Thermal modeling of a controlled environment greenhouse cum solar distillation for composite and warm humid climates of India

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Abstract

The present study is concerned with the analysis of solar desalination system combined with a greenhouse for both composite and warm humid climate of India. Analytical expressions for water temperature, greenhouse room air temperature, glass cover temperature, flowing water mass over the glass cover, hourly yield of fresh water and thermal efficiency have been derived in terms of design and climatic parameters for a typical day of summer and winter period. Temperature rise of flowing water mass with respect to distance and time in solar still unit has also been incorporated in the mathematical modeling. The effects of various still and design parameters on its performances have been discussed in detail. The yield of fresh water was found to be higher in warm humid climate than composite climate.

Keywor!s: Solar energy; Desalination; Controlled environment greenhouse; Thermal modeling

1. Introduction

The increasing pollution of underground water in composite climate and adequately available saline water in warm humid climate necessitates the search of an appropriate technology for supplying fresh water to the vegetation in the open field as well as protected cultivation. Solar distillation unit integrated with greenhouse system may be a viable solution not only for providing the modest demand of good quality water to closed system cultivation, i.e. 10% of the water requirement for irrigation in open field [1] but also maintaining controlled temperature by reducing the effect of solar radiation coming inside the greenhouse. All the incoming solar radiation may not be the cooling load for the greenhouse. About 2% of the total transmitted solar radiation is used in photosynthesis. Though the rate of transpiration varies from crop to crop but 48% of the transmitted solar radiation is used for this process. The rest of the 50% of solar radiation needs to be removed by the cooling system [2]. The utilization of that 50% solar radiation in the
distillation system in conjunction with greenhouse provides dual advantages of reducing cooling load for the greenhouse and also supplying fresh water to the inside plants. Furthermore the diurnal and seasonal fluctuations in the productivity of solar still are intrinsically linked to the fluctuating water requirements of inside plants. The major impediment in making such a system in practice is the requirement of a large basin area to meet the required water demands of the plants. Solar still cannot of course cope with the needs of crop in open field cultivation but literature suggests that the water requirement can be reduced by growing the crop inside the greenhouse and the distillate blended with local groundwater may be an alternative means of supplying necessary quantity of partially good quality water to the plants through low loss micro watering systems [3]. Increasing the volume of irrigation water through blending with f&h water can help in reducing the size of still. Earlier there has been considerable work on the theory and performance evaluation of solar still in combination with greenhouse environment. The idea of mounting a solar still on the top of a glass house to supply fresh water for irrigation purposes was apparently first proposed by Oztoker and Selcuk in 1971 [4]. Tiwari and Dhiman [5] as well as Srivastava et al. [6] have also considered such a system by developing a mathematical model of the glass house with still on the top. The problems encountered by the still on the top of the greenhouse are the accumulation of salt and the growth of algae as well as other micro flora particles on the surface of the stationary brackish water for which the transmission of solar radiation to the water used in still decreases resulting in reduction of output of the system. Recently Chaibi [7] suggested the improved concept of uniformly flowing thin water film on the glass cover of the inclined roof of the greenhouse. In his analysis the following factors are not taken into consideration:

(i) effect of length of roof on the output of fresh water;
(ii) effect of design and climatic parameters on greenhouse room air temperature; and
(iii) influence of $F$, (solar fraction) on the productivity of fresh water.

In this paper an attempt has been made to incorporate the temperature rise of the flowing water mass with respect to length and time for developing a more accurate model suitable for a closed system uneven span greenhouse with integrated water desalination unit. Numerical computations were done for typical days i.e., 15 June 2001 and 15 January 2002 both in the warm humid climate of Chennai as well as the composite climate of Delhi, India. The concept of composite climate [8] has been applied in the region where any of the climates like hot, dry, cold, cloudy, warm humid etc., does not prevail for six months or more in a year. The model based on a set of heat balance equations for the above system has been solved with the help of computer programming on Matlab software.

