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SOLAR AIR HEATER WITH SENSIBLE THERMAL STORAGE

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Abstract

This research was conducted in collaboration with the Botswana Technology Centre (BOTEC) which has since been incorporated into a new research and development institution. The research was conceived as an offshoot of another project, the Solar Chimney, whose aim was to have a working short solar chimney constructed and installed in a remote village in Botswana by 2016 [website: botec.bw (2013)]. This research is on the development of an appropriate solar thermal storage that could be incorporated into the Solar Chimney design. Several concepts have been considered both in terms of geometrical design and storage media. The proposed thermal storage model is based on a sensible thermal storage technology employing water ethylene-glycol at 50% concentration and employs thermosyphon and reverse thermosyphon in the charging and discharging modes respectively. Computer simulations over more than 24 hours have been performed. A physical prototype has also been constructed and testing is currently being undertaken. The proposed storage concept is also likely to find application in other solar thermal technologies that require thermal storage for effective operation; such applications as space heating and ventilation for comfort in residential buildings, crop drying in agriculture, etc.

Keywords: Solar Energy Storage and Release, Sensible, Water Ethylene-Glycol, Reverse Thermosyphon

1. Introduction

Concerns over global warming and climate change associated with reliance on fossil fuels as well as energy supply deficits and increases in fuel prices have generated more interest and investment potentials in renewable energies' research and development. One emphasis in this regard has been on the development of effective and reliable energy storage technologies; most renewable energies such as wind, sun, and tides are available intermittently and must be stored to be released later when required for use. This would also optimize system performance and cost by reducing the mismatch between supply and demand. In the case of solar energy, for instance, it is available from the sun only when the sun shines and only a relatively smaller amount passes through to the earth's surface on hazy days. If we are to harness and employ solar energy during day and night, we need to be able to store a great deal of energy for later use.

2. Thermal Storage

Most energy storage technologies can be classified among any of the following storage systems: mechanical energy storage, electrical energy storage, thermal energy storage and thermochemical energy storage systems. Thermal energy storage can be further subdivided into sensible thermal, latent thermal, or chemical-thermal or a combination of these. (Atul Sharma, et al. (2009)).

Currently, the greatest potential for thermal storage appears to be for ‘latent heat’ storage materials also called Phase Change Materials (PCMs). The results of the latest research show that ‘molten salt’ materials and technologies are the most promising for high-efficiency solar storage and retrieval. Molten nitrate salt has been identified as a practical thermal energy storage system for Concentrated Solar Power (CSP) at temperatures above 300oC, with hours-long storage, and has proven reliable at commercial scales (NREL Technical Report (2011)). Such systems are, however, quite costly and therefore not optimally suited to low-cost, low-temperature and small to medium-sized storage systems.

A comparative study of the properties of all possible sensible heat storage materials shows that water is the most promising ‘specific heat’ storage medium because of its very high heat capacity and hence very large energy storage capacity with minimum volume. The addition of glycol to water in a predetermined ratio could enhance the merit of using water. Properties of Propylene Glycol, chemical formula C3H8O2, reveal that its density is 1036 kg/m3, melting point -59oC and boiling point 188.2oC. The boiling point is much higher than that of water. Its thermal conductivity is 0.34 W/m-K. Glycol is miscible with water in all proportions and the density remains almost the same. It is neither flammable nor toxic or reactive.

To effectively compare sensible heat storage media, it is necessary to look at their thermal masses. Thermal mass refers to the thermal inertia or thermal storage capacity of materials. The properties required for good thermal mass are high specific heat and high density. Table 1 presents the thermal masses of typical materials used for thermal storage. The data shows that water is by far the best medium compared to all other materials like concrete, sandstone, rammed earth, bricks, etc. Water is also the cheapest of all materials. The only problem with water is its poor thermal conductivity. Water can be used if the system design induces convection currents to compensate for the lack of conductivity.

Table 1 Thermal Mass of Different Materials (website: wikipedia.org (2012))

Material	**Thermal Mass (Volumetric Heat Capacity, kJ/m^3-K)**
Water	4186
Concrete	2060
Sandstone	1800
Compressed earth blocks	1740
Rammed earth	1673

FC sheet (compressed)	1530
Brick	1360
Earth wall (adobe)	1300
AAC	550

3. Model Design

3.1 Development of the Storage Model Concept

To adequately address energy storage problems, it is necessary to initially conceive what fraction of energy collected is for immediate use and what fraction must be stored in the storage medium. Figure 1 shows the storage concept that was conceived for this research. It shows that a lot more energy, say 67 %, needs to be captured and stored during the day than what is utilized during that period or else there would be no energy available for later use.

