# CHAPTER I

# INTRODUCTION

## 1.1 General

The overall solar system consists of the solar collector, storage units, loads, auxiliary energy supplies, and the control system. The solar collector is the essential item of equipment which transforms solar radiant energy to some other useful form. The energy storage is added to store the excess of available energy over the load and return it when the available energy is less. The auxiliary energy source is introduced when the solar energy cannot meet all of the load requirements. Controls are designed to make decisions on energy flows based on preprogrammed criteria. Control system also calls upon the auxiliary energy source when solar capacity is below the demand level. The characteristics and performance of each of these elements is related to that of the others. The collector alone cannot be used directly to calculate energy delivery, since collecter delivery depends on its operating temperature, which in turn, is determined by the temperature of thermal storage. Storage temperature is, in turn, determined by the energy withdrawn to supply demand and energy inputs from the collecter. This integrated system is shown in Fig. 1.

Large amount of research efforts have been concentrated on

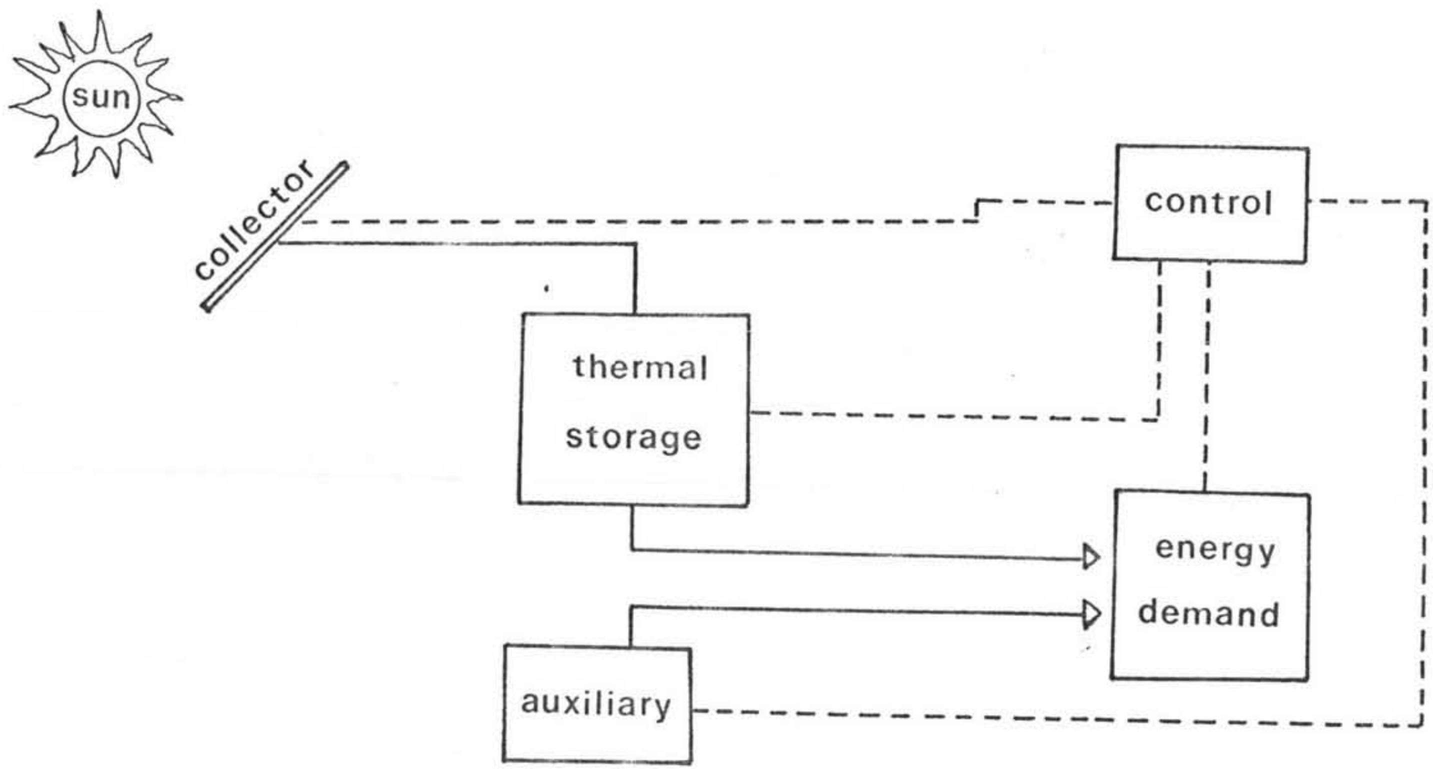


Figure 1 The overall solar-thermal system. Solid lines represent energy flows; the dash lines information flows

various parts of the system, especially for the collector characteristics and performance. This research project concentrates on energy storage with particular emphasis on stratified sensible heat storage.

