Development of a ESES Solar Thermal Lab on Full Scale System
Abstract

The main aim of this project is to develop an ESES lab on a full scale system. The solar combisystem used is available most of the time and is only used twice a year to carry out some technical courses. At the moment, there are no other laboratories about combisystems. The experiments were designed in a way to use the system to the most in order to help the students apply the theoretical knowledge in the solar thermal course as well as make them more familiar with solar systems components. The method adopted to reach this aim is to carry out several test sequences on the system, in order to help formulating at the end some educating experiments. A few tests were carried out at the beginning of the project just for the sake of understanding the system and figuring out if any additional measuring equipment is required. The level of these tests sequences was varying from a simple energy draw off or collector loop controller respond tests to more complicated tests, such as the use of the ‘collector’ heater to simulate the solar collector effect on the system. The tests results were compared and verified with the theoretical data wherever relevant. The results of the experiment about the use of the ‘collector’ heater instead of the collector were positively acceptable. Finally, the Lab guide was developed based on the results of these experiments and also the experience gotten while conducting them. The lab work covers the theories related to solar systems in general and combisystems in particular.
# Table of Contents

1. Introduction ................................................................................................................................... 1  
1.1 Aims ......................................................................................................................................... 1  
1.2 Method .................................................................................................................................... 2  
1.3 Literature Review .................................................................................................................. 4  
1.3.1. Collector circuit .................................................................................................................. 4  
1.3.2. Storage Tanks ................................................................................................................... 5  
1.3.3. Experiments with Vertical Plates for Temperature Stratification in a Heat Storage Tank (Vogelsanger et al. 2007) ......................................................................................... 5  
1.3.4. Thermal Stratification in Small Solar Domestic Storage Tanks Caused by Draw-offs (Jordan & Furbo, 2005) ................................................................................................................ 7  
1.3.5. Methods to determine stratification efficiency of thermal energy storage processes – Review and theoretical comparison (Haller et al. 2009) .......................................................... 10  
1.3.6. A method to determine stratification efficiency of thermal energy storage processes independently from storage heat losses (Haller et al. 2010) .................................................. 11  
1.3.7. Measurement Equipment ................................................................................................. 11  
1.3.7.1. Flow Meters (Doebelin, 2003) ......................................................................................... 11  
1.3.7.2. Radiation Sensors ........................................................................................................ 12  
1.3.7.3. Temperature Sensors (Thermoelectric Temperature Sensors) (Doebelin, 2003) ... 12  
1.4 Scope of Work ....................................................................................................................... 13  

2. Experimental Setup .................................................................................................................. 14  
2.1. Temperature Sensors .......................................................................................................... 14  
2.1.1. Temperature Sensors in the Collector Circuit ....................................................................... 15  
2.1.2. Temperature Sensors in the Storage Tank ........................................................................ 16  
2.1.3. Temperature Sensors in the Load Circuits ........................................................................ 16  
2.1.4. Indoor and Outdoor Temperature Sensors ......................................................................... 16  
2.1. Irradiation Sensor ................................................................................................................. 16  
2.2. Flow Meters .......................................................................................................................... 17  
2.3. Electrical Energy Meters ..................................................................................................... 18  
2.4. Data Logger ........................................................................................................................... 18  
2.5. Solar Loop Controller .......................................................................................................... 20  
2.6. PID Controller ...................................................................................................................... 20  

3. Experiments Conducted ............................................................................................................. 21  
3.1. Collector Characteristics and Load Discharge Experiment .................................................... 21  
3.1.1. System Setup .................................................................................................................... 21  
3.1.2. Conditions Required ........................................................................................................ 21  
3.1.3. Test Procedure ................................................................................................................ 21  
3.1.4. Data Analysis .................................................................................................................. 21  
3.2. Collector Simulation and Load Discharge Experiment ........................................................... 22  
3.2.1. System Setup .................................................................................................................... 22  
3.2.2. Conditions Required ........................................................................................................ 22  
3.2.3. Test Procedure ................................................................................................................ 22  
3.2.4. Data analysis .................................................................................................................... 24  

4. Calculation and Results ............................................................................................................. 25  
4.1. Collector Characteristics and Load discharge Experiment Results ........................................ 25  
4.1.1. Load Discharge ................................................................................................................. 25  
4.1.2. Storage Tank Analysis .................................................................................................... 26  
4.1.3. Stratification Analysis ...................................................................................................... 28  
4.2. Collector Simulation and Load Discharge Experiment ......................................................... 29
4.2.1. Storage Tank Analysis ................................................................. 29
4.2.2. Stratification Analysis .............................................................. 30

5. Discussion and Conclusions ......................................................... 32
5.1. Collector Characteristics and Energy Discharge Experiment ...... 32
5.1.1. Collector Characteristic Curve ................................................. 32
5.1.2. Load Discharge Calculations .................................................. 32
5.1.3. Storage Tank Analysis ............................................................ 32
5.1.4. Stratification Analysis and the Effect of the Load Discharges .... 33
5.2. Collector Simulation and Load Discharge Experiment .............. 34
5.2.1. Storage Tank Analysis ............................................................ 34
5.2.2. Stratification Analysis ............................................................ 34
5.3. General Comparison of Results of the Two Experiments ............ 34

6. Appendices .................................................................................. 35
6.1. Lab-guide .................................................................................. 35

• MÖ3015 SOLAR THERMAL .......................................................... 35
  • Solar Combisystem Lab ................................................................. 35
  • Contents of lab work ................................................................. 35
  • Aims ............................................................................................ 35
  • Introduction ................................................................................ 35
  • Theoretical Background ............................................................ 36
  • Questions .................................................................................... 37
  • Collector Characteristic Experiment .......................................... 37
  • Refining the results of the collector characteristics experiment .... 37
  • Solar Collector Simulation .......................................................... 38
  • System Setup ............................................................................. 38
  • Calculations ............................................................................... 38
  • Energy Extraction ....................................................................... 39
  • Questions .................................................................................... 39
  • Solar Collector Simulation .......................................................... 39
  • Report .......................................................................................... 40
  • Relevant Equations and Data ....................................................... 40
6.2. The Developed Excel Sheets for the Lab Calculations ............... 43

7. References ................................................................................... 44
1 Introduction

The work in this project should result in some useful and suitable experiments to be used at the end to design an ESES lab for the Solar Thermal course. The designed lab should not only help ESES student in understanding some theoretical parts mentioned in that course, but also help them to get some basic practical knowledge about solar combisystems and their components. Besides that, the work on this project should help the researcher to expand and deepen his knowledge about combisystems both in practical and theoretical aspects and learn and practice projects planning. The solar combisystem to be used in this project already exists and has been used for some courses for installers of solar systems and for technician courses. The work began with some literature survey around the main topic to help formulate the plan of work. The theoretical background of this project will depend mainly on what is already there in the solar thermal course with more knowledge depth when needed to help elaborating and formulating the experiments. The practical part will cover the used system components, either the current or those which will be added later to help in achieving the aim of the project. A few experiments will be done with the system just to test the system and to do some calibration.

Solar combisystems use is increasing but not fast enough as stated by Dr. Harald Drück in his article about the aims of CombiSol Project; “Solar combisystems are gaining importance in markets such as Germany and Austria. The project partners wanted to provide a basis for the effective application of SCS in European regions, throughout which these systems are not very common - despite very good climatic conditions,” (2010). The main obstacle against a rapid increase in the combisystems share in the market is how to make planners and installers familiar with the theoretical basis and provide the needed technical knowledge (Drück’s 2010 study as cited by Banse, 2010). Beside the need to more understanding SCS, their performance will need to improve same as all other solar technologies to cope with the current prices of conventional fuel. These two concerns are probably the main issues to be studied about SCS, with strong correlation between them. Higher solar fraction can be reached by both proper installation of the system and more optimized system. In the other hand, bad physical installation and wrong logical control over the system operation could bring down the performance of system with high solar fraction. System operation control and storage tank performance together with low system heat losses are the main factors determining the overall system performance.

1.1 Aims

The main aim of this project is to develop some experiments that could be used to create an ESES lab for the solar thermal course. The lab should not only help ESES student in understanding some theoretical parts mentioned in that course about SCS and Solar systems in general, but also help them to get some basic technical knowledge about solar combisystems. The secondary aims of the project are:

- Get some critical knowledge about the different parts in solar combisystems, their use and the theory related to them.
- Learn, practice and make some tests on the system to better understand the physics related with solar combisystems and the weight of the factors affecting their performance.
- Full Use of the possibilities of the existing system to demonstrate some experiments related with the theory in the Solar Thermal course MÖ3015
- Practice of project planning.
1.2 Method

As a start, some literature review will be needed to help formulate and specify the plan of the work. As the main aim of this project is to develop a lab that could help ESES students, with other labs, to better understand the theory in the Solar Thermal course, this course main parts have to be reviewed to specify and evaluate what could be included in as the expected theoretical parts of the lab. Some practical knowledge about the system will then be needed to determine what could really be done and if there are any practical limitations to achieve the aims.

The solar combisystem that will be used in this project consist of 5m² solar collectors, the collector circuit which supplies a 500l storage tank through an internal heat exchanger, a controller, and two heat exchangers for the hot water supply and the space heating. Space heating load is demonstrated by several radiators in an outdoor room supplied by an external heat exchanger. So far this mentioned system is considered a ‘Normal’ SCS, but in order for the system to be used during cloudy days, which is quite common in Sweden, another heater had to be connected to the solar loop to simulate the effect of the solar collector. Also, additional temperature and radiation sensors and flow meters had to be added to the system to better understand and study it is performance.

During the testing period of the system, some experiments will be developed; but these experiments will then be measured with the limitations that exist in an ESES lab. These limitations will be mainly around the time needed to perform the lab by the students and the weather conditions needed on the day of the lab. The ‘collector’ heater will need to be adjusted to keep the same energy input to the system to achieve the same result of any further experiments. In order to have a better control over this heater while simulating the effect the collector, an additional temperature sensor and a PID controller were installed in the ‘collector’ heater loop.

