An Optimal Control Approach For Determiniation Of The Heat Loss Coefficient In An Ics Solar Domestic Water Heating System

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AN OPTIMAL CONTROL APPROACH FOR DETERMINATION OF THE HEAT LOSS COEFFICIENT IN AN ICS SOLAR DOMESTIC WATER HEATING SYSTEM

by

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ABSTRACT

Water heating in a typical home in the U.S. accounts for a significant portion (between 14% and 25%) of the total home’s annual energy consumption. The objective of considerably reducing the home’s energy consumption from the utilities calls for the use of onsite renewable energy systems. Integral Collector Storage (ICS) solar domestic water heating systems are an alternative to help meet the hot water energy demands in a household. In order to evaluate the potential benefits and contributions from the ICS system, it is important that the parameter values included in the model used to estimate the system’s performance are as accurate as possible. The overall heat loss coefficient ($U_{loss}$) in the model plays an important role in the performance prediction methodology of the ICS. This work presents a new and improved methodology to determine $U_{loss}$ as a function of time in an ICS system using a systematic optimal control theoretic approach. This methodology is based on the derivation of a new nonlinear state space model of the system, and the formulation of a quadratic performance function whose minimization yields estimates of $U_{loss}$ values that can be used in computer simulations to improve the performance prediction of the ICS system, depending on the desired time of the year and hot water draw profile. Simulation results show that predictions of the system’s performance based on these estimates of $U_{loss}$ are considerably more accurate than the predictions based on current existing methods for estimating $U_{loss}$. 

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1 INTRODUCTION

The objective of considerably reducing the energy demands from the utilities in a typical home in the U.S., calls for onsite renewable energy systems. Water heating itself accounts for a significant portion (between 14% and 25% [1]) of the total annual energy consumption in a typical home. Integral Collector Storage (ICS) solar domestic water heating systems are an alternative to help meet the hot water energy demands in a household. A picture of the specific ICS system studied in this research can be seen in Figure 1.1.

![ICS picture](image)

Figure 1.1: ICS picture
In order to evaluate the potential benefits and contributions from the ICS system, it is important that the values included in the modeling scheme are as accurate as possible. The overall heat loss coefficient ($U_{loss}$) plays an important role in such a scheme and in the performance prediction methodology of the ICS. In calculations regarding ICS systems performance and certification standards, $U_{loss}$ is nowadays assumed to be constant [2]. However, in reality $U_{loss}$ is time-varying because it depends on the operating conditions of the system including the weather. By finding a time-varying $U_{loss}$, fluctuation in losses due to variations in environmental conditions could be simulated. Typically, the constant value for $U_{loss}$ is found experimentally through standards established by the Solar Rating and Certification Corporation (SRCC) and others. The optimal control approach offers a systematic method to find $U_{loss}$ based on measurements obtained from a real ICS system installed at the Florida Solar Energy Center (FSEC) where ambient and internal variables are being monitored and stored permanently.

This work presents a new applied research methodology to determine the time-varying heat loss coefficient ($U_{loss}$) in an Integral Collector Storage (ICS) solar domestic water heating system using an optimal control approach.

The contributions of this work are the nonlinear state space formulation and analysis of the system, a new and improved approach to obtain approximate heat loss coefficient values based on the use of optimal control theory, and as a result of this, a new set of $U_{loss}$ values that can be
used in computer simulations to improve the performance prediction of an ICS, depending on the desired time of the year and hot water draw profile.

1.1 General Description

Integral collector storage (ICS) solar water heaters are passive systems which combine thermal storage and solar collection functions in a single unit. They are usually roof or ground mounted. In these systems, mains water is used as the heat collecting fluid and they require neither pumps, control valves, sensors, heat exchangers, control units nor electrical components. Instead, they only require local water pressure and solar radiation to operate and, in most applications, they function as a pre-heater to a conventional water heater. There exist several different designs and configurations for ICS systems but this study focuses specifically on one of them. In the design of interest, the fluid is stored in eight (8) copper tubes that are connected (welded) in series so that the outlet of one tube feeds the inlet of the next one. Physically, the tubes are arranged in a parallel fashion and placed within a collector enclosure. Figure 1.2 shows a basic diagram for this configuration and Figure 1.3 shows the water inlet and outlet on the system itself.

The collector/storage device absorbs solar radiation and raises the temperature of the water stored in the tubes (tanks). The objective is to maximize solar radiation collection while minimizing thermal loss. Then, the unit is well insulated for increased heat retention and to reduce heat losses to ambient, especially at night time and non-solar radiation collection periods. Additionally, in order to maximize solar radiation collection while minimizing thermal loss, the
ICS in this study has a double-glazed optical cover system, glazing gaskets, selective surface coating and closed cell foam.

![ICS basic diagram](image)

Figure 1.2: ICS basic diagram

a) Top view. b) Side view.

When the tops of the absorber tanks completely fill the aperture area, the ICS unit is called non-concentrating. When internal reflectors concentrate solar radiation to an absorber tank within the
enclosure, the ICS is called concentrating ICS unit. As seen from the previous description, the system of interest is a non-concentrating ICS unit.

![ICS water inlet and outlet image](image)

**Figure 1.3: ICS water inlet and outlet**

1.2 Literature Review Summary

Experimental methods of testing solar water heaters allow users to make product comparisons through common performance indices [3]. In USA, the ASHRAE Standard-95 [4] is an industry benchmark that is used as a short-term performance testing method. In Europe, the European Solar Collector and Systems Testing Group (CSTG) [5] have developed a standard testing procedure for all forms of solar water heaters used in the European Community. Although both
test methods make provision for the testing of ICS systems, the ASHRAE Standard-95 does not provide prediction of long-term performance. Bainbridge [6] and Thomas [7] have both developed test procedures, based on the ASHRAE Standard-95, for ICS systems to provide long-term performance data.

Boussemaere and Bougard [8] as part of the CSTG project, experimentally investigated testing procedures for ICS systems. The study looked at long-term daily, short term daily and component tests. The study concluded that an input/output approach used for long-term daily evaluation must use characterization data collected from the short-term daily test procedure. Tests on component parts can be used in computer simulation programs to predict the long-term performance. An experimental methodology employed to determine ICS systems collection performance was developed by Tripanagnostopoulos and Yianoulis [9]. The test procedure is a combination of test methods proposed by the European Solar Collector and Systems Testing Group and gives a realistic ICS performance representation which allows direct comparison with other experimentally investigated ICS systems.

In a follow-up study based on previous experimental investigations, Boussemaere [10] reported on the simulation of an ICS system. The study did not seek to replace experimental testing with computer simulation but rather evaluate the effect the test procedure had on the system characterization.
Stickney and Aaboe [11] developed a simple method that allowed direct comparison of ICS systems. The method required the calculation or measurement of system variables, such as thermal efficiency of collection and tank heat loss coefficient, to produce one of four performance indices. The performance indicator could then be used by a consumer or designer to compare and select an ICS system for their requirements. Faiman [12] reported on a standard method to determine the efficiency of ICS systems through the use of a maximum useful efficiency (MUE). Weller [13] conducted work on an experimental program to predict the energy losses and heat storage delivery efficiency of a commercial integral passive solar water heater. The work was based on the earlier work by Cummings and Clark [14] on the performance prediction of an ICS system in 10 US climates. Weller showed that the energy losses through the aperture could be represented using a simple lumped cooling model. Burns [15] reported on a study to develop an analytical model to predict the performance of a stratified ICS system. Good agreement between theoretical and experimental results was reported although the work concluded that ICS systems are best suited to water pre-heating roles.

Thermal performance simulations for ICS systems of similar nature have been developed [16, 17, 18, 19]. These and other techniques [20, 21, 22] have been employed to predict the solar savings fraction from the use of an ICS system with a particular specification subject to a specified pattern of withdrawal of heated water under given weather conditions. Fanney and Klein [23] compared the experimental performance of an ICS system over a one year period with
the performance predictions of the method used by Zollner. They concluded that the agreement between the experimental results and the predicted performance was good. Garg [24] developed a nomogram for performance prediction of ICS systems, based on analysis carried out by Hobson and Norton [25].

Although some of the methods provided good agreement with experimental data in the past, the invention and addition of new materials to ICS systems leave room for further analysis. In our case, specifically, a new methodology will be used to obtain a heat loss coefficient that takes into consideration the time of the year and the specific hot water draw profile used. The goal is to show that by using the obtained $U_{loss}$ the accuracy of the ICS computer simulations is improved.

As part of the validation process of the research, an ICS system was installed at the Florida Solar Energy Center where ambient and internal variables were monitored and stored permanently.
2 SYSTEM DESCRIPTION

In order to maximize solar radiation collection while minimizing thermal loss, the ICS in this study features additional improvements such as a double-glazed optical cover system, glazing gaskets, selective surface coating and closed cell foam. These elements and their functions are explained next.

2.1 Components and Previous Work

Figure 2.1 shows the basic components of the ICS system in this study.

![ICS system basic components](image)

**Figure 2.1: ICS system basic components**

2.1.1 Tanks

The tube containing the heated water is the central component of the ICS system. Its primary function is to absorb solar radiation and transfer the thermal energy to its interior. According to
Smyth [3], the orientation, size and shape of the container, along with the tank materials and coatings affect the amount of radiation absorbed.

2.1.1.1 Tanks size and shape

The size and shape of the tank has a significant effect on the collection of solar radiation. The greater the exposed surface area to volume ratio the less time will be required for insolation to heat up the stored water. The importance of the surface area/volume ratio was noted by Haskell in 1907 [26]. In our case, the unit has eight (8) copper cylindrical tanks, which nowadays dominate the commercial market, since they are inexpensive, pressure resistant and readily available. In fact, in the system of this study the tank is pressure rated to 300psi and is coated with a high-temperature selective solar radiation absorption that maximizes heat gain and reduces heat loss [27]. Additionally, the 4” diameter tanks are welded to the interconnecting pipes to form a series flow pattern. Significant studies have been conducted to advance the understanding and development of cylindrical tanks and their use in ICS solar water heating systems [28, 29]. Due to practical constraints and financial restrictions, a compromise must be reached between heat gain and heat loss due to area/volume ratio and construction costs.

2.1.1.2 Configuration and interconnection of tanks

The number, interconnection and mounting of tanks has a significant effect on performance [30]. Regardless of the tanks mounting position, the inlet and outlet of the ICS system are always
arranged so that hot water is withdrawn from the top and cold water replenished at the bottom to minimize mixing of hot and cold water. In our case, dividing water storage over eight (8) tanks improves thermal stratification (when cold and warm water form layers that act as barriers to water mixing) within each tank as cold inlet water entering the lower tank is prevented from mixing with the hottest water in the upper (final) tank (see Figure 1.2). The amount of mixing of heated and unheated water within any tank depends on cold water charge and hot water discharge cycles, the size and location of inlets and outlets, flow temperatures and velocities and tanks geometries [31, 32, 33]. In our case, the inlet and outlet connections are made of nominal ¾” diameter type “L” hard copper pipes. This allows for fast, leak free sweat fitting plumbing connections [27].

2.1.1.3 Inclination and orientation of tanks

The optimum inclination angle tends to the horizontal at latitudes approaching the equator [34]. Horizontally mounted systems (tilted in our case) tend to be aligned in an East-West orientation. However, as cylindrical tanks mounted horizontally may allow the contained water to be weakly thermally stratified, a reduced solar saving fraction (SSF) (heat input from the solar collector divided by the total thermal energy required by the load) may take place subsequently. Tripanagnostopoulos and Souliotis [30] conducted a series of experimental investigations on the performance comparison of identical ICS solar systems with both horizontal (E-W) and vertical (N-S) mounted tanks. Their results indicated clearly that the vertical mounted approach gave
sufficient water temperature stratification, but it had a reduced mean daily efficiency and heat preservation compared to the horizontal mounted tank. A better performance of the horizontal system is achieved without extra cost.