## 1.2 Energy Storage in Solar Process Systems

Solar energy system requires a storage device because of the intermittent nature of solar radiation. Energy storage involves the collection and retention of readily available energy for later use. The concept of energy storage is important in the utilization of power. Energy can be stored in the form of thermal energy storage, mechanical energy storage, and electrical energy storage. Thermal energy storage can be accomplished through sensible heat, latent, or a reversible chemical reaction. Mechanical energy can be converted to potential energy by pumping water into an elevated reservoir during period when solar radiation is available, and the energy recovered by running the water through a turbine when energy is needed. A battery is an energy storage device that contains chemical energy which can be converted into electricity, simply connecting the load to it. Water can possibly be electrolized with solar generated electrical energy, and stored oxygen and hydrogen can be recombined in a fuel cell to regain electrical energy.

The major characteristics that may influence the design of a thermal energy storage are

1. Storage materials. The best sensible heat storage materials should have high specific heat and density. They should not be expensive, toxic, flammable, and chemical active. All storage materials

must be resistant to chemical or physical change resulting from thermal cycling.

2. The temperature range over which it operates, that is, the temperature at which heat is added to and removed from the system.

3. Temperature stratification in the storage unit. Thermal stratification may have a desirable effect on the performance of the system, and is important to the overall system design.

4. The power requirements for addition or removal of heat.

5. Storage material containers. Storage tanks for liquid can be fabricated from steel, fiber glass, aluminum, or concrete. They must be leakproof, corrosion resistant , and withstanding long exposure to temperature cycles.

6. Thermal losses from the storage units. Heat will be transfered outward through the storage walls at a rate depending on the temperature difference between the storage media and the surroundings. For long periods, thermal losses may become important.

7. Cost of the storage unit. These include the container costs which depends on the shape, material of construction, and size. The cost of storage medium, the space in which it is located, and the cost of operation.

As previously mentioned, thermal energy can be stored in the form of sensible heat, latent heat, and chemical reaction, each of these three basic modes is briefly discussed for its properties and characteristics below:

### 1.2.1 Thermal Energy Storage by Sensible Heat

Heat is simply stored by increasing the temperature of a solid or liquid. If the specific heat of the material is constant, the amount of energy stored in the system is directly proportional to the temperature rise of the substance. The sensible heat storage devices in common use are: Water storage and particle bed storage.

#### 1.2.1.1 Water Storage

Water is suitable for storing sensible heat for use with low-medium temperature solar system. It does not require any heat exchanger between transport medium and storage medium. Water is non-toxic, has a very high specific heat, is inexpensive and its vapor-liquid phase equilibrium is suitable for the temperature range required for space and water heating. Volume of water $2.66 \times 10^4$ liters raised 38 $^{\circ}C$ in temperature will store the energy equivalent to 1 barrel of petroleum. Water has a number of particularly desirable properties as shown in Table 1.

Useful energy can be stored below the boiling point of water without pressurization. The storage of water at temperature above its boiling point requires expensive pressure vessels.

Water storage unit and collectors may be operated by natural convection in domestic solar-water heater applications, or by forced circulation.

Table 1

Advantages and Disadvantages of Water as Thermal Storage Medium

| Advantages | Disadvantages |
| --- | --- |
| Abundant | High vapor pressure |
| Low cost | Difficult to stratify |
| Non toxic | Low surface tension |
| Excellent transport properties | Corrosive medium |
| High Specific heat | Freezing and consequent-destructive expansion |
| Good combined storage medium and working fluid | Non-isothermal energy delivery |
| Well-known corrosion control methodology | |

1.2.1.2 Particle Bed Storage

Sensible heat storage in solids is advantageous for some applications. For example, thermal energy from an air collector can be stored in a bed of solid material for later heating of a building. Storage beds can act as both a storage medium and heat exchanger, thereby saving the cost of a separate heat exchanger. A packed bed storage unit consists of a container, a porous structure to support the bed, a packed solid typically rocks, a few centimeters in diameter, and air distributor to minimize air channeling (the flow is faster in one area of the bed than the other). Air is circulated through the bed in one direction during addition of heat, and in the opposite direction during removal of heat. Hence the heat cannot be added to this storage unit and removed from it at the same time. This is in contrast to water storage systems where the heat can be added to and remove from the storage simultaneously. Insulation requirement at the outer surface of the packed bed is small due to a low thermal conductivity of the bed in the radial direction. Solid-phase storage has an advantage over liquid storage in the size of the maximum allowable storage temperature. Since most solid storage media do not melt readily, they are suited for use with high temperature, concentrating collectors. Care must be taken to avoid thermal fracturing. The density and specific heat values for solid-phase, thermal storage materials are shown in App. III.