The effect of the internal heat exchanger on the temperature distribution in the storage tank will be observed to help in studying its effect on the stratification level reached in the storage tank. Among the temperature sensors to be added to the system, six of them will be mounted at the storage tank to measure the temperature at different six heights, see Fig.1. Two temperature sensors will be used in each of the collector loop, the space heating circuit and the hot water circuit. In addition, a data logger will be installed in the system to monitor and record the readings of the temperatures sensors, flow meters, and the solar radiation sensor.
An internship student (Philipp Einsiedel) has contributed in this project; he has been in charge of the installation of the additional needed devices to perform the experiments and all other practical issues generally. Also, he carried out the lab trials.

The work done in this project was based on the results and experience obtained during the conduction of several tests sequences using the system, Fig.2 shows the collectors covered and uncovered during a test on the solar loop controller. These tests sequences will then help formulating the experiments to be suggested for the ESES lab and will also increase their details. The first main test sequence is a general one, which could be used as an introduction to the system and will need basic skills of collecting some basic data to find some performance measurement for the system or a specific part of it. The second test sequence is about stratification in the storage tank and the effect of load discharge. The third test sequence is about the effect of the electrical heater in the collector circuit and how to adjust its output to maintain the same performance on the system. The work in this last experiment will help in developing more interesting and useful experiments for students and will also contribute in solving the problem of using the lab during the winter/autumn period. The last step is to select the suitable test sequences and combine them into one lab and generate the lab instruction.

Figure 1 Position of the sensors used to study the stratification in the storage tank.
1.3 Literature Review

The knowledge needed to work in this project will include some theoretical background about solar combisystems, their main components, and the physics related to their performance. The literature reviewed here can be divided into two main categories; general background about SCS and specific background about the experiments to be done.

Solar combisystem in definition is a system which provides heat for both hot water (which will be called DHW as an abbreviation for Domestic Hot Water) and for heating the house (Space heating, SH).

A solar combisystem will generally consist of the following:

1. Collector circuit
2. A storage tank
3. Load circuits (for both SH and DHW loads)

1.3.1. Collector circuit

The collector circuit consists basically of the Solar Collector, to absorb the solar radiation and transfer it to the heat transfer fluid, which is then used to charge the storage through a heat exchanger. In order to keep this process going there is a pump to circulate the heat transfer fluid through the collector circuit. There are also some sensors to measure flow rates and temperature values in the circuit to get an idea about the performance of the system in general and the circuit performance in particular. In many cases, and depends on the system size, the collector should charge the storage tank and supply the load during the day time. The efficiency of the collector determines the efficiency of the circuit and it depends mainly on the design of the collector, the available radiation and the operating temperature.
The useful energy gain of a solar collector is dependent on several factors, the solar radiation amount, the optical losses and the thermal losses, and could be expressed as:

\[
\dot{Q}_u = A_c \left( S - U_L (T_{pm} - T_a) \right) \quad \text{Equation 1}
\]

Where:
- \(\dot{Q}_u\) = Useful energy gain per unit of time [J/s]
- \(A_c\) = Solar collector area [m²]
- \(S\) = Absorbed solar radiation rate [W/m²]
- \(U_L\) = Heat loss coefficient [W/m²K]
- \(T_{pm}\) = Mean absorber plate temperature [K]
- \(T_a\) = Ambient temperature [K]

Or in a more detailed equation:

\[
\dot{Q}_u = A_c F_R (G_T \cdot K_{ra} \cdot \xi_O - U_L (T_i - T_a)) \quad \text{Equation 2}
\]

Where:
- \(F_R\) = Heat removal factor
- \(G_T\) = Solar radiation rate [W]
- \(K_{ra}\) = Incident Angle Modifier (IAM)
- \(\xi_O\) = Optical efficiency
- \(T_i\) = Inlet fluid temperature [K]

1.3.2. Storage Tanks

The storage tank is considered the most important part of the solar system, due to its major impact on the overall performance of the system even more than the collector (Bales et al., 2010). Among all types of heat storages, water storages are considered an ideal option for many solar systems (Duffie & Beckman, 2006).

With the whole storage temperature below the boiling temperature of water at the designed pressure, some kind of separation happens often in the water based on the temperature. The hottest layers which have the lowest density tend to move to the top of the storage tank according to the laws of buoyancy and vice versa. This hot water on the top of the tank can be used to supply those kinds of loads with the need for highest temperatures and the cold water on the bottom of the tank can be circulated in the collector circuit to increase the thermal efficiency of the solar collector. While the water is moving to the top it will mix with the lower temperature layers and cool down. This drop in temperature due to the mixing between the layers is not desirable in storage tanks due to its effect on the energy consumption.

The process of reducing this mixing in storage tanks and enhance this natural process of stratification is done with either active or passive changes in the storage. The stratification in the storage tank mainly depends on how the energy is added to and extracted from the storage. This includes the value of the inlet and outlet flow rates and their temperatures and positions. The position of inlets and outlets on the Storage tank determines how much the coming flow will have to move up/down the storage to reach the level with the same temperature and thus how much mixing will occur.

1.3.3. Experiments with Vertical Plates for Temperature Stratification in a Heat Storage Tank (Vogelsanger et al. 2007)

There are many studies available about this process and some interesting comparisons have been made between the stratification in a storage tank with and without active stratification devices (Stratifiers). These stratification devices can help in guiding the
incoming water to the position in the tank where the water layer has the same temperature and there are several designs available to do that ranges from simple to complicated ones. 

Fig. 3 and Fig. 4 show four different types of stratifiers. Table 1.1 shows the different experiments done to compare different stratification techniques with the case of no stratifier.

Table 1 Experiments description for the four scenarios, (Vogelsanger et al. 2007)

<table>
<thead>
<tr>
<th>Number and Name</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, without stratifier</td>
<td>Reference test without stratifier. Hot water is supplied to the uniformly cold tank.</td>
</tr>
<tr>
<td>2, large gap</td>
<td>Uniform 6 mm gap open all around. Hot water supplied to the stratified tank.</td>
</tr>
<tr>
<td>3, one side closed, narrow gap on other side</td>
<td>The gap size is substantial (4 mm) on the side (inlet side), which is not open to the tank, narrow (1 mm) on the other side (outlet gap). Hot water is supplied to the stratified tank.</td>
</tr>
<tr>
<td>4, one side closed, moderate opening on other side</td>
<td>The gap size is substantial (4 mm) on the side which is not open to the tank (inlet side), moderate (3 mm) on the other side (outlet gap). Hot water is supplied to the stratified tank.</td>
</tr>
</tbody>
</table>

Water was supplied to the tank (directly) at temperature around 60°C at height of 0.5 m to 1.3 m tank, and the storage tank was at temperature around 15°C. The conclusion they got from these experiments is that with no stratifier was added, the tank was fully mixed over the point of the inlet while the other option result in an acceptable level of stratification and showed that the optimum space between the stratifier parallel plates should be around 3-4 mm.
1.3.4. Thermal Stratification in Small Solar Domestic Storage Tanks Caused by Draw-offs (Jordan & Furbo, 2005)

This study case focuses mainly on the cold water inlet design in small DHW and how it can influence the total system performance. In particular, it investigates the effect of the cold water inlet design on the thermal stratification in storage tanks. The draw-off volume, the flow rate to be used and the initial temperature in the storage tank “are the main factors determining the thermal stratification level in storage tanks” (Jordan & Furbo, 2005) and they were all tested experimentally and using a simulation tool, i.e. TRNSYS. The inlet design of the cold water was modified to reduce the mixing caused by the cold water flow into the storage tank. Fig.5 and Fig.6 show the two storage tanks and the position of the collector and auxiliary heat exchangers with a picture showing also the cold water inlet pipe design.
A small SDHW system was tested in this experiment consisting of 2.5m² solar collector, but with two different storage tanks with different cold water inlet designs. The tests were carried out on the first tank using two different draw-off volumes: 18 and 45 liters with an initial temperature of 60°C. The draw-off volumes for the second tank were 30 and 40 liters using three different initial temperatures: 30, 45 and 60°C.

Table 2 The Storage tanks parameters (Jordan & Furbo, 2005)

<table>
<thead>
<tr>
<th></th>
<th>Tank I</th>
<th>Tank II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of water</td>
<td>144/</td>
<td>182/</td>
</tr>
<tr>
<td>Tank height</td>
<td>1242mm</td>
<td>1040mm</td>
</tr>
<tr>
<td>Inner tank diameter</td>
<td>409mm</td>
<td>500mm</td>
</tr>
<tr>
<td>Volume of solar heat exchanger</td>
<td>2.9/</td>
<td>6.8/</td>
</tr>
<tr>
<td>Max. height of solar heat exchanger above tank bottom</td>
<td>530mm</td>
<td>530mm</td>
</tr>
<tr>
<td>Volume of aux. heat exchanger</td>
<td>2.9/</td>
<td>3.3/</td>
</tr>
</tbody>
</table>
The tests were carried out on the system using the two mentioned storage tanks resulted in the temperature distributions across the tank height for the different cases. Fig.7 and Fig.8 show the temperature profile in the storage tank before and after the tests. The system was then modeled using TRNSYS. Same system specifications were used, assuming hot water consumption of 100 l/min at 45°C.

The results of parametric study for both the measurement and the model simulation were in good agreement. The annual simulation results of a system uses a mantle storage tank similar to the second storage tank used in the experiment, showed a decrease of 4% in the solar fraction when using cold water inlet at 0.3% of relative tank height than when at the very bottom. The loss in solar fraction was caused by an increase in the temperature of the storage tank bottom of 2.5K.
1.3.5. Methods to determine stratification efficiency of thermal energy storage processes – Review and theoretical comparison (Haller et al. 2009)

Several methods that are used to describe thermal stratification in storages theoretically were discussed in this article.

The focus in this paper is to emphasize on the procedures that can be used to define the capability of storage tank to stimulate and maintain stratification during charging, storing and discharging, and characterize it is ability with a particular numerical number, i.e. stratification efficiency, under known experimental conditions.

The current methods for estimating stratification efficiencies were used on a storage tank during charging, discharging and storing phases. Then the rate of entropy production was used as a measure for the mixing occurred during this processes.