2. Description and basic principle of gmnhouse cum distillation unit

A schematic sketch of the greenhouse with an integrated solar still on the south roof as considered by Chaibi is shown in Fig. 1a. Both north roof and north wall of the greenhouse are taken opaque for the study. The south roof in which solar still concept has been applied is divided into two enclosures. The upper enclosure comprises of outer glass cover and inner transparent absorber. Water is allowed to flow in this enclosure from brackish water storage tank. The air space between transparent layer and insulating layer, i.e. south roof of the greenhouse in inner enclosure, is used for reducing heat conduction and then convection to greenhouse air. As a result, maximum utilization of thermal energy occurs for better distillation. The flesh water produced in solar distillation process may be blended with available brackish water to improve its quality for irrigation purposes. The basic principle for the above system is that solar radiation after transmission through outer glass cover and brackish water layer in the upper
enclosure is absorbed by the transparent absorber. A part of absorbed solar energy is convected to the water layer and the rest is conducted to inner enclosure. The water gets heated. There occurs radiative, convective and evaporative heat loss from the water layer to the inner surface of the glass cover. The evaporated water is condensed on the inner surface of the glass cover. The condensed water is trickled down under gravity to fresh water trough. The latent heat of condensation and radiative as well as convective heat received by the glass cover is lost to the ambient by convection and radiation. The rest of the absorbed energy transferred to the insulation layer is convected and radiated to the greenhouse environment for thermal heating. The distilled water obtained can be used for irrigation of plants in the greenhouse.

3. Thermal analysis

The energy balance equations for different components of the greenhouse cum solar still are written on the basis of following assumptions:

(a) The analysis is based upon quasi steady state condition.
(b) Heat capacity of greenhouse cover, materials inside the greenhouse and glass cover are negligible.
(c) No absorption of solar radiation in glass and greenhouse covers.
(d) Radiation exchange between walls and roofs is negligible.
(e) The temperature gradient along the thickness of glass cover and moving water film has not been considered.
(f) The moist air at different surfaces of solar still is saturated.
(g) Heat conduction through the bottom of still and ground is one-dimensional.

The energy balances of the system components are expressed as follows:

**Glass cover:**

\[ h(t_w - t_s) = U(t_w - t_a) \]  \hspace{1cm} (1)

**Flowing water mass:**

by referring to Fig. 1b, energy balance for the
Fig. 1b. Element thickness, dx of flowing water mass along south roof of greenhouse.

Flowing water mass for an elemental length, \(dx\) and width, \(b\) can be written as:

\[
\frac{m_w C_w}{dx} \frac{dT}{dx} = [-a_s \Phi(t) - h_1(T_w - T_g)] - \left( U_n (T_w - T_r) \right) bdx
\]  

(2)

**Insulating north wall of greenhouse:**

\[
\alpha_n \left( \sum (A_\tau \tau_i) \right) F_n = h_{c,n}(T_n - T_a) A_n + h_{id}(T_n - T_a) A_n
\]

(3)

**Floor of greenhouse:**

\[
\alpha_f \left( \sum (A_\tau \tau_i) \right) (1 - F_n) = h_{c,f}(T_f - T_r) A_f + h_{a,f}(T_f - T_a) A_f
\]

(4)

**Greenhouse room enclosure:**

\[
(1 - \alpha_n) \left( \sum (A_\tau \tau_i) \right) F_n + \left( \sum (A_\tau \tau_i) \right) (1 - F_n) + U_i (T_w - T_r) A_n + h_{c,n}(T_n - T_r) A_n + h_{i,n}(T_f - T_r) A_f
\]

\[= 0.33 NV (T_r - T_a) + h_{a,f}(T_f - T_a) A_f + \sum (A U_i) (T_r - T_a) + M_a C_a \frac{dT_r}{dt}
\]

(5)

Substituting Eq. (1) in Eq. (2) and eliminating \(T_g\), the solution of Eq. (2) becomes:

\[
T_w = f(t) (1 - R) + H_n (1 - R) + R T_M
\]

where:

\[
f(t) = \frac{a_p i (l + U_i T_a)}{a_p + U_i T_a}
\]

Similarly rearranging Eq. (3) in terms of \((T_g - T_r)\), the new equation becomes:

\[
h_{c,n}(T_n - T_r) = F_f \alpha_n \left( \sum (A_\tau \tau_i) \right) F_n A_n
\]

(7)

Likewise rearranging Eq. (4) in terms of \((q_f - T_r)\), the new equation becomes:

\[
F_f \left( \sum (A_\tau \tau_i) \right) (1 - F_n) A_f
\]

(8)

Now substituting Eqs. (6), (7) and (8) in Eq. (5) and after rearranging, final equation can be written in the following form:

\[
R = \frac{1 - e^{-a}}{A L}
\]

\[H = \frac{U_i}{U_i + U_f}
\]

and

\[A = \frac{(U_i + U_f) b}{m_w C_w}.
\]

