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UCAPAN TERIMA KASIH

VOLUME 1 No. 1, 22 Desember 2021

EDITORIAL

Sekolah Pascasarjana Universitas Gadjah Mada mempunyai minat serta program studi yang beragam. Dengan dasar keilmuan lintas disiplin, dapat menjadi bukti bahwa Sekolah Pascasarjana mengembangkan diri untuk memenuhi kebutuhan keilmuan agar dapat menyelesaikan permasalahan di dalam kehidupan manusia yang juga sangat beragam.

Tidak bisa dipungkiri bahwa kondisi pandemi covid-19 tengah melanda semua negara, tetapi ternyata hal itu tidak menyurutkan perhatian para peneliti untuk mempublikasikan hasil penelitiannya. Hal tersebut dibuktikan antara lain dengan banyaknya makalah yang masuk ke tim redaksi. Secara konsisten dan profesional tim redaksi telah memilih serta melakukan penyuntingan terhadap delapan artikel yang dipublikasi dalam penerbitan ini. Adapun penyuntingan artikel telah melibatkan para *re vie we r* yang sesuai dengan bidangnya.

Sudah sepuluh tahun Jurnal Teknosains hadir, tim redaksi terus berupaya untuk melakukan penyempurnaan. Mohon maaf apabila masih terdapat kekurangan dalam penerbitan di edisi Desember 2021, Volume 11, Nomor 1. Terima kasih yang tidak terhingga kepada semua pihak yang telah meluangkan waktu serta tenaga dalam proses penerbitan ini. Selamat membaca, semoga bermanfaat bagi pengembangan ilmu pengetahuan serta wawasan akademik kita semua.

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DETERMINATION OF THE CONVECTIVE HEAT TRANSFER CONSTANT (C AND N) IN A SOLAR STILL

PENENTUAN KONSTANTA PERPINDAHAN PANAS KONVEKSI (C DAN N) UNTUK SOLAR STILL

Dan Mugisidi*, Abdul Rahman, Pancatatva Hesti Gunawan
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ABSTRACT

The geometry of a solar still determines the convection constants C and n, which in turn affect the convection heat transfer coefficient's value and mass. A method for determining the value of convection heat transfer constants C and n has already been developed by the researchers. Therefore, this study aimed to use several methods and theories to find the value of convection heat transfer constants C and n. The results are then compared with the results of the study. The solar still used in this study has one slope. To reduce variables that cannot be controlled, the data collection was conducted indoors using a halogen lamp that can be regulated as a heat source for 24 hours nonstop. The sea surface height in the solar still was maintained at a height of 20 mm, using a height regulator. Temperature was measured using a data logger set to enter data every hour. The desalinised clean water was stored in bottles placed on scales that were recorded every one hour. Room temperature was maintained in the range of 35 to 36 ^{o}C. The data in this study were used to calculate the heat transfer constants C and n to obtain the value of the convection heat transfer coefficient and mass calculation. This study compares the calculation models of Tiwari, Dunkle and Power. The following calculation model results: Tiwari model, C = 0.082 and n = 0.612; Dunkle model, C = 0.075 and n = 1/3; Power model, C = 0.815 and n = 0.611. The C and n values obtained with these four approaches reveal that the results from the Power model calculation are the closest to the actual mass, showing a percentage deviation of 1.63%.

Keywords: *Solar Still; Distillation; Desalination; Heat Transfer Constant; Convective Coefficient*.

ABSTRAK

Geometri solar still menentukan konstanta perpindahan panas konveksi C dan n, yang pada akhirnya akan mempengaruhi nilai koefisien perpindahan panas konveksi dan massanya. Metode untuk menentukan nilai konstanta perpindahan panas konveksi C dan n telah dikembangkan oleh para peneliti. Oleh karena itu penelitian ini bertujuan untuk mencari nilai konstanta perpindahan panas konveksi C dan n menggunakan beberapa metode dan teori yang kemudian dibandingkan hasilnya dengan hasil penelitian. Solar still yang digunakan adalah solar still dengan satu kemiringan. Untuk mengurangi variabel yang tidak dapat dikendalikan, maka pengambilan data dilakukan di dalam ruangan menggunakan lampu halogen yang dapat diatur tegangannya sebagai sumber

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panas selama 24 jam tanpa henti. Tinggi permukaan air laut didalam solar still dijaga pada ketinggian 20 mm dengan menggunakan pengatur ketinggian. Temperatur diukur dengan menggunakan data logger yang diatur untuk memasukkan data setiap satu jam. Air bersih hasil desalinasi ditampung di dalam botol yang diletakkan di atas timbangan. Hasil timbangan di catat setiap 1 jam. Tenperatur ruangan dijaga pada rentang 35 – 36 oC. Data dalam penelitian ini digunakan untuk menghitung konstanta perpindahan panas C dan n sehingga diperoleh nilai koefisien perpindahan panas konveksi dan massa perhitungan. Studi ini membandingkan model perhitungan Tiwari, Dunkle, dan Power. Hasil model perhitungan berikut: Tiwari C = 0,082 dan n = 0,612; Model Dunkle C = 0,075 dan n = 1/3; Model Power C = 0,815 dan n = 0,611. Nilai-nilai C dan n yang diperoleh dengan empat pendekatan ini mengungkapkan bahwa hasil dari perhitungan model Power adalah yang paling mendekati dengan massa aktual, menunjukkan persentase deviasi 1,63%.

Keywords: *Solar Still; Destilasi; Desalinasi; Konstanta Perpindahan Panas; Koefisien konveksi.*

INTRODUCTION

Fresh water, including springs (Sudarmadji, Suprayogi, Widyastuti, & Harini, 2011) and lakes, accounts for only 2.5% of the water on Earth (Belessiotis, Kalogirou, & Delyannis, 2016). Unfortunately, fresh water is decreasing with an increase in consumption and climate change (Distefano & Kelly, 2017), compounded with breakthroughs of salt water into freshwater aquifers (Nugraha, Marwan, & Muhni, 2019). Because there is a substantial quantity of seawater, it is considered a potential source of fresh water, particularly in countries with a long coastline or that are islands, though it must first be processed using seawater desalination (Chen, Liu, Xue, Yang, & Zhang, 2015).

Seawater desalination is the process of purifying seawater by removing the salt content to produce pure water. The salt in seawater consists mostly of fluoride, hardness factors ($CaCO_3$), sodium sulphate, and potassium (Mugisidi & Heriyani, 2018). The large amount of salt in seawater makes it unsuitable for consumption as drinking water, so the salt level must be reduced by a desalination process. One such process is distillation using a solar still, which uses the sun's heat energy to separate the water and salt. The water evaporates and leaves behind the salt, thereby producing pure water without salt content (Abujazar, Fatihah, Rakmi, & Shahrom, 2016). This process is called solar still desalination (Husham M. Ahmed, 2012). Desalination technology to change seawater into fresh water is very helpful in areas that need clean water, particularly on remote coastline areas. A solar still is one of the most widely used methods (Tabrizi, Dashtban, & Moghaddam, 2010), as it is simple and inexpensive.

However, the productivity of solar stills is presently limited and requires further development. The evaporation process that occurs in a solar still is largely determined by the process of heat transfer, which is influenced by the solar still's geometry. Changes in solar still geometry affect the value of the convection heat transfer coefficient (Elango,C. Gunasekaran, & Sampathkumar, 2015) and, therefore, the amount of clean water produced in the desalination process (El-Bahi & Inan, 1999; Fath & Hosny, 2002). The value of the convection heat transfer coefficient can be determined by changes in the values of the constants C and n (Dwivedi & Tiwari, 2010; Murugan & Elumalai, 2014). The present study's objective was to determine the values of C and n based on the experiment results using several approaches to identify the method that gives values closest to the experimental results.

