Performance Analysis of Modified Solar Water Heating System for Climatic Condition of Allahabad, India

Kirti Tewari, Rahul Dev

Abstract—Solar water heating is a thermodynamic process of heating water using sunlight with the help of solar water heater. Thus, solar water heater is a device used to harness solar energy. In this paper, a modified solar water heating system (MSWHS) has been proposed over flat plate collector (FPC) and Evacuated tube collector (ETC). The modifications include selection of materials other than glass, and glass wool which are conventionally used for fabricating FPC and ETC. Some modifications in design have also been proposed. Its collector is made of double layer of semi-cylindrical acrylic tubes and fibre reinforced plastic (FRP) insulation base. Water tank is made of double layer of acrylic sheet except base and north wall. FRP is used in base and north wall of the water tank. A concept of equivalent thickness has been utilised for calculating the dimensions of collector plate, acrylic tube and tank.

A thermal model for the proposed design of MSWHS is developed and simulation is carried out on MATLAB for the capacity of 200L MSWHS having collector area of 1.6 m², length of acrylic tubes of 2m at an inclination angle 25° which is taken nearly equal to the latitude of the given location. Latitude of Allahabad is 24.45° N. The results show that the maximum temperature of water in tank and tube has been found to be 71.2°C and 73.3°C at 17:00hr and 16:00hr respectively in March for the climatic data of Allahabad.

Theoretical performance analysis has been carried out by varying number of tubes of collector, the tank capacity and climatic data for given months of winter and summer.

Keywords—Acrylic, Fibre reinforced plastic, Solar water Heating, Thermal model, Conventional water heaters.

NOMENCLATURE

<table>
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<tr>
<th>Symbol</th>
<th>Description</th>
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<td>$\text{T}_{\text{osni}}$</td>
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<td>$\text{T}_{\text{owt}}$</td>
<td>Temperature of hot water in tube ($^\circ$C)</td>
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</tbody>
</table>

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h_{nw} - Convective heat transfer coefficient between water in tank and inner surface of north wall (W/m²K)

h_{bw} - Convective heat transfer coefficient between water in tank and inner surface of bottom surface (W/m²K)

I. INTRODUCTION

WATER heating is a very common process which is being used since ancient times for getting hot water. Hot water is required for both industrial processes and household uses. Thus, such technology should be used which can fulfill all the demand of hot water without degrading natural resources and environment. Hence, move toward sustainable development have to be made which can be achieved by judicious use of fuels and by utilising renewable resource such as solar energy. Solar energy is a renewable form of energy and available in abundance which makes it highly appealing source. It can be used for direct conversion into electricity (by photovoltaic conversion) and into thermal energy by solar water heater.

Solar water heater consists of collector and storage tank. Collectors are mainly of three types- FPC, ETC and concentrating solar collectors. FPC is designed to work in low temperature range (ambient temperature-60°C) and medium temperature range (ambient temperature-100°C). Losses are very high in these type of collectors. Convective losses of FPC can be reduced by removing air between absorber and glass cover. The resulting stress will restrict the use of vacuum. Also, maintaining vacuum in FPC is a problem which can be eliminated by ETC. In ETC vacuum is created between glass cover and absorber. Its performance is high only at higher temperature. Thus, both type of collectors has certain limitations and advantages so till now many improvements have been done in this field to eliminate the limitations.

Ammari et al. [1] theoretically as well as experimentally evaluated a tar solar water heater. Here, tar acts as an absorber plate. Runge- Kutta method of fifth order was used to solve three partial differential equations of collector and compared this model with conventional water heaters. Results show that its efficiency is lower in daytime in comparison of conventional heaters but in evening and late afternoon, its performance is found to be better.

Shah et al. [2] presented theoretical study of flow investigation of all glass evacuated tubular collector. The investigations were based on a collector design with horizontal tubes connected to a vertical manifold channel. Three different varying length were modeled with five different inlet mass flow rates at a constant temperature of 333K and found that shortest tube achieved the highest efficiency.

Budiharjo et al. [3] compared experimental and numerically obtained flow rates for natural circulation for evacuated tubes connected with horizontal storage tank. Evacuated tubes used are single-ended water-in-glass and mounted over diffuse reflector. A correlation is developed in terms of aspect ratio of tubes, solar radiations, temperature of tank and inclination of collector. ±5% and ±10% error is found between measured and numerically obtained flow rates for the four tubes which are far from edge in before and after noon respectively.