2.1.1.4 *Tanks materials*

The tanks are the major components in an ICS system with the primary function of absorbing solar radiation and transfer heat to the adjacent storage fluid. Nowadays, copper (in our case), aluminum, and stainless steel are the most popular and more recently certain types of polymers pigmented black to absorb solar radiation are being used. Since metals are not good absorbers of solar radiation [3], a spectrally coating or paint is usually applied to absorber surfaces to provide good solar radiation collection. Transfer of the absorbed solar energy to the storage fluid depends on the material thermal conductivity with materials such a copper and aluminum being very effective. In addition to heat transfer, the thermal conductivity of the tank material can have a significant effect on thermal stratification within the tanks. Vertical conduction in the tanks wall, together with losses to ambient, induces convective currents that rapidly reduce thermal stratification. The degree of thermal conduction and corresponding convective motion depends on the thickness and conductivity of the wall material [33, 35, 36]. In addition to good absorption and thermal characteristics, the tanks material must be of sufficient strength and durability, lend itself to forming and fabrication, and be of an appropriate cost. Copper (in our
case) and stainless steel have good structural strength. In inappropriate combinations, certain metals are susceptible to corrosion, either externally or internally [37].

2.1.1.5 Spectrally selective coatings

To enhance solar radiation absorption, an absorbent coating, and more specifically some form of spectrally selective absorber surface is usually required. As stated previously, the tanks in our case are coated with a high-temperature selective solar radiation absorption surface that maximizes heat gain and reduces heat loss.

During the 1970s researchers and manufacturers started to take a specific interest in the surface treatment of the tanks. Stickney and Nagy [38] tested three types of ICS systems with and without a selective surface absorber. In all cases the collection efficiency improved, where a selective surface absorber was used. Burton and Zweig [39] compared systems with a selective absorber with those painted a dull black. The type of selective absorber used was a metallic nickel chrome type with an absorptance of 0.97 and a thermal emittance of 0.10 (ability to release absorbed heat). Although providing no specific details they found that the system with the selective surface coated absorber always produced the warmest water.

Several arrangements of different glazing materials combined with tanks with and without a selective absorber surface were compared by Bainbridge [6]. He found that a single-glazed unit
with a selective absorber reached a higher temperature of 77 °C than a similar system painted black which reached only 68 °C by the late afternoon, in an ambient temperature of 21 °C. A series of experiments, conducted by Tiller and Wochatz [40], used selective surface paint with a solar absorptance of 0.94 and long-wave thermal emittance of 0.45–0.60. These experiments were designed to compare the effectiveness of a glazing/selective absorber combination at reducing night-time heat loss with that of a moveable insulating lid/shutter. They found that the morning temperatures of the single-glazed shuttered design were 2.8 °C higher than those of the unshuttered selective absorber design (approximately 29.1 °C as opposed to 26.3 °C), but added that a selective absorber with lower thermal emittance would have reduced this difference. In comparing total heat gain, the single-glazed shuttered design performed best. No details of ambient temperatures during the tests were provided.

A partially validated set of computer simulations were performed by Cummings and Clark [14] on selective absorber surfaces in conjunction with various glazing materials for all the climatic zones of the USA. In their computer model they used an absorptance of 0.95 and an emittance of 0.10 to simulate the selective absorber. They recommended that a single-glazed selective absorber design would give relatively high solar collection efficiencies for all climates, ranging from 42 to 51% with a corresponding solar saving fraction of 0.27–0.64, depending on the test location. The solar collection efficiency is defined as the annual solar heat delivered to the load divided by the annual insolation on the net aperture plane. The solar savings fraction is defined
as the heat input from the solar collector divided by the total thermal energy required by the load. In mild cloudy climates the collection efficiency was high, but the SSF low. The average increase in annual delivered energy for the single-glazed selective absorber design over the single-glazed non-selective absorber design was 31%, with a range of 26–44%.

Fasulo [41] examined the performance of an ICS system in Argentina using either selective absorbent coatings or matt black paint. They concluded that using a selective absorbent coating on the ICS tank surface reduced night-time heat loss to 10 MJ/night compared to 13 MJ/night for a tank with matt black paint surface finish.

2.1.2 Glazing and case

The primary function of glazing is to reduce convective losses by restricting air movement. Glazing also protects the absorber from the environment and particularly when glass with low-iron content is used reduces radiative heat losses by reflecting thermal radiation emitted by the absorber. The most important property required of a glazing material is high transmittance of solar radiation, as any loss in transmittance will lead to a direct reduction in collection efficiency [3].

2.1.2.1 Glazing layers

The system in our study is a double glazed unit. The outer glazing is tempered low-iron solar glass with 91% transmittance. The inner glazing is Teflon® film, known for its high temperature
tolerance ($525 \, ^\circ F = 273.89 \, ^\circ C$) and its long term durability and stability, with 96% transmittance [27]. There is a ¾” air space between glazings to reduce heat loss. Tanishita [42] in early studies developed and tested both single and double glazed versions of ICS systems. Baer [43] introduced an ICS solar water heater that had a double glazed glass aperture (glazing area). McCracken [44] designed a similar simple ICS system with a double glazed glass aperture. Additional studies regarding glazing layers can be found in references [45] and [46].

2.1.2.2 Glazing gaskets

A continuous gasket made of special long life EPDM (Ethylene Propylene Diene Monomer) synthetic rubber is compressed by the glazing caps to seal out the weather. The inner glazing spline is made of high-temperature tolerant EPDM [27].

2.1.2.3 Storage volume/aperture area ratio

It is well known [3] that the lower the water storage volume per unit aperture area ratio (i.e. small volume, large glazing area), the higher temperatures and/or greater rate of heat gain per unit volume should be attained. However, it is practically and financially naive to consider an extreme ratio, as the amount of hot water delivered may be relatively small and the capital cost of the unit very high. Thus, as with most aspects of ICS systems design, a compromise between cost and performance must be considered.
Investigations by Tiller and Wochatz [40], concluded that ICS systems with high storage volume/glazing ratios (102 l/m²) operate better in warm weather than those of smaller ratios (51–69 l/m²) unless hot water is used fairly continuously throughout the day. Other studies suggested a figure of 100 l/m² should be the maximum storage volume/glazing ratio [31]. Cummings and Clark [14] found that increasing the glazing area, increased the SSF but significantly decreased the efficiency. Tripanagnostopoulos and Yianoulis [9], Tripanagnostopoulos [47, 48], and Tripanagnostopoulos and Souliotis [30] have investigated experimentally various forms of ICS systems and have used storage volume/glazing ratios of 80–130 l/m² [1]. The storage volume/aperture area ratio in our case is 56.57 l/m².

2.1.2.4 Case

The system of our study has a hard temper, extruded aluminum frame wall where all rivets and bolts are aluminum or stainless steel. The aluminum back sheet is 0.025” thick [27].

2.1.3 Insulation

Thermal insulation of the storage tanks and associated casing was overlooked completely by early Japanese and US ICS solar water heater entrepreneurs [3]. Subsequent designers have often employed less than the economically optimum thickness of insulation. Baer [43] was the first to investigate systematically the effects of varying the thickness of insulation, conducting a variety of experiments with simple ICS units. He added considerable insulation to the box and
introduced a moveable insulated lid. These design modifications resulted in a significant improvement in the heat retaining properties of the ICS solar water heater.

The system in this study features rigid closed cell polyisocyanurate foam board and it is used to maximize heat retention. Sides and ends of the unit have 1.5” board, R-value 10 (ability to oppose heat conduction given in ft² °F hr / Btu); bottom has 2” board, R-value 14; and between tank tubes there are 1.5” boards, R-value 10 [27].

2.2 Modeling and Dynamics

The main heat transfer processes in the ICS system of our interest are shown in Figure 2.2, based on the idea presented by Smyth, Eames and Norton [3].

Nevertheless, an analytical solution of the model is usually available only for an idealized system. Numerical solutions or experiments may be used to empirically quantify the non-ideal aspects of the physical problems that were avoided in the analytical solution. The following modeling procedure is based on the work developed by Zollner in reference [49].

When the water in the storage tanks of an ICS unit are at a uniform temperature, there is no thermal stratification, and the storage is termed “fully mixed”. If a fully mixed ICS system is considered, an instantaneous energy balance may be written about the unit which equates the
change in tanks internal energy with the absorbed solar radiation less losses to ambient and delivered energy to the conventional water heater.

The energy balance is expressed as:

\[ M_w c_p \frac{dT_w}{dt} = G_{alt} A_c \tau \alpha - U_{loss} A_c (T_w - T_a) - m_{def} c_p (T_w - T_m) \]  

(2.1)

The description of the variables in equation (2.1) is shown in Table 2.1.
Table 2.1: Fully-mixed ICS variables description

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_w$</td>
<td>mass of water in the ICS system tanks (kg)</td>
</tr>
<tr>
<td>$c_p$</td>
<td>specific heat of water (4186 J / kg·K)</td>
</tr>
<tr>
<td>$\frac{dT_w}{dt}$</td>
<td>rate of change in the tanks water temperature (°K / s)</td>
</tr>
<tr>
<td>$G_{tilt}$</td>
<td>instantaneous solar radiation per unit area on a tilted surface (W / m²)</td>
</tr>
<tr>
<td>$A_c$</td>
<td>aperture area (m²)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>transmittance-absorptance product (unitless)</td>
</tr>
<tr>
<td>$U_{loss}$</td>
<td>effective energy (overall heat) loss coefficient (W / m²·K)</td>
</tr>
<tr>
<td>$T_w$</td>
<td>tanks water temperature (°K)</td>
</tr>
<tr>
<td>$T_a$</td>
<td>ambient temperature (°K)</td>
</tr>
<tr>
<td>$m_{del}$</td>
<td>instantaneous draw flow rate through the ICS unit (kg / s)</td>
</tr>
<tr>
<td>$T_m$</td>
<td>mains water temperature (°K)</td>
</tr>
</tbody>
</table>

In reality, thermal stratification takes place in the ICS tanks and it is induced by draw or caused by natural convection. ICS systems are generally designed such that cold water enters at the bottom of the first tank, and hot water is drawn off the top of the last tank. This type of design leads to draw-induced stratification. Because of this, the approach developed below models draw-induced stratification by dividing the storage into a number of nodes where each of these nodes is considered isothermal (see Figure 2.3). The proposed model neglects stratification due to natural convection.
According to this, an energy balance can be proposed at every node. The rate of change in internal energy of each node is equated to the solar gain less the energy withdrawn and heat loss form the node. This is expressed in (2.2).

\[
\frac{M_w c_p}{N} \frac{dT_n}{dt} = \frac{G_{\text{net}} A \tau}{N} - \frac{U_{\text{loss}} A}{N} (T_n - T_a) - m_{\text{del}} c_p (T_n - T_{n-1})
\]

(2.2)

The subscript \(n\) refers to the particular node in question and \(N\) refers to the number of nodes being modeled. The temperature of each node, \(T_n\), is the water temperature within the node rather than the absorber temperature. This assumes the absorber-water conductance is high. The first node always receives water at mains temperature and the final node always represents the delivered water temperature. The model assumes the aperture area and the solar gain are equally divided among the nodes and also the effective loss coefficient per unit area, \(U_{\text{loss}}\), is the same for each node. The quantity \((M_w c_p) / N\) represents the thermal mass (heat capacity) of the water in
the node; the heat capacity of the ICS unit itself is neglected. The model neglects bypass through nodes and heat transfer between nodes when there is no flow. Stratification due to draw is modeled, but conduction and stratification due to natural convection are not modeled. In reality, the system presents top, back, and edge losses separately. However, only one overall heat loss coefficient (top), $U_{loss}$, is included in the model and is referenced to the aperture area. The back and edge loss coefficients may then be considered zero.

In solar energy thermal processes the input signals to the system are usually the weather and the load ($m_{del}$). The weather signals can be obtained by taking our own measurements or from the Typical Meteorological Year (TMY) [50] data sets from the National Solar Radiation Data Base (NSRDB). A brief description of TMY data is given in Appendix A.