The storage concept and the storage media based on a convective water-glycol system were further developed into the model design shown in Figure 2..

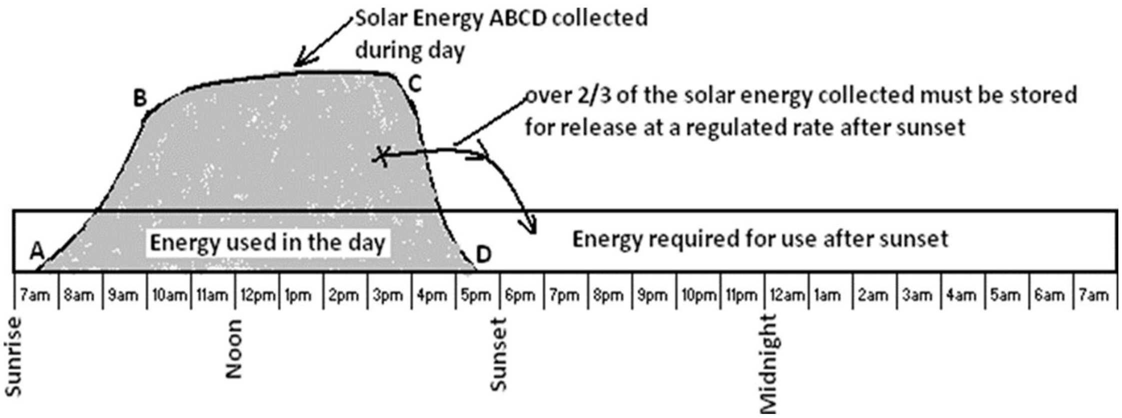

Figure 1: Concept Sketch of Solar Energy Storage and Release

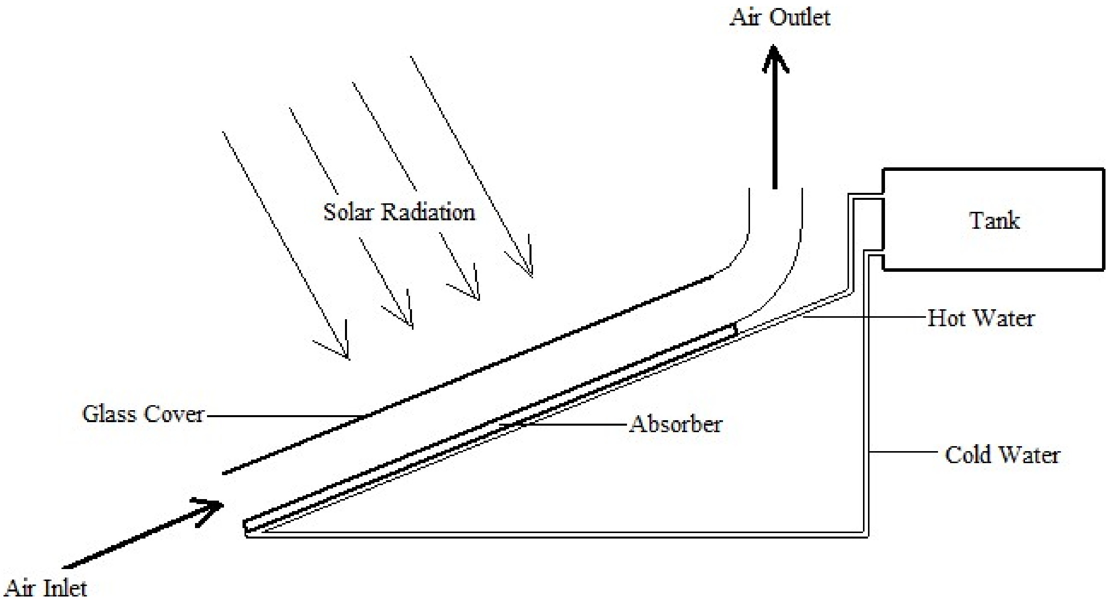

Figure 2: Solar Air Heater with a Water Thermal Storage

The storage models proposed in this research, are thus based on 'flowing water-glycol' as the main medium for solar thermal storage.

