Performances of Flat-Plate and CPC Solar Collectors in Underfloor Heating Systems

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ABSTRACT

There is a growing interest in using solar energy in the underfloor heating systems. However, the large areas required for the placing of the solar collectors can be discouraging, especially for the apartment buildings.

The objective of this study is to investigate the possibility of using Compound Parabolic Collector (CPC) collectors to replace Flat-Plat collectors in solar energy underfloor heating systems. By this way, it is aimed to explore the feasibility of area reduction required by the collectors. Secondly, the temperature profiles of the circulating water loops and the concrete slabs are sought to be examined.

The simulations were carried out under the winter weather conditions of the Cyprus. The system consists of solar thermal collectors, a storage tank and circulation of water to carry the heat to 4 floor slabs. The results of the simulations show that, a CPC collector which is commonly used in producing high grade heat can work more effectively with less area occupied in this system. It is observed from this study that the outlet fluid temperature of this collector is between 25 to 95°C, compared to that of Flat-Plate collectors which is between 25 and 75°C. The simulations suggest that a 2 m^2 CPC collector can perform satisfactorily to match the job of 8 m^2 Flat-Plate collectors. The heat that is stored in the tank can supply hot water at a temperature of 60°C which is reduced to 45°C after mixing with cold return water before entering the floor slabs. The estimated slab temperature is approximately 24°C which is compatible with the

standards. Fluid which is passing through the slabs will eventually lose its temperature as the heat transfer occurs from the slabs to the environment. Consequently the fluid outlet temperature is observed to be approximately 25°C.

Key Words: Solar energy, Floor Heating, TRNSYS, Cyprus.

ÖZ

Güneş enerjisi ile çalışan yerden ısıtma sistemlerine olan ilgi her geçen gün artmaktadır. Güneş kollektörleri için gereken geniş alanlar özellikle apartman uygulamalarında büyük bir sorun oluşturmakta ve tüketicilerin bu sistemleri kullanmalarında onları olumsuz yönde etkilemektedir.

Bu çalışmanın amacı, düz levha güneş toplayıcılarının yerine, daha az alana ihtiyaç duyan bileşik parabolik güneş toplayıcılarının (BPT) kullanılabilme olasılığını incelemektir. Böylelikle güneş toplayıcıları için gereken alanın daha aza indirilmesinin ne kadar fizibll olduğu araştırılmış olacaktır. Ayrıca sistemde devridaim eden su döngülerinin ve beton döşemelein sıcaklık profilleri de hesaplanacaktır.

Simulasyonlar Kıbrıs'ın Kış şartları dikkate alınarak kurgulanmıştır. Sistem güneş termal toplayıcılardan bir depolama tankı ve sıcak suyu 4 döşemeye taşıyan bir devri daim sisteminden oluşmaktadır. Elde edilen sonuçlar yüksek sıcaklıkta ısı üreten BPT'lerin daha az alan kullanarak daha etkili çalıştığını ortaya koymuştur. Bu toplayıcıların çıkış suyu sıcaklığının 25 ile 95°C arasında değiştiği gözlemlenmiştir. Ayni simulasyon düz levha toplaycılarında gerçekleştirildiğinde toplayıcı çıkış suy sıcaklığı 25 ile 75°C arasında değişiyordu. Simulasyonlar 2 m^2 lik BPT toplayıcılarının 8 m^2 lik düz levha toplayıcıların verdiği performansa eşdeğer bir performansı rahatlıkla yerine getirdiğini gösterdi. Tankta depolanan ısı tank çıkışında 60°C sıcak su elde

edilmesine olanak sağladığından döşeme altlarına bu suyla dönüş suyunun karışımından elde edilen 45°C sıcaklığındaki su arzedildi. Döşeme sıcaklıkları standardlarla uyumlu olması gerektiği gibi 24°C civarında olacağı hesaplanmıştır. Döşeme içinden gelen akışkanın sıcaklığı, çevreye yapılan ısı transferinden dolayı, sonunda düşer. Bu yüzden dönüş suyu sıcaklığı yaklaşık olarak 25°C olduğu gözlemlenmiştir.

Anahtar Kelimeler: Güneş enerjisi, yerden ısıtma, TRNSYS, Kıbrıs.

To

my dear parents

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A	[m^2]	Total collector array aperture or gross area (consistent with $F_R(\tau\alpha)$, F_RU_L, $F_RU_{L/T}$ and G_{test})
A_a	[m^2]	Aperture area of a single collector
A_r	[m^2]	Absorber area of a single collector module
A_s	[m^2]	Receiver area of a single collector module
a_0	[-]	Intercept (maximum) of the collector efficiency
a_1	[kJ/h-m^2-K]	Negative of the first-order coefficient in collector efficiency equation
a_2	[kJ/h-m^2-K^2]	Negative of the second-order coefficient in collector efficiency equation
b_0	[-]	Negative of the 1st-order coefficient in the Incident Angle Modifier curve
b_1	[-]	Negative of the 2nd-order coefficient in the IAM curve
Cap_{Slab}	[kJ/kg]	The capacitance of the slab
C_{pf}	[kJ/kg-K]	Specific heat of collector fluid
Cp_{fluid}	[kJ/kg.K]	The specific heat of fluid passing through the slab
Cp_{Slab}	[kJ/kg.K]	The specific heat of the slab material
C_{min}	[kJ/h-K]	Minimum capacitance rate (mass flow times specific heat) of heat exchanger flow streams
C_{min}	[kJ/kg]	The minimum of the slab capacitance and the fluid

capaciatnce

C_R	[-]	Concentration ratio
F_R	[-]	Overall collector heat removal efficiency factor
F_{av}	[-]	Modified value of FR when the efficiency is given in terms of T_{av}, not T_i
F_o	[-]	Modified value of FR when the efficiency is given in terms of T_o, not T_i
F_{sky}	[-]	View factor to the sky
F_{gnd}	[-]	View factor to the ground
h	m	Height of full CPC with half acceptance angle θ_c
$\bar{h}$	m	Truncated height of CPC
h_w	$[(W/m^2 - K)]$	Wind heat transfer coefficient
I	[kJ/h-m²]	Global (total) horizontal radiation
I_d	[kJ/h-m²]	Diffuse horizontal radiation
I_T	[kJ/h-m²]	Global radiation incident on the solar collector (Tilted surface)
I_{bT}	[kJ/h-m²]	Beam radiation incident on the solar collector
$\dot{m}$	[kg/h]	Flowrate at use conditions
$\dot{m}_{test}$	[kg/h]	Flowrate in test conditions
m_{slab}	[kg/hr]	The mass of the slab
$\dot{m}_{fluid}$	[kg/hr]	The mass flow rate of fluid passing through the slab
N_S	[-]	Number of identical collectors in series
N_G	[-]	Number of glass covers