(9)

Where:

\[
a = \left[ 0.33 N V + h_{f,n} A_f + \left( \sum (A U_i) \right) + U_i A_n
\]

\[+ U_f A_f + U_f A_n, \{1 - H(l - R)\} \frac{dT}{dt} + \frac{F_f(0 + (c A 4 L r_n)}{M_a C_a}
\]

\[F_f(t) = \frac{F_f(0 + (c A 4 L r_n)}{M_a C_a}
\]
\[ F(t) = F_0 + R_2 + F_1 a_1 F_n + F_2 a_2 (1 - F_n) \]
\[ \{ \sum (A_i \tau_i I_i) \} + (U_f f(t)(1 - R) + T, i R) A \]

Expressions for various heat transfer coefficients used in the above equations are given in the Appendix.

\[ \{UA\}_{ef} = U_A A_n + U_f A_f + h_a A_f + \{ \sum (A_i U_i) \} \]
+ \(0.33NV\)

\[ \{ \sum (A_i \tau_i I_i) \} = A_e I_e + A_{nw} I_{nw} + A_{w} I_w \]
\[ \sum (A_i U_i) = A_e U_e + A_{nw} U_{nw} + A_{w} U_w \]
\[ + A_s U_s + A_{nr} U_{nr} \]

\[ R_e = (1 - a_e) \quad \text{and} \quad R_n = (1 - a_n)(1 - F_n) \]

In order to obtain the analytical solution of Eq. (9), the following assumptions have been made:
(a) time interval \(At\) is small;
(b) function \(B(t)\) is constant i.e., \(I = B(Q)\) for the time interval \(At\).

The solution of Eq. (9) can be written as:
\[ T_r = \frac{B(t)}{a}(1 - e^{-\alpha}) + T_m e^{-\alpha} \quad (10) \]
where \(T_m\) is the temperature of greenhouse air at \(f = 0\).

After knowing \(T_r, T_m,\) and \(T_g\) can be calculated and then rate of evaporation from water to glass cover and hourly yield/unit area can be obtained from the following equations:
\[ \dot{q}_{cw} = h_{cw} (T_w - T_g) \quad (11a) \]
\[ \dot{m}_{cw} = \frac{h_{cw} (T_w - T_g) 3600}{\lambda} \quad (11b) \]

The overall thermal efficiency of the distillation can also be obtained from the following equation:
\[ \eta = \frac{\sum \dot{m}_{cw}}{A_\tau \sum I_\tau x 3600} \quad (12) \]

4. Numerical results and discussion

The hourly variations of ambient air temperature and solar intensity for Delhi and Chennai both during summer as well as winter period have been shown in Fig. 2a and Fig. 2b respectively. The design parameters mentioned in Table 1 have been used for computation of greenhouse air temperature, yield and overall thermal efficiency of greenhouse cum solar still unit. The climatic parameters have also been used to calculate the solar radiation available on each of the walls and roofs of greenhouse by referring Liu and Jordan’s formula [9].

The hourly variations of ambient air temperature, greenhouse room air temperature, brackish water temperature, and glass temperature along with the yield of fresh water for Chennai during summer as well as winter period have been presented in Fig. 3a and Fig. 3b respectively. Thermal performance of integrated solar still has been studied for atypical day of sunny condition in June representing summer time and one in January representing wintertime. Similarly the variations of above parameters for Delhi in summer and winter period are shown in Fig. 4. From these figures it is observed that the greenhouse room temperature is more than water temperature followed by glass and ambient temperature because solar radiation is entering into the room through south, east and west direction resulting in the rise of air temperature. Also the daily production of fresh water is higher in Chennai than Delhi. The lower ambient temperature in warm humid climate for Chennai favors the rate of heat loss due to evaporation resulting in better output than the composite climate in Delhi.

