The Concept of Design Space for Sizing Solar Hot Water Systems

Govind N. Kulkarni, Shireesh B. Kedare, Santanu Bandyopadhyay*
Energy Systems Engineering, Indian Institute of Technology, Bombay, Powai, Mumbai, 400 076.
*Corresponding author. *Email: santanu@me.iitb.ac.in*

Abstract
Existing methods for designing solar thermal systems identify a single design through optimizing particular objective function. In this paper, a methodology has been proposed to identify all possible designs for designing solar water heating systems through identifying design space. It has been observed that there exists a minimum as well as maximum tank size for a given solar fraction and collector area. Similarly existence of minimum and maximum collector area is also observed corresponding to a solar fraction and storage volume. For brevity, the analysis presents an example with desired unity solar fraction. The approach offers a prospect of becoming a simple and versatile design tool as well as improves the understanding of solar system behavior.

Introduction

A properly designed solar water heating system assures benefit to the user to its fullest extent. Correlation methods (viz., utilizability, *F* chart, $\bar{\phi}$ -*F* chart, etc.) and computer simulation programs (viz., TRNSYS) are widely used design tools for solar water heating systems [1, 2]. These methods identify a single design through optimizing a objective function, such as total annual cost, total life cycle cost, life cycle savings, pay back period etc. Therefore, the design of the system depends on the choice of a particular objective function. However, design of a practical solar hot water system is actually a multi-objective task. It is necessary to determine the entire range of designs possible. From the set of possible designs, which is defined as design space in this paper, designer can chose a particular design considering different objective functions.

In this paper a methodology has been proposed to identify the design space of solar water heating system satisfying the desired performance. The design space is represented on collector area versus storage volume diagram, incorporating various design constraints. Due to brevity, the analysis is presented with a unity solar fraction ($F = 1$). Though the method can also be applied for any solar fraction ($0 < F \leq 1$).

Generation of Design Space

Schematic of a general system configuration adopted is shown in Figure 1. For such a system, instantaneous solar useful heat gain is calculated [3] as,

$$q_s = A_c [I_T F_R(\tau\alpha) - F_R U_L (T_{sti} - T_a)]^+ \qquad (1)$$

where '+' indicates only positive values of the parameters are taken. Further, energy balance for the well mixed storage tank can be expressed in a differential equation as,

$$(\rho C_p V_{st}) \frac{dT_{st}}{dt} = A_c [I_T F_R(\tau\alpha) - F_R U_L (T_{st} - T_a)]^+ - q_{ls} - U_{st} A_{st} (T_{st} - T_a) \qquad (2)$$

The solution of the differential equation enables the storage temperature (T_{stf}) at the end of the time step to be estimated as,

$$\frac{\left[A_c I_T F_R(\tau\alpha) - A_c F_R U_L (T_{stf} - T_a) - q_{Ls} - U_{st} A_{st} (T_{stf} - T_a)\right]}{\left[A_c I_T F_R(\tau\alpha) - A_c F_R U_L (T_{sti} - T_a) - q_{Ls} - U_{st} A_{st} (T_{sti} - T_a)\right]} = \exp\left(-\frac{(A_c F_R U_L + U A_{st}) t}{\left(\rho C_p V_{st}\right)}\right) \qquad (3)$$

For the given type of collector, with given $F_R U_L$ and $F_R(\tau\alpha)$, storage tank loss coefficient U_{st},

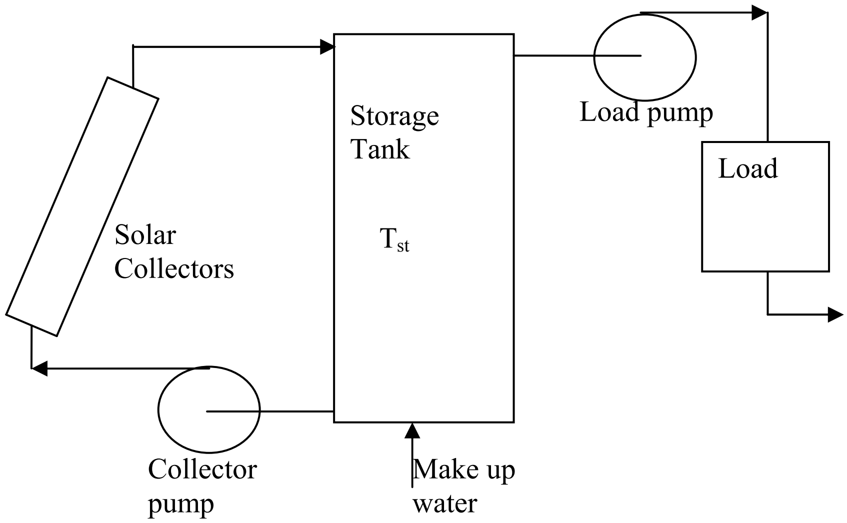

Figure 1 General configuration of solar water heating system

insolation on the tilted surface I_T and the thermal load characteristics, the above equation uniquely predicts the temperature profile inside the storage tank as a function of collector area (A_c) and storage volume (V_{st}). The surface area of the storage tank is assumed to be related to the storage volume by following relation, with equal height to diameter ratio.