$\dot{Q}_u$	[kJ/h]	Useful energy gain
$\dot{Q}_{in}$	[kJ/h]	Energy transferred from fluid to the slab
$\dot{Q}_{zone}$	[kJ/h]	Energy transferred from the slab to the zone
$\dot{Q}_{loss}$	[kJ/h]	Energy transferred from the slab to the sink
T_a	[°C]	Ambient (air) temperature
T_{av}	[°C]	Average collector fluid temperature
T_i, T_{iColl}	[°C]	Inlet temperature of fluid to collector
T_o, T_{oColl}	[°C]	Outlet temperature of fluid from collector
T_p	[°C]	Stagnation temperature
T_{Bottom}	[°C]	Outlet Temperature of fluid from tank to heat source
T_{TOP}	[°C]	Outlet Temperature of fluid from tank to heat source
$T_{fluid,in}$	[°C]	The temperature at which fluid enters the slab
$T_{fluid,out}$	[°C]	The temperature at which fluid exits the slab
T_{top}	[°C]	The temperature of the zone
T_{back}	[°C]	The temperature to which losses from the slab occur
T_{Slab}	[°C]	Temperature of the Slab
T_{FHS}	[°C]	Inlet Temperature of fluid to floor heating system
T_S	[°C]	Outlet Temperature of fluid from slabs
UA_{top}	[kJ/hr.K]	The heat transfer coefficient between slab and Zone
UA_{back}	[kJ/hr.K]	The heat transfer coefficient between the slab and the sink temperature for losses not to the zone
U_L	[kJ/h-m²-K]	Overall thermal loss coefficient of the collector per unit area

$U_{L/T}$	[kJ/h-m²-K²]	Thermal loss coefficient dependency on T
α	[-]	Short-wave absorptance of the absorber plate
β	[°]	Collector slope above the horizontal plane
γ	[°]	Collector azimuth angle
γ_s	[°]	Solar azimuth angle
θ	[°]	Incidence angle for beam radiation
θ_c	[°]	Half-acceptance angle
θ_l	[°]	Longitudinal acceptance angle
θ_t	[°]	Transversal acceptance angle
ρ_g	[-]	Ground reflectance
ε	[0..1]	The effectiveness of the fluid / slab heat exchanger
τ	[-]	Short-wave transmittance of the collector cover(s)
$(\tau\alpha)$	[-]	Product of the cover transmittance and the absorber absorptance
$(\tau\alpha)_b$	[-]	$(\tau\alpha)$ for beam radiation (depends on the incidence angle θ)
$(\tau\alpha)_n$	[-]	$(\tau\alpha)$ at normal incidence
$(\tau\alpha)_s$	[-]	$(\tau\alpha)$ for sky diffuse radiation
$(\tau\alpha)_g$	[-]	$(\tau\alpha)$ for ground reflected radiation.

Chapter 1

INTRODUCTION

Nowadays, the critical subject of each region in the world is to produce energy with less cost and air pollution. On the other hand, extensive efforts to alleviate global warming of the earth, which is the result of emission of carbon dioxide in atmosphere, forced the governments of countries to look for other alternatives. Burning of fossil fuels, which are the main source that are used for satisfying the energy demand of human beings, mainly cause the huge amount of emissions. Compared with primary energy sources, solar electric energy generation system has some outstanding benefits such as energy-regeneration, no-pollution, safety and etc. Among different technologies, which are developed in the recent years, solar photovoltaic and solar heat generation have got the high level of attraction.

1.1 Energy Brief Of North Cyprus

Cyprus is the third biggest island of Mediterranean region after Sicilia and Sardinia. The total surface area of Cyprus is 9,250 km^2 of which 3,355 km^2 in the North is occupied by the Turkish Cypriot community with a population of 290,000. In North Cyprus electricity generation is achieved by burning imported fuel-oil (No.6) costing 70,000,000 USD/year [1]. This fuel emits harmful CO_2, NO_x and SO_x gases into the atmosphere. Although Cyprus has no oil resources it has several alternative energy resources. Besides wind energy, which is felt strongly on mountains specially in south Cyprus, sun is shining in all parts of the island almost uniformly. In rare locations near to mountains perhaps the period of availability of the sun might be little lower. As sun shines nearly 300 days per year, there is a reason to believe that generating heat by solar energy can be an effective heating method in this region. The major energy consumption sector in the island is the residential sector where a great majority is utilizing solar energy for domestic water heating purposes [2].

1.2 Solar Energy And Underfloor Heating System

One of the methods of utilizing solar energy is underfloor heating systems which found ground for application in heating warehouses, schools and residential houses in the recent years [3]. The rate of heat transfer of ground-coupled (the equipment which is installed under floor) through concrete slabs is typically a significant component of the total load for heating or cooling in low-rise buildings such as residential buildings. Additionally, transients associated with floor slabs play an important role in estimating both ultimate loads for sizing of equipment and total energy requirements for economic analysis [4].

In Cyprus, there have been a number of attempts to use solar energy in the floor heating systems. The idea is to collect the solar energy during the day time (when the solar energy is available and using it for heating at night time). There are two storage media, namely the floor slab and the water stored in a tank. The solar collectors need to have the capacity to collect enough solar energy during the day to transfer the energy into the storage media.