Constants in the system, such as the aperture area and tank volume are called parameters of the system. We could study the effects of various inputs, desired outputs, or parameters, on system performance by running system simulations in which one or all these three are varied. Figure 2.4 shows a simplified block diagram of the ICS system.

![Figure 2.4: ICS block diagram](image-url)
3 SYSTEM FORMULATION AND OPTIMAL CONTROL

3.1 System Formulation

As it was stated in the introduction, the overall heat loss coefficient, $U_{\text{loss}}$ (core of this work), plays an important role in the modeling scheme and in the performance prediction methodology of the ICS. In calculations regarding ICS systems performance and certification standards, $U_{\text{loss}}$ is nowadays assumed to be constant [2]. However, in reality $U_{\text{loss}}$ is time-varying because it depends on the operating conditions of the system including the weather. In other words, $U_{\text{loss}}$ is a function of $T$. Before getting to the details of how to find $U_{\text{loss}}$ using optimal control theory, the formulation proposed in (2.2) is modified by taking into account the following considerations.

$$
\begin{align*}
  x_n &= T_n \\
  u &= U_{\text{loss}}(t) \\
  A(t) &= f(b_3(t)) \\
  B(t) &= g(T_a(t), b_2) \\
  v(t) &= h(b_1, G_{\text{tilt}}(t), b_3(t), T_m(t))
\end{align*}
$$

(3.1)

$$
\begin{align*}
  b_1 &= \frac{A_c \cdot \tau a}{M_w \cdot c_p}, \\
  b_2 &= \frac{A_c}{M_w \cdot c_p}, \\
  b_3(t) &= \frac{N \cdot m_{\text{del}}(t)}{M_w}
\end{align*}
$$

(3.2)

The above matrices are given in explicit form in (3.3).
The new system formulation in compact form is shown in (3.4).

\[
\dot{x} = A(t)x + B(t)u - b_2 xu + v(t)
\]

(3.4)

The above equation describes a non-linear time-varying system with known disturbances, where \( U_{loss} \) became the input to the system. According to this formulation and the objective of finding how \( U_{loss} \) varies with time, the problem can now be analyzed using optimal control theory.
3.2 Optimal Control Theory

In optimal control theory, we suppose the plant is described by the nonlinear time-varying dynamical equation \( \dot{x} = f(x, u, t) \) with state \( x(t) \in \mathbb{R}^N \) and control input \( u \in \mathbb{R}^d \). With this system, let us associate the performance index (3.5).

\[
J(t_o) = \phi(x(t_f), t_f) + \int_{t_o}^{t_f} L(x(t), u(t), t) \cdot dt 
\]

(3.5)

Here, \([t_o, t_f]\) is the time interval of interest. The final weighting function \( \phi(x(t_f), t_f) \) depends on the final state and final time, and the weighting function \( L(x, u, t) \) depends on the state and input at intermediate times in \([t_o, t_f]\). The performance index is selected to make the plant exhibit a desired type of performance. The optimal control problem is to find the input \( u(t) \) on the time interval \([t_o, t_f]\) that drives the plant along a trajectory \( r(t) \) such that the cost function (3.5) is minimized. In other words, the optimal control problem is an optimization problem with equality constraints (the plant), where these, rather than being static, develop dynamically through time.

To solve the optimal control problem, Lagrange multipliers theory is used to adjoin the constrains to the performance index. Since the plant equation holds at each \( t \in [t_o, t_f] \), we require an associated multiplier \( \lambda(t) \in \mathbb{R}^N \), which is a function of time. Defining the Hamiltonian function as in (3.6), the augmented performance index is given by (3.7).
\[ H(x, u, t) = L(x, u, t) + \lambda^T \cdot f(x, u, t) \]  
\[ J_a = \phi(x(t_f), t_f) + \int_o^{t_f} [H(x, u, t) - \lambda^T \cdot \dot{x}] \, dt \]

According to the Lagrange theory, the constrained minimum of \( J \) is attained at the unconstrained minimum of \( J_a \). This is achieved when the increment in \( J_a \) (as a function of increments in \( x \), \( \lambda \), \( u \) and \( t \)) is equal to zero for all independent increments in its arguments. This yields the necessary conditions for a minimum from where we obtain the so-called state (3.8) and co-state (3.9) equations, and the stationarity condition (3.10).

\[ \dot{x} = \frac{\partial H}{\partial \lambda} = f \]  
\[ -\dot{\lambda} = \frac{\partial H}{\partial x} = \frac{\partial f^T}{\partial x} \cdot \lambda + \frac{\partial L}{\partial x} \]  
\[ 0 = \frac{\partial H}{\partial u} = \frac{\partial L}{\partial u} + \frac{\partial f^T}{\partial u} \cdot \lambda \]

The (fictitious) Lagrange multiplier \( \lambda(t) \) is thus a variable that is determined by its own dynamical equation. We therefore have a particular situation: we do not really care what \( \lambda(t) \) is, but this method of solution requires us to find \( \lambda(t) \) as an intermediate step in finding the optimal control.
In the particular case of this study, it is desired to find the input \( u \) such that the system follows a desired reference \( r(t) \). Such a reference is obtained from actual measured values of the system at the Florida Solar Energy Center. It is important to note that in the input \( u \) to be found would be reflected the aspects of the physical problem that were avoided in the presently available modeling scheme. The reference data and the variables of interest are sampled and stored every 12 seconds. Then, the data for each variable are averaged every 15 minutes and this is the value for a given variable for that 15-minute interval. It is desired to solve the optimal control problem for each 15-minute interval. According to this, the quadratic performance index in (3.11) is proposed where \( i = 0,1, 2,...,95 \) and \( i = 0 \) is midnight and \( t_{i+1} - t_i \) corresponds to 15 minute intervals.

\[
J(t_i) = \frac{1}{2}(x(t_{i+1}) - r(t_{i+1}))^T S(t_{i+1}) (x(t_{i+1}) - r(t_{i+1})) + \frac{1}{2} \int_{t_i}^{t_{i+1}} x^T Q x + R u^2(t) \cdot dt
\]  

(3.11)

Here, \( S(t_{i+1}) \geq 0, Q \geq 0, R > 0 \) and the desired final-state value \( r(t_{i+1}) \) is given. Thus, we want to find the control \( u(t) \) over the interval \( [t_i, t_{i+1}] \) to minimize \( J(t_i) \). Then, we must solve the state equation (3.4), the co-state equation (3.12) and the stationarity condition (3.13).

\[
- \dot{\lambda} = (A^T - I u) \lambda
\]  

(3.12)

\[
0 = R u + (B - x)^T \lambda
\]  

(3.13)
Solving for $u$ in (3.13) we obtain (3.14). The input can be eliminated in the state and co-state equations, obtaining the Hamiltonian system given by equations (3.15) and (3.16).

\[
\dot{x} = Ax - R^{-1}B(B - x)^T\lambda + R^{-1}x(B - x)^T\lambda + v
\]

(3.15)

\[
-\dot{\lambda} = (A^T + I(R^{-1}(B - x)^T\lambda))\lambda
\]

(3.16)

The Hamiltonian system is a nonlinear ordinary differential equation in $x(t)$ and $\lambda(t)$ with split boundary conditions given as follows.

$N$ initial conditions: $x(t_i)$ specified.

$N$ final conditions ($p$ conditions plus $N-p$ conditions):

$p$ conditions given by the fixed final state function $\psi$.

\[
\psi[x(t_{i+1})] = \begin{bmatrix} x_1(t_{i+1}) - r_1(t_{i+1}) \\
\vdots \\
x_p(t_{i+1}) - r_p(t_{i+1}) \end{bmatrix} = 0
\]

(3.17)

Here, the values for $r_1(t_{i+1}), \ldots, r_p(t_{i+1})$ are specified.

$N-p$ conditions given by $\lambda_j$.

\[
\lambda_j(t_{i+1}) = \left( \frac{\partial \phi}{\partial x_j} \right)_{x=x(t_{i+1})} = x_j(t_{i+1}) - r_j(t_{i+1})
\]

(3.18)
Here, $\phi$ is the final weighting function given below and $j = p+1, \ldots, N$.

$$
\phi(x(t_{j+1})) = \frac{1}{2} (x(t_{j+1}) - r(t_{j+1}))^T S(t_{j+1}) (x(t_{j+1}) - r(t_{j+1}))
$$

(3.19)

The Hamiltonian system is solved numerically by using the principles of the neighboring extremal methods [51, 52]. These methods are known for obtaining nominal solutions that result in approaching the boundary conditions, and that satisfy the optimality conditions, the state and co-state equations. After solving the Hamiltonian system it can be determined how $U_{loss}$ varies with time. The complete code that was developed to solve the Hamiltonian system can be seen in Appendix B. Figure 3.1 shows a block diagram that illustrates the relationship between the physical system, the proposed formulation, optimal control, and the proposed input $u$ ($U_{loss}$).

![Figure 3.1: Proposed approach block diagram](image)

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3.3 Neighboring Extremal Approach

The following is a brief review of one of the neighboring extremal methods, the Transition Matrix algorithm, which principle was used as the base of the implemented solution in this work. Additional and more elaborated details can be found on references [51] and [52]. The above proposed Hamiltonian problem in this study may be treated as follows:

a. Guess the unspecified initial conditions $\lambda(t_i)$

b. Integrate the Hamiltonian system forward from $t_i$ to $t_{i+1}$

c. Record $x(t_{i+1})$ and $\lambda(t_{i+1})$

d. Determine the variation of $x(t_{i+1})$ and $\lambda(t_{i+1})$ with respect to $\lambda(t_i)$. This means the transition matrix $\frac{\partial w(t_{i+1})}{\partial \lambda(t_i)}$, where $w(t_{i+1})$ is given below.

$$
\begin{bmatrix}
  x_1(t_{i+1}) \\
  \vdots \\
  x_p(t_{i+1}) \\
  \lambda_{p+1}(t_{i+1}) \\
  \vdots \\
  \lambda_m(t_{i+1})
\end{bmatrix}
$$

(3.20)

e. Choose $\delta w(t_{i+1})$ to bring the next solution closer to desired values of $w(t_{i+1})$

$$
\delta w(t_{i+1}) = \frac{\partial w(t_{i+1})}{\partial \lambda(t_i)} \cdot \delta \lambda(t_i)
$$

(3.21)

f. Invert the transition matrix to find $\delta \lambda(t_i)$
g. Find the new candidate for $\lambda(t_i)$ using (3.22)

$$\lambda(t_i)_{new} = \lambda(t_i)_{old} + \delta\lambda(t_i)$$

(3.22)

h. Repeat from step (a) until reaching the desired accuracy
4 VARIABLES OF INTEREST

An ICS system was installed at the Florida Solar Energy Center (FSEC) in Cocoa, FL, where ambient and internal variables were monitored and stored permanently over a year period. For the purpose of this research the data analysis starts on May 1, 2009 and ends on April 30, 2010. As it was briefly mentioned on the previous chapter each hour is equally divided into four fifteen (15) minute quarters. According to this, for each day of the year there are ninety six (96) data points per variable and a total of 35040 data points per variable during the year.

After the data was obtained from FSEC database it was taken to MATLAB for further manipulation, verification and use in simulations. The main variables in this study are solar radiation, ambient temperature, mains water temperature, ICS system output temperature and hot water draw profile. Figure 4.1 shows the first four variables measured on May 6, 2009. Appendix D presents a set of graphs that illustrate the main variables collected for each month.
For each month of the year two different water draw profiles were used, ASHRAE 90.2 and NREL (National Renewal Energy Laboratory). The first one was used for approximately the first half of each month while the second one was used during the second half. The change from ASHRAE to NREL is visualized for each month in Appendix D, by an absent day (or days) about the middle of the month. During the year there were days that were not used in the analysis due to maintenance, failure or change of profile in the system. Those days are not shown in Appendix D. Due to scheduling reasons at the experimental facility, the NREL draw profile was
applied at the beginning of some months. The affected days were assumed to be part of the previous month in order to maximize the amount of useful data days, taking into consideration that some days were already lost due to maintenance, failure or change of profile aspects. Table 4.1 shows the months where this occurred and the number of days that the corresponding month “adopted” from the following month.