The design for the collector in this model had some geometrical constraints, emanating from the requirement that the developed storage model be adaptable for incorporation into the mainstream research, the updraft solar chimney, hence the trapezoidal shape as depicted in Figure 3, whereby the solar field is shown consisting of eight equal panels. In this design, each panel consists of twenty-five riser pipes. In the actual physical validation process only one panel would be constructed and tested. It was envisaged that the testing in different positions of the circular test setup could be simulated physically by simply placing one panel in different locations of the circular test field as depicted in Figure 4.

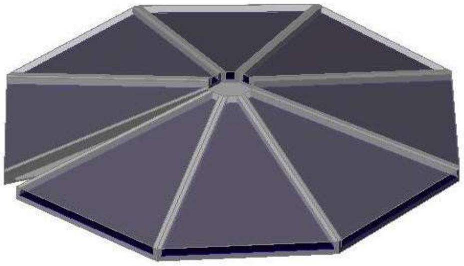

Figure 3: Final Storage Model Concept Design; 8 Panels Assembled

Figure 4: One Panel Test Setup

3.2 Mathematical Model

The mathematical model presented in this section is a set of heat transfer and fluid flow relations (Equations) specific to the one-pipe computer model and it is these that will form the basis for the implementation of the computer simulations.

3.2.1 One Riser Pipe Model

The computer model is based on a one-riser pipe model. The assumption made is that the one riser pipe model is representative of the thermal, temperature and flow profiles of the other riser pipes. The one-pipe model is geometrically presented in Figure 5 below. [dimensions are in mm]

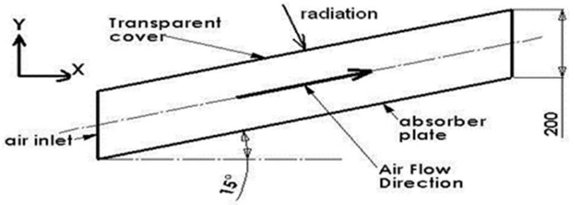

Figure 6: 2D Heat Transfer Model

The mathematical models are developed for each thermal component of the modeled segment. Output data from one segment form input data to the next segment. Also included here are models for solar radiation, thermosyphon process and thermal storage.

The segmented modeling technique requires that the one-pipe model is divided into smaller sub-elements connected in series as shown in Figure 7.

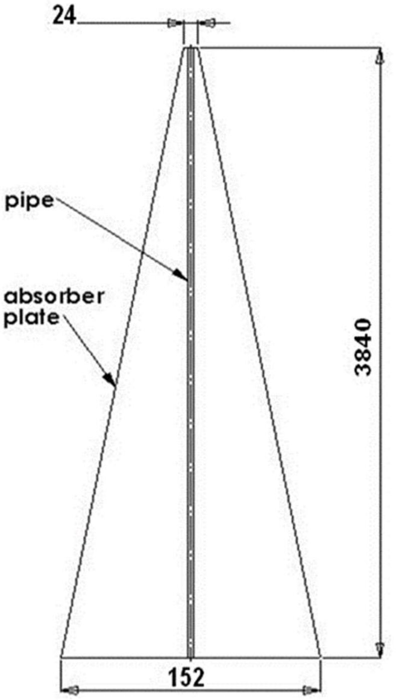

Figure 5: One Riser Pipe Model

The modeling technique adopted is the segmented model. When this is evaluated over some time it simulates the transient condition or time dependence of the model. This technique has been adopted since input data is not available as continuous functions of time but rather as discretized time-based data.

A 2-dimensional heat transfer model is adopted for the development of the computer programs; the assumption made is that heat transfer is only in the radial direction (x-axis), that is, in the direction of the air and heat transfer fluid flows and in the vertical direction (y-axis), that is, in the direction of the solar radiation. The radial vertical surfaces (z-axis; not shown) are assumed adiabatic. (see Figure 6).

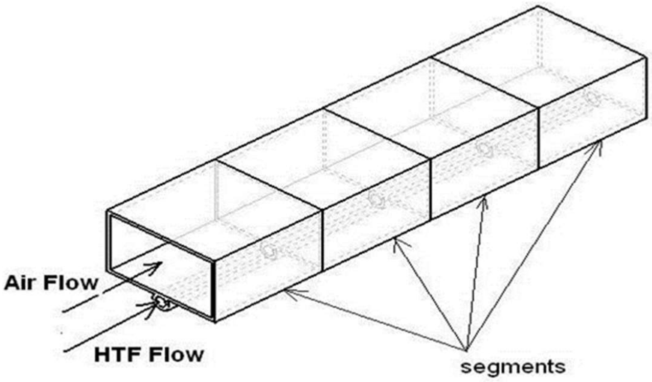

Figure 7: Segmented Model; HTF (Heat Transfer Fluid) refers to Ethylene-Glycol Water

Furthermore, each segment is broken down into individual thermal components for the development of thermal gains and losses, heat transfer and storage capacity balances (see Figure 8).