Solar still energy balance

The energy balance in a solar desalination device is the amount of energy entering the solar still compared to the energy used and the heat loss. Solar desalination is a process that produces water vapour by heating water in a basin. The sun provides the heat, which is absorbed by a black-painted heat absorber and then released to the water in the solar still, increasing its temperature (Srithar & Rajaseenivasan, 2018). The difference in temperature between the water and the inner glass cover causes a pressure difference between the water's surface and the inner glass cover (Boutriaa & Rahmani, 2017). This pressure difference then drives evaporation. Vapour flows to the inner glass cover due to buoyancy and condenses back into water, which is then directed away from the solar still.

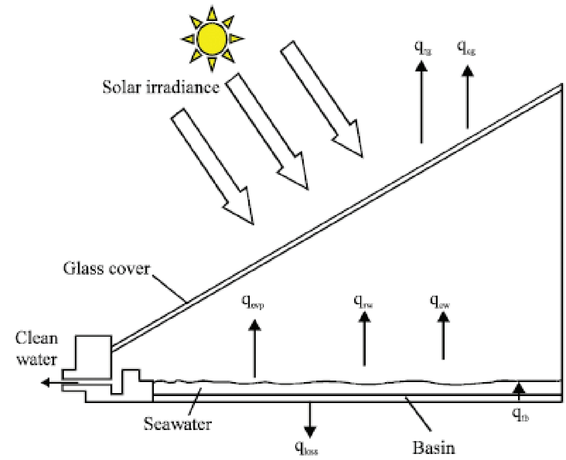

Figure 1.
Energy balance in a solar still
(Yeo, Ong, & Teo, 2014)

The energy balance for the solar still initially presented is (Cooper, 1969):

$$\left(Q_{rwg} + Q_{cwg} + Q_{ewg}\right)A_w + Q_b \cdot A_w + 2 \cdot Q_{sd} \cdot A_{sd} + C_w \cdot A_w \cdot \frac{dT_w}{dt} = I \cdot a_w \cdot A_w \quad (1)$$

Where:

A_w, A_{sd}	Water and side surfaces area [m^2]
a_w	Absorptivity of the water
C_w	Water specific heat capacity per unit of surface area [$J.m^{-2}.K^{-1}$]
I	Incident of solar radiation per hour [$J.m^{-2}.h^{-1}$]
Q_{rwg}, Q_{cwg}, Q_{ewg}	Heat flow between the water in the basin and the cover by radiation, convection and evaporation, repectively [$J.m^{-2}.K^{-1}$]
Q_{sd}	Heat loss from the side walls [$J.m^{-2}.h^{-1}$]
Tw	Water temperature [K]
dt	Time interval [h]
Q_b	Heat flow from basin bottom [$J.m^{-2}.K^{-1}$]

Evaporation

Evaporation is a process that occurs when water changes into gas or vapour (Speight, 2017). It is driven by the difference between the pressure at the water's surface and in the air above it (Sartori, 2000). Dunkle (1961) presented internal convective, radiative and evaporative as a function of water vapour:

$$q_{e,w-gi} = h_{e,w-gi}\,(T_w - T_{gi}) \quad (2)$$

The evaporation heat transfer coefficient $h_{e,w-gi}$ can be calculated as follows:

$$h_{e,w-gi} = 16{,}273 \text{ x } 10^{-3} \cdot h_{c,w-gi} \cdot \frac{P_w - P_{gi}}{T_w - T_{gi}} \quad (3)$$

Where:

P_w	Water pressure [Pa]
P_{gi}	Inner glass cover pressure [Pa]
T_{gi}	Temperature of inner glass cover [K]

Similarly, the convection coefficient $h_{c,w-gi}$ can be calculated using the following equation (Haddad, Al-Nimr, & Maqableh, 2000):

$$h_{c,w-gi} = 0.884 \times \left(T_w - T_g\right)\left[\frac{(P_w - P_{gi}) \cdot (T_w + 273{,}15)}{268900 - P_w}\right]^{\frac{1}{3}} \quad (4)$$

The overall heat transfer coefficient from water to the inner glass cover is calculated by:

$$h_{t,w-gi} = h_{c,w-gi} + h_{r,w-gi} + h_{e,w-gi} \quad (5)$$

The results of evaporation per hour (m_w) for a solar still are (Soni, Brahmatt, & Patel, 2013):

$$m_w = \frac{h_{e,w-gi}\,(T_w - T_{gi})}{h_{fg}} x3600 \quad (6)$$

where h_{fa} is the latent heat of evaporation.

The evaporation rate can be increased by enlarging either the evaporation or basin area, as evaporation rates increase with surface area (Naim & Abd El Kawi, 2003). Covering the basin with black paint can increase the heat absorption of the solar still's heat absorber and, as a result, increase the heat absorption of the basin. The heat released by the basin will transfer to the water and further increase the amount of water that evaporates from the basin (Fath & Hosny, 2002).

Dimensionless numbers

The dimensionless Nusselt, Rayleigh, Prandtl and Grashoff numbers are a function of convective and evaporative heat transfer in a water to air system. Hence, they are integrated into the energy balance of solar stills (Rubio, Fernández, & Porta-Gándara, 2004). Furthermore, the Nusselt number is developed with contants C and n that are independent of the nature of the fluid used. Constants C and n are influenced by the geometry, where they are empirical constants (Mohamed, Hegazi, Sultan, & El-Said, 2019).

$$Nu = C(Gr.Pr)^n \qquad (7)$$

The result of the multiplication between the Grashoff and Prandtl numbers gives the Rayleigh number.

$$Ra = Gr.Pr \qquad (8)$$

The convection heat transfer coefficient can be obtained from the Nusselt function (El-Bahi & Inan, 1999).

Desalination

Distillation is a change of liquid into vapour, followed by condensation of the vapour back into a liquid (Saputro, Tarigan, Jafri, Mesin, & Cendana, 2016), and is often used in desalination processes. A desalination operation unit is a method used to separate the components contained in a solution or mixture, and it depends on the distribution of these components between the vapour phase and the water phase. Simple desalination (i.e. conventional desalination) is a chemical separation technique that separates two or more components with significantly different boiling points. A mixture can be separated by conventional desalination to obtain pure compounds (Irvandi, Nugroho, & Prastowo, 2017).

Theoretical mass calculation model

The final pure water production in the desalination process is commonly called the yield (C. Elango et al., 2015). Yields can be predicted using equations derived from the calculation models developed by Dunkle (1961). These calculations relate to constants C and n, which vary according to the solar still's geometry. The constants C and n are also used to obtain the Nusselt number, which is ultimately used to determine the value of the convection heat transfer coefficient of a solar still (Elango & Murugavel, 2015).

Dunkle model. The Dunkle model, which provides many correlations for predicting solar still performance, is the first to report calculating variations in the convection heat transfer coefficient that occurs in a solar still (Tsilingiris, 2015). It uses the Nusselt-Rayleigh equation to obtain the convection heat transfer coefficient:

$$Nu = C(Ra.)^n \qquad (9)$$

C = 0,075 and n =1/3

$$h_{e,w-gi} = 0{,}0163\ x\ h_{c,w-gi}\left[\frac{P_w - P_{gi}}{T_w - T_{gi}}\right] \qquad (10)$$

$$h_{c,w-gi} = 0{,}884\ x\ \Delta T^{1/3} \qquad (11)$$

$$\Delta T = (T_w - T_{gi}) + \frac{(p_w - p_{gi})(T_w + 273)}{268.900 - p_w} \qquad (12)$$

The yield can be determined using equation (6).

