A Study on the Greenhouse Water Curtain System : Heat Transfer Characteristics

Suh, Won Myung*, Han, Gill Young**

**Associate professor, Agricultural Engineering Dept., Gyeongsang National University*
***Junior researcher, Cash Crops division, Gyeongnam Provincial Rural Development Administration*

Abstract ☐ Energy balance equations Were developed to describe the heat transfer mechanisms in a double layer plastic greenhouse with a water curtain system. Heat transfer variables were determined by using various temperature data measured in a conventional prototype semicircular cross-section greenhouse over a range of water temperatures and water flow rates. The heat transfer coefficient between flowing water and greenhouse air was independent of water flow rates. But the heat transfer coefficient between water surface and the stagnant air space within the double plastic layer was dependent on water flow rates. Substituting the heat transfer coefficients, determined from the energy balance equations in the heat transfer equations, demonstrated various relationships among ambient air temperature, greenhouse air temperature, water temperature, and water flow rates. The heating benefits were linearly related to not only the inside and outside air temperatures but also to the water temperature. The energy conservation effects of the water curtain system were found even initial water temperatures were considerably lower than the greenhouse setting temperatures. Sensitivity analysis for heat transfer coefficients demonstrated that the heat transfer coefficient between greenhouse air and the stagnant air within the plastic layers was the most significant coefficient in the estimation of heating effects.

Keywords ☐ Water Curtain System, Greenhouse, Simulation, Energy Conservation, Heat Transfer Characterisitics, Heating benefit, Sensitivity, Heat Transfer Coefficients.

I. INTRODUCTION

The greenhouse water curtain system is one of the useful energy saving techniques adopted for supplementary heating the inside air or reducing heat loss through cover film by spraying warm water such as ground water, power plant waste water, or hot spring water, on the greenhouse roof surface. The thin layer of water, flowing over the greenhouse roof, plays a role of additional thermal resistance between the greenhouse and outside environment. The major effect of the water curtain system is the reduction of heat loss from the warm greenhouse to the cool outside air. The warmer the water temperature and the greater the water flow rate, results in the greater the energy conservation effect obtained. Even when the water temperature is lower than the temperature to be maintained inside the greenhouse, considerable amounts of heating energy can be saved because the surface flowing water warms up the external surface of the greenhouse and lowers the temperature difference between inside air and stagnant air through double layers constituting a thermal neutral zone. Though some detrimental effects, such as reduction of light transmissivity derived by inappropriate water quality and surface water freezing, are indicated, the remarkable heat conservation effect of the water curtain system is widely recognized. Because, in any case, the supplemental heating system is required for the precaution against severe cold weather, the water freezing problem can be avoided and also the reduction of light transmissivity can be easily surmounted by simple modification.

Inowoe, et al. (1981) investigated the effect of water curtain systems by setting up the relationship between the water flow rate and the greenhouse temperature difference from air temperature. They sprayed about 17℃ of ground water at the rate of 512 L/m per 10a of greenhouse floor area. They reported that surface heating was effective when the minimum atmosphere temperature was lower than 5℃ and that the temperature difference between inside and outside air increased by 3-4℃ per every 5℃ drop in minimum outside air temperature.

Walker (1978) studied the relationships between roof surface flowing water temperature (W), greenhouse inside air temperature (G), and outside atmosphere temperature (A) : for a water flow rate of 0.094 L/s per m^2, $G=-2.70+0.642W+0.358A$. The temperature of water leaving the greenhouse was approximately equal to the inside air temperature.

Walker (1979) presented the early history of suface heating technology in the USSR. He demonstrated surface heating of a greenhouse by spraying water over a 3.7×7.3 m greenhouse through a nozzle. The water sprayed was the power plant cooling water. Various heat transfer variables were determined in the laboratory for surface-heated glass and corrugated fiberglass over a range of water flow rates. A 2.4 m long × 1.2 m wide × 0.6 m deep wooden box was used for his experimentation. Heat transfer coefficients for glass were found to be independent of the water flow rate at the range of 200 to 1,000 L/h. The length of the water flow path was not an important consideration for the glass greenhouse.

Walker (1982) found the surface heating system provided an 26-percent energy savings over resistance heating The water flow rate was maintained at a constant 0.04 L/s per m^2 of floor area. The heat transfer coefficient between the water and the outside air, U_{wa}, was calculated using the energy balance equation and a value for U_{wg} of 10.1 W/m^2·℃ was used. A regression analysis of the heat transfer coefficients between the water and the outside air revealed that the most important independent variable in the regression was wind speed.