Zambolin et al. [4] compared standard glazed FPC and direct flow ETC with CPC reflector under same steady state and quasi-dynamic conditions and plotted collected solar energy with solar radiation at constant operating condition (t_{in} - t_{a}) and found that FPC is more influenced by this temperature difference. Efficiency curves was obtained by standard EN 12975-2 and conclude that losses in evening and morning is more in FPC and efficiency of ETC is higher than FPC.

Chen et al. [5] calculated the efficiencies of flat plate collectors at different flow rates. Two FPC were tested, one with ETFE foil and other without ETFE foil in Technical University of Denmark. Comparing theoretical and measured values it was observed that start efficiency is higher for without ETFE foil but yearly efficiency of collector with ETFE was higher when fluid collector temperature is 60°C. Volume flow rate was found to have direct relation with incident angle modifier, start efficiency and efficiency and have inverse relation with heat loss coefficient.

Roberts et al. [6] provides analytical expression for instantaneous efficiency of FPC and showed that efficiency get influenced on changing certain parameters for a single glass cover solar hot water heater. In this paper role of absorber plate’s emittance and absorptance was studied and found that absorptance should be high for water heaters.

Dev et al. [7] studied the performance of EISS (Evacuated tubular collector integrated solar still) system for composite climatic condition of Delhi and developed thermal model and carried out experiments throughout year (January-December 2008) and obtained higher yield in summer with maximum (annual) thermal efficiency of 30.1%. This system provides distilled as well as hot water.

Taheri et al. [8] presents study of an efficient compact solar water heater. Black coloured sand in the storage tank (1.45 x 0.56 x 0.17m3) of galvanized sheet acts as absorber. Its simulation was carried out using EES software. Experiments with 0.67m2 collector area has been carried out and efficiencies for south-west situation have been found to be greater than 70% due to forced flow operation. CSWH has been found to be economical and have large storage capacity per unit volume. Validation results showed 1.09% and 2.27% as lowest and highest relative errors.

Tse et al. [9] simulated dynamic model on FORTRAN for storage tank, heat exchanger coil, thermosyphon system at night and morning time and carried out experimental validation of thermosyphon solar water heater coupled with a heat exchanger of circular tube rings type. Experimental and simulated results were compared and found to be in good agreement.

In this paper, theoretical performance analysis has been carried out of MSWHS which is a combination of FPC and ETC techniques. On the basis of thermal model, simulation has been carried out on MATLAB and various results have been found for proposed model of MSWHS. Then its various parameters like solar radiation, wind velocity, ambient temperature, capacity of MSWHS and number of tubes have been varied for its performance analysis.

ISNI:0000000091950263
II. DESIGN OF EXPERIMENTAL SETUP

Proposed model of MSWHS of 200L capacity consists of collector and storage tank. Collector is made of metallic absorber plate having double layered semi-cylindrical acrylic tubes above it and FRP sheet placed below for insulation. Absorbing area of collector is 1.6m² and number of acrylic tubes above it and FRP sheet placed below for insulation. Absorber plate having double layered semi-cylindrical acrylic collector and storage tank. Collector is made of metallic which falls on metal plate will also heat the water. Thus, water flowing between tubes and metallic plate. Solar radiation falls on acrylic tube which transmits most of it to the water having comparatively higher density will flow down into the tank will also contribute into heating of water during sunshine hours as its walls are transparent consisting of acrylic and will reduce heat loss during off sunshine hours because of its design.

Theoretical values of solar radiation, ambient temperature of MSWHS for a day of March is given in Table II and measured values of solar radiation, ambient temperature and wind velocity for summer (June) month is given in Table III.