1.3 Objectives

The aim of this study is to simulate a domestic underfloor heating system and compare the performance of two different types of solar thermal collectors in this system. One of the problems encountered by the house owners is finding enough space for the placement of collectors; therefore, it is highly desirable to use the minimum possible space without losing performance. In Figure 1, it can be seen that solar collectors occupy a large area in the house premises when they are used for underfloor heating. The present work will investigate and compare the use of Flat-Plate Collector (FPC) and Compound Parabolic Concentrating solar collector (CPC) for a possible underfloor heating application in Cyprus.

Figure.1 A house using solar collectors for underfloor heating, Nicosia, North Cyprus

1.4 Organization Of The Thesis

The structure of this research is organized as follows: Chapter 2 includes a review about the history of underfloor heating system using solar energy. The components of solar thermal systems will be explained in Chapter 3. System and mathematical model are the main topics of Chapter 4. Simulation of the system with the TRNSYS software is in Chapter 5. Moreover, the results of the analysis will be reported in Chapter 6 in various graphs and charts. The last chapter is discussing about the final result and comparing it with the conventional heating system as another alternative. The results which are obtained from this study will enable the Cyprus' residents to decrease their electricity payments by making their house equipped with this system, and besides of that will consume the energy for the next generation.

Chapter 2

LITERATURE REVIEW

At the present time, there are two major techniques available for solar energy systems, one is solar photovoltaic generation and the other one is solar-heat generation. Heating for thermal comfort can be achieved by:

1. Convective heating where the heating load is indirectly satisfied by heating the space air;
2. Radiant heating system;
3. Combination of convective and radiant heating which underfloor heating is a good example of this. The design of radiant and under floor heating systems is not as direct as the case of the conventional heating system.

C. Şerban, et. al. [5], simulated a model of a solar house by using TRNSYS located in the city of Braşov, România. In their study, they have performed an energy analysis for a small-scale solar house with two floors. The work describes the location, size and thermal regime of the solar house; they are also presented the heating system facility and equipment components, designed for the solar house located in Transilvania University Campus. The study consists of two demand sources: domestic hot water and underfloor heating. Based on the achieved simulations it is shown that compared to the ordinary control the energetically-based control provides remarkable advantages and savings concerning the auxiliary heating energy. This result should be valid for any systems similar to the particular one in Braşov [5].

Ali A. Badran and Mohammad A. Hamdan [6] did a comparative study for underfloor heating using solar collectors or solar ponds. In their work, a theoretical and experimental study is made for underfloor heating system using solar collectors. Also a study for a similar system using solar ponds is made with the same main conditions. Results obtained show that the solar collector system is 7% more efficient than the solar pond system [6].

Cüneyt Kurtay, et. al., [7] have worked on a floor heating system using solar energy in Ankara, Turkey. The aim of their study was to investigate a floor heating system for an office by applying the solar energy. Flat-plate collectors are the absorber of solar energy and the energy gained will be stored in a storage tank. The analysis method for thermal comfort of the office is performed that is affected by environmental and individual parameters. The obtained result shows that using solar energy as a supplementary heat source can increase the level of comfort in Ankara weather condition. This method of analysis of the thermal comfort is applicable for other systems as well [7]. Yeo M., et. al., [8] have investigated the changes and recent energy saving potential of residential heating in Korea, and showed that modern apartment buildings with hot water radiant floor heating yield less heat loss due to the tighter envelope, but also yield higher energy consumption due to the use of energy more effectively [8].

José A. Candanedo, et. al., [9] investigated predictive control strategies applied to radiant floor heating system in a net-zero energy solar home, through the implementation of a simplified transfer function model. Predictive control is used to maintain a comfortable indoor environment by anticipating the building's response to expected weather conditions [9].

Kamel Haddad [10] simulated a model for a house equipped with a radiant floor heating system connected to solar collectors used to evaluate the potential of using solar energy for space heating in the northern Chicago climate. The solar fraction of the system is predicted when the supply temperature to the radiant loops is constant and when this temperature is changed according to outside temperature reset control. In his study the effect of a domestic hot-water system on the performance of the solar system is not considered [10]. In two previous studies, Haddad et. al. [11] and Zhang and Pate [12] specifically dealt with solar assisted-radiant floor heating systems for residential application.

The novelty of the present study is to simulate an underfloor heating system using solar energy with TRNSYS software, comparing the performance of two types of solar collectors-Flat-plate collector and CPC collector. The model is for a domestic house in North Cyprus weather condition with the aim of finding the minimum possible space without losing the performance. In order to compare the performance of the collectors, all the parameters of the other components of the system are the same except the type of solar collectors.

Chapter 3

SOLAR THERMAL SYSTEMS

3.1 Solar heat generation

The basic process of solar heat generation is to transfer the solar radiation energy into heat with the use of thermal collectors. Depending on the grade of heat required different types of solar collectors can be used. For high-grade heat generation (i.e., high temperature applications) concentrating or evacuated tube solar collectors can be preferred instead of the flat plate collectors.

3.1.1 Components of solar thermal systems:

3.1.1.1 Collectors

In general the term "solar collector" refers to solar hot water panels that contain water pipes with insulation on its sides and bottom and glass on the top. Energy is absorbed by the absorber plate and heat is transferred. The collector therefore is the link between the sun and the hot water system. The absorption of the sun's rays by the collectors, create the heat and the task of collectors is then to transfer it to the downstream systems. Different definitions of the area are used in the manufactures' literature to describe the geometry of the collectors:

- The gross surface area (collector area) is the product of outside dimensions, and for example defines the minimum amount of the roof space which is required for installing it.

- The aperture area corresponds to the light entry area of the collector, that is the area through which the solar radiation passes to the collector itself.
- The absorber area (also called the effective collector area) corresponds to the area of the actual absorber panel [13].