Chiaple et al. (1977) studied a solar greenhouse in which a water solution containing 1%-2% of $CuCl_2$ flowed through a double translucent roof. The roof was connected to a pool for heat storage. During the night, the excess heat stored during the day was used for heating. They suggested various potential advantages of recirculation using a special gradient water solution, such as $CuCl_2$, through double translucent layers. These advantages are : 1) raising solar energy efficiency, 2) improving the qualitative and quantitative radiation effect, 3) reducing water requirements by maintaining a higher water potential.

A double layer polyethylene covered greenhouse was used for this study. The water was pumped to a perforated PVC outlet pipe located at the top of the inside roof section. Water was applied to the inside roof surface through the nozzles mounted on the outlet pipe at 100 cm intervals. Whenever necessary the water was heated to the desired temperature with 5-Kw electric heater.

The objectives of this study are as follows :

1. To determine the effects of the water flow rate on the surface heat transfer of a double layer plastic greenhouse.
2. To simulate the energy conservation effects of the water curtain system under various night time conditions, such as, water flow rates, spraying water temperatures, air temperatures, and desired greenhouse setting temperatures.
3. To analyze the sensitivity of heat transfer coefficients involved in modelled energy balance equations.

II. THEORY

Heat transfer in greenhouse results from a combination of conduction, convection, radiation, and mass transfer mechanisms. At this stage, the available data to consider in this heat transfer mechanism is limited, and the complexity of this mechanism is doubled in the water curtain system because of the additional factors involved. These additional factors are water flow rate, water temperature, the uniformity of water sprayed over the greenhouse roof, and the complicated environmental conditions within the double plastic layers. For this study, it was assumed that heat is exchanged through four different patterns with an independent heat transfer coefficient ; 1) water surface to greenhouse (U_{wg}), 2) water surface to the space between double plastic cover layer (U_{wb}), 3) inside air to the space between double plastic cover layers (U_{gb}), and 4) inbetween space to outside air (U_{ba}). When these simplified heat transfer coefficients are used in modeling greenhouse water curtain systems, each coefficient represents the combined coefficient for conduction, convection, radiation, and mass transfer of heat flow through the discretized local boundary space. This assumption can be suitable to satisfy the objectives of this study to approximate the energy saving amounts by water curtain systems in double layer plastic greenhouse.

When the water is sprayed on the surface of the lower greenhouse roof, it is cooled down or warmed up by exchanging thermal energy with boundary layers, depending upon the temperature differentials. Generally the water, sprayed over the greenhouse roof for the purpose of energy conservation, loses heat to the greenhouse air and/or the space between the two film layers. With the assumption that the sprayed water is flowing over the whole roof surface uniformly, the heat transferred from the water over a differential interval, dx, of greenhouse roof parallel to the direction of water flow is expressed as follows:

$$dQ_w = \{U_{wg}(t_w - t_g) + U_{wb}(t_w - t_b)\} \ dx \cdots\cdots (1)$$

Assuming a negligible change in flow rate caused by evaporation during flowing, total heat lost by the water is:

$$dQ_w = -FC \ dt_w \cdots\cdots (2)$$

Combining equations (1) and (2) results in:

$$-FC \ dt_w (U_{wg}(t_w - t_g) + U_{wb}(t_w - t_b))dx \quad (3)$$

Equation (3) can be transformed to:

$$-FC\frac{dt_w}{(t_w - k)} = (U_{wg} + U_{wb})dx \cdots\cdots (4)$$

$$\text{where, } k = \frac{U_{wg} t_g + U_{wb} t_b}{(U_{wg} + U_{wb})}$$

This differential equation can be solved to give

$$-FC \ln(t_w - k)\Big]_{t_{wo}}^{t_w} = (U_{wg} + U_{wb}) \ X\Big]_0^x \cdots\cdots (5)$$

$$\text{or } -FC \ \ln\frac{(t_w - k)}{(t_{wo} - k)} = (U_{wg} + U_{wb}) \ X$$

$$t_w = (t_{wo} - k)\exp\left\{\frac{-X(U_{wb} + U_{wg})}{FC}\right\} + k \cdots\cdots (6)$$