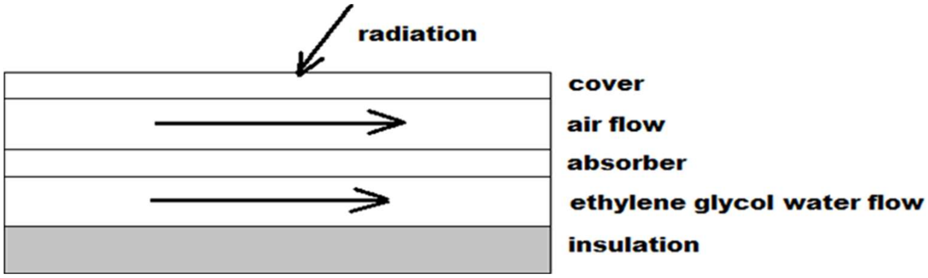

Figure 8: One Segment Model

Figure 9 shows the energy balance for the absorber segment. The energy balance is represented mathematically by equations 1 and 2.

$$\dot{Q}_{abs} = \dot{Q}_{abs-air} + \dot{Q}_{abs-\mathrm{wg}} + \dot{Q}_{r,abs-c} + \dot{Q}_{abs-back} \quad (1)$$

$$\dot{Q}abs = rc * \alpha abs * Aabs * Isol \quad (2)$$

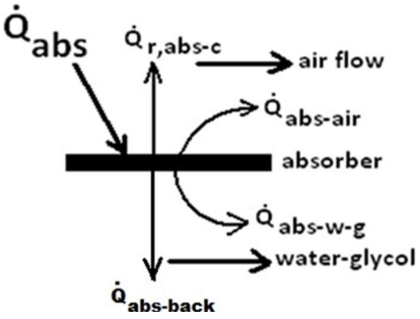

Figure 9: Absorber Segment Heat Transfer Model

The energy balance for the cover segment is shown in Figure 10 and is given by Equation 3.

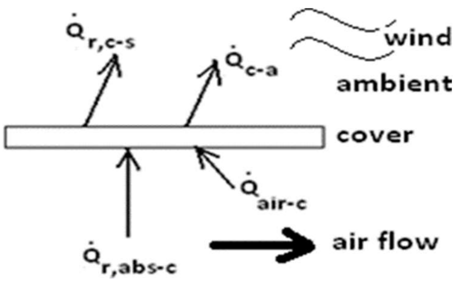

Figure 10: Cover Segment Heat Transfer Model

$$\dot{Q}_{air-c} + \dot{Q}_{r,abs-c} = \dot{Q}_{c-a} + \dot{Q}_{r,c-sky} \quad (3)$$

The energy balance on the airflow segment is represented by Figure 11 and Equations 4 and 5.

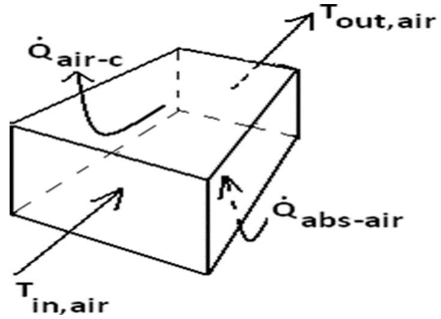

Figure 11: Air Flow Segment Heat Transfer Model

$$\dot{Q}_{abs-air} - \dot{Q}_{air-c} = \dot{Q}_{air} \quad (4)$$

$$\dot{Q}_{air} = \dot{m}_{air} * c_{p,air} * (T_{out,air} - T_{in,air}) \quad (5)$$

Figure 12 and equations 6 and 7 show the energy balance on the ethylene-glycol water flow segment.

