SOLAR WATER HEATING SYSTEM

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ABSTRACT

Uncertainty over future sources of energy provides strong motivation to explore technologies that free systems from traditional energy inputs. This project investigated home built solar water heating systems that can be used in any climates.

A computational model was developed to assist homeowners in the design of their own system.

ABSTRAK

Ketidakpastian mengenai sumber tenaga di masa hadapan memberikan satu motivasi yang kuat untuk meneroka teknologi-teknologi yang dapat membebaskan sistem sedia ada daripada input tenaga konvensional. Projek ini menyiasat sistem pemanas air suria buatan rumah supaya boleh digunakan dalam apa jua keadaan cuaca.

Satu model matematik telah dibina untuk membantu pemilik-pemilik rumah dalam mereka bentuk sistem mereka sendiri.

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CHAPTER 1

INTRODUCTION

1.1 Background Information

Many technologies have been developed to free houses from traditional energy dependency [1]. When implemented, these technologies often affect the layout and structure of a house. Some technologies are also very sophisticated and costly. As fuel prices rise, the cost of the construction of a new building by traditional methods is inflating rapidly. These facts make the development of sustainable technologies that can be easily retrofitted onto existing buildings a worthy pursuit. Space and water heating account for approximately 65 % of the total energy use in an average home in the United States [3] [11]. A solar hot water heater uses the energy from the sun to directly heat water. These systems can be retrofitted with relative ease onto existing structures. The main component of a solar hot water system is the collector, which allows incident solar energy to heat a fluid. An example of a flat plate solar thermal collector can be found in Figure 1.1 [10]. Incident solar energy enters the insulated collector through a glazed covering and increases the temperature of the absorber plate. The absorber plate is made of a material with a high thermal conductivity, usually copper. An array of tubes is attached to the plate and fluid is pumped through them. The circulating liquid in the tubes is heated by the hot absorber plate. Both the absorber plate and the tube array are usually painted black.

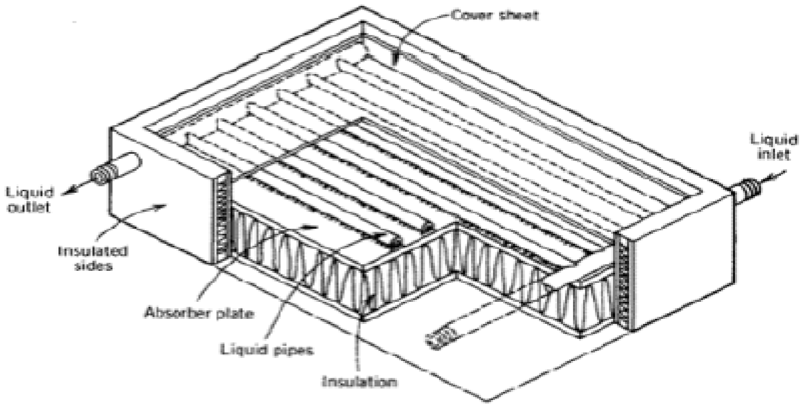

Figure 1.1: Flat Plate Solar Thermal Collector

Two main types of solar hot water systems are available, open loop and closed loop. An open loop system circulates potable water in a solar thermal collector. A closed loop system circulates an anti-freeze solution in the collector and uses a heat exchanger to warm potable water. Open loop systems are less costly then closed loop systems, but they cannot be used in climates where the temperature drops below freezing for a significant amount of time. Closed loop systems can be used in freezing climates, and are the topic of this thesis. It is worthwhile to study systems that are usable in colder climates since many home built solar hot water solutions are already available for climates that are suitable for open loop systems.

A closed loop solar water heating system can be seen in Figure 1.2 [4]. The working fluid of the system is warmed in the collector and travels into a heat exchanger. After leaving the heat exchanger, the working fluid is pumped back into the collector. The potable water is kept separate from the working fluid in a storage tank. The tank allows the heated water to accumulate, but also contains the heat exchanger and an auxiliary heater. The heat exchanger facilitates energy transfer between the collector working fluid and potable water. An auxiliary heater is necessary for the system to maintain a usable hot water temperature in unfavorable conditions. This thesis investigates systems with natural gas auxiliary heat. Many commercial examples of solar water heating systems are available. The cost of a closed loop system begins at approximately $3000. Professional installation of these systems also adds significant cost to the project. However, a motivated homeowner can construct and install an effective system without commercial components.