$$A_{st} = 5.54\,(V_{st})^{2/3} \tag{4}$$

For the design purpose, it may be assumed that the temperature profile reaches a steady state condition, i.e., the net gain or loss of thermal energy from the storage tank over a given time period of analysis is zero.

$$\int_0^T \rho C_p V_{st} \left(\frac{dT_{st}}{dt} \right) dt = 0 \tag{5}$$

By varying collector area and storage volume, different designs may be obtained. As it is assumed to supply complete thermal load ($F = 1$), the temperature of the storage tank during load has to be greater than the desired load temperature.

$$T_{st} \geq T_{load} \tag{6}$$

Since, water is used as a working fluid; the system cannot be designed for two-phase condition. The storage tank temperature, therefore, has to be less than the saturated temperature of working fluid.

$$T_{st} \leq T_{sat}\ (=100°C) \tag{7}$$

An acceptable design must satisfy the above two constraints stated by Eq.(6) and (7). For the specified load, all possible combinations of collector area and storage volume that satisfy these two constraints define the design space. It may be identified on a collector area- storage volume diagram. The same is demonstrated through an example.

Example and discussion

For demonstration of the concept of design space, single day analysis is performed. 15th April is chosen as a sample day. Monthly mean values of hourly solar radiation on this day are obtained from the literature [4]. The time step t is 3600 seconds. The various system parameters adopted are given in Table 1.

Table 1 Solar system parameters adopted

Location	Domestic hot water for an apartment building at Pune, India (Latitude -18.53° Longitude – 73.85° Ground reflectance = 0.2)
Load	4500 LPD at 60°C, Consumption pattern as per ISO 9459–3:1997(E), [5]
Collectors	Flat plate collectors (single cover, selective coated, south facing Tilt = 33.53°) Collector parameters [6]: $F_R\ (\tau\alpha) = 0.675$, $F_R\ U_L = 5.656\ W/m^2K$.
Storage	Insulation: 0.14 m glass wool (k = 0.04 W/mK)

With a typical system size (A_c and V_{st} combination) Figure 2 shows storage temperature profile. In the context of the example the design constraints (Eq. 6 and 7) may be stated as, the tank temperature has to be greater than 60°C during load and has to be always less than 100°C. A_c and V_{st} combinations may be varied to represent the design space (Figure 3). A characteristic of collector area versus storage volume at constant solar fraction 1 is plotted in Figure 3**.**

Point 'm' in Figure 3 corresponds to a minimum collector area of 76 m^2 (V_{st} = 28 m^3) required for a desired output. Any decrease in the collector area from 'm' will not be able to supply the desire load. Point 'a' is the intersection of two characteristics which serves as a lower limit to storage size of 2.6 m^3 (A_c = 111 m^2). This is the point where the storage temperature profile touches both the limiting conditions. Any reduction in storage volume will result in boiling of water leading to a reduction in solar fraction.

In Figure 3, it may be noted that any horizontal line will intersect the limiting curves at two different points. This signifies that there exist a maximum and a minimum collector area for a given storage volume. For example, a constant storage volume line (V_{st} = 28 m^3) intersects the limiting curves at 'm' and 'o'. Point 'o' indicates a maximum limit of collector area of 213 m^2. Collector area more 213 m^2 will result in boiling of water in the storage tank.

Similarly, it may be noted that any vertical line will intersect the limiting curves at two different points. This signifies that there exist a maximum and a minimum storage volume for a given collector area. For example, a constant collector area line (V_{st} = 111 m^2) intersects the limiting curves at 'a' and 'b'. Point 'b' indicates a maximum limit of storage volume of 1227.2 m^3. Beyond point 'b', thermal losses from the storage tank will dominate and it will result in loss of solar fraction.