Tiwari model. Tiwari and Kumar conducted a study to evaluate the existing theoretical models by determining the convective coefficient using experimental data. In their approach, they calculated the constants C and n to determine the Nusselt number and the value of the convection heat transfer coefficient. The Nusselt number for the Tiwari model derivation of the convection heat transfer coefficient can be written as follows (Dwivedi & Tiwari, 2010):

$$N_u = \frac{h_{c,w-g} d_f}{k_f} = C(G_r P_r)^n \qquad (13)$$

or

$$h_{c,w-g} = \frac{k_f}{d_f} C(G_r P_r)^n \qquad (14)$$

where the Grashof and Prandtl numbers are obtained by the following equations.

$$G_r = \frac{\beta g d_f^3 \rho_f^2 (T_w - T_{gi})}{\mu_f^2} \quad (15)$$

$$P_r = \frac{\mu_f C_w}{k_f} \quad (16)$$

$$\mu_f = (T_f \,.\, 0{,}0000000462) + 0{,}00001718 \quad (17)$$

$$\beta = \frac{1}{T_w + 273{,}15} \quad (18)$$

$$\rho = \frac{353{,}44}{T_w + 273{,}15} \quad (19)$$

The desalination output from the solar still during the time *t* can be determined by the following equation:

$$m_{ew} = \frac{0{,}01623}{h_{fg}} x \frac{k_f}{d_f} x C (G_r P_r)^n x (P_w - P_v) A_b x t \quad (20)$$

Where:

$$C_o = \frac{(\sum y)(\sum x^2) - (\sum x)(\sum xy)}{(\sum x^2) - (\sum x)^2} \quad (21)$$

C = exp (C_0) C

Thus, the value of n is:

$$n = \frac{(\sum xy) - (\sum x)(\sum y)}{(\sum x^2) - (\sum x)^2} \quad (22)$$

Where:

b Thermal expansion coefficient [K^{-1}]
g Gravity acceleration [m/s^2]
df Average distance between the water surface and glass cover [m]
r_f Density (kg/m3)
m_f Dynamic viscosity (Ns/m2)
k_f Thermal conductivity (W/m °C)

Power model regression. The Power model determines the convection heat transfer constants C and n using empirical correlations or power-law equations to approach or to obtain the same pattern as the mass of the experimental results (Mohamed et al., 2019). In this model, the values of C and n are obtained from the Nusselt-Rayleigh curve, calculated from equation (13) (Nazar, 2017). Here, $h_{e,w-gi}$ is calculated from equation (6) using the experimental results and then used to calculate the convection heat transfer coefficient in equation (10) (Elango. C et al., 2015).

METHOD

The aim of this study was to determine the output of fresh water resulting from the desalination process in a solar still and to determine the heat transfer constants C and n at the theoretical mass that is closest to the real conditions.

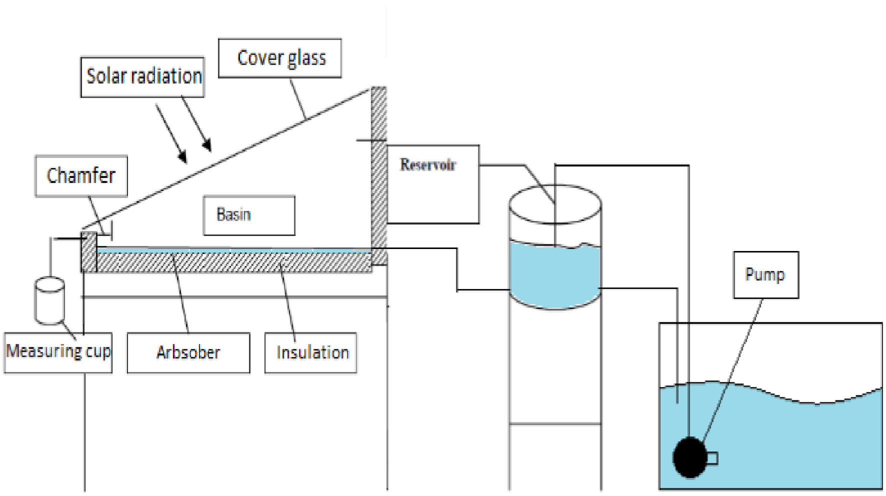

Figure 2
Schematic diagram of the experiment

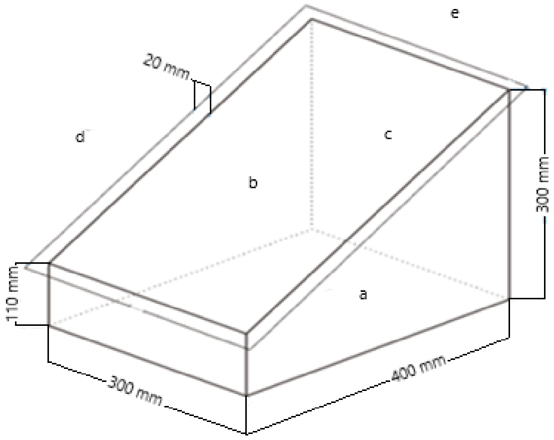

Figure 3
Desalination unit. Measurement point:
a = water temperature, b = evaporation temperature, c= inner glass temperature, d = solar radiation, e = ambient temperature

Figure 4
Indoor solar still experimental setup

Temperature data were collected using a J-type thermocouple connected to an ADAM 4018+ temperature data logger. Temperatures were taken hourly. Solar intensity was measured using a solar power meter, and yields were measured by weighing, using a load cell, with data collected hourly. An ambient temperature was maintained at 35–36 ^{o}C. All experiments were carried out indoors in the Energy Conversion Laboratorium, Uhamka Technical Faculty, Jakarta, Indonesia.

The solar still (Figure 4) was constructed of 3 mm aluminium and insulated with 40 mm Styrofoam. The heat absorber of the solar still was painted with black, conductive paint. The experiment was conducted continuously for 24 h using a 1000 watt halogen bulb with the arrangement for a solar simulator (Moria, 2017).

RESULTS AND DISCUSSION

The parameters that affect water yield in a solar still are water temperature (^{0}C), vapour temperature (^{0}C), bottom glass temperature (^{0}C), ambient temperature (^{0}C) and radiation intensity (W/m^{2}).

In this experiment, seawater was pumped into the level control box, which was connected to the solar still. The water level inside the solar still was as high as in the level control box. The height was maintained using an overflow channel. The level control box had an overflow channel with a height of 2 cm from the bottom. The overflow flowed back into the reservoir.

In this basin-type, solar-still device, evaporation occurs because of the difference in saturation pressure at the surface of the water and the pressure in the evaporation chamber. The pressure difference between the water and the vapour in the evaporation chamber causes the water vapour to move spontaneously from high to low pressure (Frank P. Incropera David P. Dewitt, Theodore L. Bergman, 1993). The difference in pressure is proportional to the difference in temperature between the water and the space above it. The higher the temperature, the higher the pressure at that point (Elango. T & Kalidasa Murugavel, 2015).

The halogen lamp heats the base of the solar still, which then sends some of the heat flow into the seawater above it. The increase in water temperature increases the pressure on the surface of the water, causing evaporation. Water vapour rises to the top because of its buoyancy and condenses on the inner surface of the cover glass. The water temperature is higher than the evaporation temperature, which indicates that the evaporation process has occurred due to pressure differences caused by temperature differences (Anggara, Widhiyanuriyawan, & Sasongko, 2016).