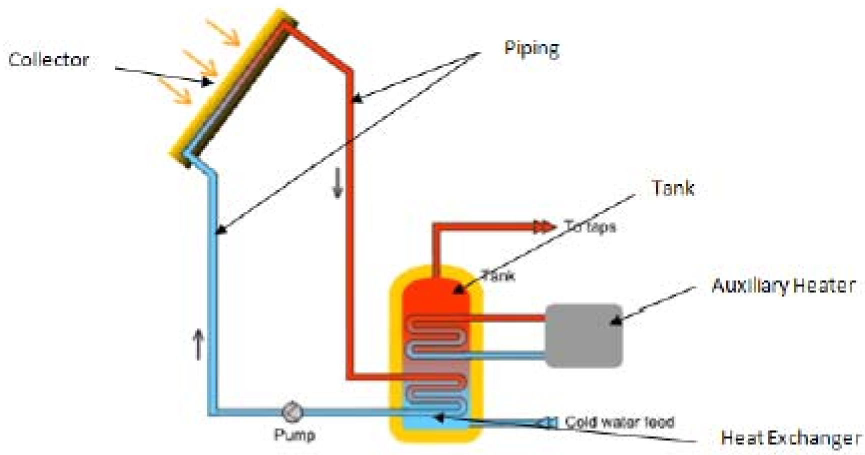

Figure 1.2: Closed Loop Solar Water Heating System

A rigorous analysis of solar swimming pool heaters was published by de Winter [5] in 1975. The publication included details of collector sizing, design, and construction. De Winter developed an expression for the steady state output of a solar thermal collector. This expression can be seen in Equation 1.1 below. In the expression, F_3 is the collector efficiency, Ac is the area of the collector, α is the absorptivity of the radiation coating, Q_i is the amount of incident solar radiation, U_l is the loss coefficient, T_{Ci} is the temperature of the incoming fluid, and T_a is the ambient temperature. The efficiency term was developed in three steps, beginning with the fin efficiency of the absorber plate. The Florida Solar Energy Center published a detailed guide on the general applications of solar thermal systems [2] in 2006. This manual provides guidelines for the implementation of solar thermal collectors for potable hot water use.

$$Q_{coil} = F_3 A c(\alpha Q_i - U_l(T_{ci} - T_a)) \quad (1.1)$$

The goal of this thesis was to develop a computational model to simulate the performance of a closed loop solar hot water heating system. After formulating equations, a Matlab and Simulink program will be created to model of a solar hot water system. The model also computed the economic consequences of installing a proposed system. Future work on the project includes integrating an optimization routine into the system model.

1.1.1 Formulation of Equations

A closed loop solar hot water system is comprised of three thermally significant components. These include a collector, piping, and a tank with an integral heat exchanger. A governing equation was developed for each component. Two notable assumptions were made while developing these relationships. First, that the specific heat of fluids is constant. Second, that the collector and tank fluid are at a uniform temperature. The thermally lumped analysis of the collector and tank are considered appropriate because of the high thermal conductivity of the collector material and the mixing action in the tank. Of the components, the collector and tank have a time and temperature dependency. The time dependency comes from the fact that these two components have a large thermal capacity. The piping is assumed to have no thermal capacity, and therefore only has a temperature dependency. Table 1.1 shows the unknowns and functional dependency for the collector and tank. The two components are first order systems, but they are coupled, so the entire system is second order.