The heat transferred from the running water into the greenhouse throuth a differential distance, dx, is then:

$$dQ_{wg} = U_{wg}(t_w - t_g)dX \cdots\cdots (7)$$

Substituting t_w from equation (6) into equation (7) and solving the differential equation for a water flow path length of L:

$$Q_{wg} = U_{wg}\Big[-FC\frac{(t_{wo} - k)}{(U_{wg} + U_{wb})}[\exp\{-$$

$$L(U_{wg} - U_{wb})/(FC)\} - 1] - (t_g - k)L\Big] \cdots\cdots (8)$$

Replacing Q_{wg}/L with q_{wg} and replacing F/L with f:

$$q_{wg} = U_{wg}[-fC\frac{t_{wo} - k}{(U_{wg} + U_{wb})}[\exp\{-(U_{wg} -$$

$$U_{wb})/(fC)\} - 1] - (t_g - k)] \cdots\cdots (9)$$

The resultant heating benefit, q_b, obtained by the water curtain system is the sum of the heat transferred from the water to the greenhouse, q_{wg}, and the heat to be lost without the water curtain system, q_{ga}:

$$q_b = q_{wg} + q_{ga} \cdots\cdots (10)$$

$$\text{where, } q_{ga} = (1 + \frac{A_{east} + A_{west}}{A_w}) \times \frac{U_{ba} \times U_{gb}}{U_{ba} + U_{gb}} \times (t_g - t_a)$$

A_{east}, A_{west} = surface areas of each end of the greenhouse

A_w = water flowing surface area

III. EXPERIMENTAL WORK

Heat transfer coefficients for U_{wg}, U_{wa}, U_{gb}, and U_{ba} were determined by analyzing measured data collected from the prototype greenhouse equipped with a water curtain system. The experimental greenhouse system was constructed at Weather Station in Gyeongsang National University during the fall of 1989. A 6 × 15 m semicircular cross-section greenhouse was constructed with a peak height of 2.5 m and front height of 1.5 m. The lower layer roof contacting the running water surface was constructed about 40 cm apart from the upper layer. Both layers were covered with 0.06 mm double polyethylene film over a pipe frame. During the night time, the greenhouse was heated by spraying water over the outside surface of its lower layer roof. The water was pumped to a perforated PVC outlet pipe located under the outside roof section. Water was applied to the inside roof surface throuth the nozzles mounted on the outlet pipe at 100 cm intervals. Cucumbers were grown in the greenhouse and supplemental heat was provided by 2-stage electric heater whenever the greenhouse air temperature dropped below desired temperatures. The heated water was obtained by heating the water to the desired temperature with 5-KW electric heater set up in the water tank. The water spraying rate was controlled by a by-passing water pipe in the pump. All of the lower roof surface, with the exception of both ends, was uniformly covered with a thin layer of running water. Self-recording thermographs were used to record the outside air temperature, the greenhouse air temperature, the stagnant air temperature between the upper and lower layers, and the temperatures of the heated water entering and leaving the greenhouse. Data was collected from January 24 to March 31, 1990.

IV. RESULTS

The energy balance equation for the water was :

$$fC(t_{wo}-t_{wl})=U_{wg}(t_{wave}-t_g)+U_{wb}(t_{wave}-t_b) \cdots\cdots (11)$$

The left side term in Equation (11) is the total heat amounts lost by sprayed water per unit of roof surface area while water was flowing over the greenhouse roof. The first and the second terms of the right side represent the heat amounts transferred from the water to the greenhouse and the energy amounts emitted to the space between upper and lower surface layer respectively.

Assuming the thermal capacity of air is negligible, an equilibrium energy balance equation can be developed for the stagnant air between the upper and lower film surface layers as :

$$A_aU_{ba}(t_b-t_a)=A_wU_{wb}(t_{wave}-t_b)+2\ A_{east}(t_g-t_b)U_{gb} \cdots\cdots (12)$$

Equation (12) was derived with the assumption that the total energy loss from the stagnant air space between the double roof layers is equivalent to the sum of the energy emitted by the water to the stagnant air space and the energy transferred from the greenhouse air to the stagnant air through east and west end surfaces not covered with a film of running water. The second term on the right side of Equation (12) represents the heat transfer through both end sides of the lower layer film cover. Therefore, the conventional considerations concerning relative greenhouse dimensions, such as the ratio of surface area to growing area or the ratio of end side area to water flowing area, will be important optimization criteria.

In Equations (11) and (12), all of the factors were either calculated based on the greenhouse dimension or temperature data measured through experimentation except for 4 overall heat transfer coefficients, U_{wg}, U_{wb}, U_{ba}, and U_{gb}.