<table>
<thead>
<tr>
<th>Month</th>
<th>Next month adopted days</th>
</tr>
</thead>
<tbody>
<tr>
<td>July</td>
<td>2</td>
</tr>
<tr>
<td>August</td>
<td>3</td>
</tr>
<tr>
<td>October</td>
<td>1</td>
</tr>
<tr>
<td>November</td>
<td>1</td>
</tr>
<tr>
<td>December</td>
<td>3</td>
</tr>
</tbody>
</table>

The ASHRAE 90.2 draw profile shown in Figure 4.2 was used for all months where the total amount of hot water drawn each day is 64.3 gallons. The NREL draw profile shown in Figure 4.3 shows the percentage per hour of the total amount of hot water drawn in a day for any month. In this profile, every month has a fixed amount of hot water drawn per day. Table 4.2 shows the daily amount of hot water drawn for each month in gallons.
Figure 4.2: ASHRAE 90.2 Hot water draw profile

Figure 4.4 shows a comparison of percentage per hour of the total amount of hot water drawn for the ASHRAE and NREL profiles. Figure 4.5 illustrates the ASHRAE draw profile in gallons compared to the NREL profile for the months of January and July which have the highest and the lowest hot demand respectively through the year. Notice that although for the 22\textsuperscript{nd} hour of the day (between 9pm and 10pm) the percentage of ASHRAE is smaller than NREL, the amount of hot water drawn for the month of July is higher in ASHRAE compared to NREL.
Figure 4.3: NREL Hot water draw profile (%)

Table 4.2: NREL daily hot water draw in gallons

<table>
<thead>
<tr>
<th>Month</th>
<th>Draw in Gallons</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>67.8</td>
</tr>
<tr>
<td>February</td>
<td>66.9</td>
</tr>
<tr>
<td>March</td>
<td>66.9</td>
</tr>
<tr>
<td>April</td>
<td>64.3</td>
</tr>
<tr>
<td>May</td>
<td>54.6</td>
</tr>
<tr>
<td>June</td>
<td>48.4</td>
</tr>
<tr>
<td>July</td>
<td>42.2</td>
</tr>
<tr>
<td>August</td>
<td>44.0</td>
</tr>
<tr>
<td>September</td>
<td>44.9</td>
</tr>
<tr>
<td>October</td>
<td>47.5</td>
</tr>
<tr>
<td>November</td>
<td>53.7</td>
</tr>
<tr>
<td>December</td>
<td>59.0</td>
</tr>
</tbody>
</table>
Figure 4.4: ASHRAE and NREL comparison (%)

Figure 4.5: Profiles comparison in gallons for the months of January and July
5 SIMULATIONS AND RESULTS

MATLAB was used to implement the solution to the Hamiltonian system proposed in section 3.2 and to perform simulations of the system. In the ICS system simulations the model was assumed to have 24 nodes \((N = 24)\). Several simulations were performed with higher number of nodes where slightly more accurate results were obtained. However, in these cases the simulation time increased. By having \(N = 24\), a good balance between accuracy and simulation time was obtained.

5.1 NREL Draw Profile

The \(U_{\text{loss}}\) obtained for each month is shown in Figure 5.1 with the corresponding NREL draw profile. As it can be seen, in general, the heat loss is lower when there are high volume draws. This means that when this case occurs, the majority of the absorbed energy is transferred to the load. When there is little or no draw, the heat loss increases since there is some or no energy transferred to the load. Instead, this is being transferred to the environment. Between hour 23 and hour 6 of the next day, when there is no draw, \(U_{\text{loss}}\) was found to have a small variation for each month. For comparison purposes, the typical heat loss for the system in this study is 1.82 W/m²K [53].
Figure 5.1: Monthly $U_{\text{loss}}$ for the NREL draw profile

Figure 5.2 shows the obtained $U_{\text{loss}}$ and the NREL draw profile with the monthly hourly averages for the ICS output and ambient temperatures.
Figure 5.2: NREL $U_{loss}$, ICS output and ambient temperatures

It was found that in general, the heat loss is higher around 3pm (hour 15) when there is little or no draw, and where the ICS output temperature is also high. As it was highlighted before, this happens because if the absorbed energy (high temperature) cannot be transferred to the load or kept inside the system, it will be transferred to the environment.
5.1.1 NREL energy delivered

In order to obtain approximate constant values for $U_{loss}$ for different segments of the day and perform simulations of the system, the day 24 hour period was divided into 5 segments according to the draw profile. Here, the division depends on whether there is a high draw or a low draw. Table 5.1 shows how the day was split and the average heat loss (W / m$^2$ K) for each segment in each month.

<table>
<thead>
<tr>
<th>Month</th>
<th>Hour 1 to 6</th>
<th>Hour 7 to 10</th>
<th>Hour 11 to 20</th>
<th>Hour 21 to 22</th>
<th>Hour 23 to 24</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>4.52</td>
<td>2.09</td>
<td>6.06</td>
<td>4.55</td>
<td>5.56</td>
</tr>
<tr>
<td>February</td>
<td>5.01</td>
<td>2.25</td>
<td>6.54</td>
<td>4.78</td>
<td>6.68</td>
</tr>
<tr>
<td>March</td>
<td>5.02</td>
<td>2.28</td>
<td>7.01</td>
<td>4.33</td>
<td>6.51</td>
</tr>
<tr>
<td>April</td>
<td>5.01</td>
<td>2.40</td>
<td>7.39</td>
<td>4.25</td>
<td>6.39</td>
</tr>
<tr>
<td>May</td>
<td>5.64</td>
<td>2.60</td>
<td>9.04</td>
<td>3.41</td>
<td>7.66</td>
</tr>
<tr>
<td>June</td>
<td>5.64</td>
<td>2.52</td>
<td>8.19</td>
<td>3.45</td>
<td>7.01</td>
</tr>
<tr>
<td>July</td>
<td>5.34</td>
<td>2.47</td>
<td>8.06</td>
<td>3.87</td>
<td>6.73</td>
</tr>
<tr>
<td>August</td>
<td>4.74</td>
<td>2.74</td>
<td>7.12</td>
<td>3.88</td>
<td>5.88</td>
</tr>
<tr>
<td>September</td>
<td>5.26</td>
<td>2.53</td>
<td>7.00</td>
<td>3.42</td>
<td>6.47</td>
</tr>
<tr>
<td>October</td>
<td>4.93</td>
<td>1.88</td>
<td>5.43</td>
<td>3.39</td>
<td>5.83</td>
</tr>
<tr>
<td>November</td>
<td>4.64</td>
<td>1.91</td>
<td>6.06</td>
<td>4.22</td>
<td>5.83</td>
</tr>
<tr>
<td>December</td>
<td>4.17</td>
<td>2.26</td>
<td>5.52</td>
<td>4.28</td>
<td>5.29</td>
</tr>
</tbody>
</table>

The ICS system was simulated for the NREL days over a year period using the values on Table 5.1. The simulated energy delivered was 503.69 kWh and the calculated actual energy delivered was 497.97 kWh. This means that the simulated value is 1.15 % higher than the actual value.
This shows that the proposed $U_{loss}$ partition in segments according to the draw profile was an acceptable approach.

The average heat loss through the year for the NREL draw profile is 5.7 W/m²K. The ICS system was also simulated over a year period using this value and the obtained energy delivered was 524.94 kWh. This means that the simulated value is 5.93 % higher than the actual value (497.97 kWh) which shows good agreement when performing annual simulations. Table 5.2 shows the monthly simulated and actual energy delivered in kWh for the NREL draw profile when using the annual average $U_{loss}$. The last column shows the difference of the simulated vs. the actual value as a percentage.

<table>
<thead>
<tr>
<th>Month</th>
<th>Actual (kWh)</th>
<th>Simulated (kWh)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>37.33</td>
<td>39.40</td>
<td>5.56</td>
</tr>
<tr>
<td>February</td>
<td>43.88</td>
<td>45.18</td>
<td>2.97</td>
</tr>
<tr>
<td>March</td>
<td>57.62</td>
<td>63.86</td>
<td>10.84</td>
</tr>
<tr>
<td>April</td>
<td>55.45</td>
<td>64.06</td>
<td>15.53</td>
</tr>
<tr>
<td>May</td>
<td>33.69</td>
<td>38.28</td>
<td>13.62</td>
</tr>
<tr>
<td>June</td>
<td>52.90</td>
<td>58.80</td>
<td>11.15</td>
</tr>
<tr>
<td>July</td>
<td>50.17</td>
<td>56.00</td>
<td>11.61</td>
</tr>
<tr>
<td>August</td>
<td>33.80</td>
<td>36.29</td>
<td>7.36</td>
</tr>
<tr>
<td>September</td>
<td>28.42</td>
<td>28.36</td>
<td>-0.22</td>
</tr>
<tr>
<td>October</td>
<td>36.40</td>
<td>31.79</td>
<td>-12.68</td>
</tr>
<tr>
<td>November</td>
<td>33.97</td>
<td>30.64</td>
<td>-9.78</td>
</tr>
<tr>
<td>December</td>
<td>34.33</td>
<td>32.27</td>
<td>-6.01</td>
</tr>
</tbody>
</table>
As it can be seen in Table 5.2, if a monthly analysis is desired, using the annual average $U_{loss}$ does not provide the same type of agreement as when an annual analysis is performed. Table 5.3 shows the monthly simulated and actual energy delivered in kWh for the NREL draw profile when using the monthly split average $U_{loss}$. The last column shows the difference of the simulated vs. the actual value as a percentage.

<table>
<thead>
<tr>
<th>Month</th>
<th>Actual (kWh)</th>
<th>Simulated (kWh)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>37.33</td>
<td>39.88</td>
<td>6.85</td>
</tr>
<tr>
<td>February</td>
<td>43.88</td>
<td>44.06</td>
<td>0.42</td>
</tr>
<tr>
<td>March</td>
<td>57.62</td>
<td>59.84</td>
<td>3.85</td>
</tr>
<tr>
<td>April</td>
<td>55.45</td>
<td>58.67</td>
<td>5.81</td>
</tr>
<tr>
<td>May</td>
<td>33.69</td>
<td>32.43</td>
<td>-3.73</td>
</tr>
<tr>
<td>June</td>
<td>52.90</td>
<td>52.29</td>
<td>-1.16</td>
</tr>
<tr>
<td>July</td>
<td>50.17</td>
<td>50.50</td>
<td>0.65</td>
</tr>
<tr>
<td>August</td>
<td>33.80</td>
<td>35.53</td>
<td>5.11</td>
</tr>
<tr>
<td>September</td>
<td>28.42</td>
<td>27.66</td>
<td>-2.67</td>
</tr>
<tr>
<td>October</td>
<td>36.40</td>
<td>34.15</td>
<td>-6.19</td>
</tr>
<tr>
<td>November</td>
<td>33.97</td>
<td>32.06</td>
<td>-5.61</td>
</tr>
<tr>
<td>December</td>
<td>34.33</td>
<td>36.61</td>
<td>6.62</td>
</tr>
</tbody>
</table>

By comparing Table 5.2 and Table 5.3 it can be seen that when a monthly analysis is desired, the use of a monthly split average $U_{loss}$ is better than using the annual average value. With the first one, the monthly discrepancies are less than 6.86%. However, when using the second one the monthly discrepancies go up to 15.53%.
5.2 ASHRAE Draw Profile

The $U_{\text{loss}}$ obtained for each month is shown in Figure 5.3 with the corresponding ASHRAE draw profile and the monthly hourly averages for the ICS output and ambient temperatures. In contrast with the NREL draw profile, in the ASHRAE profile there are draws every hour of the day. These consecutive and “small” draws during the entire day generate a $U_{\text{loss}}$ profile with high variation compared to the NREL case, but with a similar upper envelope.