3.1.1.2 Thermal Storage

The energy supplied by the sun cannot be so much effective itself when the heat is required in the thermal system; therefore the generated solar heat must be stored. It would be ideal if this heat stored in the tanks in the mornings (when the rate of sun light is high) to the nights (when there is no sun shine). In this case, it’s appropriate to use thermal storage tank which can store water and also improve the efficiency of solar thermal systems [13].

3.1.1.3 Solar Circuit

The heat generated in the collector is transported to the thermal storage tank by means of the solar circuit. This consists of the following elements:

- The pipelines, which connect the collectors on the roof to the thermal storage unit,
- The solar liquid or transport medium, which transports the heat from the collector to the store,
- The solar pump which circulates the solar liquid in the solar circuit,
- The solar circuit heat exchanger, which transfers the heat gained to the domestic hot water to the store,
- The fittings and the equipment for filling, emptying and bleeding,

- The safety equipment. The expansion vessel and safety valve to protect the system from damage (leakage) by volume expansion or high pressures [13].

3.1.1.4 Controller

The controller of a thermal solar system has the task of controlling the circulating pump so as to harvest the sun's energy in the optimum way. In most cases this involves simple electronic temperature difference regulation.

Increasingly, controllers are coming onto the market that can control different system circuits as one single device, and in addition are equipped with functions such as heat measurement, data logging and error diagnostics [13].

3.2 Underfloor heating system

Underfloor heating provides a moderate heat, it radiates upwards from the floor; moving the heat through the air and heating the surroundings progressively and positively. This system avoids the cold currents of air created by Radiators which, in spite of their name, actually spread the heat by convection, a process that involves moving the air itself. Underfloor heating is constant throughout the room and adds to superior level of personal comfort by avoiding the hot and cold spots that are inevitable with radiators. In fact, underfloor heating is like having sunshine in the room all of the time. The trend in heating private and public buildings is quite clearly towards modern underfloor heating. There are many reasons for this. Not only are living comfort and health an important decision criteria, but energy, cost efficiency and sustainability are also key advantages of underfloor heating.

Advantages of underfloor heating system:

- Comfort and cosiness through large surface, moderate heat,
- Ideal distribution of temperature (Figure 3.1),
- Reduced airborne dust compared with traditional radiators (convection),
- Healthier atmosphere (ideal for sufferer of dust allergies).

In comparison with radiator systems, underfloor heating system has low flow temperatures which is equipped with modern heating generators such as condensing boilers, heat pumps and solar panels and can cut energy costs by up to 13% (Calculation according to DIN 4108-6 and DIN 4701-10/12) [14].

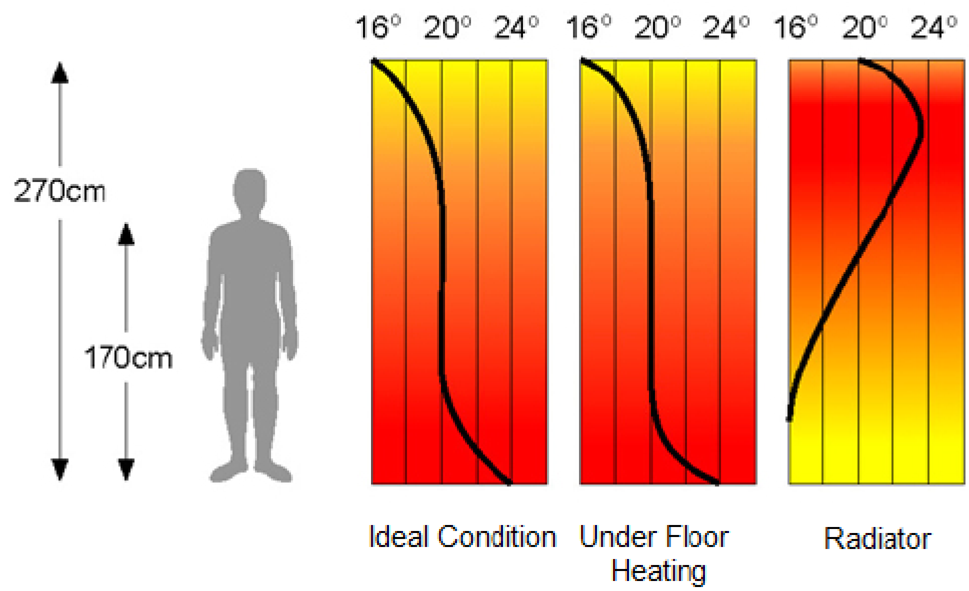

Figure 3.1 Comparison of underfloor and traditional radiator systems [14]

At present, the amount of heat that is lost may decrease to 30-50% for a well- designed house [15]. Transients associated with floor slabs can be very significant and important to consider in estimating both peak loads for sizing of equipment and total energy requirements for economic analyses. Nowadays, utilizing energy storage within floor slabs and other building materials is a very important topic [15].

Chapter 4

SYSTEM AND MATHEMATICAL MODEL

4.1 The underfloor heating system using solar energy

A schematic diagram of the underfloor heating system using solar energy in the present study is shown in Figure 4.1.