Assuming that the coefficients U_{wg} and U_{wb} are expressed as a function of water flow rare only, equation (11) can be transformed as :

$$\frac{fC(t_{wo}-t_{wl})}{(t_{wave}-t_b)}U_{wg}=\frac{(t_{wave}-t_g)}{(t_{wave}-t_b)}+U_{wb} \cdots\cdots (13)$$

Substituting $fc(t_{wo}-t_{wl})\ (t_{wave}-t_b)=Y$ and $(t_{wave}-t_g)/t_{wave}-t_b)=X$, Equation (13) can be expressed as :

$$Y=U_{wg}X+U_{wb} \cdots\cdots (14)$$

In Equation (14), U_{wg} and U_{wb} represent the slope and intercept of a linear equation developed for a range of controlled water flow rates and a set of uncontrolled temperatures obtained through greenhouse experimentation respectively. These types of equations were applied to 4 different water flow rates. These relationships are shown in Fig. 2. and show sample correlation coefficients from 0.773 to 0.932 depending upon the different data set. Much of the variation found in the data points in Fig. 2 is presumably due to weather factors other than measured temperatures such as wind speed, wind direction, and cloud cover.

The least mean squares that fit linear equations for 4 different water flow rates are :

(1) $Y=9.88X+13.99$: for $f=2.57\times10^{-3}$ L/s per m^2 of roof surface area

(2) $Y=9.87X+18.73$: for $f=3.13\times10^{-3}$ L/s per m^2 of roof surface area

(3) $Y=9.97X+28.37$: for $f=5.12\times10^{-3}$ L/s per m^2 of roof surface area

(4) $Y=11.70X+30.64$: for $f=7.16\times10^{-3}$ L/

s per m^2 of roof surface area

Coefficient, U_{wb}, representing the heat transfer between water and stagnant air space, appearing as the intercepts in the above linear equations, shows significant variations according to the water flow rates. On the other hand, the heat transfer coefficient between the water and the greenhouse air, U_{wg}, shows almost constant value around 10.0 W/℃ per m^2 of surface area for each water flow rate except for the largest water flow rate. The variation of U_{wb} depending upon the water flow rate is assumed to be attributed to the fact that the greenhouse air film separated by a plastic cover contacting the running water path was disturbed in accordance with the increase of the water flow rate and so the heat transfer phenomenon was stimulated. But coefficient U_{wb} is also expected to be converged to an extreme limit beyond a certain range of water flow rate.

Some of this assumption can be indirectly proved through other experimental results reported by Walker (1979). Walker demonstrated through his greenhouse box tests that the coefficient, U_{wa}, representing the heat transfer between the outside air and the water layer in direct contact with the outside air were found to be constant at 38.4 W/m^2·℃ and independent of the water flow rate ranging 50 to 300 L/h per m^2 of surface area. The water flow rates adopted in Walker's experiment for using power plant cooling water in greenhouse heating is far more than 18 L/s per m^2 of surface area which was the maximum flow rate used in this study.

Based on the limited experimental results obtained from 4-different water flow rates, the relationship between water flow rate, f, and heat transfer coefficients, U_{wb} and U_{wg}, were plotted in Fig. 3. the variation of U_{wb} according to water flow rates were approximately represented by a cubic spline curve and coefficient U_{wb} was assumed to be constant at 10.3 W/m^2·℃ which was determined by selecting the mean of the four different slopes which appeared in the above 4 linear relationships.

The other two coefficients, U_{gb}, U_{ba}, were calculated from Equation (12) by substituting the determined U_{wb} for the corresponding water flow rate in the equation and also assuming the two coefficients U_{gb} and U_{ba} to be the same.

Some variations were found among the calculated values of U_{ga} and U_{gb} for all measured data sets, but they did not deviate much from the mean value of 5.0 W/m^2·℃ which was independent of the water flow rates. The standard deviation from the mean was 0.21.

V. ANALYSIS AND DISCUSSION

The heat transfer coefficients determined from experimental data set were used in the derived heat transfer equations to evaluate the effect of several environmental and greenhouse operational conditions on surface heat transfer.