The results of the experiments showed that none of the methods used to calculate the stratification efficiencies was able to distinguish between the change in entropy caused due to mixing and the one caused due to heat transfer.

In addition, only one of the methods managed to get results in qualitative agreement with the rate of entropy production.
1.3.6. A method to determine stratification efficiency of thermal energy storage processes independently from storage heat losses (Haller et al. 2010)

This article is about developing a new method to calculate a stratification efficiency of thermal energy storages based on the second law of thermodynamics.

The effect of heat losses was studied both on theoretical and experimental point of view.

The experiments results have showed the effect of the bases for calculating this number; i.e. either the entropy number or the Exergy balances. This was not the case for the theoretical analysis as it makes no difference which of them is used.

If the measurement uncertainties were not adjusted in a way that the energy balance of the storage process is in agreement with the first law of thermodynamics then the result of using the Exergy balance is more trustable than those of using the entropy balances in experiments.

An evaluation of the stratification efficiencies was acquired from experimental results of charging, standby, and discharging processes provided crucial awareness into the different mixing manners of a storage tank that is charged and discharged directly, and a tank-in-tank system whose outer tank is charged and the inner tank is discharged later. The new method has a great potential for the assessment of the stratification efficiencies of thermal energy storages and storage components such as stratifying devices.

1.3.7. Measurement Equipment

1.3.7.1. Flow Meters (Doebelin, 2003)

Two types of flow meters were used in this project; Ultrasonic flow meters and turbine flow meters. Ultrasonic flow meters depend on their operation on the different reaction to pressure disturbances propagated in a flow. The reaction to these disturbances depends on the fluid type, temperature and velocity. Since flow rate could be calculated based on the fluid velocity, the reaction to the pressure disturbance has been used as the operating principle of the ‘Ultrasonic’ flow meters. Pressure waves (traveling at the speed of sound) are created at a ‘transmitter’ into or against the direction of the flow and the time for these waves to travel through the fluid and reach a ‘receiver’ is measured. Based on the fluid properties, the pressure wave will have a specific ‘acoustic’ speed. Equ.1 gives the transient time required for a pulse to travel from the transmitter to the receiver under zero flow velocity:

\[ t_0 = \frac{L}{c} \]  

Equation 3

Where:

- \( t_0 \): Transient time for the pulse to reach the receiver
- \( L \): Distance between transmitter and receiver
- \( c \): Acoustic velocity in fluid

For water, \( c \approx 1500 \text{ m/s} \) and if \( L = 0.1 \text{ m} \) then \( t_0 \approx 7 \times 10^{-5} \text{s} \)

And for a fluid moving at a velocity(\( v \)), the transient time will be:

\[ t = \frac{L}{c+v} = L \left( \frac{1}{c} - \frac{v}{c^2} + \frac{v^2}{c^3} - \cdots \right) \approx \frac{L}{c} \left( 1 - \frac{v}{c} \right) \]  

Equation 4

And if \( \Delta t \) is defined as \( (t_0 - t) \), then:

\[ \Delta t = \frac{Lv}{c^2} \]  

Equation 5
With the value of \((L)\) known for the flow meter used and \((c)\) is calculated under a range of fluid properties, the calculation of the fluid velocity and hence the flow rate is possible.

The other flow meter used in this project is of turbine flow meters type, which is considered a mechanical type flow meter. Its design is based on the drag effect caused by a fluid flow on a rotating object ‘Turbine wheel’ placed on the fluid path. The rotating speed of the turbine wheel, if designed properly, varies linearly with the flow velocity.

The rotational speed of the wheel could easily be measured with great accuracy using a magnetic proximity pickup to generate voltage pulses as the wheel rotate. Counting these pulses during a period of time can give the retinal speed of the wheel. Then using the relation between the two speeds will give the velocity of the fluid. The governing equation used to calculate the flow speed:

\[
\omega = \frac{v \tan \beta}{r}
\]

Equation 6

Where:
\(\omega\): Wheel rotating speed
\(\beta\): Angular offset
\(r\): Wheel radius

1.3.7.2. Radiation Sensors

The solar radiation sensors are either Thermal or PV based sensors. The one used in the system is a PV based sensor, shown in Fig.13, which means that the absorbed solar radiation will generate current in the mono crystalline cell. The output voltage of the device is measured to as scale of 10 volts to measure the solar radiation.

1.3.7.3. Temperature Sensors (Thermoelectric Temperature Sensors)

(Doebelin, 2003)

All the temperature sensors used in the experiments are of Thermocouples type. An electromotive force is generated when two wires of different materials are connected in a circuit with the two connection points (thermo junctions) are at different temperatures. The amount of the voltage generated depends on the materials type and their corresponding temperatures. This physical property has been developed to design temperature sensors; ‘Thermocouples’. In fact, there is an EMF generated in each material even if it is connected to anything and its amount depends on the temperature distribution and a material property known as the absolute Seebeck coefficient. The Seebeck is given by the relation:

\[
\sigma(T) = \frac{dE_\sigma}{dT}
\]

Equation 7

Then:

\[
E_\sigma(T) = \int \sigma(T)dT + C
\]

Equation 8

This could be derived to:

\[
E_\sigma = E_\sigma(T_1) - E_\sigma(T_2)
\]

Equation 9

The impurities within the material could cause the same effect and cause the same measurements errors. The accuracy of the thermocouples is extremely affected by the existence of these impurities.

There are many materials that proved to have the thermoelectric use to some extent, but a few of those are commonly used; such as Platinum/Rhodium, Chromel/Alumel,
Copper/Constantan and Iron/Constantan. Each one of these pairs has its range of application based on its properties.

As the thermoelectric reaction varies nonlinearly with the application temperature, hence the thermocouple sensitivity does too. This fact leads to different accuracy for the same thermocouple temperature sensor under different operation condition, i.e. temperature. Thus, each temperature range has its preferred thermocouple sensor pair to operate at its highest accuracy region. The highest sensitivity is for the Copper/Constantan pair and the lowest is for the Platinum/Rhodium and equals to $60 \mu V/\degree C$ at $350\degree C$ and $6 \mu V/\degree C$ at 0-100$\degree C$ respectively. The accuracy of Platinum/Rhodium thermocouples are the highest among all of them and equal to $\pm0.25 \%$ of reading and often used in the range of $(0 - 1500\degree C)$. Another important feature of this thermocouple is its chemical stability at high temperature in oxidizing environment.

1.4 Scope of Work

The work in this project was limited by the time available for a thesis project. The main result of this project is the lab instructions for the experiments to be used in the lab. Further improvement could be suggested by students/instructor; if the lab is to be approved.

The experiments on stratification in the storage tank are considered simple and further work is possible to achieve more elaboration in this task. Also, not all of the results obtained were verified with other similar experiments due to time restriction and the difficulty to find a similar work about solar combsystems lab. Also, the performance of the system in general was not studied due the same reason. An additional simulation part is strongly suggested where the students use one of the available software in the ESES computer lab to model the system and get some data about the parameter used to measure solar systems performance; such as solar fraction, annual savings, payback period and other common parameters.

The stratification analysis could be easier to understand and could be even more interesting for the students if they could simulate the system and find the difference in the total system performance for a fully mixed storage tank compared with stratified one.
2. Experimental Setup

The system used to carry out the mentioned experiment is shown in Fig. 9. All the connected sensors and meters needed to do the experiment are discussed in this chapter.

![Diagram of the system used](image)

**2.1. Temperature Sensors**

There are three types of temperature sensors used in the system, shown in Fig. 10. The first one is called sleeve sensor and is used to measure the temperature of the flow in pipes with direct contact between the sensor and the fluid. The sensor is installed in the system with the help of a ball valve designed in a way to have the sensor mounted into the valve body, see Fig. 11.

The outdoor sensor has a different design to offer protection to the sensing element against overheating from direct sun radiation exposure or rain by means of a plastic cover. The sensors used to measure the temperature distribution in the storage tank are physically different, i.e., smaller and have no protection cover, to be able to mount them in contact with the tank walls. Mounting the thermocouples into the tank would have given more accurate measurements due to the smaller time constant for the readings, but due to some practical difficulties this idea was not adopted.
There also another temperature sensors used by the PID controller to adjust the power supplied to the ‘collector’ heater. All the temperature sensors used in the system are of the type PT1000 except two the sensors connected to the solar loop controller, Table 3 shows their specifications.

Table 3 the used temperature sensors specifications and usage in the system, (Helmke, 2009)

<table>
<thead>
<tr>
<th>Name</th>
<th>Manufacturer</th>
<th>Type</th>
<th>Temp. range</th>
<th>Accuracy</th>
<th>Application</th>
<th>Usage in the Sys.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTF Pt1000</td>
<td>S+S Regeltechnik</td>
<td>Sleeve sensor, 2 wires, passive output</td>
<td>-50 to +150 °C</td>
<td>Class B; ±0.3K (0°C)</td>
<td>Liquid and gaseous media</td>
<td>Hot and cold water/glycol in all circuits- Indoor temp.</td>
</tr>
<tr>
<td>ATF Pt1000</td>
<td>S+S Regeltechnik</td>
<td>2 wires, passive output</td>
<td>-50 to +90 °C</td>
<td>Class B; ±0.3K (0°C)</td>
<td>Ambient air</td>
<td>Outdoor Temperature</td>
</tr>
<tr>
<td>PCA/L Style Pt1000</td>
<td>JUMBO Instruments CO. Ltd.</td>
<td>Platinum-chip with connecting wires</td>
<td>-70 to +600 °C</td>
<td>Class B; ±0.3K (0°C)</td>
<td>Dry measurements</td>
<td>Storage tank Strat. Temp.</td>
</tr>
</tbody>
</table>

Figure 10 the used sensors in the system, to the left the stratification sensors (JUMO Instruments, 2011), to the right the sleeve sensor also used as an indoor temperature sensor, and in the middle outdoor temperature sensors (Helmke, 2009)

Figure 11 the ball valve used to mount the Sleeve sensors, (Helmke, 2009)

2.1.1. Temperature Sensors in the Collector Circuit
There are 4 sensors in the collector circuit. Two of them are connected to the Data logger and the other two are connected to the controller. Each pair measures the temperature of the flow to and from the collector and they are all of PT1000 type. The pair connected to
the data logger is in direct contact with the fluid in the collector loop and their readings are recorded simultaneously. The two sensors connected to the collector controller are used to control the flow to collector. At each temperature difference there is a pre-adjusted suitable flow rate. The controller adjust the pump speed, hence the flow rate based on the difference between these two sensors reading to get the maximum useful energy.