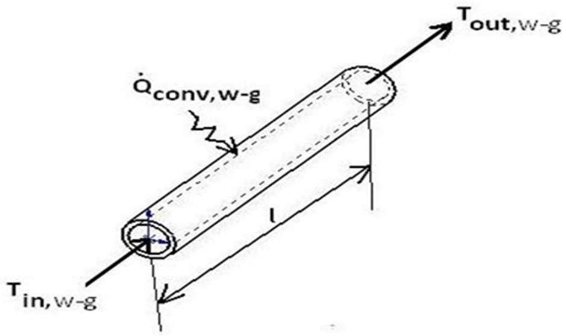

Figure 12: Ethylene-Glycol Water Flow Segment Heat Transfer Model

$$\dot{Q}_{conv,wg} = \dot{m}_{wg} * c_{p,wg} * (T_{out,wg} - T_{in,wg}) \quad (6)$$

$$\dot{Q}_{conv,wg} = h_{abs-wg} * A_{l,wg} * (T_{abs} - T_{m,wg}) \quad (7)$$

The total energy incident on the absorber, total energy transferred to the air, and total energy transferred to the heat transfer fluid are obtained by summations of the segment energies as in the following set of Equations; number 8 below:

$$\dot{Q}_{abs} = \sum_{i=1}^{i=N} \dot{Q}_{abs}(i)$$

$$\dot{Q}_{air} = \sum_{i=1}^{i=N} \dot{Q}_{air}(i) \quad (8)$$

$$\dot{Q}_{w-g} = \sum_{i=1}^{i=N} \dot{Q}_{w-g}(i)$$

3.2.2 Thermosyphon Model

This is based on Poiseulle's Law for Laminar flow which gives the volumetric flow rate and the buoyancy pressure difference as shown in Equations 9 and 10:

$$Vol = \pi \left(\frac{D}{2}\right)^4 * \Delta P/8\mu L \qquad (9)$$

$$\Delta P = g * \Delta\rho * L * \sin\theta \qquad (10)$$

3.2.3 Chimney Draft Model

The draft required to promote airflow is represented by the Boussinesq approximation. The airflow exit velocity is modeled by equation 11 as:

$$V_{Nn} = \sqrt{2gH \frac{(T_{air,Nn} - T_a)}{T_a}} \qquad (11)$$

Where H is included as if there were a chimney, Tair,Nn is the temperature of the airflow exiting the collector and Ta is the ambient temperature (also equals the temperature of the airflow entering the collector)

3.2.4 Storage Tank Model

The thermal storage model consists of an energy balance consisting of Charging, Discharging and Thermal Losses. In this model, thermal losses are assumed insignificant. That means during 'Day Time Simulation' the storage model assumes the 'Charging Mode' and during the 'Nighttime Simulation', the 'Discharging Mode'. Reverse thermosyphon is assumed for the 'Discharging Mode'. A further assumption made is that there is no stratification in the storage tank, that is, the storage has one uniform temperature.

The charging model is given by equations 12 and 13:

$$Q_{tank} = \dot{m}_{wg} * Cp_{wg} * (T_{wg,out,Nn} - T_{tank}) \qquad (12)$$

$$Q_{tank} = = m_{wg,tank} * Cp_{wg} * [T_{tank} - T_{wg,in,Nn,o}] / t_{cycle} \qquad (13)$$

Where $\dot{Q}tank$ is the heat transfer rate to the thermal storage; $\dot{m}$ wg is the mass flow rate of the water
ethylene glycol working fluid; $m$wg,$tank$ is the mass of the water ethylene glycol in the storage tank;
Cpwg is the specific heat capacity of the water
ethylene glycol and $tcycle$ is the cycle time. The other parameters Twg,ut,Nn, Twg,in,O, and $Ttank$ are temperatures of the working fluid exiting the collector model and entering the storage tank, of the working fluid entering the collector model at the previous cycle (also the previous storage tank temperature) and the new storage tank temperature respectively.

The discharging model is given by the equations 14 and 15:

$$\dot{Q}_{tank} = \dot{m}_{wg} * Cp_{wg} * (T_{wg,\ out,O} - T_{tank}) \qquad (14)$$

$$\dot{Q}_{tank} = m_{wg,tank} * Cp_{wg} * [T_{tank} - T_{wg,in,Nn}]/t_{cycle} \qquad (15)$$

Where the reversed flow now means that $T_{wg,out,O}$ and $T_{wg,in,Nn}$, are now temperatures of the working fluid exiting the collector model and entering the storage tank, and of the working fluid entering the collector model at the previous cycle (also the previous storage tank temperature) respectively.