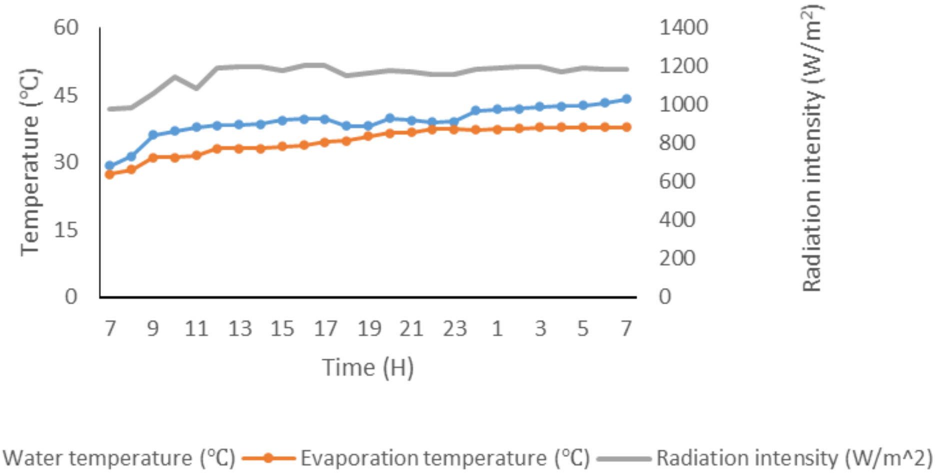

Figure 5
Water temperature air (T_w) and evaporation temperature (T_v) at pada radiation intensity 900 W/m²–1000 W/m²

The experimental results, shown in Figure 5, were then used to calculate the values of C and n using the three methods. These constants C and n determine the value of the Nusselt number, as in equation (13), and are then used to obtain the convection heat transfer coefficient in the system (Rahmani, Boutriaa, & Hadef, 2015).

Dunkle model

The values of the constants C and n in the Dunkle model are C = 0.075 and n = 1/3, using equation (10) to obtain the convection heat transfer coefficient (Rahmani et al., 2015). Furthermore, equation (11) can be used to obtain the value of h_cw in the Dunkle model, while the yield can be determined using equation (6).

Tiwari model

Tiwari used equations (21) and (22) to obtain the constants C and n, where the values of x and y are the results of experimental data (Dwivedi & Tiwari, 2010). In the Tiwari model, the value of the theoretical mass can be obtained using equation (20). From Tiwari's model, the constants C and n are 0.082 and 0.611, respectively.

Power model

While at their base, the Tiwari and Power models use a regression formula, the Power model is simpler than the Tiwari one. The convection heat transfer coefficient is calculated using the following equation:

$$h_{ew} = \frac{mw\ .L_{ev}}{(T_w - T_v).3600} \quad \text{.......................................(23)}$$

The result from equation (23) is then substituted into equation (24):

$$h_{cw} = \frac{h_{ew}}{0{,}0163\ x \left[\frac{P_w - P_v}{T_w - T_v}\right]} \quad \text{.................................(24)}$$

The Nusselt number can then be determined from the water convection heat transfer coefficient:

$$N_u = h_{c,w}\frac{d_f}{k_f} \quad \text{...(25)}$$

Rayleigh numbers can be obtained by multiplying the Grashoff numbers and Prandtl numbers. The values of the constants C and n in this model can be obtained using the Nusselt-Rayleigh graph, where y is the Nusselt number and x is the Rayleigh number, as shown in Figure 6.

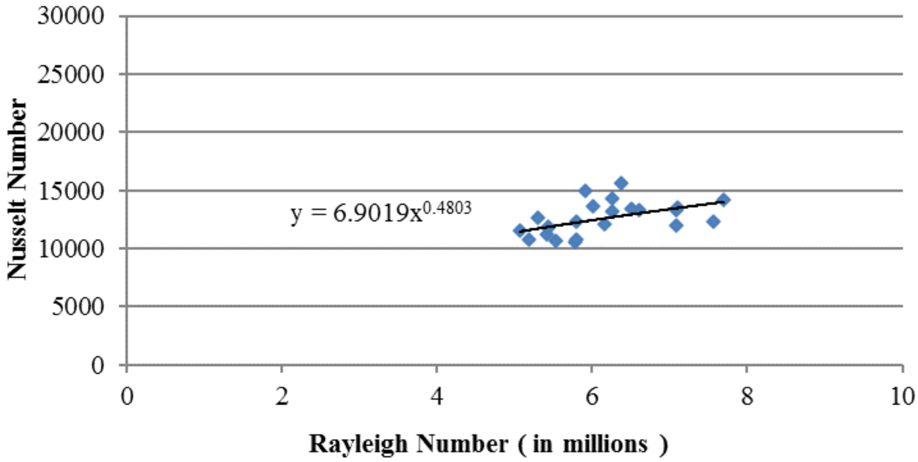

Figure 6
Rayleigh-Nusselt graph for determining constants C and n

In Figure 6, the line follows the equation $y=6{,}902x^{0{,}4803}$. Although the lines are not very fit with the data, the equation of the line obtained using with power regression can be compared to the equation $Nu = C(R_a)^n$, the value of the constant C and n can be determined as 0,8154 and 0.6119, respectively.

The convective and evaporative heat transfer coefficients are shown in Figure 7.

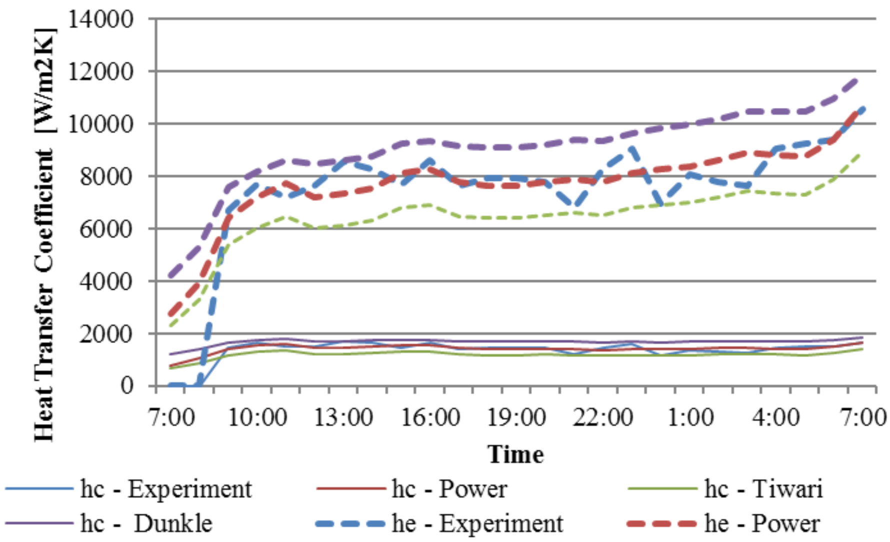

Figure 7
Convective and evaporative heat transfer coefficients

The evaporation heat transfer coefficient (he) in Figure 7, for the Tiwari, power and Dunkle models is obtained from the calculation using equation (3) while the convection heat transfer coefficient is obtained using equation (14). It appears that the heat transfer coefficient calculated by the values of the constants C and n obtained using the power model is closer to the experimental results and looks like the average value of the heat transfer coefficient of the experiment, compared to the results obtained using the Tiwari and Dunkle models. This heat transfer coefficient is used to calculate the yield of fresh water obtained. The calculation results are compared with the experimental results and are shown in Figure 8.

Figure 8 shows that the mass flow rate of each model gives different results. The approach with the Power model match the experimental results. as can be seen, the daily mass accumulation of clean water calculated by the constants C and n resulting from the power model is coincide to the daily mass accumulation of clean water from the experimental results.

The mass of clean water calculated by the heat transfer coefficient C and n of the Tiwari model gets lower yields, while those calculated using Dunkle get higher yields. The deviation of the mass of clean water from experimental results with the mass of clean water from calculations using the heat transfer constants C and n in the power, Tiwari and Dunkle methods are 1.69%, 15.12% and 19.11%, respectively.

