order to analyze the thermal efficiency, enthalpy increase of brine water along the tilted-wick portions can be considered. Therefore thermal efficiency can be expressed in terms of enthalpy and can be expressed as

$$\Delta_n = \frac{m_n C\,(T_{on} - T_{in})}{Ql}\ [North\ facing]$$

15

$$\Delta_s = \frac{m_s C\,(T_{os} - T_{is})}{Ql}\ [South\ facing]$$

16

Figs.8 and 9 represents the thermal efficiency Δ_n and Δ_s for varying floe rate of brine water along y-axis in north and south facing tilted-wick portion. From the graphs, it is clear that the thermal efficiency decreases with increases of flow rate.

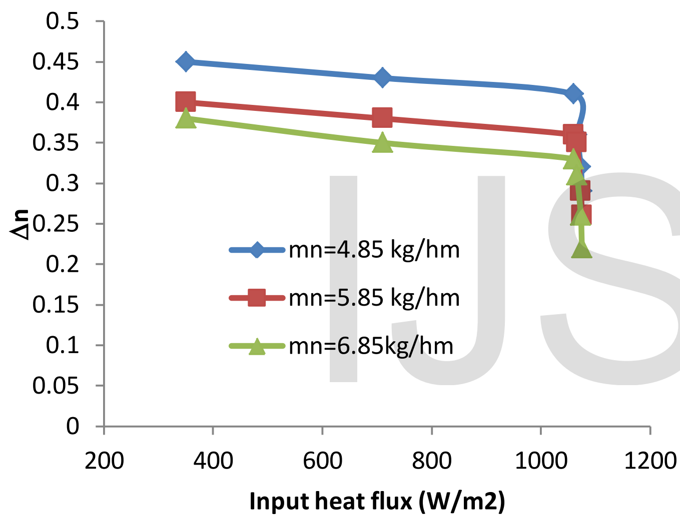

Fig.8. Δn vs input heat flux and brine water flow rate

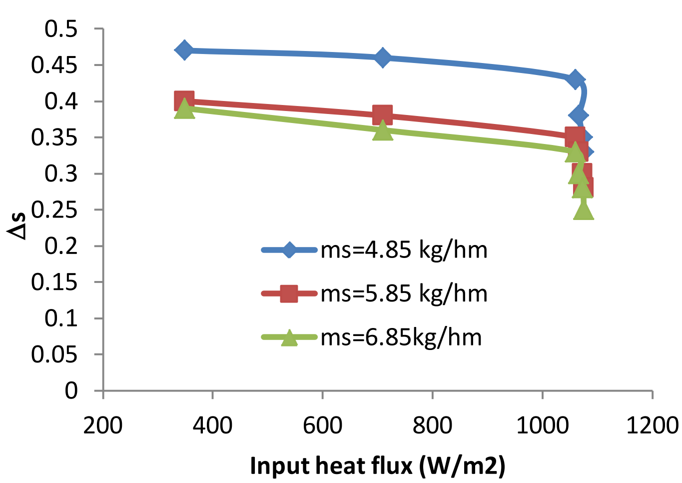

Fig.9. Δs vs input heat flux and brine water flow rate

The variations of production rate with respect to input heat flux on north and south facing tilted-wick surface are depicted in Figs.10 and 11. It is observed that for the brine water flow rate of 4.85 kg/hm along the y-axis in both sides, the production rate varies significantly with input heat flux.