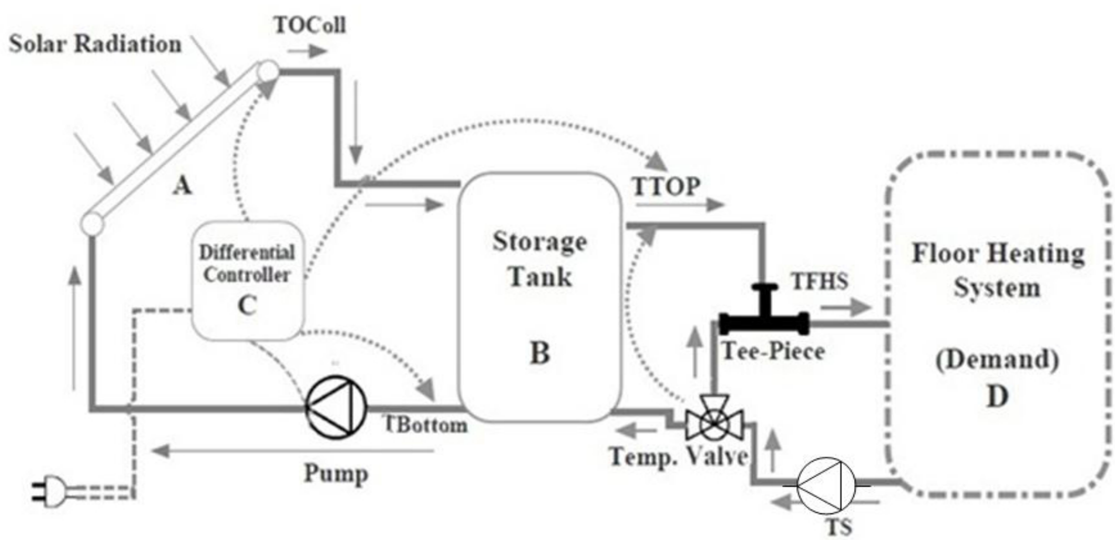

Figure 4.1 Schematic diagram of the system

The Solar collector (A) absorbs the sun radiation with the specific weather data in different days of the year. Two types of solar collectors are used in this study in order to compare their performance under the same conditions:

- Flat Plate Collector (FPC): The collectors are connecting to each other in a way that their array consists of series and parallel collectors. In this case, the total collector array thermal performance is determined by the specific properties of each module and the number of them in series.
- Compound Parabolic Collector (CPC): This type has two parts, concentrating reflector and an absorber. The CPC collects both beam and diffuse radiation which approach the aperture within a critical angle called the half-acceptance angle.

A stratified storage tank (B) has been used for this study in which thermal stratification improves the overall performance of the systems. Significant improvements in yearly performance of solar energy systems may be realized if stratification can be maintained in the storage tank. In solar thermal tanks, the cold fluid is withdrawn from the bottom to be heated at the heat source, i.e. solar collectors, and returned to the top of the tank at a relatively higher temperature. As a result, a temperature difference between the top and the bottom parts of the tank arises with the consequent variation of the density in the medium. At the inlet zone appears a mixing fluid region that is gradually pushed down as more fluid enters the tank. As a consequence, a region with a steep temperature gradient is formed, which is known as the thermocline region. Once the thermocline is developed, it travels down as the charging process continues, limiting the mixing between the cold and the hot regions. In fact, the thickness of the thermocline has been used as a means of quantifying how well a stratified tank has been designed. The higher the mixing at the inlet, the thicker is the thermocline zone [16]. The stratified storage tank will store the water during the night time or the times which weather conditions are not favorable. Figure 4.2 shows the stratified tank in a simple model.

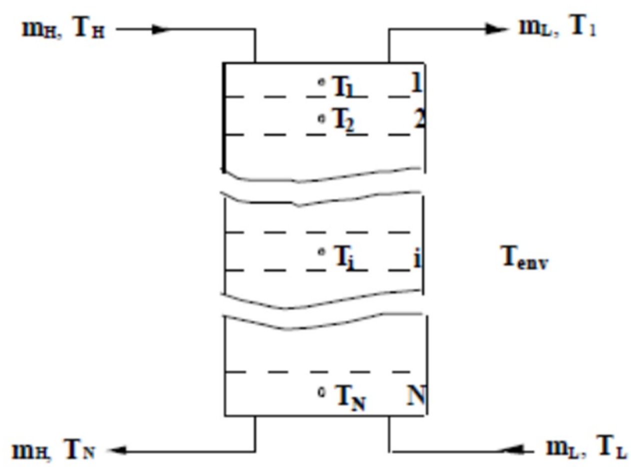

Figure 4.2. Multinode Model

An on/off differential controller (C) generates a control function between the TOColl and TBottom. Controlling the temperature can have a significant effect on the final result. In this case, the TOColl is adjusted as the Upper input temperature Th, TBottom is adjusted as Lower input temperature Tl and TTOP is adjusted as Monitoring temperature Tin. The differential controller is investigating the temperature difference between Th and Tl and sends the appropriate signal to the pump according to the dead bands. There is a high limit cut out temperature that can be defined as desired.

Hot water coming from of the tank mixes with the cold return water at the Tee-Piece; reaching a moderate temperature before entering the underfloor heating slabs (D). In this study, simple floor heating system is used which models a simple radiant slab (floor heating) system that operates under the assumption that the slab can be treated as a single lump of isothermal mass and that the fluid to slab energy transfer can be modeled using a heat exchanger effectiveness approach.

At this time, the water will pass through the slabs and the heat will be transferred to the room by convection, so the outlet water from the slabs will have lower temperature from the inlet at the slabs. This water returns back to the tempering valve (3-way valve).

4.2 Mathematical descriptions

4.2.1 Theoretical Flat-Plate Collector

The energy collection of each module in an array of Ns modules in series is modeled according to the Hottel-Whillier equation [17] such that (j is the module number):

$$\dot{Q}_u = \frac{A}{N_s}\sum_{j=1}^{N_s} F_{R,j}\left(I_T(\tau\alpha) - U_{L,j}(T_{i,j} - T_a)\right) \tag{4.1}$$

Where $\dot{Q}_u$is useful energy gained by the collector, A is the gross area of the collector, N_s is the number of identical collectors in series, I_T is the global radiation incident on the solar collector, $(\tau\alpha)$ is product of the cover transmittance and the absorber absorptance, U_L is the overall thermal loss coefficient of the collector per unit area, T_i is the inlet temperature of the fluid to the collector and T_a is the ambient temperature.