Table 1.1: Unknowns and Functional Dependency of Components

Component	Unknowns	Functional Dependency
Collector	Lumped Collector Temperature Outlet Fluid Temperature	Time Inlet Fluid Temperature
Tank	Lumped Tank Temperature Outlet Fluid Temperature	Time Inlet Fluid Temperature

The governing expression for the solar thermal collector was developed using the results of Equation 1.1 [5]. With the assumption of constant specific heat, the steady state temperature increase of circulating fluid can be seen in Equation 1.2

below. In the expression, $\dot{m}_h$, C_{phf}, and T_{co} are the mass flow rate, specific heat,and temperature of fluid leaving the collector. Equation 1.3 results when the time dependent energy storage of the collector material is incorporated with Equation 1.2. In Equation 1.3,m_c, C_{pc}, and T_c are the mass, specific heat, and temperature of the collector itself. Equation 1.3 was employed as the governing expression for the solar thermal collector.

$$m_h C_{phf}(T_{co} - T_{ci}) = F_3 A_c(\alpha Q_i - U_l(T_{ci} - T_a)) \quad (1.2)$$

$$m_c C_{pc} dT_c dt = \dot{m}_h C_{phf} T_{co} + F_3 \alpha Q_i A_c - (F_3 U_l A_c - \dot{m}_h C_{phf}) T_{ci} + F_3 U_l A_c T_a \quad (1.3)$$

The development of the U_l term in Equation 1.3 relies on heat transfer coefficient correlations as developed in Korpela [7]. The correlations used for the convective heat transfer coefficients within the collector airspace, for the forced convection on the surfaces of the collector, and between the working fluid and collector tubing can be seen in Equations 1.4, 1.5, and 1.6. In these equations, Ra, Pr, and Re are the dimensionless Rayleigh, Prandtl, and Reynolds numbers. Additionally, H_c and W_c are the height and width of the enclosed cavity of the collector.

$$Nu = 0.42Ra^{0.25} Pr^{0.012} (H_c / W_c)^{-3} \quad (1.4)$$

$$Nu = (0.37Re^{4/5} - 871)Pr^{1/3} \quad (1.5)$$

$$Nu = 3.66 + \{0.0688(D/L)RePr / (1 + .04[(D/L)RePr]^{2/3})\} \quad (1.6)$$

Like the collector, the expression for the tank fluid temperature was developed using a thermally lumped technique. The expression for tank temperature in Equation 1.7 was developed first. In this expression, the m_t, C_{pw}, and T_t are the mass, specific heat, and temperature of the fluid within the hot water tank. Furthermore, R_t is the thermal resistance of the tank, $\dot{m}_t$ is the mass flow of water leaving the tank, and T_{fw} is the temperature of feed water ending the tank. The Q_{hex} term accounts for the energy input from the heat exchanger.

$$m_t C_{pw} dT_t/dt + (1/R_t + \dot{m}_t C_{pw}) T_t = Q_{hex} + T_a/R_t + \dot{m}_t C_{pw} T_{fw} \quad (1.7)$$

The temperature drop for the fluid on the collector side of the heat exchanger was found using the expression for heat transfer in pipe flow with a constant wall temperature. The assumption of constant wall temperature was made because of the high thermal conductivity of the tubing material. The expression for the temperature drop can be seen in Equation 1.8. In this expression, T_{hi}, T_s, and T_{co} are the temperatures of fluid entering the heat exchanger, the pipe wall, and fluid exiting the collector. Additionally, P,L, and U are the wetted perimeter, length, and heat transfer coefficient of the pipes. The rate of heat transfer from the heat exchanger with the assumption constant wall temperature is found in Equation 2.8. Equation 1.10 results upon combining and rearranging equations 1.7 and 1.9. Equation 1.10 was employed as the governing expression for the tank.

$$T_{hi} = T_s - \exp(-PLU)\dot{}/m_h C_{phf} (T_s - T_{co}) \quad (1.8)$$

$$Q_{hex} = \dot{m}_h C_{phf} [(T_t - T_{hi}) - (T_t - T_{ho})] \quad (1.9)$$

$$m_t C_{pw} dT_t/dt + (1/R_t + \dot{m}_t C_{pw}) T_t = T_a/R_t + \dot{m}_t C_{pw} T_{fw} + \dot{m}_h C_{phf} (T_{ho} - T_{hi}) \quad (1.10)$$

Energy loss was considered from the piping in the collector loop between the collector and heat exchanger. The temperature of the working fluid after piping loss is given as in Equation 1.8 above. Again, the uniform wall temperature assumption was made because of the high thermal conductivity of the pipe walls. The losses encountered between the tank and the hot water use point were not taken into account. When hot water is used in a home, the temperature is often regulated by the mixing of hot and cold water streams. This was taken into account with Equation 1.11 below.