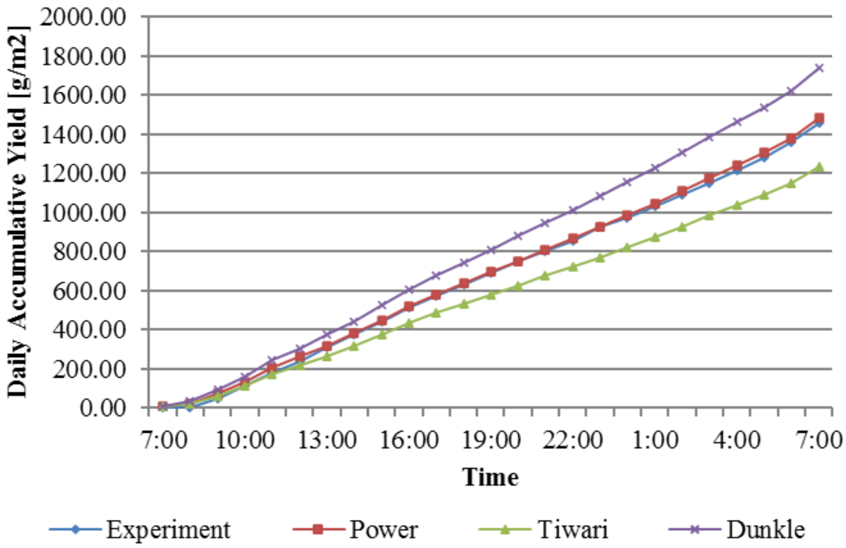

Figure 8
Calculated and experimental yields

CONCLUSION

The results for the convection heat transfer constants C and n of each model are as follows. The Dunkle model gives values for C and n of 0.075 and 1/3, respectively, and the calculated yields are 1737,01 g/h. The result of the Tiwari model gives values for C and n of 0.082 and 0.6119, respectively, and the daily calculated yields are 1237,86 g/h. Finally, the Power model gives values for C and n of 0.8154 and 0.6119, respectively. The calculated yields are 1482,04 g/h. The experiment's daily cumulative yields are 1458 g/h.

Based on research conducted using the three calculation models, the Power model calculation produces the result closest to the experimental yields, with an deviation percentage of 1,69%.

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Dan Mugisidi - DETERMINATION OF THE CONVECTIVE HEAT TRANSFER CONSTANT (C AND N) IN A SOLAR STILL: PENENTUAN KONSTANTA PERPINDAHAN PANAS KONVEKSI (C DAN N) UNTUK SOLAR STILL

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DETERMINATION OF THE CONVECTIVE HEAT TRANSFER CONSTANT (C AND N) IN A SOLAR STILL

PENENTUAN KONSTANTA PERPINDAHAN PANAS KONVEKSI (C DAN N) UNTUK SOLAR STILL

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ABSTRACT

The geometry of a solar still determines the convection constants C and n, which in turn affect the convection heat transfer coefficient's value and mass. A method for determining the value of convection heat transfer constants C and n has already been developed by the researchers. Therefore, this study aimed to use several methods and theories to find the value of convection heat transfer constants C and n. The results are then compared with the results of the study. The solar still used in this study has one slope. To reduce variables that cannot be controlled, the data collection was conducted indoors using a halogen lamp that can be regulated as a heat source for 24 hours nonstop. The sea surface height in the solar still was maintained at a height of 20 mm, using a height regulator. Temperature was measured using a data logger set to enter data every hour. The desalinised clean water was stored in bottles placed on scales that were recorded every one hour. Room temperature was maintained in the range of 35 to 36 °C. The data in this study were used to calculate the heat transfer constants C and n to obtain the value of the convection heat transfer coefficient and mass calculation. This study compares the calculation models of Tiwari, Dunkle and Power. The following calculation model results: Tiwari model, C = 0.082 and n = 0.612; Dunkle model, C = 0.075 and n = 1/3; Power model, C = 0.815 and n = 0.611. The C and n values obtained with these four approaches reveal that the results from the Power model calculation are the closest to the actual mass, showing a percentage deviation of 1.63%.

Keywords: *Solar Still; Distillation; Desalination; Heat Transfer Constant; Convective Coefficient.*

ABSTRAK

Geometri solar still menentukan konstanta perpindahan panas konveksi C dan n, yang pada akhirnya akan mempengaruhi nilai koefisien perpindahan panas konveksi dan massanya. Metode untuk menentukan nilai konstanta perpindahan panas konveksi C dan n telah dikembangkan oleh para peneliti. Oleh karena itu penelitian ini bertujuan untuk mencari nilai konstanta perpindahan panas konveksi C dan n menggunakan beberapa metode dan teori yang kemudian dibandingkan hasilnya dengan hasil penelitian. Solar still yang digunakan adalah solar still dengan satu kemiringan. Untuk mengurangi variabel yang tidak dapat dikendalikan, maka pengambilan data dilakukan di dalam ruangan menggunakan lampu halogen yang dapat diatur tegangannya sebagai sumber

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panas selama 24 jam tanpa henti. Tinggi permukaan air laut didalam solar still dijaga pada ketinggian 20 mm dengan menggunakan pengatur ketinggian. Temperatur diukur dengan menggunakan data logger yang diatur untuk memasukkan data setiap satu jam. Air bersih hasil desalinasi ditampung di dalam botol yang diletakkan di atas timbangan. Hasil timbangan di catat setiap 1 jam. Temperatur ruangan dijaga pada rentang 35 – 36 oC. Data dalam penelitian ini digunakan untuk menghitung konstanta perpindahan panas C dan n sehingga diperoleh nilai koefisien perpindahan panas konveksi dan massa perhitungan. Studi ini membandingkan model perhitungan Tiwari, Dunkle, dan Power. Hasil model perhitungan berikut: Tiwari C = 0,082 dan n = 0,612; Model Dunkle C = 0,075 dan n = 1/3; Model Power C = 0,815 dan n = 0,611. Nilai-nilai C dan n yang diperoleh dengan empat pendekatan ini mengungkapkan bahwa hasil dari perhitungan model Power adalah yang paling mendekati dengan massa aktual, menunjukkan persentase deviasi 1,63%.

Keywords: *Solar Still; Destilasi; Desalinasi; Konstanta Perpindahan Panas; Koefisien konveksi.*

INTRODUCTION

Fresh water, including springs (Sudarmadji, Suprayogi, Widyastuti, & Harini, 2011) and lakes, accounts for only 2.5% of the water on Earth (Belessiotis, Kalogirou, & Delyannis, 2016). Unfortunately, fresh water is decreasing with an increase in consumption and climate change (Distefano & Kelly, 2017), compounded with breakthroughs of salt water into freshwater aquifers (Nugraha, Marwan, & Muhni, 2019). Because there is a substantial quantity of seawater, it is considered a potential source of fresh water, particularly in countries with a long coastline or that are islands, though it must first be processed using seawater desalination (Chen, Liu, Xue, Yang, & Zhang, 2015).

Seawater desalination is the process of purifying seawater by removing the salt content to produce pure water. The salt in seawater consists mostly of fluoride, hardness factors ($CaCO_3$), sodium sulphate, and potassium (Mugisidi & Heriyani, 2018). The large amount of salt in seawater makes it unsuitable for consumption as drinking water, so the salt level must be reduced by a desalination process. One such process is distillation using a solar still, which uses the sun's heat energy to separate the water and salt. The water evaporates and leaves behind the salt, thereby producing pure water without salt content (Abujazar, Fatihah, Rakmi, & Shahrom, 2016). This process is called solar still desalination (Husham M. Ahmed, 2012). Desalination technology to change seawater into fresh water is very helpful in areas that need clean water, particularly on remote coastline areas. A solar still is one of the most widely used methods (Tabrizi, Dashtban, & Moghaddam, 2010), as it is simple and inexpensive.

However, the productivity of solar stills is presently limited and requires further development. The evaporation process that occurs in a solar still is largely determined by the process of heat transfer, which is influenced by the solar still's geometry. Changes in solar still geometry affect the value of the convection heat transfer coefficient (Elango,C. Gunasekaran, & Sampathkumar, 2015) and, therefore, the amount of clean water produced in the desalination process (El-Bahi & Inan, 1999; Fath & Hosny, 2002). The value of the convection heat transfer coefficient can be determined by changes in the values of the constants C and n (Dwivedi & Tiwari, 2010; Murugan & Elumalai, 2014). The present study's objective was to determine the values of C and n based on the experiment results using several approaches to identify the method that gives values closest to the experimental results.