where $F_{R,j}$ can be explained as follows:

$$F_{R,j} = \frac{N_s \dot{m}_c C_{pc}}{A U_{L,j}}\left(1 - \exp\left(-\frac{F' U_{L,j} A}{N_s \dot{m}_c C_{pc}}\right)\right) \tag{4.2}$$

where $\dot{m}_c$ is the flowrate at use conditions, and C_{pc} is the specific heat of collector fluid. The collector fin efficiency factor, F', can be determined [18]. The overall loss coefficient is a complicated function of the collector construction and its operating conditions. The following expression, developed by Klein [19], is used to approximate $U_{L,j}$ (in kJ/h-m^2-K). Equation (4.3) is described as:

$$U_{L,j} = \frac{\frac{3.6}{N_G}}{\frac{C}{T_{P,j}}\left[\frac{\left(T_{av,j} - T_a\right)}{N_G + f}\right]^{.33} + \frac{1}{h_W}} + \frac{3.6\,\sigma\left(T_{av,j}^2 + T_a^2\right)\left(T_{av,j} + T_a\right)}{\frac{1}{\varepsilon_P + .05N_G(1-\varepsilon_P)} + \frac{2N_G + f - 1}{\varepsilon_g} - N_G} + U_{be}$$

where N_G is number of glass covers, C is the collector concentration ratio, T_p is stagnation temperature, T_{av} is average collector fluid temperature, ε_p absorber plate emittance, ε_g emissivity of glass covers. And:

$$h_W = 5.7 + 3.8\,W \qquad (W/m^2\text{-}K) \tag{4.4}$$

$$f = (I - 0.04\,hw + 0.0005\,hw^2)(1 + 0.091N_G) \tag{4.5}$$

The overall transmittance-absorptance product is determined as:

$$(\tau\alpha) = \frac{I_{bT}(\tau\alpha)_b + I_d\left(\frac{1+\cos\beta}{2}\right)(\tau\alpha)_s + \rho I\left(\frac{1-\cos\beta}{2}\right)(\tau\alpha)_g}{I_T} \tag{4.6}$$

where I_{bt} is beam radiation incident on the solar collector, I_d is diffuse horizontal radiation and I_T is global radiation incident on the solar collector (Tilted surface).

The outlet temperature of one module is used as the inlet to the next and is given as:

$$T_{o,j} = \frac{AF_{R,j}(I_T(\tau\alpha) - U_{L.j}(T_{i,j} - T_a))}{N_s \dot{m}_c C_{pc}} + T_i \tag{4.7}$$

If the collector flow is zero, the collector stagnation temperature is:

$$T_p = \frac{I_T(\tau\alpha)}{U_L} + T_a \tag{4.8}$$

4.2.2 CPC Collector

A compound parabolic concentrating (CPC) collector consists of a concentrating reflector and an absorber. The walls of a 2-dimensional (trough-like) CPC are parabolic in shape. The focus of each parabola coincides with the intersection of the absorber and the opposite wall (see Figure 4.3). The CPC collects both beam and diffuse radiation, which approach the aperture within a critical angle θ_c, called the half-acceptance angle. A full CPC is one in which the walls extend upward to a height h which gives an aperture area of $l/\sin\theta_c$ times the absorber area. Optimal concentration is achieved in a full CPC, but a very large reflector area is required. In practice, most CPC's are truncated to a height $\bar{h} < h$. A CPC collector can be modeled in three steps. First, the total beam and diffuse radiation within the acceptance angle are determined. Next, reflector concentration and reflective loss are considered and the effective radiation striking the absorber is calculated. This effective radiation is then used to find the energy transferred to the collector flowstream and the resulting outlet temperature [18].

There are two possible orientations considered for a CPC receiver. First of all, the CPC axis may be located in a vertical plane that contains the surface azimuth. This is termed the longitudinal plane (see Figure 4.3). Beam radiation enters the CPC whenever $\theta_l \leq \theta_c$ where:

$$\theta_l = |\tan^{-1}(\tan\theta_z \cos(\gamma - \gamma_s)) - \beta| \tag{4.9}$$

where γ is collector azimuth angle, γs is solar azimuth angle and β is collector slope above the horizontal plane.

Alternatively, the CPC receiver may be located in a transverse plane 90° from the longitudinal orientation. In this case, beam radiation enters the CPC when $\theta_t \leq \theta_c$ where:

$$\theta_t = \tan^{-1}(\frac{\sin\theta_z \sin(\gamma-\gamma_s)}{\cos\theta}) \tag{4.10}$$

Diffuse radiation entering the aperture is estimated using view factors to the sky and ground. For the longitudinal receiver orientation:

$$F_{sky} = \frac{1+\cos\beta}{2CR} \tag{4.11}$$

$$F_{gnd} = \frac{1-\cos\beta}{2CR} \tag{4.12}$$

where C collector concentration ratio and R is receiver radius. F_{sky} is view factor to the sky and F_{gnd} is view factor to the ground. And for the transverse receiver orientation:

$$F_{sky} = \frac{\frac{1}{CR}+\min(\frac{1}{CR},\cos\beta)}{2} \tag{4.13}$$

$$F_{gnd} = \frac{\max\left(\frac{1}{CR}.\cos\beta\right)-\cos\beta}{2} \tag{4.14}$$

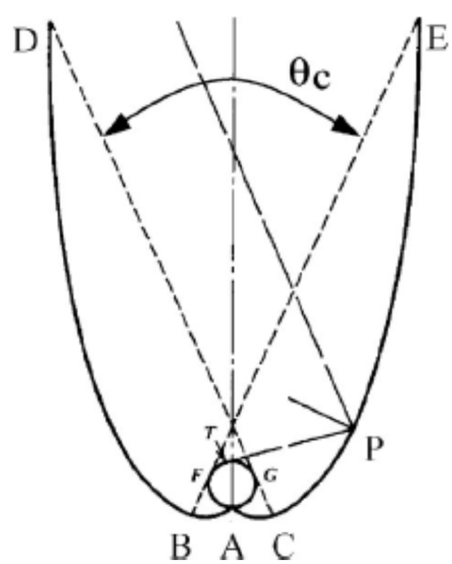

Figure 4.3 Cross-Section of a Non-Truncated CPC

The total radiation entering the reflector aperture within the acceptance angle is:

$$l_{in} = F_b l_{bT} + F_{sky} l_d + F_{gnd\rho g} l \tag{4.15}$$

where I_{bT} is beam radiation incident on the solar collector, I_d is diffuse horizontal radiation and I is global (total) horizontal radiation. In this equation when F_b=1 if the sun is within the acceptance angle, and F_b=0 otherwise.