Fig. 4 shows the thermal benefits of different water flow rates for a double layer plastic greenhouse. This curve was produced using equation (10) and shows that the heating benefit increment is diminishing gradually according to the increment of water flow rate, but the heat flow into the greenhouse continuously increases. This fact results from the reason that a higher flow rate reduces the temperature drop in the water as it flow over the greenhouse roof surface. Observing the tendency of this curve, the heating benefit presumably will be diminished to a certain limit above 0.01 L/s per m^2 of roof surface area. This means that any increment of the water flow rate beyond this limit will not contribute to the greenhouse heating and will cool down the greenhouse environment. This phenomenon is beyond the limit of this study.

If the specified flow rate can be delivered to the top of the greenhouse with a head loss of less than $h_e=(\xi\ \nu\, qb)/(f \rho g)$, surface heating is economical with respect to energy. This parameter is important in determining the optimum water flow rate. For example when the water flow rate is 0.003 L/m^2·s, the thermal energy benefit determined from Fig. 4. is equivalent to 60 W/m^2. If the water pumping efficiency, ξ, is 0.6 and the cost ratio of gasoline to electricity for water pumping, ν, is 0.5 then the actual equivalent head, h_e, will be $0.6\times0.5\times60/(0.003\times1.0\times9.8)=612$m. Accordigly, if the delivering head loss is within 612 m, then the water flow rate of 0.003 L/m^2·s can be concluded to be ecomomical for greenhouse heating on the temperature conditions of $t_g=10$℃, $t_a=-5$ ℃, and $t_{wo}=17$ ℃.

Figs. 4, 5, and 6 show that the heating benefit is related linearly to changes in outside air temperature, t_a, greenhouse setting temperature, t_g, and initial water temperature, t_{wo}.

In Fig. 4, the heating benefit decreases linearly to the increase of the outside air temperature. But the trend is somewhat different among the different water flow rates. The heating benefit beyond the lines can be interpreted by interpolation from the plotted lines. Comparing the simulation results of the double layer plastic cover greenhouse with the single layer glass greenhouse used by Walker (1981) in the aspect of heating benefits, the thermal efficiency of this system is about 45 to 53% higher than an uncovered water layer at least within the range of simulated conditions as shown in Table 1.

Table 1. The comparison of heating benefitssimulated for both the double layer plastic greenhouse (this study) and the uncovered water layer (Walker's study).**

Outside Air Temperature (℃)	Heating Benefits ($W/m^2 \cdot ℃$) Walker's Uncovered (1)	Double Plastic Covered(2)	Ratio (2)/(1) (decimal)
−10	100.0	153.0	1.53
−5	94.3	142.0	1.51
0	88.6	132.0	1.49
+5	83.0	121.0	1.46
+10	77.3	112.0	1.45

**For $f=0.0138$ $L/m^2 \cdot sec$, $t_g=20.0$℃, $t_{wo}=30$℃

In Fig. 5, the heating benefit increases linearly to the increase of the initial water temperature. The rate of increment becomes more obvious with the increase of the water flow rate. When 30 ℃ of hot spring water is available for greenhouse heating, the heating benefit is almost 120 $W/m^2 \cdot ℃$ with not more than 0.002 $L/m^2 \cdot s$ of water flow rate. This heating benefit is equivalent to the one barely obtainable by using 5 times as much water at 20 ℃. On the other hand, even when the initial water temperature is below the greenhouse setting temperature, some benefit will still be obtained at all of the simulated water flow rates. This effect is attributed to both the decreasing temperature slope and the increasing thermal resistance developed by surface water film.

In Fig. 6, the heating benefit decreases as the desired greenhouse setting temperature increases. Some heating benefit is found even when the greenhouse setting temperature is more than 6 ℃ higher than the initial water temperature.

Fig. 7, which was generated for the conditions of the conventional greenhouse with a water curtain system, shows the sensitivities of 4 heat transfer coefficients involved in energy balance equations adopted in this study. The conditions of conventional greenhouse equipped with water curtain systems were assumed to be : $f=1.8\times10^{-3}$ $L/m^2 \cdot s$, $t_a=-5$℃, $t_g=10$℃, and $t_{wo}=17.0$℃.