III. WORKING PRINCIPLE

MSWHS is based on thermo-syphon effect. Solar energy falls on acrylic tube which transmits most of it to the water flowing between tubes and metallic plate. Solar radiation which falls on metal plate will also heat the water. Thus, water gets heated by combined effect of both metal plate and heat energy transmitted through tubes. This hot water moves up because of its lower density and cold water from the tank having comparatively higher density will flow down into the tubes. Tank also contributes into heating of water during sunshine hours as its walls are transparent consisting of acrylic and will reduce heat loss during off sunshine hours because of its design.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>DIFFERENT PARAMETERS OF MSWHS</th>
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<tbody>
<tr>
<td>Specifications</td>
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<td>AAc</td>
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<table>
<thead>
<tr>
<th>TABLE II</th>
<th>HOURLY OBSERVATION OF MSWHS OF MARCH 15 AT ALLAHABAD, INDIA</th>
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<td>Time (hr)</td>
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TABLE III
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<th>It(t) (W/m²)</th>
<th>IE(t) (W/m²)</th>
<th>IW(t) (W/m²)</th>
<th>IS(t) (W/m²)</th>
<th>Itop(t) (W/m²)</th>
<th>Ta (°C)</th>
<th>Va (m/s)</th>
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<td>660</td>
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TABLE IV
HOURLY OBSERVATION OF MSWHS FOR A DAY OF WINTER (NOVEMBER 14) MONTH AT ALLAHABAD, INDIA

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<th>Itop(t) (W/m²)</th>
<th>Ta (°C)</th>
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<td>15</td>
<td>22</td>
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</table>

IV. THERMAL MODELING

The energy balance for each component of the MSWH has been carried out with the following assumptions,

a. The setup is completely water and vapour leakage proof.
b. The heat capacities of plate, insulations, FRP, Acrylic are negligible.
c. Temperature dependent heat transfer coefficients have been considered.
d. System operates in quasi-steady state regime during the day.
e. The temperature of metal plate and FRP base are considered to be uniform throughout.

A. For Collector

1. For metal plate:

   \[ \alpha_p \left[ T_{\text{cry}} K_{\text{ap}} A_p \right] \frac{\partial}{\partial t} h_p A_p (T_p - T_{\text{in}}) = M_{\text{in}} c_w \frac{dT_p}{dt} \]

   (3)

2. For FRP:

   \[ \frac{K_{\text{FRP}} A_{\text{FRP}} (T_p - T_{\text{FRP}})}{t_{\text{FRP}}} = h_p A_{\text{FRP}} (T_{\text{FRP}} - T_a) \]

   (4)

3. For water in Acrylic tube:

   \[ \alpha_w \left[ T_{\text{cry}} K_{\text{aw}} A_w \right] \frac{\partial}{\partial t} h_w A_w (T_w - T_{\text{in}}) = M_{\text{in}} c_w \frac{dT_w}{dt} \]

   \[ + n_c C_w (T_{\text{w}} - T_{\text{in}}) + h_{\text{acrylic}} A_{\text{w}} N_{\text{w}} (T_{\text{w}} - T_{\text{in}}) \]

   (5)

4. For outer surface of inner tube:

   \[ A_{\text{li}} N_{\text{w}} h_{\text{acrylic}} (T_{\text{w}} - T_{\text{in}}) = h_{\text{li}} A_{\text{li}} N_{\text{w}} (T_{\text{w}} - T_{\text{li}}) \]

   (6)

5. For inner surface of outer tube:

   \[ h_{\text{li}} A_{\text{li}} N_{\text{w}} (T_{\text{w}} - T_{\text{li}}) = h_{\text{acrylic}} A_{\text{w}} N_{\text{w}} (T_{\text{w}} - T_{\text{in}}) \]

   (7)

6. For outer surface of outer tube:

   \[ h_{\text{acrylic}} A_{\text{w}} N_{\text{w}} (T_{\text{w}} - T_{\text{in}}) = A_{\text{out}} N_{\text{w}} h_{\text{w}} (T_{\text{w}} - T_a) \]

   (8)

Various temperatures will be calculated with the help of above equations and putting the values of \( T_{\text{li}} \) and \( T_{\text{p}} \) in (5), following equation is obtained

\[ \frac{dT_w}{dt} + a T_w + b T_{\text{w}} = g(t) \]

(9)
B. For Storage Tank

1. For water in storage tank:
   \[ \alpha_i \{ T(t) A_i + I(t) A_y \} \frac{dT_c}{dt} + \alpha_x \{ T(t) A_x + I(t) A_y \} T^2_x + h_w A_c (T_{cw} - T_c) + h_w A_w (T_{cw} - T_{cw}) + m_w C_w (T_{bw} - T_c) = \]
   \[ M_{cw} \frac{dT_{cw}}{dt} \quad \text{for small time interval} \]