In discussing the reflector characteristics, it is helpful to use the coordinate system of Rabl [20] shown in Figure 4.4. As given by Rabl, a branch of the CPC satisfies:

$$y = \frac{x^2}{2s(1+\sin\theta_c)} \tag{4.16}$$

where s is absorber width, and the x-coordinates of its endpoints are:

$$x_s = s\cos\theta_c \tag{4.17}$$

and:

$$\bar{x} = s\left[\frac{1+\sin\theta_c}{\cos\theta_c}\right]\left[-\sin\theta_c + (1+\frac{\bar{h}}{h}\cot{\theta_c}^2)^{1/2}\right] \tag{4.18}$$

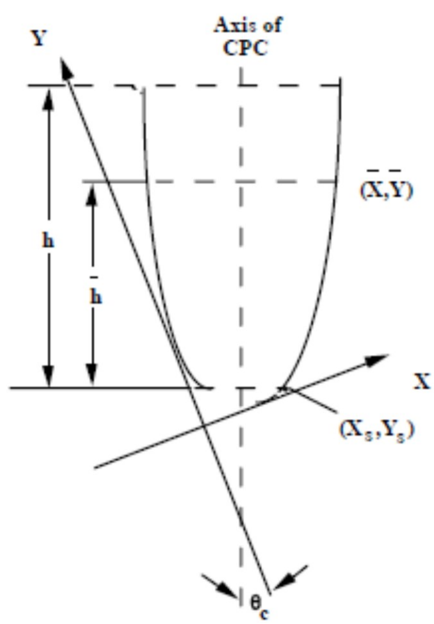

Figure 4.4 Geometry for Truncated CPC

The total radiation entering the collector aperture is (I_{in}.A_a) which A_a is aperture area of a single collector. The total radiation incident on the absorber, ignoring reflective loss, may be written ($I_R.A_s$) which A_s is receiver area of a single collector module. Therefore, in passing from the aperture to the absorber, the radiation per unit area is increased by the concentration ratio:

$$CR = \frac{A_a}{A_s} = 2\left(\frac{\bar{x}}{s}\right)\cos\theta_c - \left(\frac{\bar{x}}{s}\right)^2 \frac{\sin\theta_c}{\sin\theta_c + 1} + \sin\theta_c - \cos{\theta_c}^2 \qquad (4.19)$$

For full CPC's, i.e. when $\bar{h}/h = 1$, the concentration ratio is $1/\sin\theta_c$. The concentration ratio falls off from $1/\sin\theta_c$, as $\bar{h}/h$ decreases.

As radiation travels from the aperture to the absorber, some of it is reflected by the walls of the trough. If the walls are not perfect reflectors, there is some loss of radiation. To account for this reflective loss, one may define the effective reflectance of the reflector system as:

$$\rho_{eff} = \frac{I_R}{I_{in}.CR} \qquad (4.20)$$

As in the analysis of Rabl,

$$\rho_{eff} \approx {\rho_R}^n \qquad (4.21)$$

Where ρ_R is the wall reflectance and n is the average number of internal relections.

The average number of internal reflections can be expressed as:

$$n = \frac{A_r}{A_s}\left(\frac{1}{2} - \frac{\bar{x} - {x_s}^2}{2A_r s(1+\sin\theta_c)}\right. \qquad (4.22)$$

where A_r is absorber area of a single collector module. With:

$$\frac{A_r}{A_s} = (1 + \sin\theta_c)\log\left[\frac{(\bar{x}/s) + \sqrt{(1+\sin\theta_c)^2 + (\bar{x}/s)^2}}{\cos\theta_c + \sqrt{2(1+\sin\theta_c)}}\right] + \left(\frac{\bar{x}}{s}\right)\sqrt{1 + \left(\frac{\bar{x}}{s(1+\sin\theta_c)}\right)^2} - \frac{\cos\theta_c\sqrt{2}}{\sqrt{1+\sin\theta_c}}$$

(4.23).

It is interesting to note that both n and CR are independent of the absorber width s. The CPC absorber is modeled using the Hottel-Whillier collector equation [17] such that:

$$Q_u = \frac{AF_R}{N_s}\sum_{J=1}^{N_s}(I_{In}(\tau\alpha) - U_{L,J}(T_{I,J} - T_a)) \tag{4.24}$$

where F_R is determined as in equation (4.2). The overall transmittance-absorbtance product is calculated as:

$$(\tau\alpha) = \frac{I_{bT}(\tau\alpha)_b + I_{dT}(\tau\alpha)_d}{I_T} \tag{4.25}$$

The transmittance-absorbtance products for beam and diffuse radiation are determined with function routine using an effective absorbtance of ρ_{eff} . α. An equivalent incidence angle is defined for diffuse radiation as:

$$\theta_d = 44.86 - 0.07\theta_c + 0.005120{\theta_c}^2 = 0.00002798\,{\theta_c}^3 \tag{4.26}$$

Outlet and stagnation temperatures are calculated as in Flat-Plate collcetor.

4.2.3 Simple Floor Heating System

This system operates under two main assumptions, combined these assumptions mean that the radiant slab can be modeled using a simple differential equation of the form dT/dt=aT+b where a and b are constants.

In making a lumped capacitance assumption concerning the slab, it is assumed that there are no temperature gradients throughout the slab as heats up and cools down: that the slab is isothermal throughout. This is obviously an idealized assumption since it is temperature gradients that drive conduction heat transfer within the slab. However, if the internal resistance to heat transfer is high in comparison to the rate at which energy is transferred away from the surface of the slab, it is reasonable to assume that the slab is isothermal and that it can be treated as a lumped capacitance.