2.1.2. Temperature Sensors in the Storage Tank
There are 8 temperature sensors in the tank. Six of them are connected to the data logger and two are connected to the controller. The six sensors connected to the data logger are spread over the tank height in order to show the temperature profile in the storage tank, Fig.2, while the other two sensors are mounted on the top and bottom of the tank. These two sensors are used together with the two sensors in the collector loop by controller to operate the solar loop pump in way that maximize the useful gain from the collector.

2.1.3. Temperature Sensors in the Load Circuits
There are two temperature sensors in the boiler side of the heat exchanger which supplies the space heating loop to measure the temperature of the water going to and coming back from the heat exchanger. There are also two temperature sensors in the DHW loop to measure the temperature of the cold water supplied to the DHW internal heat exchanger and the temperature of the hot water out.

2.1.4. Indoor and Outdoor Temperature Sensors
The indoor temperature sensor type is PT1000 and so is the outdoor one but with a cover to protect the sensor, Fig.12 shows the position of the outdoor sensors.

Figure 12 the solar collector and the position of the irradiance and outdoor temperature sensors

2.1. Irradiation Sensor
This sensor is mounted closed to the collector and with the same tilt to measure the solar radiation incident on the solar collector. The used sensor type is “Spektron300”. A picture of the device and its specification is shown in Fig.13 and its position is shown in Fig.12.
2.2. Flow Meters

There are three flow meters in the system and. All of them are connected to the data logger to measure and record the flow rates in the collector, DHW and SH loops. The flow meter measuring the flow rate of the glycol-water mixture in the collector loop is a mechanical-based one and is connected to the cold side of the circuit, see Fig.14.

The other two flow meters use the ultrasonic technology to measure the flow rate and higher accuracy, see Fig.14. The one measuring the flow rate in the DHW is mounted in the cold water supply to DHW heat exchanger and the other one measures the flow rate of the water in the SH circuit and is mounted in the return line from the heat exchanger. The mechanical one and has a relatively lower resolution and the only reason that it has been used here that the ultra-sonic flow meter cannot be used with the glycol mixture.

The mechanical flow meter has a resolution of about 1pulse/liter and so it can only show the flow rates after ‘one’ liter of fluid has passed through it. The ultrasonic flow meter has a relatively high accuracy but some limitation regarding the fluid type. The resolution of the used flow meter is 0.1 liter per pulse which is a high value compared with the accuracy of other flow meters types; Table 4 shows the specification for the used flow meters.

<table>
<thead>
<tr>
<th>SPEKTRON 300</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
</tr>
<tr>
<td><strong>Irradiation range</strong></td>
</tr>
<tr>
<td><strong>Electrical output</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Annual mean error</strong></td>
</tr>
</tbody>
</table>

Figure 13 the used irradiance sensor and its specification, (Tritec Energy 2011)

Figure 14 the used flow meters, to the left the mechanical meter and to the right the Ultra-sonic flow meter, (Hydrometer 2011)
Table 4 the used flow meters specifications, (Helmke, 2009)

<table>
<thead>
<tr>
<th>Name</th>
<th>Manufacturer</th>
<th>Type</th>
<th>Resolution pulse/litre</th>
<th>Flow range m³/h</th>
<th>Nominal flow m³/h</th>
<th>Temperature range °C</th>
<th>Accuracy</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharky FS, Model 474</td>
<td>Hydrometer</td>
<td>ultrasonic</td>
<td>0.1</td>
<td>0.03...2</td>
<td>1.5</td>
<td>5...120</td>
<td>class 2 (EN 1434)</td>
<td>water</td>
</tr>
<tr>
<td>E-TH60A/444</td>
<td>Hydrometer</td>
<td>mechanical</td>
<td>1</td>
<td>0.03...2</td>
<td>1.5</td>
<td>5...120</td>
<td>class 2 (EN 1434)</td>
<td>fluids (water, glycol etc.)</td>
</tr>
</tbody>
</table>

2.3. Electrical Energy Meters

Using electricity meters in Solar systems is common and crucial factor of analysis. Without measuring the used electricity and comparing it to other conventional system consumption of energy, the savings of the solar systems in a matter of money and CO2 emissions reduction is impossible. The electricity is used in solar systems to run the backup heaters, pump and solar loop controllers. There are two electrical meters used in the system, Fig.15 shows a picture of the used meters. A single-phase meter is used to measure the electricity consumption of the SH pumps, solar loop pump and the controller. The other is a Three-phase meter and is connected to the auxiliary heater in the storage tank.

Figure 15 The electricity meters, to the right the Single-Phase meter, to the left the three-Phase meter

2.4. Data Logger

The used data logger type is ‘Smartbox’ from Ennovatis. It is connected to the system and can be accessed by a computer using a network data cable and the data logger software installed in the computer. There are two versions of the software available to communicate with the software, Smartbox Manager and Ennovatis. The Smartbox manager, see Fig.16, which is free version, offers an easy way to read and copy the data but with limited options and possibilities. The Ennovatis main software, see Fig.17, offers much more possibilities and tools to be used by the user in the matter of post processing the data with the already included graphical tools.

Unfortunately, the main software is available only in German and not possible to acquire an English version. The solution for this issue was to use an excel sheet to extract the data directly from the software. In order to use the excel sheet to extract the data from the logger, only the date is needed, see Fig.18, but not the date of the actual experiment;
instead, the date of the day after. Also, the main software has to be running for the excel sheet to be used. Data is read by the data logger each 15 second then the average is taken, either for each 5 minutes for the stratification sensors and for every minute for the other sensors. How often the average is taken could be modified by the user and these two values were used. Data recorded by the data logger are actualized by the software, only when it is running, every half an hour and this time could be decreased if a faster computer is acquired.

Figure 16 Smartbox Manager Main screen (Ennovatis, 2011)

Figure 17 Innovatis main screen and the graphic tool included in the software (Ennovatis, 2011)
2.5. Solar Loop Controller

The solar loop controller is used to control the flow rate of the glycol mixture based on the available useful energy. The difference in temperature between a point just after and before the collector is measured. This difference is used to determine the suitable pump speed/flow rate to get the highest useful gain out of the solar collector.

2.6. PID Controller

The PID controller is used during the experiments to operate the ‘collector’ heater, see Fig. 19. This is done by controlling the temperature at the outlet of the collector heater. The input of the controller is the set temperature required by the user and the actual temperature at the outlet of the heater and the outlet is the voltage to the ‘collector’ heater.
3. Experiments Conducted

Several Experiments sequences have been done in order to get better understanding of the possibilities of the system used. The limitations presented by the fact that these experiments would be used as an ESES lab are then applied to choose between these possibilities. In addition, several methods of organizing these experimental sequences in order to fully and conveniently use the time of the lab. In general these experiments sequences could be divided into two main groups; Experiments sequences, one that need to be conducted under good weather condition; the collector characteristics experiment, and other do not require these condition; the solar collector simulation experiment.

3.1. Collector Characteristics and Load Discharge Experiment

The experiments in this section will be carried out using the system in the regular way, i.e. using the solar collector to supply the energy to the collector loop. The results of this section will be then the reference for using the system is this way during the lab. Several test sequences have been done in order to develop the experiments mentioned here. This experiment will be adopted as the main experiment under good weather conditions; i.e. should be carried out on a sunny day.

3.1.1. System Setup

The system will run without the use of the electrical heater in the solar collector loop. Quick check up for the flow meters and the data logger and the whole system in general is required before the experiment starts to make sure that the needed parameters are measured and recorded and that the system is working properly.

3.1.2. Conditions Required

The weather condition is the main requirement for this experiment. Also, the tank should be as cold as possible in the beginning of the second step, i.e. the charging process.

3.1.3. Test Procedure

The test starts, preferably, in the night before the day of the experience, by using SH and DHW loads to discharge the tank off energy. The SH pumps could be kept working during the night if it is cold enough outside. This step will reduce the time needed in the day of the lab. Next day the SH load pumps will be closed and the process of charging the storage will then start. This step takes about 4-6 hours based on the weather condition and the average temperature to be reached in the tank. The electrical heater in the tank could be used in this step to heat up the storage tank. After the storage is charged discharging process starts by DHW load and then SH load. The energy in the tank is roughly estimated and a fraction of that is extracted from the tank by both means of direct and indirect processes. After the discharging process ends, the temperature in the tank is mathematically calculated using the fully mixed tank model and compared with the measured average temperature in the storage.

3.1.4. Data Analysis

The result of the experiment will be analyzed using the following procedure:

1- Characteristics curve of the collector
2- Calculation results of the Energy extraction part
3- The temperature profile in the storage tank in the beginning and end of each part of the experiment, and in particular the effect of the energy extraction directly (through the SH load) and indirectly (through the DHW load) on the stratification in the storage tank
4- Comparison between the results obtained and the theoretical curves and values will be done to verify the results of the experiments

3.2. Collector Simulation and Load Discharge Experiment

In this section the experiments will be performed assuming that there is not enough solar radiation to heat up the storage. Instead, the heat will be supplied to the system by means of an electrical heater in the collector loop to simulate the outcome of the solar collector under good weather conditions, i.e., on a sunny day. This is based on the assumption that the collector will be working at a constant temperature during each hour of charging period which is not the actual case.

A comparison between the two cases results (with and without the use of the ‘Collector’ heater) will also be done to analyze the differences between the system performances in the two cases.