### 1.2.2 Thermal Energy Storage by Latent Heat

Thermal energy storage by latent heat occurs in an isothermal process. The material undergoes a phase change such as a phase change from solid to solid, solid to liquid (heat of fusion) or from liquid to gas (heat of vaporization). The most suitable phase change is the solid-liquid transition; vaporization is impractical due to the large volume change and solid-solid transitions do not usually involve sufficient quantities of heat. Latent heat storage has the advantage of compactness, because the heat of fusion of most materials is very much larger than their specific heat. For example, for water the ratio of latent heat to specific heat equals 80/ $^{\circ}C$. This means, it takes eighty times as much energy to melt one pound of ice as to raise the temperature of one pound of water by one degree celcius. On the other hand, latent heat storage requires an additional heat exchanger, and most latent heat thermal energy storage materials are more expensive than the cheapest sensible heat thermal energy storage material which is water. In the two phase latent heat system, additional considerations must be given to the problems of melting, expansion, solidification, thermal stabilities, and the choice of material of the storage media.

### 1.2.3 Thermal Energy Storage by Chemical Reaction

In this system thermal energy is converted into Chemical energy in a reversible endothermic reaction that takes place at constant temperature. To reverse the process, the equilibrium constant is changed by changing the concentration, the pressure, and/or the temperature of the reactants. The system of the reversible process act like a sensible heat system with a high specific heat. Chemical energy storage is a very complex system. In order to reverse the maximum rate of energy addition or removal, the operating temperature, corrosion and material of construction, the environmental effect, and the system economics must be considered.

Since this project is related directly to stratified sensible heat. The characteristics and performance of stratified tank storage are discussed in further details below:

## 1.3 Stratified Sensible Heat Storage

### 1.3.1 General Characteristics

In solar heating systems, there are two basic types of sensible thermal energy storage: Stratified storage and well-mixed storage. Currently well-mixed storage is most common in space-heating systems, while stratified storage is more often used for domestic hot water system. Stratified storage is advantageous when quality of heat storage (high temperature) is of primary concerned, moreover in a thermal syphon system it influences the overall performance of the system significantly.

The storage is said to be stratified if the incoming water seeks its own density level. Water storage may operate with significant degrees of stratification, that is, with water not at uniform temperature over the vertical dimension of the tank. With perfectly stratified water storage, heated water from the collector is returned to the top of the tank and will remain there because it is less dense than the water below. When there is hotter water already at the top, the returned water will descend until it reaches a level in the tank having the same temperature. Imperfection in water storage occurs because the descending water tends to carry over some of the hotter water as it moves down, and result in mixing of the hot and cold water. Water tanks will stratify automatically if they are constructed like ordinary hot water tanks with a height greater than the tank diameter. Flow should enter the tank in such a way that the velocity of the entering water does not tend to mix the tank. As water storage tanks get large enough for space heating a vertical configuration becomes less practical and horizontal tanks are most often installed.

In the design of stratified tank storage, one of the problems arises from the effectiveness of extracting energy out for use in another system due to the problem of mixing between the stored hot water and the incoming cold water. If the stored hot water is mixed with cold inlet water, the extraction temperature is lowered and the usefulness of the collected energy is degraded. This adverse effect of mixing should be minimized if stable thermal stratification can be attained. Heat conduction through the storage medium and through the containing materials may be of importance to the stability of thermal stratification. It is the purpose of this research project to investigate various parameters affecting the stability of thermal stratification.

### 1.3.2 Previous Work on Stratified Hot Water Storage

Some analytical studies of the effect of thermal stratification in storage systems were carried out by a number of investigators. Earlier simulations by Gutierrez, Hincapie, Duffie and Beckman (4) and Sheridan, Bullock, and Duffie (10) were carried out on analog and hybrid computers using series of well stirred tanks to simulate a stratificated hot water storage tank. Close (1) studied the effect of stratification on the performance of the overall system. These studies have shown that stratification improves the performance of solar systems. Hawlader (5) has carried out an analytical and experimental study of a storage system which include direct solar energy input and fluid circulation from collectors. This work has direct application toward swimming pool heating. Laven and Thompson (6) have reported some experimental study of thermally stratified hot water storage system. Tanthapanichkoon and Laohakul (11) have carried out a theoretical investigation into the dynamic responses of the stratified sensible heat storage tank. They have concluded that conduction through wall in most application can be neglected. Nevertheless, reliable predictions without the aid of sophisticated computer program are not presently available and systematic studies of the parameters affecting the system are far from complete.

## 1.4 Purpose of Research

The objective of this study is to experimentally determine a method of removing hot water from the storage tank and adding cold water to it while maintaining a stable thermal stratification. Results of theoretical analysis will be compared with experimental results in order to gain confidence of the proposed model. Various important parameters affecting the extraction efficiency of the storage tank will be investigated, including

1. The effect of length to diameter ratio.
2. The effect of tank diameter to inlet diameter.
3. The effect of inlet $Re_d$
4. The effect of inlet-exit temperature difference.
5. The effect of cold water inlet location.
6. The effect of heat conduction through the tank wall.