Figure 5.3: ASHRAE $U_{\text{loss}}$, ICS output and ambient temperatures
Between midnight and 8am the variation of the ICS output temperature is small compared to the rest of the day. During this period of mostly very small draws, the heat loss goes down or tends to go down when water is drawn. The opposite effect occurs when there is no draw. As in the NREL case, if the energy is neither transferred to the load nor kept in the system, then it goes to the environment. In the ASHRAE case, $U_{loss}$ presents its highest variation after 3pm when the ICS output temperature reaches its highest point and then starts decreasing.

In general, between 8am and 2pm the heat loss goes up or has a tendency to go up. This can be due to the fact that during this period of the day, the ICS output temperature increases the most, causing a higher flux of energy to the environment. This type of behavior was also observed in the NREL case for the same period of time.

5.2.1 ASHRAE energy delivered

In contrast with the NREL case, the ASHRAE profile does not present very high or very low volume draws grouped at specific segments of the day. Instead, it has a “smoother” look with consecutive and small draws during the entire 24 hour period. In this case, it was found that there is no need to segment the day to obtain approximate constant $U_{loss}$ values to perform simulations for a given month. As a matter of fact, there is no need to have different heat loss values for different moths. The methodology followed in this study provided a very good $U_{loss}$ annual value for this profile as will be seen later.
The average heat loss obtained through the year for the ASHRAE draw profile was 7.6 W/m²K, and it was used in simulations of the ICS system for the ASHRAE days over a year period. The simulated energy delivered was 768.86 kWh and the calculated actual energy delivered was 767.49 kWh. This means that the simulated value is 0.18 % higher than the actual value. This shows that the obtained constant $U_{loss}$ is an acceptable value when performing annual simulations. Table 5.4 shows the monthly simulated and actual energy delivered in kWh for the ASHRAE draw profile when using the annual average $U_{loss}$. The last column shows the difference of the simulated vs. the actual value as a percentage.

<table>
<thead>
<tr>
<th>Month</th>
<th>Actual (kWh)</th>
<th>Simulated (kWh)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>56.72</td>
<td>54.09</td>
<td>-4.64</td>
</tr>
<tr>
<td>February</td>
<td>42.21</td>
<td>42.71</td>
<td>1.19</td>
</tr>
<tr>
<td>March</td>
<td>59.75</td>
<td>62.31</td>
<td>4.28</td>
</tr>
<tr>
<td>April</td>
<td>72.12</td>
<td>76.79</td>
<td>6.47</td>
</tr>
<tr>
<td>May</td>
<td>102.70</td>
<td>101.38</td>
<td>-1.28</td>
</tr>
<tr>
<td>June</td>
<td>67.70</td>
<td>69.98</td>
<td>3.37</td>
</tr>
<tr>
<td>July</td>
<td>65.21</td>
<td>68.96</td>
<td>5.75</td>
</tr>
<tr>
<td>August</td>
<td>93.34</td>
<td>92.79</td>
<td>-0.59</td>
</tr>
<tr>
<td>September</td>
<td>66.22</td>
<td>62.75</td>
<td>-5.24</td>
</tr>
<tr>
<td>October</td>
<td>64.30</td>
<td>61.54</td>
<td>-4.29</td>
</tr>
<tr>
<td>November</td>
<td>48.82</td>
<td>47.29</td>
<td>-3.14</td>
</tr>
<tr>
<td>December</td>
<td>28.40</td>
<td>28.28</td>
<td>-0.43</td>
</tr>
</tbody>
</table>

As it can be seen in Table 5.4, if a monthly analysis is desired, the use of the annual average $U_{loss}$ also provides good results. Here, the monthly discrepancies in all cases are less than 6.5 %.
5.3 NREL, ASHRAE, and $U_{loss}$

The $U_{loss}$ values obtained for the NREL and ASHRAE profiles are not the same. This shows clearly a strong dependence of the heat loss with respect to the hot water draw used. Table 5.5 shows the estimated energy delivered over a year using the NREL profile and assuming the ASHRAE heat loss obtained.

<table>
<thead>
<tr>
<th>Month</th>
<th>Actual (kWh)</th>
<th>Simulated (kWh)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>37.33</td>
<td>26.72</td>
<td>-28.40</td>
</tr>
<tr>
<td>February</td>
<td>43.88</td>
<td>28.96</td>
<td>-34.01</td>
</tr>
<tr>
<td>March</td>
<td>57.62</td>
<td>43.52</td>
<td>-24.46</td>
</tr>
<tr>
<td>April</td>
<td>55.45</td>
<td>44.91</td>
<td>-19.01</td>
</tr>
<tr>
<td>May</td>
<td>33.69</td>
<td>27.80</td>
<td>-17.50</td>
</tr>
<tr>
<td>June</td>
<td>52.90</td>
<td>42.65</td>
<td>-19.38</td>
</tr>
<tr>
<td>July</td>
<td>50.17</td>
<td>40.39</td>
<td>-19.51</td>
</tr>
<tr>
<td>August</td>
<td>33.80</td>
<td>24.90</td>
<td>-26.33</td>
</tr>
<tr>
<td>September</td>
<td>28.42</td>
<td>19.06</td>
<td>-32.94</td>
</tr>
<tr>
<td>October</td>
<td>36.40</td>
<td>19.70</td>
<td>-45.88</td>
</tr>
<tr>
<td>November</td>
<td>33.97</td>
<td>17.84</td>
<td>-47.47</td>
</tr>
<tr>
<td>December</td>
<td>34.33</td>
<td>17.36</td>
<td>-49.44</td>
</tr>
</tbody>
</table>

As it was expected, since the ASHRAE $U_{loss}$ is higher, the estimated energy delivered for the NREL profile is lower than the actual value for all months. Here, the monthly discrepancies range from –17.5 % in the best case, to –49.44 % for the worst case. The total annual estimated energy delivered is 353.81 kWh, which is 28.95 % lower than the actual value (497.97 kWh).
This shows that the use of an ASHRAE $U_{\text{loss}}$, when simulating an NREL profile, significantly underestimates the energy delivered, and therefore it is not appropriate for an NREL simulation.

Table 5.6 shows the estimated energy delivered over a year using the ASHRAE profile and assuming the annual average NREL heat loss obtained.

<table>
<thead>
<tr>
<th>Month</th>
<th>Actual (kWh)</th>
<th>Simulated (kWh)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>56.72</td>
<td>65.64</td>
<td>15.73</td>
</tr>
<tr>
<td>February</td>
<td>42.21</td>
<td>52.02</td>
<td>23.24</td>
</tr>
<tr>
<td>March</td>
<td>59.75</td>
<td>73.93</td>
<td>23.73</td>
</tr>
<tr>
<td>April</td>
<td>72.12</td>
<td>90.54</td>
<td>25.54</td>
</tr>
<tr>
<td>May</td>
<td>102.70</td>
<td>119.56</td>
<td>16.42</td>
</tr>
<tr>
<td>June</td>
<td>67.70</td>
<td>81.84</td>
<td>20.88</td>
</tr>
<tr>
<td>July</td>
<td>65.21</td>
<td>80.62</td>
<td>23.64</td>
</tr>
<tr>
<td>August</td>
<td>93.34</td>
<td>108.65</td>
<td>16.41</td>
</tr>
<tr>
<td>September</td>
<td>66.22</td>
<td>71.65</td>
<td>8.20</td>
</tr>
<tr>
<td>October</td>
<td>64.30</td>
<td>70.35</td>
<td>9.41</td>
</tr>
<tr>
<td>November</td>
<td>48.82</td>
<td>56.96</td>
<td>16.67</td>
</tr>
<tr>
<td>December</td>
<td>28.40</td>
<td>33.67</td>
<td>18.56</td>
</tr>
</tbody>
</table>

As it was expected, since the NREL $U_{\text{loss}}$ is smaller, the estimated energy delivered for the ASHRAE profile is higher than the actual value for all months. Here, the monthly discrepancies range from 8.2 % in the best case, to 23.73 % for the worst case. The total annual estimated energy delivered is 905.44 kWh, which is 17.97 % higher than the actual value (767.49 kWh).
Although there was overestimation in this case, the deviation was smaller than in the NREL case. This was expected since in the ASHRAE case the $U_{loss}$ variation was $-25\%$ (from 7.6 to 5.7) vs. a $33\%$ variation in the NREL case (from 5.7 to 7.6). In general, the use of an NREL $U_{loss}$ when simulating an ASHRAE profile is not the best option.

According to what was previously exposed, profile-based heat loss values should be used when simulating an ICS system to obtain better performance predictions.

### 5.4 TRNSYS Comparisons

TRNSYS [54, 55] is a transient system simulation program widely used to simulate ICS systems. A solar domestic hot water analysis based on TRNSYS was used as a reference tool in this section. Using this tool and its model, annual simulations were performed for both profiles (NREL and ASHRAE) using typical meteorological year data (TMY). Then, the ICS system model of this work was simulated in MATLAB in the same way. Table 5.7 shows the annual estimated energy delivered for both programs, where it is assumed a heat loss equal to 4.6 W/m²K in the MATLAB case for both profiles and through the entire year.

<table>
<thead>
<tr>
<th>Profile Program</th>
<th>NREL (kWh)</th>
<th>ASHRAE (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATLAB</td>
<td>1224</td>
<td>1967</td>
</tr>
<tr>
<td>TRNSYS</td>
<td>1282</td>
<td>1869</td>
</tr>
</tbody>
</table>
It can be verified from Table 5.7 that the discrepancy between the results of both programs for both profiles is less than 5.3 % with respect to the TRNSYS values. This represents a reasonably close agreement between both programs for the annual simulation. According to what was exposed earlier, heat loss values can be selected according to the hot water draw profile used. Table 5.8 shows the MATLAB annual estimated energy delivered using the annual average heat loss values found earlier for each profile (5.7 W/m²K for NREL and 7.6 W/m²K for ASHRAE). The TRNSYS results from Table 5.7 are also shown for comparison purposes.

<table>
<thead>
<tr>
<th>Profile Program</th>
<th>NREL (kWh)</th>
<th>ASHRAE (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATLAB</td>
<td>961</td>
<td>1419</td>
</tr>
<tr>
<td>TRNSYS</td>
<td>1282</td>
<td>1869</td>
</tr>
</tbody>
</table>

As it was expected, the MATLAB simulated values are smaller than the ones on Table 5.7 since the heat loss used for both profiles is higher. However, the MATLAB values are reasonable, taking into account that the actual energy delivered during 168 days using the NREL profile was 497.97 kWh, and 767.49 kWh in the ASHRAE case for 166 days.

The split average $U_{loss}$ values presented in the NREL energy delivered section were also used to perform an annual simulation in MATLAB with TMY data. Table 5.9 shows the results of this simulation along with the results obtained when using the annual average heat loss in the NREL case.
Table 5.9: NREL estimated energy delivered using annual and split average $U_{loss}$

<table>
<thead>
<tr>
<th>Month</th>
<th>Estimated energy delivered with annual $U_{loss}$ (kWh)</th>
<th>Estimated energy delivered with split $U_{loss}$ (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>17.17</td>
<td>28.03</td>
</tr>
<tr>
<td>February</td>
<td>33.88</td>
<td>36.81</td>
</tr>
<tr>
<td>March</td>
<td>85.33</td>
<td>83.78</td>
</tr>
<tr>
<td>April</td>
<td>109.56</td>
<td>103.79</td>
</tr>
<tr>
<td>May</td>
<td>124.18</td>
<td>99.38</td>
</tr>
<tr>
<td>June</td>
<td>117.25</td>
<td>102.55</td>
</tr>
<tr>
<td>July</td>
<td>114.74</td>
<td>103.39</td>
</tr>
<tr>
<td>August</td>
<td>111.71</td>
<td>111.70</td>
</tr>
<tr>
<td>September</td>
<td>98.26</td>
<td>97.21</td>
</tr>
<tr>
<td>October</td>
<td>76.75</td>
<td>90.51</td>
</tr>
<tr>
<td>November</td>
<td>45.96</td>
<td>54.51</td>
</tr>
<tr>
<td>December</td>
<td>26.27</td>
<td>41.04</td>
</tr>
</tbody>
</table>

The total annual estimated energy delivered when using the split average $U_{loss}$ is 952.7 kWh. This is very close to the value obtained when using the annual average heat loss (961.06 kWh).