3.2.1. System Setup

There are a few changes must be done in order to use the system in this experiment. The solar loop pump will need to be stopped first then the collector bypass valve could be closed. This pump is normally set to ‘Auto’ and the flow in the collector loop is determined by the temperature difference available between the collector and the storage tank. After that the valve to the ‘collector’ heater is opened then the pump is started again but on forced or manual mood using the function ‘on’ in the pump operation options. The flow rate in this mode is around 5.8 L/min. This last step will guarantee that the pump will keep running even if there is no energy to be absorbed in the collector. The collector heater will be connected to the electricity supply but not turned on until the temperature to be set by the PID controller is calculated. The PID controller is already calibrated at 60 °C using the auto tuning option and will keep the temperature in the ‘collector’ heater loop constant at the set value.

3.2.2. Conditions Required

The main difference between this experiment and the first one is no specific weather requirement. The experiment could be carried out at any time using the electrical heater in the collector loop.

3.2.3. Test Procedure

After applying the mentioned system setup, the experiment starts with the same conditioning procedure used in the first experiment. During this step, which will take some time (between 1-2 hours, based on the average temperature in the storage tank at the beginning) some calculation will be carried out in order to determine the set temperatures to be applied using the PID controller every hour. Based on the expected/decided average temperature in the tank at the end of the conditioning step, the following calculation will be done:

1- Insolation is assumed to be 1000 W/m² on the collector as it common value in sunny days in summer day in Sweden. Then using Equ.10 the solar radiation incident on the collector could be estimated. Table5 shows the result of the calculations.

\[ G_T = I \ast \cos \theta \]  
\( Equation \ 10 \)

Where:
\( G_T \) : Solar Irradiance on a tilted plane
\( I \) : Insolation
\( \theta \) : Incident angle
2- To simplify calculation of the solar irradiance, the sun will be assumed to be perpendicular on the collector, which is at slope of 45° and 0° solar azimuth angle. This assumption represents a specific state during the year and will result in simple incident angle calculations; as it will just follow the hour angle if the time is assumed to be solar time.

Table 5 The weather profile to be used in the experiment

<table>
<thead>
<tr>
<th>Exp. Time</th>
<th>( \theta ) [°]</th>
<th>( \cos \theta )</th>
<th>( K_{ta} )</th>
<th>( G_T ) [W]</th>
<th>Ambient Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>9:00</td>
<td>45</td>
<td>0.71</td>
<td>0.707</td>
<td>707</td>
<td>16</td>
</tr>
<tr>
<td>10:00</td>
<td>30</td>
<td>0.87</td>
<td>0.989</td>
<td>866</td>
<td>18</td>
</tr>
<tr>
<td>11:00</td>
<td>15</td>
<td>0.97</td>
<td>0.997</td>
<td>966</td>
<td>21</td>
</tr>
<tr>
<td>12:00</td>
<td>0</td>
<td>1.00</td>
<td>1</td>
<td>1000</td>
<td>23</td>
</tr>
<tr>
<td>13:00</td>
<td>15</td>
<td>0.97</td>
<td>0.997</td>
<td>966</td>
<td>24</td>
</tr>
<tr>
<td>14:00</td>
<td>30</td>
<td>0.87</td>
<td>0.989</td>
<td>866</td>
<td>24</td>
</tr>
<tr>
<td>15:00</td>
<td>45</td>
<td>0.71</td>
<td>0.707</td>
<td>707</td>
<td>24</td>
</tr>
<tr>
<td>16:00</td>
<td>60</td>
<td>0.50</td>
<td>0.928</td>
<td>500</td>
<td>24</td>
</tr>
<tr>
<td>17:00</td>
<td>75</td>
<td>0.26</td>
<td>0.793</td>
<td>259</td>
<td>25</td>
</tr>
</tbody>
</table>

3- The ambient temperature profile could be assumed based on data from a sunny day which could be provided later in the lab instruction; Table 5 lists the ambient temperature profile to be used through the experiment.

4- The average temperature in the storage tank after the conditioning procedure will be assumed to be 15°C. This value will then be used as the temperature of the flow to the collector in the first hour. The next hour temperature will be calculated using the fully mixed storage equation and the \((UA)\) value of the storage tank will be assumed to be 10 W/°C.

5- The difference between the average temperature of the collector plate and the inlet temperature to the collector will be assumed constant and equal to 7°C. Then the value of \((\Delta T)/G_T\) will be calculated and the efficiency of the collector under the assumed conditions could be obtained based on the collector characteristic.

6- Efficiency of the collector can be calculated using Equ. 11 and Equ. 12.

\[
\zeta_C = \zeta_0 * K_{ta} = -a_1 \left( \frac{\Delta T}{G_T} \right) - a_2 \left( \frac{\Delta T}{G_T} \right)^2
\]

\textit{Equation 11}

Where:

- \(\zeta_C\): Collector efficiency
- \(\zeta_0\): Optical efficiency or the zero loss efficiency
\( \Delta T \): Temperature difference between collector plate and ambient air, collector plate temperature to be taken here as the average temperature for the flow in and out

\( a_1, a_2 \): Collector constants

\( K_{ta} \) =: Incident Angle Modifier

\[
K_{ta}(\theta_b) = \frac{(\tau \alpha)_b}{(\tau \alpha)_n} = 1 - b_0 \times \left( \frac{1}{\cos \theta} - 1 \right) \quad Equation \ 12
\]

Where:

\( \theta_b \): Incident angle of beam radiation

\( (\tau \alpha)_b \): Transmittance-Absorbance product under beam incident

\( (\tau \alpha)_n \): Transmittance-Absorbance under normal incident

\( b_0 \): Incident angle modifier coefficient

7- The useful energy rate of the collector could be calculated using the efficiency and the irradiance during each hour. The same value will then be supplied by the ‘collector’ heater using the maximum flow rate. Knowing the amount of power to be supplied and the flow rate to be used; the set temperature for the PID controller could then be calculated for each hour.

8- After the storage tank is heated up (the average temperature is over 50°C) the DHW and SH discharging test will be conducted.

3.2.4. Data analysis

1- The calculated average temperature in the storage tank during the experiment will be compared with the temperature profile extracted from the logger.

2- The energy extracted through DHW and SH is verified with the real data from the logger to see how much energy was really discharged during the two tests.

3- The temperature profile in the storage tank is compared with the one generated in the first experiment; where the collector was used to heat the storage tank instead and so is the effect of the load discharge.
4. Calculation and Results

4.1. Collector Characteristics and Load discharge Experiment Results

The characteristics curve of the collector could be found out of the data recorded. The manufacturer data was used also to find the ideal curve, see Fig.20.

![Figure 20 Certified and measured characteristic curves of the used solar collector](image)

4.1.1. Load Discharge

The energy in the tank is roughly assumed to be equal to the energy supplied by the collector. The tank is assumed to be fully mixed at the point after it has been filled with cold water and after it has been charged.

Assuming:
- $t_0$ = the average temperature in storage tank at the beginning of the experiment
- $t_f$ = the average temperature of the storage tank at the end of the charging stage
- $V$ = Volume of the water in the storage tank
- $\rho$ = Water density
- $E_S$ = the energy supplied to the tank during the charging step

Then $E_S$ could be calculated using the equation:

$$E_S = \rho V \int_0^t [t_f - t_0] dt$$

*Equation 13*
\[ E_S = 0.5 \times 998 \times 4182 \times (50.5 - 20.3) = 63 \text{ MJ} \]

The test implies extracting roughly the same amount of energy, measured as a fraction of the energy in the storage tank through both the DHW and SH heat exchangers. Assuming that 10% of the heat energy supplied to the tank will be extracted through each heat exchanger:

\[ 0.1 \times 63 \approx 6 \text{ MJ} \]

### 4.1.1.1. DHW Load Calculation

\[ E_{\text{DHW}} = V \times \rho \times C_p \times \Delta T \quad \text{Equation 14} \]

Or:

\[ E_{\text{DHW}} = [\dot{V} \times t] \times \rho \times C_p \times \Delta T \quad \text{Equation 15} \]

Assuming the following:

\[ \Delta T \approx 40 \degree C (T_{\text{Hot}} = 50, T_{\text{Cold}} = 10) \]

\[ V = \frac{6 \times 10^6}{998 \times 4182 \times 40} = 36 \text{l} \]

And assuming the discharge process will be done at flow rate of 1.5 l/min:

\[ t = \frac{36}{1.5} = 24 \text{ min} \]

### 4.1.1.2. SH Load Calculation

The pump offers three fixed speed which result in three different flow rates. Assuming the temperature lift in the heat exchanger will be around 10\degree C and the flow rate is set at 0.314 m\(^3\)/h = 5.2 l/min; then the test will take approximately 30 minutes. So:

\[ t = \frac{6 \times 6 \times 3600}{0.314 \times 998 \times 4182 \times 10} \approx 30 \text{ min} \]

So if the temperature difference could be maintained at 10 \degree C the time need will be 30 minutes. Maintaining the temperature difference will be difficult because of the temperature drop in the storage tank and the increase in the temperature of return water from the SH radiator as time goes on.

### 4.1.2. Storage Tank Analysis

The storage tank will be assumed to be fully mixed and if the [UA] value of the tank is assumed to be 10 W/\degree C, then the temperature in the tank could be calculated using Eqn.16

\[ T_{S+} = T_S + \frac{\Delta t}{m \times C_p} \times (Q_u - L_s - UA \times [T_s - T_a]) \quad \text{Equation 16} \]

Where:

- \( T_s \): Current storage tank temperature [\degree C]
- \( T_{s+} \): Expected temperature of the tank after one hour [\degree C]
- \( T_a \): Room temperature [\degree C]
- \( \Delta t \): The time period used, equals to 1 hour [hour]
- \( m \) & \( C_p \): Mass of the water in the tank and the heat capacity [kg] & [J/kg\degree C]
- \( Q_u \): Heat energy supplied by the solar collector during the time period [MJ]
- \( L_s \): Energy discharged from the storage tank during the time period
The result of the calculations is shown in both Fig. 21 and Table 6.