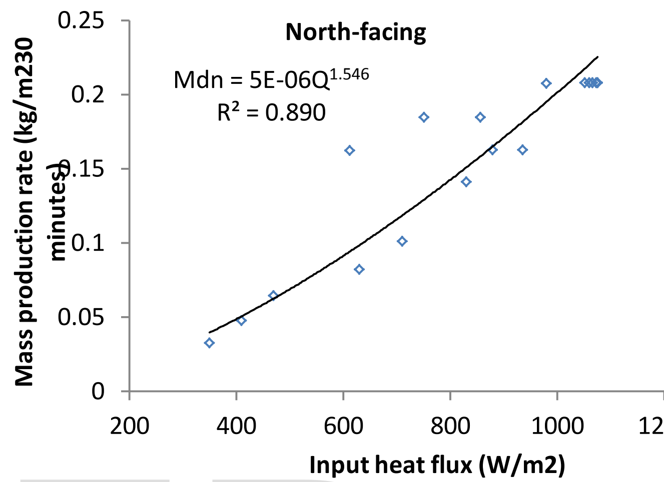

Fig.10. Mass production rate from North-facing wick surface vs input heat flux

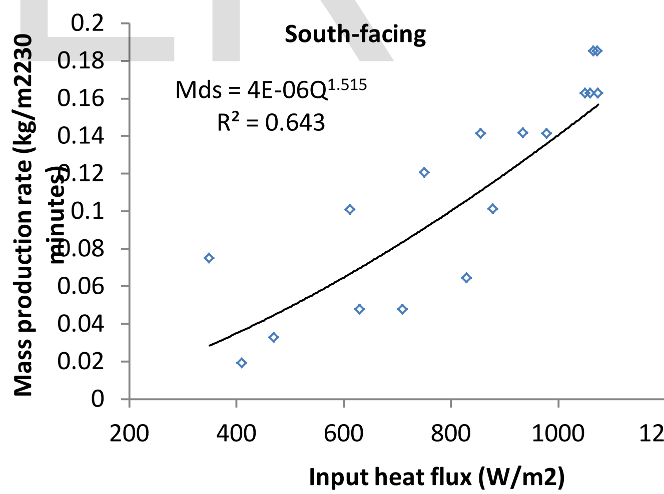

Fig.11. Mass production rate from South-facing wick surface vs input heat flux

The experimental data of input heat flux and production rate in terms of input flux obtained for both sides.

For North-facing

$$M_{dn} = 5 \times 10^{-6}\,[Q]^{1.545}[R^2 = 0.890]$$ 17

For South-facing

$$M_{ds} = 4 \times 10^{-6}\,[Q]^{1.515}[R^2 = 0.643]$$ 18

The average production rate M_d has been found and plotted against the input heat flux and depicted in Fig. 12. It has been observed that when total productions rate total is considered separately. Therefore the power correlation for total production rate with respect to input heat flux is represented as a

$$M_d = 1 \times 10^{-5}\,[Q]^{1.454}[R^2 = 0.830]$$ 19

From the above equation, it is concluded that the mass production rate increases with decrease of brine water flow rate along the tilted-wick portion and increase of input heat flux.

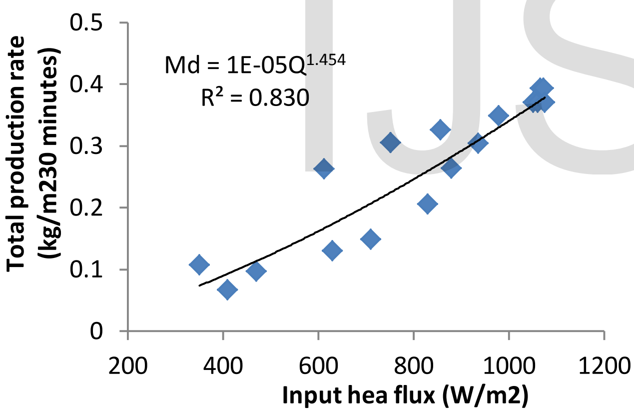

Fig.12. Total production rate

5 Conclusion

The experimental correlation developed for total production rate of double slope tilted-wick type solar still i.e., $M_d = 1 \times 10^{-5}\,[Q]^{1.454}[R^2 = 0.830]$ is found to be better when the brine water flow rate is 4.85kg/hm. Beyond that the correlation over predict the distilled water output than the experimental observation. Moreover the thermal efficiency of the proposed still did not exceed 40% on average in summer days and can be used for simulation in winter days and other location. The production rate of the proposed still increased with decrease brine water mass flow rate and increased amount of input heat flux.

Nomenclature

Q- Total heat flux (W/m²)
m_n- Brine water mass flow rate on north facing tilted-wick portion (kg/hm)
m_s- Brine water mass flow rate on south facing tilted-wick portion (kg/hm)
C- Specific heat capacity of water (J/kg°C)
dt- Time interval
dl- Elemental length along y-axis
q_{en}- Evaporative heat transfer from north-facing tilted-wick portion (W/m²)
q_{cn}- Convective heat transfer from north-facing tilted-wick portion (W/m²)
q_{rn}- Radiative heat transfer from north-facing tilted-wick portion (W/m²)
q_{es}- Evaporative heat transfer from south-facing tilted-wick portion (W/m²)
q_{cs}- Convective heat transfer from south-facing tilted-wick portion (W/m²)
q_{rs}- Radiative heat transfer from south-facing tilted-wick portion (W/m²)
M_{dn}- Production rate of north facing tilted wick portion (kg/m² 30 minutes)
M_{ds}- Production rate of south facing tilted wick portion (kg/m² 30 minutes)
M_d- Total production rate from the still (kg/m²30minutes)

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