The effect of mass flow rate of brackish water on maximum as well as minimum room temperature and total yield/d for Delhi and Chennai is depicted in Fig. 5a and Fig. 5b respectively as flow rate has an important influence on the productivity of fresh
Fig. 2. Hourly variation of solar intensity and ambient temperature for Delhi and Chennai during (a) summer period and (b) winter period.
Fig. 3. Hourly variation of various temperature and yield for Chennai during (a) summer period and (b) winter period.
Table 1
Design parameters for greenhouse cum solar still

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Heat transfer coefficients and their values, Wm⁻²°C⁻¹</th>
<th>Area of walls/roofs and their values, m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>6m</td>
<td>1.87</td>
<td>A₇                              1.7</td>
</tr>
<tr>
<td>C</td>
<td>2.8 Wm⁻¹m²⁻¹</td>
<td>2.8</td>
<td>A₅                              6.8</td>
</tr>
<tr>
<td>$C_{cl}$</td>
<td>1012 Jkg⁻¹°C⁻¹</td>
<td>5.7</td>
<td>A₆                               2.4</td>
</tr>
<tr>
<td>$C_w$</td>
<td>4190 Jkg⁻¹°C⁻¹</td>
<td>0.043</td>
<td>A₇                               12.0</td>
</tr>
<tr>
<td>F/l</td>
<td>0.01-0.3</td>
<td>1.98</td>
<td>A₈                               8.4</td>
</tr>
<tr>
<td>L</td>
<td>3.6 m</td>
<td>2.8</td>
<td>A₉                               6.0</td>
</tr>
<tr>
<td>$m_w$</td>
<td>0.03-0.15 kg.s⁻¹</td>
<td>2.8</td>
<td>A₁₀                             21.6</td>
</tr>
<tr>
<td>$M_d$</td>
<td>61.2 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>1-3 m s⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V$</td>
<td>51 m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X$</td>
<td>2400x10² kg⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ab</td>
<td>0.4-0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_f$</td>
<td>0.3-0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_n$</td>
<td>0.24.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>0.4-0.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4. Hourly variation of various temperature and yield for Delhi during summer and winter period.
It is evident from these figures that with the increase of mass flow rate the maximum, minimum room temperature and yield both in summer and winter period decreases. Since the increased flow rate of water mass is exposed to sun for a shorter period causing the decreased rate of evaporation and more heat transfer from room air to flowing water. Also it is found that the decrease of maximum room temperature \((AT_{rm})\) in case of Delhi is more than Chennai. It is due to the fact that the room temperature of greenhouse in Delhi is higher than that of Chennai resulting in more heat loss in the former than the latter. However the minimum room temperature does not change significantly with the increase of mass flow rate for winter condition as minimum temperature occurs during off sunshine hour causing negligible change due to the above effect.

The influence of length of the roof of greenhouse, i.e., the length of flowing water mass needs to be emphasized for design as well as over all performance of solar distillation system. The effect of length on room temperature, water temperature and total yield in case of Delhi and Chennai during summer period has been presented in Fig. 6a and Fig. 6b respectively. It is evident from these figures that with increase of length, the yield and water temperature increases but room temperature decreases due to more heat losses through walls. This may be due to the reason that the water absorbs more thermal energy from the upper glass cover while moving longer distance on it. As a result there occurs more evaporation of brackish water for producing higher yield. Also it is observed that the yield increases from 0.5 kg to 4 kg/d by changing the length from 1 m to 4.5 m. The decrease of maximum room air temperature by 5°C during summer period is due to the reduction of heat fluxes to the greenhouse as major part of the transmitted solar radiation is utilized for distillation purposes.

The effect of absorptivity of transparent absorber on hourly yield during summer period for Delhi and Chennai has been illustrated in Fig. 7a and Fig. 7b respectively. It is clear from these figures that output increase from 0.005 to 0.035 kg.m\(^2\) in Chennai and from 0.005 to 0.03 kg.m\(^2\) in Delhi during summer period when the values of absorptivity increase from 0.2 to 0.8. This is due to the fact that by increasing absorptivity, the transparent absorber absorbs more solar radiation resulting in the rise of water temperature for enhancing the rate of evaporation to occur. Similarly the effect of the fraction of incoming solar radiation \((F_s)\) on the yield of fresh water for Delhi and Chennai is depicted in Fig. 8a and Fig. 8b respectively. It is understood from the figures that the distillate output decreases as \(F_s\) increases from 0.10 to 0.70 due to loss of solar thermal energy through north wall to ambient. The effect of mass flow rate on the overall thermal efficiency of solar still is shown in Fig. 9. It indicates that with the increase of mass flow rate the efficiency decreases. It is due to the fact that rate of evaporation decreases with increased mass flow rate resulting in lower output of fresh water.