In the expression, $\dot{m}_t$ and $\dot{m}_u$ are the mass flow rates of fluid leaving the tank and being used. Temperature of the hot water is denoted by T_u. The mass flow of the hot water leaving the tank is dependent on the tank temperature because the T_u term is constant. This relationship has the effect of decreasing the mass flow of water from the tank when its temperature is hot in comparison to the use temperature.

$$\dot{m}_t = \dot{m}_u (T_{fw} - T_u)/(T_{fw} - T_t) \qquad (1.11)$$

1.1.2 Economics

The economic payoff of installing a solar hot water system was investigated using the principles of engineering economics as presented in Arora [6]. An investment is considered viable if it possesses a positive net present value, or NPV. A positive NPV results if the return on investment for the initial capital is greater than the minimum acceptable rate of return, or MARR. The MARR is framed as the interest rate that is expected for an investment of a certain risk level. To find present value, the expected future cost savings on natural gas must be discounted at the MARR rate. This is carried out using Equation 1.1.1 below. The present value of each year's expected savings is then summed, and the initial investment of the system is subtracted. Because the price of natural gas does not stay constant, the expected yearly cost savings from the system fluctuates. The future cost of natural gas can be found using the current price and estimations for the annual percentage rate increase. After rearranging, Equation 1.1.1 is also used for this task. In the expression, PV,FV,i, and n are the present value, future value, interest rate, and compounding periods of an investment.

$$PV = FV\,(1 + i)^{-n} \qquad (1.1.1)$$

The sizing of a solar hot water system provides an economic optimization problem. The output of the collector is much greater in the summertime than the wintertime. This is because the amount of solar radiation is higher in the summer, as is the ambient temperature. Figure 1.3 below illustrates this fact. In the figure, the normalized system output is plotted for a year. The time scale is that of months, with 1 corresponding to January and 12 corresponding to December. As can be seen from the plot, if the solar system was designed to provide 100% of the hot water for a home in the middle of the winter, the system would have large a amount of unutilized capacity in the summer. The unutilized capacity is a waste of the capital investment of the system. Thus, an economically optimum system will require some degree of auxiliary heat.

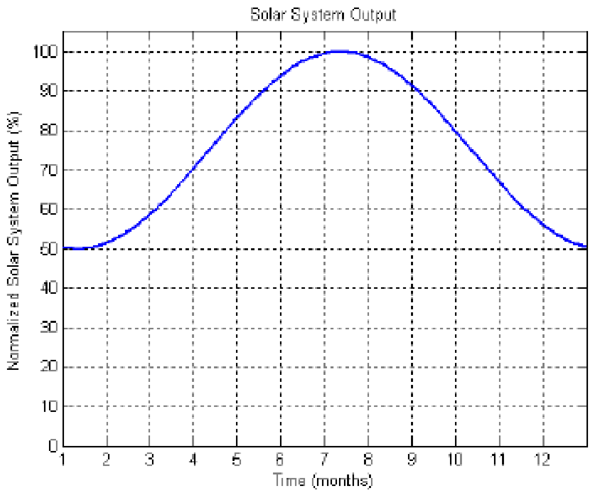

Figure 1.3: Normalized Solar System Output for a Year

1.1 Objectives

Uncertainty over future sources of energy provides strong motivation to explore technologies that free systems from traditional energy inputs. The objective of this project is to investigate home built solar water heating systems that can be used in any climates.

1.2 Scope

The scopes are:

- To develope computational model of Solar Water Heating system.
- To validate the predictions given by the model.
- To create Matlab and Simulink program of a solar hot water system.

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