2. For east wall (inner surface of inner layer):
   \[ a_{wy} \{ T(t) A_{wy} \} T_{wy} + h_{wy} A_w (T_{cw} - T_{wy}) = \]
   \[ K_{wy} A_w (T_{cw} - T_{wy}) \quad \text{for small time interval} \]

3. For east wall (outer surface of inner layer):
   \[ h_{hwy} A_{wy} (T_{cw} - T_{wy}) = h_w A_w (T_{cw} - T_{ew}) \]

4. For east wall (inner surface of outer layer):
   \[ h A_{xw} (T_{cw} - T_{ew}) = h A_{xw} (T_{cw} - T_{ew}) \]

5. For east wall (outer surface of outer layer):
   \[ h_{hwy} A_{wy} (T_{cw} - T_{ew}) = h A_{xw} (T_{cw} - T_a) \]

6. For north wall (inner surface):
   \[ \alpha_{gy} f(t) A_{gy} - h_{ny} A_{y} (T_{ny} - T_w) - K_{nguy} A_{y} (T_{ny} - T_{ny}) \quad \text{for small time interval} \]

7. For north wall (outer surface):
   \[ h_{ngw} A_{y} (T_{ny} - T_{ny}) = h_{ny} A_{y} (T_{ny} - T_a) \]

By putting the values of \( T_{cw}, T_{cw}, T_{cw}, T_{cw} \), \( T_{cw}, T_{cw}, T_{cw} \) & \( T_{cw} \) in (10) and get

\[ \frac{dT_{cw}}{dt} + a_2 T_{cw} + b_2 T_{cw} = g_2 (t) \]

Adding (9) and (17) (after multiplying (17) by \( \beta \)) and solving (after multiplying by \( e^{\beta t} \)) further to get,

\[ \frac{d}{dt} (e^{\beta t} (T_{cw} + \beta T_{cw})) = [g_1 (t) + \beta g_2 (t)] e^{\beta t} \]

Further, some assumptions have been made for solving (18),

i. small time interval \( dt \) (0 < \( t < \eta dt \))

ii. function \( f (t) \) are constant, i.e., \( f (t) = \frac{1}{T (t)} \) for small interval \( dt \).

iii. \( \alpha \) is a constant during the time interval

iv. Initial values of hot water and cold water temperatures have been used to determine value of internal heat transfer coefficients.

From (18) following equations can be obtained:

Temperature of cold water in tank:

\[ T_{cw} = \frac{1}{\beta - \beta} \left[ \frac{g_1 (t)}{c} \left( \frac{1 - e^{-\beta t}}{c} \right) - \frac{1 - e^{-\beta t}}{c} \right] + g_2 (t) \]

\[ \frac{1}{\beta - \beta} \left[ \frac{1 - e^{-\beta t}}{c} - \frac{1 - e^{-\beta t}}{c} \right] + T_{cw} (e^{-\beta t} - e^{-\beta t}) \]

Temperature of hot water in tube:

\[ T_{wh} = \frac{1}{\beta - \beta} \left[ \frac{g_1 (t)}{c} \left( \frac{1 - e^{-\beta t}}{c} \right) - \frac{1 - e^{-\beta t}}{c} \right] + T_{wh} (e^{-\beta t} - \beta e^{-\beta t}) \]

\[ \frac{1}{\beta - \beta} \left[ \frac{1 - e^{-\beta t}}{c} - \frac{1 - e^{-\beta t}}{c} \right] + T_{wh} (e^{-\beta t} - \beta e^{-\beta t}) \]

IV. RESULT AND DISCUSSION

Hot water temperatures (\( T_{wh} \)) and cold water temperatures (\( T_{cw} \)) have been computed for all the variations with the help of modeling and plotted against time for 07:00hr to 17:00 hr.

Fig. 3 shows the hourly variation of cold water temperatures in water tank with solar radiation and wind velocity from 07:00hr to 17:00 hr. Here, measured values of solar radiations for climatic condition of Allahabad in the month of March, July and November have been used to study its performance.