Solar still energy balance

The energy balance in a solar desalination device is the amount of energy entering the solar still compared to the energy used and the heat loss. Solar desalination is a process that produces water vapour by heating water in a basin. The sun provides the heat, which is absorbed by a black-painted heat absorber and then released to the water in the solar still, increasing its temperature (Srithar & Rajaseenivasan, 2018). The difference in temperature between the water and the inner glass cover causes a pressure difference between the water's surface and the inner glass cover (Boutriaa & Rahmani, 2017). This pressure difference then drives evaporation. Vapour flows to the inner glass cover due to buoyancy and condenses back into water, which is then directed away from the solar still.

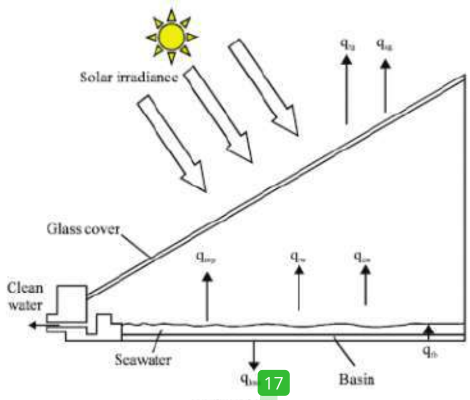

Figure 1.
Energy balance in a solar still
(Yeo, Ong, & Teo, 2014)

The energy balance for the solar still initially presented is (Cooper, 1969):

$$(Q_{rwg} + Q_{cwg} + Q_{ewg})A_w + Q_b \cdot A_w + 2 \cdot Q_{sd} \cdot A_{sd} + C_w \cdot A_w \cdot \frac{dT_w}{dt} = I \cdot a_w \cdot A_w \quad (1)$$

Where:

A_w, A_{sd}	Water and side surfaces area [m^2]
a_w	Absorptivity of the water
C_w	Water specific heat capacity per unit of surface area [J.m^{-2}.K^{-1}]
I	Incident of solar radiation per hour [J.m^{-2}.h^{-1}]
Q_{rwg}, Q_{cwg}, Q_{ewg}	Heat flow between the water in the basin and the cover by radiation, convection and evaporation, repectively [J.m^{-2}.K^{-1}]
Q_{sd}	Heat loss from the side walls [J.m^{-2}.h^{-1}]
Tw	Water temperature [K]
dt	Time interval [h]
Q_b	Heat flow from basin bottom [J.m^{-2}.K^{-1}]

Evaporation

Evaporation is a process that occurs when water changes into gas or vapour (Speight, 2017). It is driven by the difference between the pressure at the water's surface and in the air above it (Sartori, 2000). Dunkle (1961) presented internal convective, radiative and evaporative as a function of water vapour:

$$q_{e,w-gi} = h_{e,w-gi}\,(T_w - T_{gi}) \quad (2)$$

The evaporation heat transfer coefficient $h_{e,w-gi}$ can be calculated as follows:

$$h_{e,w-gi} = 16{,}273 \times 10^{-3} \cdot h_{c,w-gi} \cdot \frac{P_w - P_{gi}}{T_w - T_{gi}} \quad (3)$$

Where:

P_w	Water pressure [Pa]
P_{gi}	Inner glass cover pressure [Pa]
T_{gi}	Temperature of inner glass cover [K]

Similarly, the convection coefficient $h_{c,w-gi}$ can be calculated using the following equation (Haddad, Al-Nimr, & Maqableh, 2000):

$$h_{c,w-gi} = 0.884 \times (T_w - T_g)\left[\frac{(P_w - P_{gi}) \cdot (T_w + 273{,}15)}{268900 - P_w}\right]^{\frac{1}{3}} \quad (4)$$

The overall heat transfer coefficient from water to the inner glass cover is calculated by:

$$h_{t,w-gi} = h_{c,w-gi} + h_{r,w-gi} + h_{e,w-gi} \quad (5)$$

The results of evaporation per hour (m_w) for a solar still are (Soni, Brahmatt, & Patel, 2013):

$$m_w = \frac{h_{e,w-gi}\,(T_w - T_{gi})}{h_{fg}} x3600 \quad (6)$$

where h_{fa} is the latent heat of evaporation.

The evaporation rate can be increased by enlarging either the evaporation or basin area, as evaporation rates increase with surface area (Naim & Abd El Kawi, 2003). Covering the basin with black paint can increase the heat absorption of the solar still's heat absorber and, as a result, increase the heat absorption of the basin. The heat released by the basin will transfer to the water and further increase the amount of water that evaporates from the basin (Fath & Hosny, 2002).

Dimensionless numbers

The dimensionless Nusselt, Rayleigh, Prandtl and Grashoff numbers are a function of convective and evaporative heat transfer in a water to air system. Hence, they are integrated into the energy balance of solar stills (Rubio, Fernández, & Porta-Gándara, 2004). Furthermore, the Nusselt number is developed with contants C and n that are independent of the nature of the fluid used. Constants C and n are influenced by the geometry, where they are empirical constants (Mohamed, Hegazi, Sultan, & El-Said, 2019).

$$Nu = C(Gr.Pr)^n \qquad (7)$$

The result of the multiplication between the Grashoff and Prandtl numbers gives the Rayleigh number.

$$Ra = Gr.Pr \qquad (8)$$

The convection heat transfer coefficient can be obtained from the Nusselt function (El-Bahi & Inan, 1999).

Desalination

Distillation is a change of liquid into vapour, followed by condensation of the vapour back into a liquid (Saputro, Tarigan, Jafri, Mesin, & Cendana, 2016), and is often used in desalination processes. A desalination operation unit is a method used to separate the components contained in a solution or mixture, and it depends on the distribution of these components between the vapour phase and the water phase. Simple desalination (i.e. conventional desalination) is a chemical separation technique that separates two or more components with significantly different boiling points. A mixture can be separated by conventional desalination to obtain pure compounds (Irvandi, Nugroho, & Prastowo, 2017).

Theoretical mass calculation model

The final pure water production in the desalination process is commonly called the yield (C. Elango et al., 2015). Yields can be predicted using equations derived from the calculation models developed by Dunkle (1961). These calculations relate to constants C and n, which vary according to the solar still's geometry. The constants C and n are also used to obtain the Nusselt number, which is ultimately used to determine the value of the convection heat transfer coefficient of a solar still (Elango & Murugavel, 2015).

Dunkle model. The Dunkle model, which provides many correlations for predicting solar still performance, is the first to report calculating variations in the convection heat transfer coefficient that occurs in a solar still (Tsilingiris, 2015). It uses the Nusselt-Rayleigh equation to obtain the convection heat transfer coefficient:

$$Nu = C(Ra.)^n \qquad (9)$$

C = 0,075 and n =1/3

$$h_{e,w-gi} = 0{,}0163\ x\ h_{c,w-gi}\left[\frac{P_w - P_{gi}}{T_w - T_{gi}}\right] \qquad (10)$$

$$h_{c,w-gi} = 0{,}884\ x\ \Delta T^{1/3} \qquad (11)$$

$$\Delta T = (T_w - T_{gi}) + \frac{(p_w - p_{gi})(T_w + 273)}{268.900 - p_w} \qquad (12)$$

The yield can be determined using equation (6).