Table 6 Calculations result for the temperature in the storage tank

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>28</td>
<td>10</td>
<td>24.4</td>
<td>7.4</td>
<td>0</td>
<td>31.5</td>
<td>30.2</td>
</tr>
<tr>
<td>1</td>
<td>31.5</td>
<td>10</td>
<td>24.9</td>
<td>9.8</td>
<td>0</td>
<td>36.1</td>
<td>34.4</td>
</tr>
<tr>
<td>2</td>
<td>36.1</td>
<td>10</td>
<td>25.4</td>
<td>11.3</td>
<td>0</td>
<td>41.3</td>
<td>38.9</td>
</tr>
<tr>
<td>3</td>
<td>41.3</td>
<td>10</td>
<td>25.9</td>
<td>11.6</td>
<td>0</td>
<td>46.6</td>
<td>43.8</td>
</tr>
<tr>
<td>4</td>
<td>46.6</td>
<td>10</td>
<td>26.2</td>
<td>11.5</td>
<td>0</td>
<td>51.7</td>
<td>48.3</td>
</tr>
<tr>
<td>5</td>
<td>51.7</td>
<td>10</td>
<td>26.5</td>
<td>9.5</td>
<td>0</td>
<td>55.8</td>
<td>51.6</td>
</tr>
<tr>
<td>6</td>
<td>55.8</td>
<td>10</td>
<td>25.8</td>
<td>3.3</td>
<td>6.3</td>
<td>53.9</td>
<td>50.1</td>
</tr>
<tr>
<td>7</td>
<td>53.9</td>
<td>10</td>
<td>26.7</td>
<td>0</td>
<td>6.6</td>
<td>50.3</td>
<td>47</td>
</tr>
</tbody>
</table>

Figure 21 Measured and calculated average storage tank temperature
4.1.3. Stratification Analysis

The tank temperature profile during the experiment is shown in Fig. 22. The effect of the energy extraction through the SH and DHW can be seen in this figure and more clearly in Fig. 23 where it shows only the load discharge part of the experiment. The DHW has its effect on the lower part of the tank while the SH load extraction has result in lowering the temperature of the middle part of the storage tank more than what occurred during DHW test. That is mainly due to the position of the mixing valve in the SH loop. Fig. 24 shows the temperature profile in the tank versus the tank height after charging and discharging.

Figure 22 Temperature profile in the storage tank during the experiment

Figure 23 Temperature profile in the storage tank during energy extraction
4.2. Collector Simulation and Load Discharge Experiment

4.2.1. Storage Tank Analysis

The temperature to be set using the PID controller was determined based on the calculation of the temperature in the tank at the beginning of each hour. In order to find this temperature; the tank was assumed to be fully mixed and the equation for fully mixed storage tanks was used. Fig.25 shows the difference between the measured and calculated average temperature in the storage tank while Fig.26 shows the measured and calculated useful energy supplied to the storage.
4.2.2. Stratification Analysis

The temperature distribution in the tank is shown in Fig. 27 and the effect of the energy discharge is easy to notice in Fig. 28.
Figure 28 Temperature profile in the storage tank during the DHW and SH tests

The temperature variations across the tank height was also generated in this experiment to reflect the status of the tank at three main points in time; before starting the load test and after each test ends. These three statuses are shown in Fig. 29.

Figure 29 Temperature variations across the storage tank height before and after load tests
5. Discussion and Conclusions

5.1. Collector Characteristics and Energy Discharge Experiment

5.1.1. Collector Characteristic Curve
The collector characteristic curve, see Fig. 20, shows some differences between the certified characteristic and actual curves acquired from the data during the experiment. These differences could be referred to the aging of the collector and the measurement errors. Beside the errors in measuring devices, the assumption that the useful energy from collector is calculated using the temperature values measured at the storage tank and not directly in and out of the collector. This means the value of the heat losses from the pipes in the solar loop are considered as a loss from the collector and the actual useful energy of the collector is higher than the calculated value.

There were a few points far away from the ideal curve. These points were eliminated from the calculated curve because they do not present the actual state of the collector but just instantaneous values occurred due to the high frequency of measurement of some of the sensors, such as the Irradiance sensor. Any change in the irradiance will result in a big change in the instantaneous collector efficiency due to effect of time constant of the collector. This leads to the reason of listing the weather condition as a requirement to do the experiment and how it would be quite helpful if the weather is sunny and stable throughout the experiment.

This test could be used in the lab to help the students understand the main parameters determining the collector efficiency. The solar thermal course cover the theoretical aspects of the part and further calculation and test on the collector could help to better understand the course. The main issue will be the weather conditions required to carry out this test. So, instead of actually doing the test on the collector, the students could be given the data of an already done test. This could help saving the time so other test could be performed and to compensate for the less work to be done; the students could be asked to answer some questions about the collector and the other parts of the system and their functions, such as the solar loop and the heat exchangers used and their impact on the collector and system performance.

5.1.2. Load Discharge Calculations
To exactly get the right amount of energy out of the storage tank is difficult, but if the tank is really hot (average temperature 50+) the results will be acceptable.

This test is a good revision for the thermal background and type of calculations needed to follow the solar thermal course. Also, the effect of the load discharge on the storage tank could be used to discuss the stratification and its importance in solar systems. In this test the students will be asked to actually calculate and extract the heat from the storage tank, which will introduce them to interact with some common devices in solar systems, such as temperature sensors, flow meters and heat exchangers.

5.1.3. Storage Tank Analysis
Equation 4.1 results were compared to the actual measured average temperature in the storage tank. The result of this comparison showed a good correlation between the two values. This could be due to errors in the sensors which are just stacked to the tank walls and to the accuracy of the calculation. The equation used is for fully mixed tanks, and it is not the case in this storage tank. The measured values are not so precise for sure to be real because of the mathematical average used to find the ‘actual’ measured average temperature of the tank is not completely correct. The sensors are not distributed at equal spaces between them across the tank length and instead are mounted at the top and the
bottom of the storage tank. In general it is fair to say that the results of the calculation showed some kind of consistency with measured values and the difference was about 2-6 degrees.

How to create and maintain temperature stratification in storage tanks is of a great value in solar thermal systems. During the solar thermal course students will be introduced to stratification and this test could be used to encourage the students to search about and discuss it.

5.1.4. Stratification Analysis and the Effect of the Load Discharges

As can be seen in Fig.22, the tank is not a fully mixed and there is a degree of stratification. The first three lines from the top (Ts6, Ts5 and Ts6) represent the temperature profile in the top third of the storage tank and the other three curves represent the tank bottom third with no data for the middle part of the storage tank due some technical difficulties. The difference in the temperature between the top three sensors is less than what is there between the other three. Based on this result we can say that the storage tank top is almost at the same temperature and can be treated as a fully mixed. It is not the same for the bottom of the storage tank where the differences are bigger and easily noticeable. This different pattern in the temperature profile could be the result of the existence of the internal heat exchanger for the collector loop i.e., the present of the collector heat exchanger has created and maintained a better stratification level. Also, as heat is supplied from the solar heat exchanger to the tank, the hot water will move up and heat the top of the tank by convection which increases the mixing process and rapidly disturb the stratification there.

Fig.23 and Fig.28 perfectly reflects the effect of the load discharge on the temperature distribution in the storage tank. The DHW load test has affected the reading of the lower three sensors (bottom of the tank). Although the upper part of the heat exchanger is going through the top of the storage tank; the temperature profile there was not disturbed by the energy discharge at all. This is mainly due to the amount of energy extracted, i.e., the storage tank was hot enough to heat up the cold water pumped through the first stage of the DHW heat exchanger. In another words, the average temperature of the two DHW heat exchanger stages were close and no further heating was possible at this low temperature difference with the used flow rate. The bottom of the storage tank was obviously the most part to be affected by the energy extraction, mainly due to effect of the cold water at the heat exchanger inlet. As a conclusion, we can say that the temperature stratification in the storage tank was mannerly affected by the load discharge.

In between the DHW and SH load tests, there was a gap of time. During this gap of time the temperature profile kept changing even though there was no energy added to or discharged from the storage tank. This is mainly due to late respond from the stratification sensors, as they are not in contact with the water in the tank and instead just plugged to be in contact with the tank walls. The time needed for the tank walls to drop to the same temperature as the water inside or the ‘time constant’ was accepted as a measurement error and to reduce its impact on the results the time between the two load discharges was prolonged. The figure also shows a reduction in the temperature of water at Ts4 sensor height due to the heat transfer and mixing with the colder layers. This is visible on the lower layer too but less in the bottom.

During the SH load test, the temperature of the tank bottom was barely affected. Unfortunately there are no more temperature sensors in the middle of the tank, but we can roughly say, based on the reading of S3 and S4, that the effect was mainly on the middle of the storage tank. The SH load depends on the mixing valve on the tank side of the SH heat exchanger. This mixing valve mix the return line from the SH heat exchanger with two lines from the storage tank; one from the top of the tank and the other from the middle.
This mixing valve determines the temperature of the output roughly by deciding how to mix these three lines. It was set at maximum during the experience. Fig. 24 shows the temperature profile across the storage tank height. The reading form the six sensors at the end of the charging, DHW and SH test were used in the graph against their respective height. This figure focuses more on the position on the storage tank and what have occurred after each test. It is though single point figure and just show the storage tank state directly after each test ends and does not reflect correctly the phase of ‘Mixing’ after each test.

Another thing to note in Fig. 23 and Fig. 24 is the difference between the direct energy discharge and the indirect discharge through the SH and DHW load respectively.

5.2. Collector Simulation and Load Discharge Experiment

5.2.1. Storage Tank Analysis
The tank average temperature calculated and used during the experiment was slightly higher than the measured temperature. One more point added to the reasons mentioned in the first experiment; where the solar collector was used, is the fact that this calculated temperature was assumed to be the inlet temperature in the next hour in the experiment. This assumption has increased the effect of the error.

5.2.2. Stratification Analysis
The temperature profile in the storage tank was different in this experiment than the first one. The tank now is closer to the fully mixed model. This could be referred to fixed conditions applied for each hour, which was not the case for the first experiment. With the more stable heat source supplying the storage tank; the mixing process between the water layers occurred more effectively and that helped the tank to reach to almost fully mixed state.