Solar radiations on every walls, ambient temperature and wind velocity of MSWHS are shown in Table II for March 15. Measured values of solar radiations, wind velocity and ambient temperature for the month of March, July and November have been used to study its performance.

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32°C at 07:00hr for June and March respectively and maximum for measured solar data of June is 76.8°C at 15:00hr. Maximum hot water temperature for March is 73.3°C at 16:00hr. In winter (November) minimum temperature of hot water has been obtained in morning at 07:00hr. With increase in solar radiation temperature increases up to 52.76°C at 16:00hr. Thus, in winter month comparatively lower temperatures have been obtained due to lower solar radiation and ambient temperatures.

After varying solar data, number of tubes of collector has been varied and hot water and cold water temperatures have been computed for eleven hours (07:00hr to 17:00hr) for the month of March. Fig. 5 shows hourly variation of hot water temperature with number of tubes. It is clearly shown in figure that hot water temperature of tubes increases with increase in number of tubes. Maximum and minimum temperature for 18 number of tubes has been found to be 76°C at 16:00hr and 35°C at 07:00hr respectively while for 14 number of tubes it is found to be 71°C and 35°C at 16:00hr and 07:00hr respectively.

Fig. 6 shows hourly variation of cold water temperature with number of tubes. As number of tubes increases temperature of cold water in tank also increase because absorbing area of collector and length of tank will increase with number of tubes. 73.6°C and 30°C has been found to be maximum and minimum temperature of cold water in tank at 17:00hr and 07:00hr respectively for MSWHS with 18 number of tubes.

Capacity of MSWHS has also been varied to study its performance by computing hot water and cold water temperatures. Hourly variation of hot water temperature with capacity of MSWHS for the month of March has been shown in Fig. 7. Figure shows inverse relation of capacity of MSWHS with temperature obtained. As capacity increases hot water temperature get reduced. For 300L capacity maximum and minimum temperatures have been found to be 65.4°C and 35°C at 16:00hr and 07:00hr respectively. For 100L capacity maximum and minimum temperatures have been found to be 93.1°C and 35°C at 16:00hr and 07:00hr respectively.

Fig. 8 shows hourly variation of cold water temperature with capacity of MSWHS. Here also, inverse relation between cold water temperature and capacity of MSWHS has been obtained. 91.9°C and 30°C has found to be maximum and minimum temperatures for 100L capacity of MSWHS at 17:00hr and 07:00hr respectively while 62.6°C and 30°C has been found to be maximum and minimum temperatures for 300L capacity of MSWHS at 17:00hr and 07:00hr respectively.
V. CONCLUSION

The influence of integration of features of FPC and ETC has been studied in this paper. Due to improvement in material, shape and working principle, the performance of MSWHS has been improved and it is concluded from present study that on increasing the number of tubes of collector or on reducing the capacity of MSWHS, hot water temperatures in tubes of collector and cold water temperatures in tank get increased.

Variation in hot and cold water temperatures are found with change of weather conditions. Maximum variation of hot water temperature between summer and winter month has been found to be 24.3°C at 15:00hr and 21.9°C at 17:00hr for cold water temperature.

Maximum variation in hot water temperature of MSWHS with 18 and 14 number of collector tubes has been found to be 5.1°C at 16:00hr. Maximum cold water temperatures obtained are 73.68°C and 69.1°C for 18 and 14 number of tubes at 17:00hr respectively. Thus, increment of 4.6°C has been obtained by increasing 4 number of tubes of collector.

Maximum temperature of hot water temperature has been found to be 93.16°C when capacity of MSWHS is 100L and 65.41°C at 16:00hr for 300L. Thus, maximum of 27.6°C variation has been obtained by varying capacity of MSWHS from 100L to 300L. Maximum cold water temperature has been found to be 91.9°C for 100L capacity and 62.68°C for 300L of MSWHS.