However, when looking at the values for each month, it can be seen a couple of differences. With the split average $U_{loss}$, the performance of cold months like January and December, increased considerably (63.25 % and 56.25% respectively). Hotter months like May, June and July were less affected where their estimated performance was reduced. Nevertheless, these months continued being the ones that deliver the highest estimated amount of energy. This result shows that when using the split average $U_{loss}$ a more equitable performance through the year is obtained.
This work presented a methodology to find the overall heat loss for an ICS system. The same approach could be expanded in future developments to find the heat loss associated with each modeled node. This would provide a more detailed analysis and understanding of the heat loss through the system.

The proposed methodology could also be used in the future for effective determination of $U_{loss}$ in other climates and under other draw profiles, taking into account the aspects of the physical system avoided in the model, and other variables that affect the ICS performance over a one year period.
6 CONCLUSIONS

The non-linear state space formulation of the system made it suitable for the proposed optimal control theoretic analysis. This new analysis proved to be a convenient method for determination of the overall heat loss coefficient and showed that profile based heat loss values should be used when simulating ICS systems to obtain better performance predictions. The capability of the obtained $U_{loss}$ to reduce the performance prediction error makes the optimal control approach useful for determination of the heat loss coefficient in an ICS system. Also, it can be concluded that the use of monthly heat loss values is more suitable when a monthly analysis is desired and an NREL profile is used.

The results of this work imply the potential for effective determination of $U_{loss}$ in other climates and under other draw profiles, which takes into account the aspects of the physical system avoided in the model, and other variables that affect the ICS performance over a one year period. The technique developed in this work offers an improvement in the overall heat loss determination and consequently in the predictions of the system’s performance.
Description

The TMY data sets hold hourly values of solar radiation and meteorological elements for a 1-year period. Their intended use is for computer simulations of solar energy conversion systems and building systems to facilitate performance comparisons of different system types, configurations, and locations in the United States and its territories. Because they represent typical rather than extreme conditions, they are not suited for designing systems to meet the worst-case conditions occurring at a location.

The typical meteorological year version 3 (TMY3) data sets were produced by the National Renewable Energy Laboratory (NREL) Electric and Systems Center under the Solar Resource Characterization Project, which is funded and monitored by the U.S. Department of Energy's Energy Efficiency and Renewable Energy Office. These data sets provide greater geographical coverage than previous TMY sets with 1020 locations in the United States and its territories and are an update to, and expansion of, the TMY2 data released by NREL in 1994.

A typical meteorological year (TMY) data set provides designers and other users with a reasonably sized annual data set that holds hourly meteorological values that typify conditions at a specific location over a longer period of time, such as 30 years. TMY data sets are widely used by building designers and others for modeling renewable energy conversion systems. Although not designed to provide meteorological extremes, TMY data have natural diurnal and seasonal variations and represent a year of typical climatic conditions for a location.
Important note: Some of the meteorological data in this data set have been filled. The data-filling process was designed to provide serially complete records as input for modeling the solar radiation fields. Filled meteorological data fields may also be useful for certain renewable energy applications. However, the filled data are not suitable for climatological studies.

The TMY data set is composed of 12 typical meteorological months (January through December) that are concatenated essentially without modification to form a single year with a serially complete data record for primary measurements. These monthly data sets contain actual time-series meteorological measurements and modeled solar values, although some hourly records may contain filled or interpolated data for periods when original observations are missing from the data archive.

Source Data for the TMY3 Data Set

Because the 1961-1990 NSRDB has 239 sites and the 1991-2005 NSRDB update has more than 1,400 sites, production of the TMY3 data was designed to maximize both the number of stations and the number of years from which to characterize the typical conditions. At sites where data are available for 30 years, the base time period for the TMY algorithm spans 1976-2005. For the remaining sites, the base time period spans 1991-2005.

The 12 selected typical months for each station were chosen using statistics determined by considering five elements: global horizontal radiation, direct normal radiation, dry bulb temperature, dew point temperature, and wind speed. These elements are considered the most important for simulating solar energy conversion systems and building systems.

**TMY3 Site Selection**

To optimize both temporal and spatial considerations, the TMY3 combines these scenarios so that the 30-year data were used at sites where they were available and the 15-year data were used for the remaining sites. The sites in the 1991-2005 NSRDB were chosen based on data availability rather than geographic location (all sites meeting minimum data criteria were included). For this reason, in the both the NSRDB update and the TMY3, sites may occur in close proximity, for example in major metropolitan areas.
The NSRDB update subdivided stations by class: Class I sites are those with the lowest uncertainty data, Class II sites have higher uncertainty data, and Class III sites have an incomplete period of record. For additional information regarding TMY3 see reference [50].
%% **** Program to solve the Hamiltonian system: Fwd Integration
%% **** coupled nonlinear ordinary differential equations ****
%% **** with optimal and smooth control for Nnodes
%% **** 2010-05-20-R ****

for mk=1:1,
clc
mdel=0.002817;
BNL=0;
ind=0;
errenersimf=0;
daydelensimf=0;
daydelenrea=0;
daydelensimk=0;
daydelensfrk=0;
daysdelensrk=0;
err=0;
err2=0;
error=0;
Ulosscreate=1; % 1=create, 0=do not create, just simulate
nods=16; %
month=mk;
profc=1; % 0=all month both profiles
   % 1= ash
   % 2= ba per each month
%[prof]=daysauto(month,profc);
prof=1; % # days in selected profile
profcm=0; % manual=1, auto=0;
nodsc=nods/8;
if nods<8,
   if nods==1,
      nodsc=11;
   end
   if nods==2;
      nodsc=12;
   end
   if nods==4;
      nodsc=13;
end
end
plotuloss=1; % plot=1; no plot=0
plotulossk=1;
prof=0; % actual profile to be used
% fstday=5;
% fnlday=5;
detail=0; %
y=0;
y1=0;
y1fhist=0;
y1simhist=0;
y1simhistk=0;
y1simhistop=0;
y1simhistsm=0;
y2=0;
y2fhist=0;
y2t=0;
yi=0;
minx=0;
maxx=24;
miny=-5;
maxy=80;
Ulossmean=0;
%f=0;
%
[ashia,ashfa,ashir,baia,bafa,bair,off]=monthsplt(month);
[fstday,fnlday]=profst(profc,prof,off,ashia,ashfa,baia,bafa);
%
if Ulosscreate==1,
%% BEG Calculating optimal Uloss
 dayr=0;
 daym2=0;
 for daya=fstday:fnlday,
 dayr=dayr+1;
 inter=2;
 temp=A(daya*96-95:daya*96,1);
 [u1,u2,u3b,T_N]=inputsraw2adjust(temp);
 if daya<=ashfa,
 prof=ash;
 end
 if daya>=baia,
 prof=ba_1_12(month*96-95:month*96,1);
 daydelenrea(dayr,1)=(1/3600000)*900*4186*prof(1:96,2)'*(T_N(1:96,2)-u3b(1:96,2));
 %delenreahist(1:inter,1)=(1/3600000)*4186*(T_N(1:inter,2)-u3b(1:inter,2));
 %daydelenrea=sum(delenreahist(1:inter,1));
 for ctrl=0:0, % 0=optimal, 1=smooth
 Ulosscte=0;
 Ulosslamxsim=0;
 y1fhist=0;
 y2fhist=0;
 ind=0;
 ti=0; tip1=899; % initial and final times for each interval
 [y1]=initemps(nods,u3b(1,2),T_N(1,2)); %43.806; % initial value for x's (temperatures)
 y2(1:nods,1)=0.000002; % initial value for lambda
 %initial value for lambda 0.0001***************************
 for i=1:inter,
 mdel=prof(i,2);
 u1k=u1(i,2);
 u2k=u2(i,2);
 u3k=u3b(i,2);
 if i>1,
 ti=ti+900; % initial time of the interval
 tip1=tip1+900; % final time of the interval
 [y1]=initemps(nods,u3k,T_N(i-1,2));% x init cond for the above interval
 end
 if ctrl==1,
 [ty]=ode45(@hsN,[ti tip1],[y1;y2],[],mdel,u1k,u2k,u3k,0);
 end
 %
 y1simhist(i,1:nods)=y(row,1:nods); % history of simulated x
 y1simhist(i,nods+1)=T_N(i,2);
 156.7*4186)/(2.77*200))*(-BNL+y(row,1:nods)*(y(row,nods+1:nods*2))^2;
 if i==1, % from inter
 y1simhist(i,1:nods)=y(row,1:nods); % history of simulated x
 end
 if i>1, % from inter
 yl=finalynext;
 end
 % 156.7*4186)/(2.77*200))*(-BNL+y(row,1:nods)*(y(row,nods+1:nods*2))^2;
 y1simhist(i,1:nods)=y(row,1:nods); % history of simulated x
 y1simhist(i,nods+1)=T_N(i,2);
 y1simhist(i,nods+2)=(y1simhist(i,nods)-T_N(i,2))^2;
% delensimhist(i,1)=(1/3600000)*900*mdel*4186*(y1simhist(i,nods)-u3k);
% finallynext=y1simhist(i,1:nods)';
% % END simulation of current Uloss current interval
% end %if ctrl==1,
% %
% if ctrl==0,
% %if abs(y1hist(i,nods+2))>0.2, % to calculate the transition matrix
% y2t=2.87*1000000;
% %
% for j=1:1:12,%j=1:11,50,20 ****************************************************
% [t,y]=ode45(@hsN,[ti tip1],[y1;y2t],[],mdel,u1k,u2k,u3k,nods);
% [row,col]=size(y);
% BNL(1:nods,1)=u2k;
% for k=1:row,
% Ulosslamxsimtstime(k,j)=((156.7*4186)/(2.77*200))*(-BNL+y(k,1:nods)')'*y(k,nods+1:nods*2)';
% end
% Ulosslamxsimtst(j,1)=((156.7*4186)/(2.77*200))*(-BNL+y(row,1:nods)')'*y(row,nods+1:nods*2);
% if i==1, % from inter
% [yi]=initemps(nods,u3b(1,2),T_N(1,2)); %43.806; initial value for x's (temperatures)
% end
% if i>1, % from inter
% yi=finalynext;
% end
% % BEGIN simulation of current Uloss current interval
% [t,y]=ode45(@sNn,[ti tip1],[yi],[],mdel,u1k,u2k,u3k,Ulosslamxsimtst(j,1),nods);
% %[t,y]=ode45(@sNnop,[ti tip1],[yi],[],mdel,u1k,u2k,u3k,T',Ulosslamxsimtstime(:,j)',nods);
% [row,col]=size(y);
% y1simhisttstime(1:row,1:nods,j)=y(1:row,1:nods); %history of all simulated x
% y1simhisttst(j,1:nods)=y(row,1:nods); % history of final simulated x
% y1simhisttst(j,nods+1)=T_N(1,2);
% y1simhisttst(j,nods+2)=abs(y1simhistst(j,nods)-T_N(1,2));
% % END simulation of current Uloss current interval
% y2t=y2t+0.000004;  %% y2t/10;
% end%for j=1:1:10,%j=1:11,
% % [aa,bb]=min(y1simhistst(1:j,nods+2));
% Ulosslamxsim(i,2)=Ulosslamxsimtst(bb,1);
% y1simhist(i,1:nods)=y1simhisttst(bb,1:nods); % history of simulated x
% %vec=interemps(nods,u3k,T_N(1,2));
% %y1simhist(i,1:nods)=vec*(y1simhist(i,1:nods)'-vec)'
% y1simhist(i,nods+1)=T_N(i,2);
% y1simhist(i,nods+2)=y1simhist(i,nods)-T_N(i,2);^2;
% delensimhist(i,1)=(1/3600000)*900*mdel*4186*(y1simhist(i,nods)-u3k);
% finallynext=y1simhist(i,1:nods)';
% %end
% end %if ctrl==0,**************
%
% figure
% % plot(t,y(:,1),',t,y(:,2),--');
% % title('Fwd Integration for x and lambda');
% % xlabel('time t in seconds');
% % ylabel('solution x and lambda');
% % legend('x','lambda');
% %
% end %for inter
% %
% errnersim=sqrt(sum(y1simhist(1:inter,nods+2))/96);
% % daydelensim=sum(delensimhist(1:inter,1));
% % %Ulosscte(1:inter,1)=prof(1:inter,1);
% Ulosscte(1:inter+1,2)=3.82;
% Ulosslamxsim(inter+1,2)=Ulosslamxsim(inter,2);
% Ulosslamxsim(1:inter+1,1)=prof(1:inter+1,1);
% y1hist(1:inter,nods+3)=abs(y1hist(1:inter,nods+2));
% error(1,1)=sum(sqrt(y1simhist(1:inter,nods+2))); 
% error(1,2)=min(Ulosslamxsim(1,inter,2));
% error(1,3)=mean(Ulosslamxsim(1,inter,2));
% error(1,4)=max(Ulosslamxsim(1,inter,2));
% seg1=24; %32 36 Djight nov-mar********** ********** **************************************
% seg2=40; %60 64 Djight nov-mar********** **************************************
% seg3=80;
% seg4=88;
% seg5=inter;
% %36=10am %41 11am3pm %49 1pm8pm %41 11am5pm | good #s good shape
% %60=3pm %40 61 %48 81 %40 69 
% % %60 %80 %68
% if ctrl==0,
% Ulossop=Ulosslamxsim; err(dayr,1:4)=error;
% %ABUyear(dayr,1:inter,nodsc,month,profc)=Ulossop(1:inter,2);
% errenersimf(dayr,1)=errenersim;
% daydelensimf(dayr,1)=daydelensim;
% y1simhistop=y1simhist;
% %if nods==8, %24
% %err2(dayr,1)=mean(Ulosslamxsim(1:seg1,2)); %********************
% %err2(dayr,2)=mean(Ulosslamxsim(seg1+1:seg2,2));
% %err2(dayr,3)=mean(Ulosslamxsim(seg2+1:seg3,2));
% %err2(dayr,4)=mean(Ulosslamxsim(seg3+1:seg4,2));
% %err2(dayr,5)=mean(Ulosslamxsim(seg4+1:inter,2));
% %end
% if nods==8,
% %err2(dayr,1)=mean(Ulosslamxsim(1:inter,2)); %********************
% %err2(dayr,2)=mean(Ulosslamxsim(seg1+1:seg2,2));
% %err2(dayr,3)=mean(Ulosslamxsim(seg2+1:inter,2));
% %err2(dayr,4)=mean(Ulosslamxsim(seg3+1:seg4,2));
% %err2(dayr,5)=mean(Ulosslamxsim(seg4+1:inter,2));
% %end
% if ctrl==1,
% Ulosssmt=Ulosslamxsim; err(dayr,5:8)=error;
% errenersimf(dayr,2)=errenersim;
% daydelensimf(dayr,2)=daydelensim;
% y1simhistop=y1simhist;
% end
end %% for ctrl=0:1
%
% %%% BEG Plotting 'Gt','Ta','Tm','T_N','wSmU','wOpU','Prof'
% if plotuloss==1,
% tim=0.25:0.25:24;
% figure
% %
% % u1_10=u1(1:inter,2)/10;
% % if profc==1,
% % prof_mod=(3600/3.78)*10*ash(1:inter,2); % Mapping ASHRAE to Temperatures scale
% % end
% % if profc==2,
% % prof_mod=(3600/3.78)*5*ba_1_12(month*96-95:month*96,2); % Mapping NREL/BA to Temperatures scale
% % end
% subplot(2,1,1),
% plot(tim,u1_10,y-,tim,u2(1:inter,2),k-,tim,u3b(1:inter,2),b-,tim,T_N(1:inter,2),y--';
% tim,y1simhistop(1:inter,nods),k',tim,y1simhistop(1:inter,nods),b',tim,prof_mod,c-);
% axis([0 24 -5 110]);%axis([0 24 -5 80])
% axis([0 24 -5 110]);
% %text(1,72,[num2str(bad)]);
% if profc==1,
%     daym=ashir+dayr-1;
%     monthaux=month;
% end
% if profc==2,
%     monthd=monthslct2(month);
%     if (bair+dayr-1)<=monthd,
%     daym=bair+dayr-1;
%     monthaux=month;
% end
% if (bair+dayr-1)>monthd,
%     daym2=daym2+1;
%     daym=daym2;
%     monthaux=month+1;
%     if monthaux==13,
%         monthaux=1;
%     end
% end
% end
% end
% title([num2str(monthaux),' / ',num2str(daym)]);%title([num2str(monthaux),' / ',num2str(daym)]);
% xlabel('time t in hours');
% ylabel('Gt x10 (W/m^2) and Temperatures (°C)');
% legend('Gt','Ta','Tm','T_N','wSmU','wOpU','Prof',0);
% %
% u1_100=u1(1:inter,2)/100;
% if profc==1,
%     prof_mod=(3600/3.78)*1*ash(1:inter,2); %% Mapping ASHRAE to Temperatures scale
% end
% if profc==2,
%     prof_mod=(3600/3.78)*1*ba_1_12(month*96-95:month*96,2); %% Mapping NREL/BA to Temperatures scale
% end
% subplot(2,1,2),
% plot(tim,u1_100,'y-',tim,Ulossop(1:inter,2),'b-',tim,Ulosssmt(1:inter,2),'r:',tim,prof_mod,'c-');
% axis([0 24 -1 20]);
% %title('Uloss Smooth');
% xlabel('Time (hours)');%,'fontsize',15);
% ylabel('U_l_o_s_s op and smt');
% legend('Gt',',Ulossop',',Ulosssmt',',Prof',0);
% % subplot(4,1,4),plot(tim,Ulosssmt(1:inter,2),',r');
% % %title('Uloss Smooth');
% % xlabel('time t in hours');
% % ylabel('Uloss Smooth');
% % legend('Ulosssmt');
% % end % if plotuloss==1,
% % % END Plotting 'Gt','Ta','Tm','T_N','wSmU','wOpU','Prof'
% end
% % for daya=fstday:fnlday,
% err
% % END Calculating optimal Uloss
% end % if Ulosscreate==1,