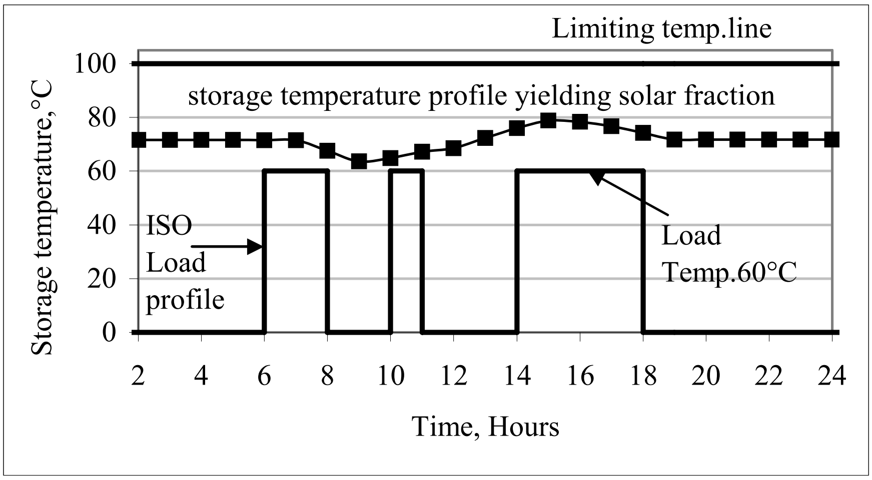

Figure 2 Load and storage temperature profile over a typical day.

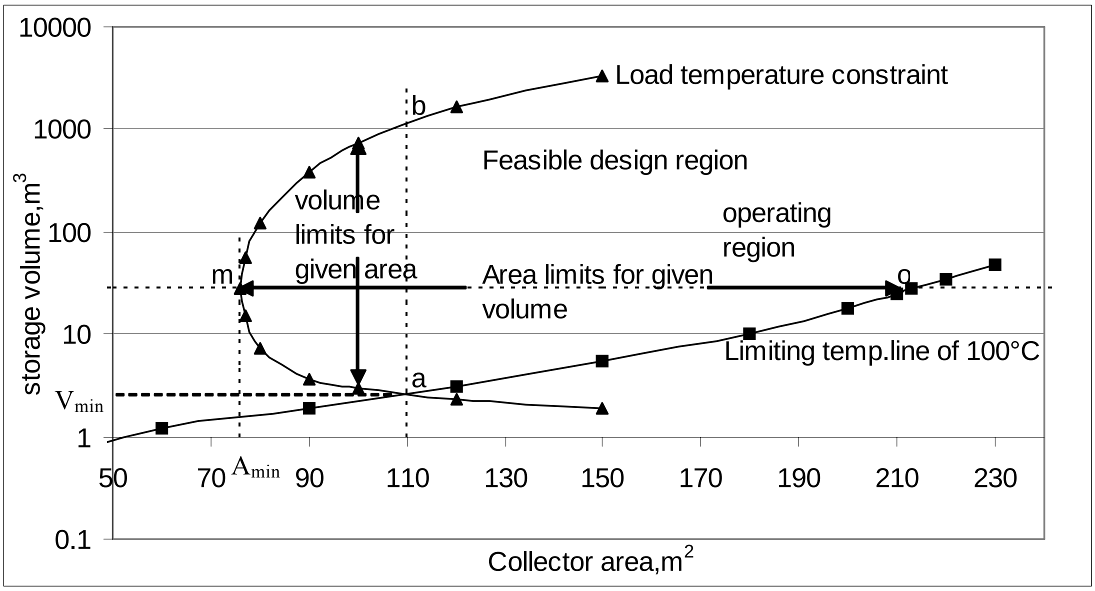

Figure 3 The design space for F = 1

The region bounded by the limiting curves includes all possible designs of the system and may be called as the design space for solar fraction 1. Any suitable objective function may be optimized to select a feasible design from the entire design space. Since all the feasible designs are known, even multi-objective design can easily be performed by the designer. However, it may be noted that the methodology, proposed in this paper, can be employed for designing systems on annual basis and with different values of solar fractions. It can thus be observed that the design space concept may work as a simple and strong tool for design as well as analysis of solar thermal systems.

Conclusion

The concept of design space approach for design of solar thermal system is presented with an example. Existence of design space is attributed to the specification demand and limiting storage condition. Design space offers flexibility in system sizing however, it is specific for a given configuration. Employment of the design space approach for design optimization and parametric analysis of solar thermal systems may reduce the labor, expertise and expense involved. The methodology is simple, flexible and doesn't need any special computational setup, thus offering a prospect of application in domestic as well as industrial configurations.

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