3.2.5 Solar Radiation Model

The total hourly radiation can be estimated from the average daily radiation by using the following equation:

$$I_{sol} = H * r_t \qquad (16)$$

The coefficient to convert total daily radiation to total hourly radiation is given by equation 17:

$$r_t = \frac{\pi}{24}(a + b\cos w)\,\frac{\cos w - \cos w_s}{\sin w_s - \frac{\pi w_s}{180}\cos w_s} \qquad (17)$$

Where ‘w’ is the hour angle and ‘ws’ is the sunset hour angle in degrees. The coefficients ‘a’ and ‘b’ are given by equations 18:

$$a = 0.409 + 0.5016\sin(w_s - 60)$$
$$b = 0.6609 - 0.4767\sin(w_s - 60) \qquad (18)$$

3.3 Computer Simulations

The Computer Simulations are performed on the Engineering Equation Solver (EES) platform. The computer simulation developed consists of the following EES codes:

- One code for daytime simulation,
- One code for nighttime simulation,
- One code for the solar model – to simulate the hourly solar radiation, and
- One code for lengths and area calculations

4. Results

The simulations were run over 24 hours, starting at 7 am and ending at 6 am the following day. The computer code computed how many cycles to run in each hour. The input data was updated after each cycle as well as at the start of a new hour. The results for each cycle were saved. The summary and sampled results are shown here. Ambient temperatures were obtained for a typical April Day in Gaborone from website timeanddate.com (2012). Figures 13 and 14 show the hourly temperature and energy transfer rates for the simulated day. The temperatures shown for the air and ethylene glycol water flows are those at the exit flow’s exit from the collector. The energy rates are summations for the entire computer model as represented in Equation 8.

5. Conclusions

The computer simulations have been presented using Engineering Equation Solver (EES) software.

The concept design of the solar storage model consisted of eight panels thus forming an octagon shape on the periphery rather than a circular one; with each panel consisting of twenty-five riser pipes, a bottom header pipe and a top header pipe; with both header pipes connecting to a storage tank.

For the computer simulation further simplification has been done thus only a one-riser model has been considered. The computer simulation is based on a two-dimensional heat transfer segmented model.

Mathematical models have been developed for this simplified one-riser pipe, two-dimensional heat transfer, and segmented model.

Models have also been developed for hourly solar radiation, thermosyphon and storage.

Results are presented in chart form. Figure 13 shows the hourly temperature plots for the exit airflow temperature, exit ethylene glycol water temperature, storage temperature and the ambient temperature. The results can show growth in thermal storage as well as the reversal of the heat transfer from solar hours to non-solar hours. Figure 14 shows the heat transfer rates at the end of each hour.

The simulations have shown the potential for implementation of the concept storage model based on ethylene glycol water heat transfer fluid at 50% concentration. Further simulations are recommended for other types or mixes of heat transfer fluid. Extended simulations covering several days are required to gain useful insight into the effectiveness of the proposed storage model. Further validations on other software platforms such as TRANSYS and CFD may be necessary.

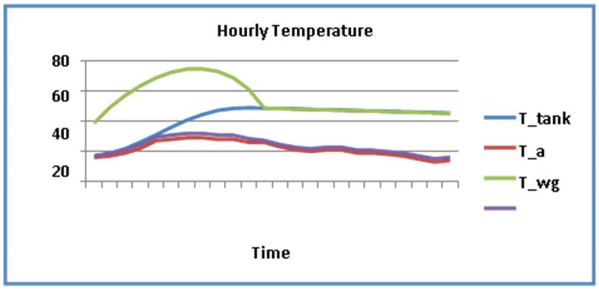

Figure 13: Hourly Temperatures

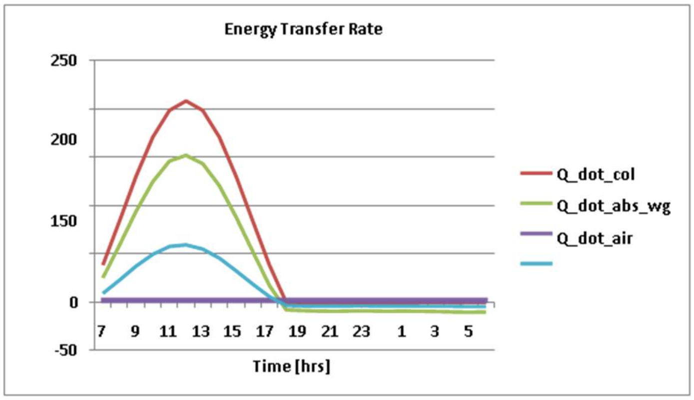

Figure 14: Energy Rates at the End of Each Hour

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