Tiwari model. Tiwari and Kumar conducted a study to evaluate the existing theoretical models by determining the convective coefficient using experimental data. In their approach, they calculated the constants C and n to determine the Nusselt number and the value of the convection heat transfer coefficient. The Nusselt number for the Tiwari model derivation of the convection heat transfer coefficient can be written as follows (Dwivedi & Tiwari, 2010):

$$N_u = \frac{h_{c,w-g} d_f}{k_f} = C(G_r P_r)^n \qquad (13)$$

or

$$h_{c,w-g} = \frac{k_f}{d_f} C(G_r P_r)^n \qquad (14)$$

where the Grashof and Prandtl numbers are obtained by the following equations.

$$G_r = \frac{\beta g d_f^3 \rho_f^2 (T_w - T_{gi})}{\mu_f^2} \quad (15)$$

$$P_r = \frac{\mu_f C_w}{k_f} \quad (16)$$

$$\mu_f = (T_f \,.\, 0{,}0000000462) + 0{,}00001718 \quad (17)$$

$$\beta = \frac{1}{T_w + 273{,}15} \quad (18)$$

$$\rho = \frac{353{,}44}{T_w + 273{,}15} \quad (19)$$

The desalination output from the solar still during the time *t* can be determined by the following equation:

$$m_{ew} = \frac{0{,}01623}{h_{fg}} x \frac{k_f}{d_f} x C (G_r P_r)^n x (P_w - P_v) A_b x t \quad (20)$$

Where:

$$C_o = \frac{(\Sigma y)(\Sigma x^2) - (\Sigma x)(\Sigma xy)}{(\Sigma x^2) - (\Sigma x)^2} \quad (21)$$

C = exp (C_0) C

Thus, the value of n is:

$$n = \frac{(\Sigma xy) - (\Sigma x)(\Sigma y)}{(\Sigma x^2) - (\Sigma x)^2} \quad (22)$$

Where:

b Thermal expansion coefficient [K^{-1}]
g Gravity acceleration [m/s^2]
df Average distance between the water surface and glass cover [m]
r_f Density (kg/m3)
m_f Dynamic viscosity (Ns/m2)
k_f Thermal conductivity (W/m °C)

Power model regression. The Power model determines the convection heat transfer constants C and n using empirical correlations or power-law equations to approach or to obtain the same pattern as the mass of the experimental results (Mohamed et al., 2019). In this model, the values of C and n are obtained from the Nusselt-Rayleigh curve, calculated from equation (13) (Nazar, 2017). Here, $h_{c,w-gi}$ is calculated from equation (6) using the experimental results and then used to calculate the convection heat transfer coefficient in equation (10) (Elango. C et al., 2015).

METHOD

The aim of this study was to determine the output of fresh water resulting from the desalination process in a solar still and to determine the heat transfer constants C and n at the theoretical mass that is closest to the real conditions.

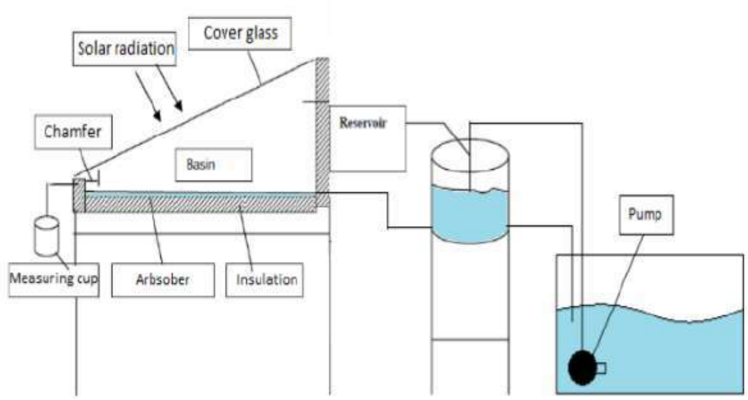

Figure 2
Schematic diagram of the experiment

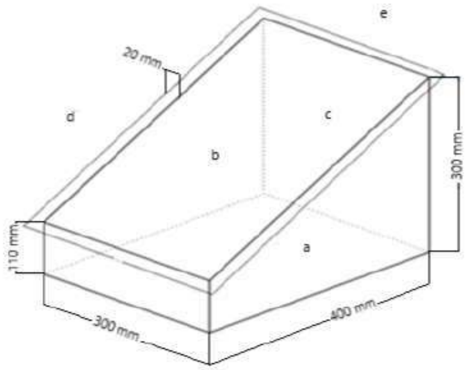

Figure 3
Desalination unit. Measurement point:
a = water temperature, b = evaporation temperature, c= inner glass temperature, d = solar radiation, e = ambient temperature

Temperature data were collected using a J-type thermocouple connected to an ADAM 4018+ temperature data logger. Temperatures were taken hourly. Solar intensity was measured using a solar power meter, and yields were measured by weighing, using a load cell, with data collected hourly. An ambient temperature was maintained at 35–36 °C. All experiments were carried out indoors in the Energy Conversion Laboratorium, Uhamka Technical Faculty, Jakarta, Indonesia.

The solar still (Figure 4) was constructed of 3 mm aluminium and insulated with 40 mm Styrofoam. The heat absorber of the solar still was painted with black, conductive paint. The experiment was conducted continuously for 24 h using a 1000 watt halogen bulb with the arrangement for a solar simulator (Moria, 2017).

RESULTS AND DISCUSSION

The parameters that affect water yield in a solar still are water temperature (°C), vapour temperature (°C), bottom glass temperature (°C), ambient temperature (°C) and radiation intensity (W/m^2).

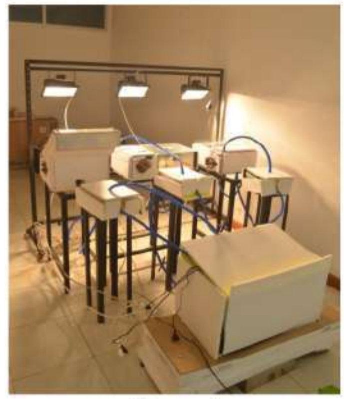

Figure 4
Indoor solar still experimental setup

In this experiment, seawater was pumped into the level control box, which was connected to the solar still. The water level inside the solar still was as high as in the level control box. The height was maintained using an overflow channel. The level control box had an overflow channel with a height of 2 cm from the bottom. The overflow flowed back into the reservoir.

In this basin-type, solar-still device, evaporation occurs because of the difference in saturation pressure at the surface of the water and the pressure in the evaporation chamber. The pressure difference between the water and the vapour in the evaporation chamber causes the water vapour to move spontaneously from high to low pressure (Frank P. Incropera David P. Dewitt, Theodore L. Bergman, 1993). The difference in pressure is proportional to the difference in temperature between the water and the space above it. The higher the temperature, the higher the pressure at that point (Elango. T & Kalidasa Murugavel, 2015).

The halogen lamp heats the base of the solar still, which then sends some of the heat flow into the seawater above it. The increase water temperature increases the pressure on the surface of the water, causing evaporation. Water vapour rises to the top because of its buoyancy and condenses on the inner surface of the cover glass. The water temperature is higher than the evaporation temperature, which indicates that the evaporation process has occurred due to pressure differences caused by temperature differences (Anggara, Widhiyanuriyawan, & Sasongko, 2016).

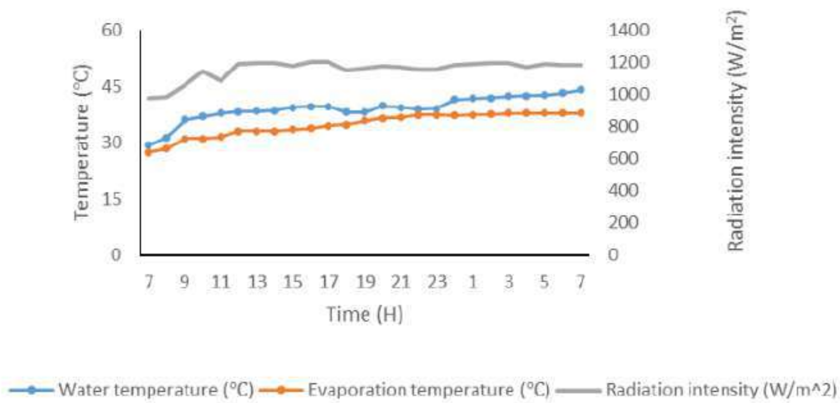

Figure 5
Water temperature air (T_w) and evaporation temperature (T_v)
at pada radiation intensity 900 W/m^2–1000 W/m^2

The experimental results, shown in Figure 5, were then used to calculate the values of C and n using the three methods. These constants C and n determine the value of the Nusselt number, as in equation (13), and are then used to obtain the convection heat transfer coefficient in the system (Rahmani, Boutriaa, & Hadef, 2015).