APPENDIX

Various Intermediate Expressions for Thermal Modeling of MSWHS

\[ T_p = \alpha_{FRP}^2 (t) \left[ \frac{2}{h_f (t) \alpha_{CRY} \tau_w} + h_f \frac{P_{HW} + h_{FRP} \cdot O_{T_a}}{U_O} \right] \]

\[ T_{sw} = \frac{T_h \alpha_{CRY} \tau_a + A_t \tau_a \cdot h_i}{U} \]

\[ T_{eo} = \frac{h_o \cdot T_a + h_{CRY} \cdot T_{eo}}{h_o + h_{CRY}} \]

\[ T_{sw} = \frac{T_v + A_t \cdot h_{CRY} \cdot T_e}{V_i} \]

\[ T_{eo} = \frac{\alpha_{cry} \cdot I_e (t) \cdot \tau_o + h_{cry} \cdot T_v \cdot h_i}{U_i} \]

\[ T_{bh} = \frac{\alpha_{FRP}^2 (t) \left[ \frac{2}{h_f (t) \alpha_{CRY} \tau_w} + h_f \frac{P_{HW} \cdot T_{cw} + T_a \cdot h_{FRP} \cdot O_{T_a}}{U_{2b}} \right]}{2b} \]

\[ T_{topi} = \frac{\alpha_{cry} \cdot I_e (t) \cdot \tau_o + h_{HW} \cdot T_v + h_i \cdot T_a}{U_i} \]

\[ T_{eo} = \frac{h_o \cdot T_{eo} + h_i \cdot T_a}{h_o + h_i} \]

\[ T_{eo} = \frac{T_v + A_t \cdot h_{cry} \cdot T_e}{h_i + h_{cry}} \]

\[ T_{N_j} = \frac{\alpha_{FRP}^2 (t) \left[ \frac{2}{h_f (t) \alpha_{CRY} \tau_w} + h_f \cdot T_{cw} + T_a \cdot h_{FRP} \cdot O_{T_a}}{U_{2N}} \right]}{2N} \]

\[ \beta = \frac{a_1 \pm \sqrt{a_1^2 - 4 \cdot a_2 \cdot (-b)}}{2 \cdot a_2} \]

\[ U_O = h_p + \frac{K_{FRP} \cdot t_{FRP}}{t_{FRP} \cdot (K_{FRP} + h_{FRP})} \]

\[ V_o = h_{cry} \cdot e_h \cdot \frac{A_2}{U} \]

\[ U = \frac{h_{cry} \cdot A_2 + A_1 \cdot h_{cry} \cdot h_i}{h_i + h_{cry}} \]

\[ V_i = h_i \cdot h_{cry} \cdot A_2 \cdot \frac{A_1^2}{U} \]

\[ h_{cry} = \frac{K_{cry} \cdot t_{cry}}{t_{cry}} \]

\[ a_1 = \frac{m_C + A \cdot N_{h_{cry}} + h_{cry} \cdot \frac{A \cdot K_{cry}}{V_M \cdot C_y} + A \cdot N_{h_{cry}}}{V_M \cdot C_y} \]

\[ b_i = \frac{m_C}{M_C} \]

\[ h_1 = \frac{h_A + h_A}{M_C} \]

\[ h_2 = \frac{

\[ g \cdot (t) = \alpha_{cry} \cdot I_e (t) \cdot A_n \cdot \tau_{cw} + h_{cry} \cdot A \cdot \tau_{cw} \cdot \frac{T_v}{U_M \cdot C_y} + \frac{A_n \cdot h_{cry} \cdot V_{T_a}}{U_M \cdot C_y} + A_n \cdot h_{cry} \cdot V_{T_a} \cdot V_{M_c} \]
$$g(t) = \frac{\alpha_{acry}}{M_p C_p} \left( I_a(t) + \alpha_{acry} I(t) + \alpha_{acry} I(t) \right) + \frac{\alpha_{acry}}{M_p C_p} \left( \frac{2}{U_{2N}} \right)$$

$$+ h_{acry} \left( \frac{A_p}{M_p C_p U_2} \right) \left( \frac{A_p}{M_p C_p U_2} \right) \left( A_p + A_p + A_p \right)$$

$$T_{so} = \frac{\alpha_{acry} I_{acry}(t) + h_{FRP} T_{so} + h_{so} T_{so}}{U_{11}}$$

$$T_{as} = \frac{\alpha_{acry} I_{acry}(t) + h_{FRP} T_{as} + h_{so} T_{as}}{U_{11}}$$

REFERENCES