## 5. Conclusions

Based on the above results, the following conclusions have been drawn:

(a) The rate of increase in the yield of fresh water becomes steady after the length \((L)\) of south roof is 2.5 m (Figs. 6a and 6b).

(b) The yield and the fall in greenhouse maximum room air temperature \((AT_{rm})\) decrease with increase of flow rate.

(c) The yield in Chennai (warm humid climate) is higher than Delhi (composite climate) due to lower ambient temperature in Chennai.

The fresh water obtained from the built-in solar distillation system in the greenhouse can be blended with available brackish water in order to improve its quality for use as irrigation water in protected cultivation.

### Symbols

\[A\] — Area, m\(^2\)
Fig. 5. Effect of mass flow rate on room temperature and total yield during summer and winter period (a) for Delhi; (b) for Chennai.
Fig. 6. Effect of length of greenhouse roof on various temperature and total yield during summer period (a) for Delhi; (b) for Chennai.
Fig. 7. Effect of absorptivity on hourly variation of yield during summer period (a) for Delhi; (b) for Chennai.
Fig. 8. Effect of solar fraction on hourly variation of yield during summer period (a) for Delhi; (b) for Chemk.
Fig. 9. Effect of thermal efficiency on mass flow rate for Delhi and Chennai during summer period.

- $b$ — Width of south roof of greenhouse, m
- $C$ — Air conductance, Wm$^{-2}$C$^{-1}$
- $C_a$ — Specific heat of air, J kg$^{-1}$°C$^{-1}$
- $c_w$ — Specific heat of water, J kg$^{-1}$°C$^{-1}$
- $F_n$ — Solar fraction, dimensionless
- $h_z$ — Total heat transfer coefficient from water surface to glass cover, Wm$^{-2}$°C$^{-1}$
- $h_{d}$ — Overall heat transfer coefficient from greenhouse to ambient through door, Wm$^{-2}$°C$^{-1}$
- $h_i$ — Convective heat transfer coefficient from insulating layer to greenhouse, Wm$^{-2}$°C$^{-1}$
- $h_{l}$ — Convective and radiative heat transfer coefficient from greenhouse to ambient, Wm$^{-2}$°C$^{-1}$
- $h^\wedge$ — Heat transfer coefficient from floor to larger depth of ground through conduction Wm$^{-1}$°C$^{-1}$
- $A_w$ — Convective heat transfer coefficient from water to glass cover, Wm$^{-2}$°C$^{-1}$
- $h_{ev}$ — Evaporative heat transfer coefficient from water to glass cover, Wm$^{-2}$°C$^{-1}$
- $h_{nb}$ — Heat transfer coefficient from north wall to ambient, Wm$^{-2}$°C$^{-1}$
- $h_{nw}$ — Radiative heat transfer coefficient from water to glass cover, Wm$^{-2}$°C$^{-1}$
- $h_{fr}$ — Convective heat transfer coefficient from floor to greenhouse air, Wm$^{-2}$°C$^{-1}$
- $h_{nr}$ — Convective heat transfer coefficient from north wall to greenhouse air, Wm$^{-2}$°C$^{-1}$
- $nt$ — Total solar radiation, Wm$^{-2}$
- $Id$ — Diffused solar radiation, Wm$^{-2}$
- $K_B$ — Thermal conductivity of brick used in north wall of greenhouse, Wm$^{-1}$°C$^{-1}$
- $K_g$ — Thermal conductivity of ground, Wm$^{-1}$°C$^{-1}$
- $K_i$ — Thermal conductivity of insulating layer, Wm$^{-1}$°C$^{-1}$
- $L$ — Length of south roof, m
- $L_B$ — Thickness of brick north wall, m
- $L_g$ — Thickness of ground, m
Z_f  — Thickness of insulating layer, m
m_w  — Mass flow rate of water, kg s^{-1}
\dot{m}_m  — Hourly yield of fresh water per unit area of solar still, kg m^{-2}
M_a  — Total mass of air in greenhouse, kg
N  — Number of air changes/h
P  — Saturated vapor pressure, Pa (Pascal)
\dot{q}_{mw}  — Rate of evaporation loss from water to glass cover, W m^{-2}
t  — Time, s
T  — Temperature, “C
U  — Overall heat transfer coefficient for greenhouse cover, W m^{-2} “C^{-1}
U_f  — Overall heat transfer coefficient from floor to greenhouse and ground, W m^{-2} “C^{-1}
U_i  — Over all heat transfer coefficient from insulating layer to greenhouse air, W m^{-2} “C^{-1}
U_n  — Over all heat transfer coefficient for north wall W m^{-2} “C^{-1}
U_l  — Over all hkat transfer coefficient from insulating layer to greenhouse air, W m^{-2} “C^{-1}
U  — Over all heat transfer coefficient from north roof to greenhouse air and ambient, W m^{-2} “C^{-1}
(UA)  — Over all heat loss from greenhouse, W “C
v  — Velocity of air, m s^{-1}
V  — Volume of greenhouse, m^3