Dunkle model

The values of the constants C and n in the Dunkle model are C = 0.075 and n = 1/3, using equation (10) to obtain the convection heat transfer coefficient (Rahmani et al., 2015). Furthermore, equation (11) can be used to obtain the value of h_cw in the Dunkle model, while the yield can be determined using equation (6).

Tiwari model

Tiwari used equations (21) and (22) to obtain the constants C and n, where the values of x and y are the results of experimental data (Dwivedi & Tiwari, 2010). In the Tiwari model, the value of the theoretical mass can be obtained using equation (20). From Tiwari's model, the constants C and n are 0.082 and 0.611, respectively.

Power model

While at their base, the Tiwari and Power models use a regression formula, the Power model is simpler than the Tiwari one. The convection heat transfer coefficient is calculated using the following equation:

$$h_{ew} = \frac{mw \, .L_{ev}}{(T_w - T_v).3600} \quad \text{......................................(23)}$$

The result from equation (23) is then substituted into equation (24):

$$h_{cw} = \frac{h_{ew}}{0{,}0163 \, x \left[\frac{P_w - P_v}{T_w - T_v}\right]} \quad \text{................................(24)}$$

The Nusselt number can then be determined from the water convection heat transfer coefficient:

$$N_u = h_{c.w} \frac{d_f}{k_f} \quad \text{..(25)}$$

Rayleigh numbers can be obtained by multiplying the Grashoff numbers and Prandtl numbers. The values of the constants C and n in this model can be obtained using the Nusselt-Rayleigh graph, where y is the Nusselt number and x is the Rayleigh number, as shown in Figure 6.

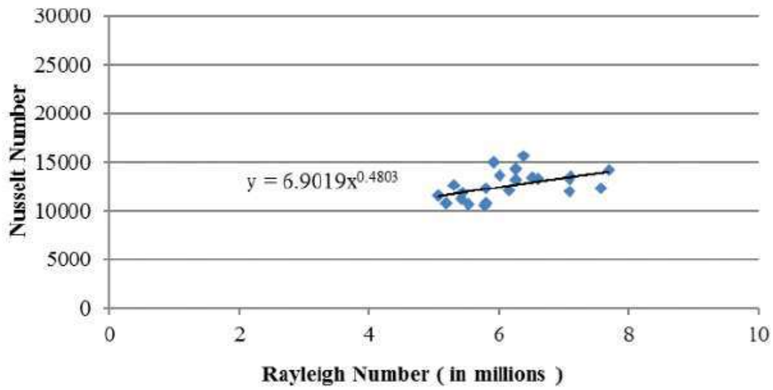

Figure 6
Rayleigh-Nusselt graph for determining constants C and n

In Figure 6, the line follows the equation $y=6{,}902x^{0{,}4803}$. Although the lines are not very fit with the data, the equation of the line obtained using with power regression can be compared to the equation $Nu = C(R_a)^n$, the value of the constant C and n can be determined as 0,8154 and 0.6119, respectively.

The convective and evaporative heat transfer coefficients are shown in Figure 7.

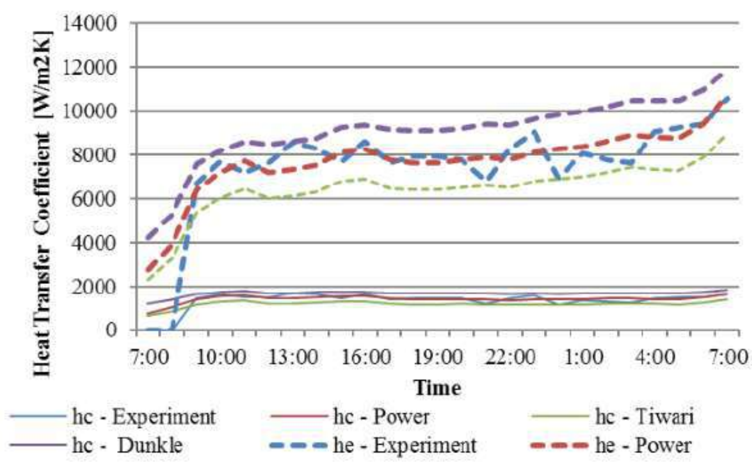

Figure 7
Convective and evaporative heat transfer coefficients

The evaporation heat transfer coefficient (he) in Figure 7, for the Tiwari, power and Dunkle models is obtained from the calculation using equation (3) while the convection heat transfer coefficient is obtained using equation (14). It appears that the heat transfer coefficient calculated by the values of the constants C and n obtained using the power model is closer to the experimental results and looks like the average value of the heat transfer coefficient of the experiment, compared to the results obtained using the Tiwari and Dunkle models. This heat transfer coefficient is used to calculate the yield of fresh water obtained. The calculation results are compared with the experimental results and are shown in Figure 8.

Figure 8 shows that the mass flow rate of each model gives different results. The approach with the Power model match the experimental results. as can be seen, the daily mass accumulation of clean water calculated by the constants C and n resulting from the power model is coincide to the daily mass accumulation of clean water from the experimental results.

The mass of clean water calculated by the heat transfer coefficient C and n of the Tiwari model gets lower yields, while those calculated using Dunkle get higher yields. The deviation of the mass of clean water from experimental results with the mass of clean water from calculations using the heat transfer constants C and n in the power, Tiwari and Dunkle methods are 1.69%, 15.12% and 19.11%, respectively.

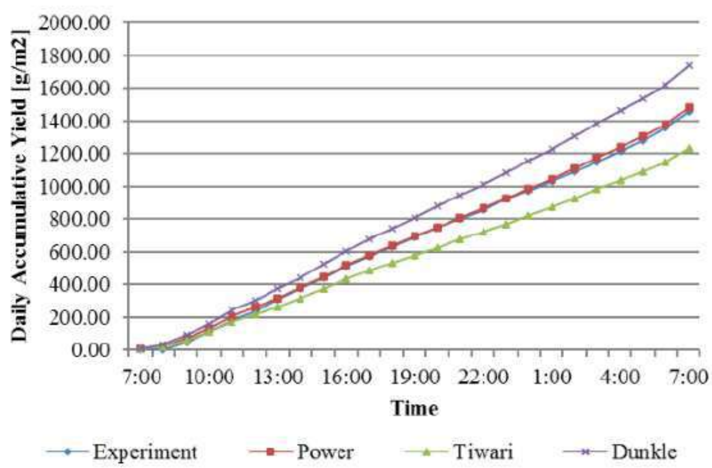

Figure 8
Calculated and experimental yields

CONCLUSION

The results for the convection heat transfer constants C and n of each model are as follows. The Dunkle model gives values for C and n of 0.075 and 1/3, respectively, and the calculated yields are 1737,01 g/h. The result of the Tiwari model gives values for C and n of 0.082 and 0.6119, respectively, and the daily calculated yields are 1237,86 g/h. Finally, the Power model gives values for C and n of 0.8154 and 0.6119, respectively. The calculated yields are 1482,04 g/h. The experiment's daily cumulative yields are 1458 g/h.

Based on research conducted using the three calculation models, the Power model calculation produces the result closest to the experimental yields, with an deviation percentage of 1,69%.

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