% % BEGIN simulation with calculated semiconstant Uloss for each day
% day=0;
% daym2=0;
% for daya=fstday:fnlday,
%     temp=A(daya*96-95:daya*96,:);
%     [u1,u2,a3b,T_N]=inputsraw2adjust(temp);
% if daya<=ashfa,
% prof=ash(1:inter,:);%prof=ash(1:inter,:);% end
% if daya>=baia,
% prof=ba_1_12(month*96-95:month*96,:);% end
% ti=0; tip1=899; % initial and final times for each interval
% for i=1:inter,
% mdel=prof(i,2);
% u1k=u1(i,2);
% u2k=u2(i,2);
% u3k=u3b(i,2);
% if i==1, % from inter
% [yi]=initemps(nods,u3b(1,2),T_N(1,2)); %43.806; initial value for x's (temperatures)
% end
% if i>1,
% ti=ti+900; % initial time of the interval
% tip1=tip1+900; % final time of the interval
% yi=finalynextk;
% end
% if profc==1,%ash,
% Ulossmean96(1,i)=(1)*mean(ABUyear(1:profd,i,nodsc,month,profc));
% [t,y]=ode45(@sNn,[ti tip1],[yi]],[],mdel,u1k,u2k,u3k,Ulossmean96(1,i),nods);
% if i<61,
% [t,y]=ode45(@sNn,[ti tip1],[yi]],[],mdel,u1k,u2k,u3k,mean(err(1:profd,3)),nods);
% end
% if i>60,
% [t,y]=ode45(@sNn,[ti tip1],[yi]],[],mdel,u1k,u2k,u3k,mean(err(1:profd,3)),nods);
% end
% end
% if profc==2, %ba_1_12(month*96-95:month*96,2), %ba05
% if nods==8,
% [t,y]=ode45(@sNn,[ti tip1],[yi]],[],mdel,u1k,u2k,u3k,(1)*mean(err2(1:profd,1)),nods);
% end
% if seg1+1, %36=9am %41 10am3pm %49 12pm8pm
% [t,y]=ode45(@sNn,[ti tip1],[yi]],[],mdel,u1k,u2k,u3k,(1)*mean(err2(1:profd,1)),nods);%2* 7/1/3* 1/3*
% % end
% if seg4+1, %60 8pm
% [t,y]=ode45(@sNn,[ti tip1],[yi]],[],mdel,u1k,u2k,u3k,(1)*mean(err2(1:profd,1)),nods);%2* 7/1/3* 1/3*
% % end
% % Ulossmean96(1,i)=(1)*mean(ABUyear(1:profd,i,nodsc,month,profc));
% [t,y]=ode45(@sNn,[ti tip1],[yi]],[],mdel,u1k,u2k,u3k,Ulossmean96(1,i),nods);
% if segm==96,
% end
% if profc==2,
% [row,cell]=size(y);
% ysimhistk(i,1:nods)=y(row,1:nods); % history of simulated x
% ysimhistk(i,nods+1)=T_N(i,2);
% %y1simhistk(i,3)=(y1simhistk(i,1)-T_N(i,2))^2;
% delensimhistk(i,1)=(1/3600000)*900*mdeI*4186*(y1simhistk(i,nods)-u3k);
% finalynextk=y1simhistk(i,1:nods)';
% end % for i=1:inter,
% %
% daydelensimk(dayr,1)=sum(delensimhistk(1:inter,1));
% % BEG plotting 'Ta','Tm','T_N','wkU','u1','prof'
% if plotulossk==1,
% tim=0.25:0.25:24;
% figure%subplot(5,7,dayr)
% if miny<0,
% minyv(1:inter,1)=0;minys=0;
% end
% if miny>=0,
% minyv(1:inter,1)=miny;minys=miny;
% end
% u1b=((maxy-minys)/1100)*u1(1:inter,2)+minyv; %% Mapping Solar Radiation to Temperatures scale
% if profc==1,
% prof1=3600*ash(1:inter,2); %% Mapping ASHRAE to Temperatures scale in litters
% end
% if profc==2,
% prof1=3600*ba_1_12(month*96-95:month*96,2); %% Mapping NREL/BA to Temperatures scale in litters
% end
% plot(tim,u2(1:inter,2),'k-',tim,u3b(1:inter,2),'b-',tim, T_N(1:inter,2),'r-',tim,y1simhistk(1:inter,nods),'g:',tim,u1b(1:inter,1),'m-,'
% tim,prof1 (1:inter,1),'c-',tim,Ulossmean96(1,1:inter),'k:');
% simwkUloss(1:inter,dayr)=y1simhistk(1:inter,nods);
% if profc==1,
% daym=ashir+dayr-1;
% monthaux=month;
% end
% if profc==2,
% monthday=monthsclt2(month);
% if (bair+dayr-1)<=monthd,
% daym=bair+dayr-1;
% monthaux=month;
% end
% if (bair+dayr-1)>monthd,
% daym2=daym2+1;
% daym=daym2;
% monthaux=month+1;
% if monthaux==13,
% monthaux=1;
% end
% end
% end
% text(1,73,[num2str(monthaux),' / ',num2str(daym)]);
% axis([minx maxx miny maxy]);
% %title('Uloss Optimal and Smooth');
% %xlabel('Time (hours)');
% %ylabel('Temperatures ( ^oC)');
% %legend('Ta','Tm','T_N','wkU','u1','prof');
% end % if plotulossk==1,
% % END plotting 'Ta','Tm','T_N','wkU','u1','prof'
% %
% end % for days=fstday:fnday
% % END simulation with calculated semiconstant Uloss for each day

% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%BEG INACTIVE%%%%%%%%%%%%%%%%%%%%%%
% % % BEG Plot detailed date