Greek
\alpha  — Absorptivity
\epsilon  — Emissivity
\eta  — Over all efficiency of solar still
\lambda  — Latent heat of vaporization, J kg^{-1}
a  — Stefan’s constant, 5.66 \times 10^4 W m^{-2} “K^{-4}
x  — Transmittivity
\infty  — Infinity (at larger depth)

Subscripts
a  — Ambient
b  — Absorber
d  — Door of greenhouse
ea  — East wall of greenhouse
/l  — Floor of greenhouse
g  — Glass cover
/l  — Different walls and roofs of greenhouse
n  — North wall of greenhouse
r  — Greenhouse room
s  — South wall of greenhouse
w  — Water
nr  — North roof of greenhouse
sr  — South roof of greenhouse
wi  — Inlet water
ww  — West wall of greenhouse
efl  — Effective

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References
Appendix

\[ h_1 = 5.7 + 3.8v \text{[10]} \quad \text{(A.1)} \]

\[ \rho_1 = 2.8 + 3.0v \quad \text{[11]} \quad \text{(A.2)} \]

\[ h = h_{cw} + h_{cw} + h_{cw} \quad \text{[11]} \quad \text{(A.3)} \]

\[ h_{cw} = \varepsilon_{cw} \left[ \frac{(T_2 + 273) - (T_1 + 273)}{T_2 - T_1} \right] \quad \text{(A.4)} \]

\[ \varepsilon_{cw} = -U - L - i \quad \text{[12]} \quad \text{(A.5)} \]

\[ K_w = 0.884 \left[ (T - T_2) \cdot \frac{(P_w - P)(T_2 + 273)}{268 \times 1.1 \times 10^3} \right]^{1} \quad \text{(A.6)} \]

\[ h_{cw} = 16.2 \times 10^{-3} h_{cw} h_{cw} \frac{P - P}{T_2 + 273} \quad \text{[13]} \quad \text{(A.7)} \]

\[ P_g = \exp \left[ 25.317 \frac{5144}{T_g + 273.15} \right] \quad \text{[14]} \quad \text{(A.8)} \]

\[ P_w = \exp \left[ 25.317 \frac{5144}{T_w + 273.15} \right] \quad \text{[15]} \quad \text{(A.9)} \]

\[ U_{r} = \left[ \frac{1}{h_1 + h_0} \right]^{-1} \quad \text{[16]} \quad \text{(A.10)} \]

\[ U_{r} = \left[ \frac{1}{C_N \cdot L \cdot h_1} \right]^{-1} \quad \text{(A.11)} \]

\[ U_{w} = \left[ \frac{1}{h_1 + \frac{L_w}{K_w} + \frac{1}{h_0}} \right]^{-1} \quad \text{(A.12)} \]

\[ h_{eb} = \left[ \frac{L}{K_B} + \frac{1}{h_0} \right]^{-1} \quad \text{(A.13)} \]

\[ U_{r} = \left[ \frac{L}{K_B} + \frac{1}{h_0} \right]^{-1} \quad \text{(A.14)} \]

\[ U = U_{r} = U_{w} = U_{s} = \left[ \frac{1}{h_1 + h_0} \right]^{-1} \quad \text{(A.15)} \]

\[ h_{cw} = h_{i} \quad \text{(A.16)} \]

\[ h_{cw} = h_{i} \quad \text{(A.17)} \]

\[ h_{fr} = h_{i} \quad \text{(A.18)} \]

\[ h_{d} = \left[ \frac{1}{h_1 + h_0} \right]^{-1} \quad \text{(A.19)} \]

\[ U_{f} = \left[ \frac{1}{K_{fr} + h_{d}} \right]^{-1} \quad \text{(A.20)} \]