In the DHW load discharge part, two different flow rates were used in each test. In the experiment where the collector was used; a lower flow rate was adopted, 1.5 l/min, while during the collector simulation experiment a higher flow rate was adopted, 9 l/min. Keeping in mind that the same amount of energy, relatively to the total amount heat energy in the storage tank, was extracted in each case; the stratification in the storage tank was affected in a different way each time. In the first experiment, see Fig. 23, only the very bottom of the storage tank was affected by the hot water discharge while in the other experiment, when using a much higher flow rate, the whole lower half of the tank was disturbed by the hot water discharged, see Fig. 28.

5.3. General Comparison of Results of the Two Experiments
The temperature profile in the storage tank during the two experiments, see Fig. 25 and Fig. 27, were almost similar, which indicates the possibility of using the ‘collector’ heater to simulate the effect of the solar collector during a sunny day. This result was obtained using a rough estimation for the weather profile with one hour time step and further improvements are possible. One thing to mention is the stratification level in the storage tank after each test; in the case when the solar collector was used to heat the storage the tank was more stratified. At the end of the charge stage, the differences in the temperature between the bottom and the top of the tank were 14°C and 10°C for the case of normal system and simulation experiments respectively. This conclusion is based on the assumption that the weather profile assumed in the case of the collector simulation experiment was similar to the weather in the first experiment. Also, the temperature profile in the tank looks closer to linear distribution in the case of the use of the ‘collector’ heater than when the collector was used. The cause for this is probably the hourly based weather profile applied by the heater.
6. Appendices

6.1. Lab-guide

• MÖ3015 SOLAR THERMAL

• Solar CombiSystem Lab

• Contents of lab work

  ➢ Drawing of system schematic
  ➢ Description of components in the system
  ➢ Calculation of performance characteristics
  ➢ Collector Simulation experiment and energy discharge test
  ➢ Evaluation and discussion of results

• Aims

  The aims of this lab work are to:
  ➢ Get basic knowledge about the different parts in solar combisystems, their use and the theory and equations governing their operation and performance.
  ➢ Learn, practice and make some tests on the system to better understand the physics related with solar combisystems and the weight of the factors affecting their performance.

• Introduction

  This lab was designed to be carried out on both; sunny and cloudy day, thought the first part, concerning the collector characteristics results is highly affected by the weather condition.

![Diagram of solar combisystem](image)

*Figure 30 Standard Swedish solar combisystem (Vela Solaris, 2011)*

The solar combisystem that will be used in this lab consist of 5m² solar collectors with selective coating and anti-reflective double glass cover. The collector circuit supplies a 500l storage tank through an internal heat exchanger. Additional two heat exchangers are used to supply the hot water while the space heating loads is connected directly to the store via
a four way-valve, is simulated with two three-valves in series). Space heating load is simulated by several radiators in an outdoor room. The solar and the DHW loops use an internal heat exchanger while the SH loop uses an external one. Glycol mixture is used in the collector loop to avoid frost problems while water is used in the storage tank and SH loop. So far, this mentioned system is considered a ‘Normal’ Swedish Solar CombiSystem (SCS), see Fig. 30, but in order for the system to be used to carry out some experiments during autumn/winter conditions or cloudy days, which is quite common in Sweden, another heater (beside the axillary heater in the storage tank) has to be used in the solar loop to simulate the effect of the solar collector. Also, additional temperature and radiation sensors and flow meters had to be added to the system to do some extra measurements needed in the lab.

- **Theoretical Background**

The efficiency of a solar collector drops down as the temperature difference between the collector and the ambient increases, due to the increase in the heat losses. The efficiency of the collector determines how much of the solar radiation can be transformed into useful gain. If a solar collector is heating up a storage tank with no loads, the efficiency of it will drop as the storage temperature increases. Usually, at the beginning of the test the glycol mixture flowing through the collector is relatively cold causing the collector to work under low temperature, thus the collector efficiency will be at its maximum, i.e. zero loss efficiency. Vice versa, and as time goes on, the storage gets heated up and the temperature of the fluid in collector increases so the efficiency decreases. Fig. 31 shows the certified collector characteristic curve and the measured one. The measured data had to be refined to get rid of the wrong instantaneous readings. This was done using Microsoft excel sort tool to arrange the data in ascending order. Then an equation was also used to omit any measurement point with a value that increases or decreases more than 10% than the previous measurement. The result was found to be in consistent with the certified curve.

![Certified and measured characteristic curves of the used solar collector](image)

**Figure 31** Certified and measured characteristic curves of the used solar collector

The storage tank is considered as the most important part of the solar system, due to its major impact on the overall performance of the system even more than the collector (Bales et al., 2010). Water storages are an ideal option for many solar systems (Duffie &
Beckman, 2006). With the whole storage temperature below the boiling temperature of water at the designed pressure, some kind of separation happens often in the water based on the temperature. The hottest layers which have the lowest density tend to move to the top of the storage tank according to the laws of buoyancy and vice versa. This hot water on the top of the tank can be used to supply loads at higher temperatures (such as DHW) and the coldest water on the bottom of the storage tank will be circulated through the solar collector which would theoretically increase the thermal efficiency of the collector. While the water is moving to the top of the storage tank, it will mix with the lower temperature layers and cool down. This drop in temperature due to the mixing between the layers is not desirable in storage tanks due to its effect on the ‘Exergy’. The process of reducing this mixing in storage tanks and enhancing the natural process of stratification is done with either active or passive methods. Stratification in storage tanks mainly depends on how the heat is added to or removed from the storage tank.

• Questions
  1- Follow the three loop in the systems (Solar, SH, DHW) and look for differences between this system and a standard one. Create a drawing for the whole system showing the storage tank and all the loops and all the measuring and recording equipment connected to the system. Explain each part usage in either a ‘normal’ combisystem or in this particular system if it is not common part in solar combisystems.
  2- How could the performance of this system get improved?
  3- What are the advantages and disadvantages of the use of internal and external heat exchangers in solar systems?

• Collector Characteristic Experiment
  This experiment will need the storage tank to be cooled down first. This will be done in advance by the lab assistant using the SH and DHW loads to discharge the energy from the tank. After the tank is cooled down, i.e. its average temperature is below $20 \, ^\circ\text{C}$, you can start the experiment by turning on the collector pump. This will be done by the lab instructor. Make sure that there is no load discharged from the system during the experiment. You should check the cold water supply to tank valve and the SH pumps status, they should both be closed. At the end of the experiment, i.e. when the tank is heated up to an average temperature of around $50 \, ^\circ\text{C}$, the instructor will extract the data from the data logger and it will be available on fronter. The data will include the readings of all the sensors and meters used in the system during the experiment period. You will need to calculate the average flow rate in the collector loop for each several readings to reduce the measurement errors of the flow meter; as this meter has a relatively high resolution, $1 \, \text{l/min}$. This means any increase or decrease in the flow rate less that $1 \, \text{l/min}$ will not be recorded until more volume of the fluid passes through the meter. This measurement error results in a continuously changing flow rate which is not the real case.

  The experiment will take about (4~5) hours based on the weather conditions. During this time you can proceed to the next experiment calculations.
  The collector data given in Table 7 is needed to find both the certified and measured characteristics of the collector.

• Refining the results of the collector characteristics experiment
  You should have noticed that the resultant curve is not in consistency with the certified curve. In order to offset the measuring devices errors, a mathematical equation could be applied to omit the abnormal points. Most of the inconsistency is from the radiation sensor due to its high measuring frequency which results in instantaneous readings for the value of the solar radiation. The idea is to assume maximum and minimum range for the
difference between each point and the one after, use ±10% in your calculations, which is acceptable. This assumption is following the theoretical fact concerning the efficiency curves of the collector. As mentioned in the guide to experiment, the efficiency should drop down slowly due to increased thermal losses. Any point that drifts more or less than the assumed difference will be given the value zero. This correction could be applied using the tool insert formula under the insert tab in Excel form Microsoft. The proper function to be used in this case would be ‘if’. Look on the help provided by the software about this function for more information.

- **Solar Collector Simulation**
  In this the experiment the ‘collector’ heater will be used to supply the heat to the storage tank instead of the solar collector, so the bypass valve in the solar loop will be closed. The flow path in the solar loop will be through the internal heat exchanger in the storage tank to the ‘collector’ heater chamber and then back to the heat exchanger. The operation of the heater is controlled by the PID controller and the temperature at the outlet will be set at the beginning of each hour during this experiment.

- **System Setup**
  Start by checking the system with the help of the lab assistant to assure the following is already applied:
  - The bypass valve is closed
  - The solar loop pump is at manual control and operating at 100% flow rate (Maximum flow rate \(\approx 5.8 \text{ l/min}\))
  - The Data logger is connected to the power supply
  - The Storage tank heater and the ‘collector’ heater are both turned off
  - The space heating pumps are turned off and there is no hot water discharge

- **Calculations**
  In order to find the temperature to be set by the PID controller you have to start by using the weather profile to find the corresponding Irradiance at the time of the experiment. The inlet temperature to the ‘collector’ (\(T_{in}\)) and the inlet temperature (\(T_i\)), you can calculate what would be the collector efficiency under the same conditions and thus the useful collector output (\(Q_U\)) and finally the outlet temperature of the collector (\(T_{co}\)) based on (\(Q_U\)) and not on the (\(T_{in}\)) you have assume for the calculation of the efficiency. The useful energy rate will be kept constant for each hour and the PID controller set temperature will be set to the value of (\(T_{co}\)) that you have calculated. The average temperature of the storage tank at the end of each hour will be estimated to be used for the next hour. Do the calculation for 7 hours.
  Assume the following to fill the tables in the excel sheet and find the PID set temperature

Summarizing the assumptions needed:
- **Start with the weather profile to be used in the simulation. Assuming solar time steps in your experiment**
- **Insolation on the tilted plan of the collector (solar energy irradiation for an hour),**\(I_T = 1000 \text{ [W/m}^2\] as it would be in sunny day in Sweden. Also, to make calculation simpler, assume the sun is perpendicular on the collector which is at slop of 45° and 0° solar azimuth angle.
- The useful gain of the collector is constant during each hour and so is the weather profile.
• The inlet temperature for the solar collector is equal to the average temperature of the storage tank. This value will be measured at the beginning of the experiment and then will be calculated for each hour assuming the tank is fully mixed. Assume the \((UA)\) value of the tank to be \(10 \text{ W/m}^2\text{K}\) 
• The average temperature of the collector plate \((T_p)\) is 7°C higher than the flow inlet temperature

**Energy Extraction**

Using the calculated total energy to be supplied by the ‘collector’ heater \((Qu_{tot})\) in [MJ] during the collector simulation experiment, discharge 10% of this amount through each of the SH and DHW circuits. Start by calculating how much time the DHW test will take to discharge 10% of \((Qu_{tot})\) based on the flow to be used of 9l/min which is a typical value for a shower load. After carrying out the DHW test do the calculations for the SH test while the system reaches some stability and the storage tank sensors update their readings. This time period between the two tests should be around 10 – 15 minutes. For the DHW test if not possible to measure the temperature of the hot water out; assume the hot water discharged is 5°C less than the average storage tank temperature, and for the SH test assume a 10°C temperature drop in the SH heat exchanger. Change the control of the SH pump from ‘Auto’ to the middle constant speed and record the flow rate. The mixing valve in the SH loop should be such that the flow comes from both outlets from the store. Remember to keep a record of time for each test, i.e. the start and end of each test and to check whether this time is the same as that used by the logger. You will need this to calculate the real energy discharged using the logged data.