The sensitivity analysis was attempted to show the influence of variation of each coefficient to the estimation of the overall heating benefit. When each coefficent was changed ± 20% with 5% intervals from the datum values selected for generating the datum heating benefit, $q_{b\text{-datum}}$, the corresponding variation of index, $q_b/q_{b\text{-datum}}$, appeared as shown in Fig. 7. Coefficient U_{gb} was the most sensitive coefficient and U_{wb} was the next. So these two coefficients are required to be estimated more carefully than the others. The sensitivities of U_{ba} and U_{wg} were not so high. The average variation percentage of heating benefit per unit percentage change of each coefficient within the simulation rage was calculated as follows :

U_{gb} : +0.40, U_{wb} : −0.21, U_{ba} : +0.12, U_{wg} : +0.09

VI. CONCLUSIONS

The heat transfer coefficient between the flowing water and the stagnant air space, U_{wb}, shows significant variations according to the water flow rates. On the other hand, the heat transfer coefficient between the water and the greenhouse air, U_{wg}, shows almost constant value around 10.0 W/℃ per m^2 of surface area for each water flow rate.

The variation of U_{wb} depending upon the water flow rate is assumed to be caused by the level of air film disturbance. But it is also expected to be converged to an extreme limit beyond a certain range of the water flow rate.

The other two coefficients, U_{ba} and U_{gb}, could be calculated by substituting the determined U_{wb} for the corresponding water flow rate in the energy balance equation.

Some variations were found among the calculated values of U_{ga} and U_{gb} for all the measured data sets, but they did not deviate far from the mean value of 5.0 $W/m^2 \cdot ℃$ regardless of the water flow rates.

The increments of heating benefit were gradually diminished according to the increment of the water flow rate, but the heat flow into the greenhouse continuously increased. Observing the tendency of the heating benefit curve, the heating benefit presumably will be diminished completely at certain limit above 0.01 L/s per m^2 of roof surface area.

The heating benefit decreased linearly with the increase of outside air temperature, but the trend was somewhat different among the different water flow rates. The thermal efficiency of the double layer plastic system was about 50% higher than for an uncovered water layer.

With the increase of initial water temperature, the heating benefit was increased linearly and this phenomenon became more obvious of the higher water flow rates. The heating benefit of applying 30 ℃ water was equivalent to 5 times as much as that of the 20 ℃ water. On the other hand, even when the initial water temperature is below the greenhouse setting temperature, some benefit was still obtained.

The heating benefit decreases according to the increase of the desired greenhouse setting temperature. Some heating benefit is found even when the greenhouse setting temperature is more than 6 ℃ higher than the initial water temperature.

According to the sensitivity analysis to see the influence of the estimated heat transfer coefficients on the heating benefit, coefficient U_{gb} was the most sensitive and U_{wb} was the next. So it is expected that special care should be taken in the estimation of these two coefficients. But the sensitivities of both U_{ba} and U_{wg} were not so high. The average variation percentage of heating benefit per unit percent change of each coefficient within the simulation range is determined by analyzing the variation of heating benefit around datum value adopted in the simulation.

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LIST OF SYMBOLS

Symbol	Description	Units
A_a	lower cover surface area, Aw+2Aeast	m^2
A_w	water flowing surface area	m^2
A_{east}, A_{west}	greenhouse end surface area	m^2
C	specific heat of water	J/L·℃
f	water flow rate per unit area, F/L	L/s·m^2
F	water flow rate per unit width of water flow path	L/s·m
g	gravitational acceleration	9.8 m/s
h_e	equivalent head	m

L	length of water flow path	m
q_{ga}	heat transfer out of greenhouse without water over greenhouse surface area	W/m^2
q_{wg}	heat transfer into greenhouse from water	W/m^2
q_b	net heat transfer into greenhouse from water plus heat transfer out of greenhouse wihtout water over same gross area($=q_{ga}+q_{wg}$)	W/m^2
Q_w	rate of heat flow from water per unit width of water flow	W/m
Q_{wg}	rate of heat flow from water into greenhouse per unit width of water flow	W/m
t_a	temperature of atmosphere	℃
t_b	air temperature between double layers	℃
t_g	temperature of greenhouse air	℃
t_{wo}	temperature of applied water	℃
t_{w1}	temperature of water leaving greenhouse	℃
t_{wave}	$(t_{wo}+t_{wl})/2$	℃
U_{gb}	heat transfer coefficient between greenhouse air and stagnant air within double layers	$W/m^2\cdot$℃
U_{wb}	heat transfer coefficient between water and air within double layers	$W/m^2\cdot$℃
U_{ba}	heat transfer coefficient between layers	$W/m^2\cdot$℃
aU_{wg}	heat transfer coefficient between water and greenhouse air	$W/m^2\cdot$℃
x	distance along water flow path	m
ξ	water pumpint efficiency	unitless
ν	cost ratio of electricity to gasolin	unitless
ρ	density of water	kg/L