66
% if detail>0,
% temp=A2009_05(detail*96-95:detail*96,:);
% if temp(1,1)>-1,
% [u1,u2,ash,T_N]=inputsraw2adjust(temp);
% if temp(1,1)>-1,
% [u1,u2,ash,T_N]=inputsraw2adjust(temp);
% if temp(1,1)>-1,
% [u1,u2,ash,T_N]=inputsraw2adjust(temp);
% end % detail>0,
% end
% END Plot detailed date

errenersimf
daydelensimf
daydelenrea
daydelensimk

% **************************************************END INACTIVE******************************************

% daydelensfrk(1:dayr,1)=daydelensimf(1:dayr,2);
% daydelensfrk(1:dayr,2)=daydelensimf(1:dayr,1);
% daydelensfrk(1:dayr,3)=daydelensimf(1:dayr,1);
% daydelensfrk(1:dayr,5)=daydelenrea(1:dayr);
% daydelensfrk(1:dayr,8)=daydelensimk(1:dayr);
% daydelensfrk(1:dayr,5)=daydelensfrk(1:dayr,2)-daydelensfrk(1:dayr,5);
% [daysrv]=daysr(profc,ashir,dayr,month,bair,off);
% daydelensfrk(1:dayr,9)=daysrv;
% err(1:dayr,9)=daysrv;
% err(dayr+1,3)=mean(err(1:profd,3));
% err(dayr+1,7)=mean(err(1:profd,7));
% for i=1:profd,
% daydelensfrk(i,4)=daydelensfrk(i,3)/daydelensfrk(i,5)*100;
% daydelensfrk(i,6)=daydelensfrk(i,7)/daydelensfrk(i,5)*100;
% end
% daysdelensrk(1,6)=profd;%fndday-fstday+1;
% daysdelensrk(1,1)=sum(daydelensfrk(1:dayr,2));
% daysdelensrk(1,3)=sum(daydelensfrk(1:dayr,5));
% daysdelensrk(1,5)=sum(daydelensfrk(1:dayr,8));
% daysdelensrk(1,2)=(daysdelensrk(1,1)-daysdelensrk(1,3))/daysdelensrk(1,3)*100;
% daysdelensrk(1,4)=(daysdelensrk(1,5)-daysdelensrk(1,3))/daysdelensrk(1,3)*100;
% daysdelensfrk(1:dayr,3)=daysdelensrk(1,1)-daysdelensrk(1,3);
% daysdelensfrk(1:dayr,8)=daysdelensrk(1,5)-daysdelensrk(1,3);
% daysdelensfrk(1:dayr,5)=daysdelensrk(1,3); %daydelensfrk(1:dayr,8)=daysdelensrk(1,1)-daysdelensrk(1,3);
% daysdelensfrk(1:dayr,8)=daysdelensrk(1,5)-daysdelensrk(1,3);
% daysdelensfrk(1:dayr,8)=daysdelensrk(1,5)-daysdelensrk(1,3);
% daysdelensfrk(1:dayr,8)=daysdelensrk(1,5)-daysdelensrk(1,3);
% daysdelensfrk(1:dayr,8)=daysdelensrk(1,5)-daysdelensrk(1,3);
% daysdelensfrk(1:dayr,8)=daysdelensrk(1,5)-daysdelensrk(1,3);
% daysdelensfrk(1:dayr,8)=daysdelensrk(1,5)-daysdelensrk(1,3);
% end % for mk=9:12,
APPENDIX C: SYSTEM SPECIFICATIONS
# ProgressivTube® Specifications

<table>
<thead>
<tr>
<th></th>
<th>PT-20-CN</th>
<th>PT-30-CN</th>
<th>PT-40-CN</th>
<th>PT-50-CN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volumetric Capacity</td>
<td>67.2 L / 17.9 gal</td>
<td>116.7 L / 30.84 gal</td>
<td>156.7 L / 41.4 gal</td>
<td>186.2 L / 49.2 gal</td>
</tr>
<tr>
<td>Gross Area</td>
<td>1.17 m² / 12.56 ft²</td>
<td>2.23 m² / 23.98 ft²</td>
<td>2.98 m² / 32.10 ft²</td>
<td>2.98 m² / 32.10 ft²</td>
</tr>
<tr>
<td>Frontal Area</td>
<td>1.0 m² / 10.77 ft²</td>
<td>2.04 m² / 21.91 ft²</td>
<td>2.77 m² / 29.84 ft²</td>
<td>2.77 m² / 29.84 ft²</td>
</tr>
<tr>
<td>Dry Weight</td>
<td>41.7 kg / 92.0 lbs</td>
<td>76.2 kg / 174 lbs</td>
<td>99.7 kg / 220 lbs</td>
<td>120.0 kg / 265 lbs</td>
</tr>
<tr>
<td>Wet Weight</td>
<td>106.7 kg / 235.2 lbs</td>
<td>192.7 kg / 425 lbs</td>
<td>255.4 kg / 563 lbs</td>
<td>301.0 kg / 664 lbs</td>
</tr>
<tr>
<td>Flow Pattern</td>
<td>Series</td>
<td>Series</td>
<td>Series</td>
<td>Series</td>
</tr>
<tr>
<td>Test Pressure</td>
<td>1103 KPa / 160 psi</td>
<td>2068 KPa / 300 psi</td>
<td>2068 KPa / 300 psi</td>
<td>2068 KPa / 300 psi</td>
</tr>
<tr>
<td>Design Pressure</td>
<td>1034 KPa / 150 psi</td>
<td>1034 KPa / 150 psi</td>
<td>1034 KPa / 150 psi</td>
<td>1034 KPa / 150 psi</td>
</tr>
<tr>
<td>Max Design Temp</td>
<td>176°C / 350°F</td>
<td>176°C / 350°F</td>
<td>176°C / 350°F</td>
<td>176°C / 350°F</td>
</tr>
<tr>
<td>Operating Temp</td>
<td>4-93°C / 40-200°F</td>
<td>4-93°C / 40-200°F</td>
<td>4-93°C / 40-200°F</td>
<td>4-93°C / 40-200°F</td>
</tr>
</tbody>
</table>

**DIMENSIONS - Metric / Inches**

<table>
<thead>
<tr>
<th>A</th>
<th>211.9 cm / 83.44&quot;</th>
<th>247.5 cm / 97.44&quot;</th>
<th>247.5 cm / 97.44&quot;</th>
<th>247.5 cm / 97.44&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>55.8 cm / 22&quot;</td>
<td>90.0 cm / 35.44&quot;</td>
<td>120.5 cm / 47.44&quot;</td>
<td>120.5 cm / 47.44&quot;</td>
</tr>
<tr>
<td>C</td>
<td>210.5 cm / 82.88&quot;</td>
<td>241.9 cm / 95.25&quot;</td>
<td>241.9 cm / 95.25&quot;</td>
<td>241.9 cm / 95.25&quot;</td>
</tr>
<tr>
<td>D</td>
<td>54.3 cm / 21.36&quot;</td>
<td>84.1 cm / 33.125&quot;</td>
<td>114.6 cm / 45.13&quot;</td>
<td>114.6 cm / 45.13&quot;</td>
</tr>
<tr>
<td>E</td>
<td>215.6 cm / 84.88&quot;</td>
<td>250.0 cm / 98.44&quot;</td>
<td>250.0 cm / 98.44&quot;</td>
<td>250.0 cm / 98.44&quot;</td>
</tr>
<tr>
<td>F</td>
<td>19.7 cm / 7.75&quot;</td>
<td>19.7 cm / 7.75&quot;</td>
<td>19.7 cm / 7.75&quot;</td>
<td>19.7 cm / 7.75&quot;</td>
</tr>
<tr>
<td>G</td>
<td>212.1 cm / 83.50&quot;</td>
<td>247.2 cm / 97.31&quot;</td>
<td>247.2 cm / 97.31&quot;</td>
<td>247.2 cm / 97.31&quot;</td>
</tr>
<tr>
<td>H</td>
<td>6.0 cm / 0.24&quot;</td>
<td>6.9 cm / 0.275&quot;</td>
<td>6.9 cm / 0.275&quot;</td>
<td>6.9 cm / 0.275&quot;</td>
</tr>
<tr>
<td>I</td>
<td>4.1 cm / 0.16&quot;</td>
<td>2.5 cm / 0.10&quot;</td>
<td>2.5 cm / 0.10&quot;</td>
<td>2.5 cm / 0.10&quot;</td>
</tr>
<tr>
<td>J</td>
<td>7.6 cm / 0.3&quot;</td>
<td>8.9 cm / 0.35&quot;</td>
<td>8.9 cm / 0.35&quot;</td>
<td>8.9 cm / 0.35&quot;</td>
</tr>
<tr>
<td>K</td>
<td>7.0 cm / 0.28&quot;</td>
<td>7.6 cm / 0.30&quot;</td>
<td>7.6 cm / 0.30&quot;</td>
<td>7.6 cm / 0.30&quot;</td>
</tr>
<tr>
<td>L</td>
<td>12.7 cm / 0.5&quot;</td>
<td>13.9 cm / 0.55&quot;</td>
<td>13.9 cm / 0.55&quot;</td>
<td>13.9 cm / 0.55&quot;</td>
</tr>
<tr>
<td>M</td>
<td>37.1 cm / 1.46&quot;</td>
<td>70.5 cm / 27.75&quot;</td>
<td>100.0 cm / 39.75&quot;</td>
<td>100.0 cm / 39.75&quot;</td>
</tr>
<tr>
<td>N</td>
<td>56.2 cm / 2.21&quot;</td>
<td>89.7 cm / 35.3&quot;</td>
<td>120.2 cm / 47.31&quot;</td>
<td>120.2 cm / 47.31&quot;</td>
</tr>
<tr>
<td>P</td>
<td>8.3 cm / 0.33&quot;</td>
<td>9.2 cm / 0.36&quot;</td>
<td>9.2 cm / 0.36&quot;</td>
<td>9.2 cm / 0.36&quot;</td>
</tr>
<tr>
<td>Q</td>
<td>13.0 cm / 0.51&quot;</td>
<td>15.6 cm / 0.61&quot;</td>
<td>15.6 cm / 0.61&quot;</td>
<td>15.6 cm / 0.61&quot;</td>
</tr>
<tr>
<td>R</td>
<td>6.0 cm / 0.24&quot;</td>
<td>6.2 cm / 0.24&quot;</td>
<td>6.2 cm / 0.24&quot;</td>
<td>6.2 cm / 0.24&quot;</td>
</tr>
</tbody>
</table>

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69
May 2009

71
June 2009

Graphs showing daily temperature and radiation levels for each day of June 2009.

Legend:
- Solar Radiation ×10 (W/m²)
- Ambient Temperature (°C)
- Mains Water Temperature (°C)
- ICS Output Temperature (°C)
- Time (hours)
September 2009

Legend:
- Pink line: Solar Radiation x10 (W/m²)
- Gray line: Ambient Temperature (°C)
- Blue line: Mains Water Temperature (°C)
- Red line: ICS Output Temperature (°C)
- X-axis: Time (hours)
October 2009

Solar Radiation x10 (W/m²)
Ambient Temperature (°C)
Mains Water Temperature (°C)
TDS Output Temperature (°C)
Time (hours)
December 2009

Legend:
- Solar Radiation x10 (W/m²)
- Ambient Temperature (°C)
- Mains Water Temperature (°C)
- ICS Output Temperature (°C)
- Time (hours)
January 2010

- Solar Radiation x10 (W/m²)
- Ambient Temperature (°C)
- Mains Water Temperature (°C)
- ICS Output Temperature (°C)
- Time (hours)
February 2010

[Graphs showing daily data for February 2010 with various lines representing different parameters such as Solar Radiation, Ambient Temperature, Mains Water Temperature, and ICS Output Temperature.]
REFERENCES


[53] FSEC website http://www.fsec.ucf.edu/en/industry/testing/STcollectors/hot_water_ratings/t