**Questions**

- Complete the tables in the Collector characteristic experiment calculation sheet using the suitable equation, then generate the collector characteristic and plot it with the certified one and give your comments and conclusions about the result

**Solar Collector Simulation**

- Fill the table in the excel sheet using the correct equations and the data given in the excel sheet
- Compare the measured and the calculated values for the useful energy gain and the average tank temperature
- Extract the data from the logger using the excel tool designed for that, Fig.32. Study the stratification in the storage tank; show temperature profile during the whole experiment, during the load discharges and the temperature profile across the tank height at three points, i.e. before and after DHW test and after SH test. Discuss your results
  *Hint: you will need to measure the height of each sensor*

- Indicate any deviations and non-realistic results during your results discussion. List and discuss in details all the reasons which may have caused any divergences, issues or mistakes in your results, i.e. include any measurements errors, simplification, assumptions taken or occurred while and before conducting the experiments or the calculation that followed; such as sensors and other measurement errors, weather condition, the weather profile used in the collector simulation and any other relevant factors.
Figure 32: the excel sheet used to extract the data of the logger software and how it could be used

- **Report**
  
  Your report should include the system drawing, calculation and result, discussion and conclusion, make sure to cover all the mentioned questions in this guide

- **Relevant Equations and Data**

  **Table 7: the solar collector data**

  | Aperture area [m²] | 2.50 |
  | Gross area [m²]    | 2.69 |
  | Optical efficiency (ζ₀) | 0.844 |
  | a₁               | 3.52 |
  | a₂               | 0.012 |
  | b₀               | 0.072 |

  For normal incident radiation:

  \[ \zeta_C = \zeta_0 - a_1 \left( \frac{\Delta T}{G_T} \right) - a_2 \left( \frac{(\Delta T)^2}{G_T} \right) \]  
  \[ \text{Equation 17} \]

  And generally:

  \[ \zeta_C = \zeta_0 \ast K_{ta}(\theta_b) - a_1 \left( \frac{\Delta T}{G_T} \right) - a_2 \left( \frac{(\Delta T)^2}{G_T} \right) \]  
  \[ \text{Equation 18} \]

  \[ K_{ta}(\theta_b) = \frac{(\tau a)_{h}}{(\tau a)_n} = 1 - b_0 \ast \left( \frac{1}{\cos \theta} - 1 \right) \]  
  \[ \text{Equation 19} \]

  \[ \zeta_C = \frac{q_U}{A_C \cdot G_T} \]  
  \[ \text{Equation 20} \]
\[ Q_u = V \cdot \rho \cdot C_p \cdot (T_{ci} - T_{co}) \]  \hspace{1cm} \text{Equation 21}

\[ T_s^+ = T_s + \frac{\Delta t}{m \cdot C_p} \cdot [Q_u - L_s - U \cdot A \cdot (T_s - T_a)] \]  \hspace{1cm} \text{Equation 22}

Where:
- \( \xi_C \): Collector efficiency
- \( \xi_O \): Optical efficiency or the zero loss efficiency
- \( \Delta T \): The temperature difference between the collector and the ambient air
- \( a_1, a_2 \): Collector constants
- \( K_{ta}(\theta_b) \): Incident Angle Modifier
- \( \theta_b \): Incident angle of beam radiation
- \( (ta)_b \): Transmittance-Absorbance product under beam incident
- \( (ta)_n \): Transmittance-Absorbance under normal incident
- \( b_0 \): Incident angle modifier coefficient

- \( A_C \): Aperture area of the collector \([m^2]\)
- \( G_T \): Total irradiance on the plane of the collector \([W/m^2]\)

- \( Q_u \): Rate of useful energy gain in the collector \([W]\)
- \( V \): Volumetric flow rate in the collector \([m^3/s]\)
- \( \rho \): Density of the fluid; Glycol mixture, 1015 \([kg/m^3]\) at 45°C
- \( C_p \): Heat capacity of the fluid; 3700 \([J/kg.K]\) at 45°C
- \( T_{ci}, T_{co} \): Temperature of the fluid to and from of the collector \(^[\circ C]\)

- \( T_s \): Current tank temperature \([\circ C]\)
- \( T_s^+ \): Expected temperature of the tank after one hour \([\circ C]\)
- \( \Delta t \): Time period, equals to 1 hour \([\text{hour}]\)
- \( m, T_p \): Mass of the water in the tank and the heat capacity \([kg], [J/kg.K]\)
- \( Q_u \): Heat energy supplied by the solar collector during the time period \([MJ]\)
- \( L_s \): Energy extracted from the tank during the time period
Figure 33 to the left the storage tank, the solar loop controller and DHW circuit, to the right the solar collector and the irradiance sensor and the SH circuit in the bottom right.
6.2. The Developed Excel Sheets for the Lab Calculations

In order to make the work in lab easier to understand and follow, an excel sheet was designed to carry out the calculation needed for the two experiments. This excel sheet could simplify the not only the calculation for the students, but also the correction and grading for the lab work. All the parameters needed or given in the lab are listed in one table and arranged according to their usage in the equations to be used, see Table 8. Also, some instructions were provided again in this excel sheet to make the work in the lab more convenient for the students.

Table 8 Part excel sheet to be used in the collector simulation experiment

<table>
<thead>
<tr>
<th>Exp Time</th>
<th>Θ</th>
<th>GT 1°cosΘ</th>
<th>IAM=1-[log(1/cosΘ -1)]</th>
<th>Using fully mixed storage equ</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:00-9:00</td>
<td>45</td>
<td>707</td>
<td>0.707</td>
<td>16</td>
</tr>
<tr>
<td>9:00-10:00</td>
<td>30</td>
<td>866</td>
<td>0.989</td>
<td>18</td>
</tr>
<tr>
<td>10:00-11:00</td>
<td>15</td>
<td>966</td>
<td>0.997</td>
<td>21</td>
</tr>
<tr>
<td>11:00-12:00</td>
<td>0</td>
<td>1000</td>
<td>1.000</td>
<td>23</td>
</tr>
<tr>
<td>12:00-13:00</td>
<td>15</td>
<td>966</td>
<td>0.997</td>
<td>24</td>
</tr>
<tr>
<td>13:00-14:00</td>
<td>30</td>
<td>866</td>
<td>0.989</td>
<td>24</td>
</tr>
<tr>
<td>14:00-15:00</td>
<td>45</td>
<td>707</td>
<td>0.707</td>
<td>24</td>
</tr>
</tbody>
</table>

You will need to fill the whole first arrow first then the second and so on.

Weather profile/ Fields to enter data
- Measured
- Hints/given data

<table>
<thead>
<tr>
<th>Tp</th>
<th>(ΔT)/GT</th>
<th>Eff.</th>
<th>Q(u[W])</th>
<th>Q(u[MJ])</th>
<th>Tco</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>0.0113</td>
<td>56%</td>
<td>1965</td>
<td>7.1</td>
<td>22</td>
</tr>
<tr>
<td>28</td>
<td>0.0110</td>
<td>79%</td>
<td>3441</td>
<td>12.4</td>
<td>30</td>
</tr>
<tr>
<td>34</td>
<td>0.0130</td>
<td>79%</td>
<td>3834</td>
<td>13.8</td>
<td>37</td>
</tr>
<tr>
<td>40</td>
<td>0.0171</td>
<td>78%</td>
<td>3902</td>
<td>14.0</td>
<td>44</td>
</tr>
<tr>
<td>47</td>
<td>0.0235</td>
<td>75%</td>
<td>3634</td>
<td>13.1</td>
<td>49</td>
</tr>
<tr>
<td>53</td>
<td>0.0331</td>
<td>71%</td>
<td>3060</td>
<td>11.0</td>
<td>54</td>
</tr>
<tr>
<td>58</td>
<td>0.0475</td>
<td>41%</td>
<td>1451</td>
<td>5.2</td>
<td>54</td>
</tr>
</tbody>
</table>

Efficiency Equation

\[ \eta_C = \eta_0 \times K_{\text{ta}}(\Theta) - \alpha_1 (\frac{\Delta T}{\Delta T}) - \alpha_2 \left( \frac{\Delta T}{\Delta T} \right)^2 \]

<table>
<thead>
<tr>
<th>Aperture area [m2]</th>
<th>2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross area [m2]</td>
<td>2.69</td>
</tr>
<tr>
<td>Optical efficiency (%)</td>
<td>0.844</td>
</tr>
<tr>
<td>a1</td>
<td>3.52</td>
</tr>
<tr>
<td>a2</td>
<td>0.012</td>
</tr>
<tr>
<td>t0</td>
<td>0.072</td>
</tr>
</tbody>
</table>
References


5- EINSIEDEL, P. (2011), Exchange study period report, University of Ulm

6- ENNOVATIS CONTROLLING (2009), Ennovatis Energimanagement, Version 5.6.4.1195.