The effectiveness approach to modeling heat exchangers is a helpful simplification of the complex and piping configuration dependent heat transfer that goes on between the two heat exchange mediums. In case of fluid filled pipes embedded within a slab, the two mediums between which energy is exchanged are the fluid and the slab material. The effectiveness of the heat exchanger is defined as the actual energy transferred divided by the maximum possible energy transfer between the two mediums. In the slab, the maximum possible energy transfer would occur if the fluid exited the slab at the slab temperature or if the slab temperature rose to fluid inlet temperature. The medium (slab or fluid) which could undergo the maximum energy transfer would be the one with the minimum capacitance because the energy balance requires that the energy given up by one medium must be absorbed by the other. If the medium with the larger capacitance undergoes the maximum temperature difference, this would cause the other medium to go through a temperature change larger than the maximum in order for the energy balance to work out. The minimum capacitance side of the fluid / slab heat exchanger can be using equation 4.27 [18].

$$\mathrm{C_{min}} = \mathrm{MIN}\left((\dot{\mathrm{m}}_{\mathrm{fluid}}\ \mathrm{Cp_{fluid}}), (\mathrm{m_{slab}}\ \mathrm{Cp_{slab}})\right) \tag{4.27}$$

The slab mass multiplied by the slab specific heat is referred to as the slab capacity. Figure 4.5 shows a schematic of the energy balance on the slab / fluid system.

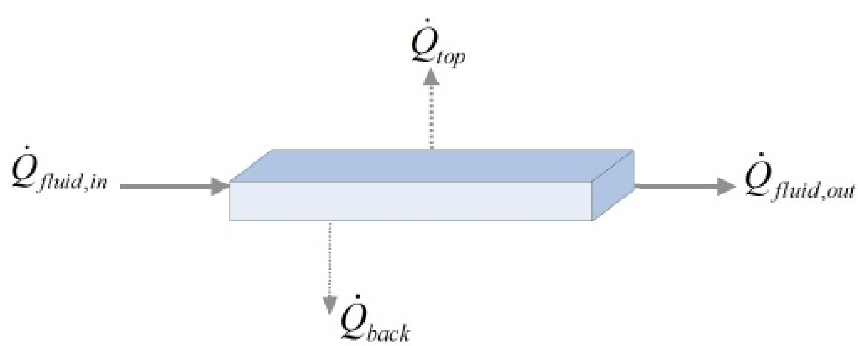

Figure 4.5 Slab / Fluid System Energy Balance

The energy balance can be written mathematically as follows [18]:

$$\mathrm{m_{slab}}\ \mathrm{Cp_{slab}}\ \frac{\mathrm{dT_{slab}}}{\mathrm{dt}} =$$

$$-\mathrm{UA_{top}}\left(\mathrm{T_{slab}} - \mathrm{T_{top}}\right) - \mathrm{UA_{back}}\left(\mathrm{T_{slab}} - \mathrm{T_{back}}\right) + \varepsilon\, \mathrm{C_{min}}\left(\mathrm{T_{fluid,in}} - \mathrm{T_{slab}}\right) \tag{4.28}$$

The differential equations can be solved using two methods which will be explained in chapter 5.

Chapter 5

SIMULATION USING TRNSYS SOFTWARE

5.1 The TRNSYS simulation program

Transient Systems Simulations (TRNSYS) software is a complete simulation program for the simulation of thermal systems. It is used widespread around the world by engineers and researchers to investigate alternative energy applications, from some simple systems such as domestic hot water system to the design and simulation of buildings and their equipment, including residents behavior, control strategies, alternative energy systems (wind, solar, etc.).

TRNSYS is made up of two parts. The first is an engine (called the kernel) that reads and processes the input file, iteratively solves the system, determines convergence, and plots system variables. The kernel also provides utilities that (among other things) determine thermophysical properties, invert matrices, perform linear regressions, and interpolate external data files. The second part of TRNSYS is an extensive library of components, each of which models the performance of one part of the system. The standard library includes approximately 150 models ranging from pumps to multizone buildings, wind turbines to electrolyzers, weather data processors to economics routines, and basic HVAC equipment to cutting edge emerging technologies. Models are constructed in such a way that users can modify existing components or write their own, extending the capabilities of the environment.

After 35 years of commercial availability, TRNSYS continues to be a flexible, component-based software package that accommodates the ever-changing needs of both researchers and practitioners in the energy simulation community.

TRNSYS consists of a suite of programs:

- The TRNSYS simulation Studio,
- the simulation engine (TRNDll.dll) and its executable (TRNExe.exe),
- the Building input data visual interface (TRNBuild.exe), and
- The Editor used to create stand-alone redistributable programs known as TRNSED applications (TRNEdit.exe).

5.1.1 The TRNSYS Simulation Studio

The main visual interface is the TRNSYS Simulation Studio (formerly known as IISiBat). From there, you can create projects by drag-and-dropping components to the workspace, connecting them together and setting the global simulation parameters. The Simulation Studio creates the TRNSYS saves the project information in a TRNSYS Project File (*.tpf). When you run a simulation, the Studio also creates a TRNSYS input file (text file that contains all the information on the simulation but no graphical information).

The simulation Studio also includes an output manager from where you control which variables are integrated, printed and/or plotted, and a log/error manager that allows you to study in detail what happened during a simulation. Generating a skeleton for new components using the Fortran Wizard, viewing and editing the components Proformas (a Proforma is the input/output/parameters description of a component) and viewing output files can all be performed in the simulation studio.

5.1.2 The TRNSYS Simulation Engine

The simulation engine is programmed in Fortran and the source is distributed (see the \SourceCode directory). The engine is compiled into a Windows Dynamic Link Library (DLL), TRNDll. The TRNSYS kernel reads all the information on the simulation (which components are used and how they are connected) in the TRNSYS input file, known as the deck file (*.dck). It also opens additional input files (e.g. weather data) and creates output files. The simulation engine is called by an executable program, TRNExe, which also implements the online plotter, a very useful tool that allows you to view dozens of output variables during a simulation. The online plotter provides some advanced features such as zooming and display of numerical values of the variables at any time step.

5.1.3 TRNSYS add-ons

TRNSYS offers a broad variety of standard components, and many additional libraries are available to expand its capabilities:

- TRNLIB: sel.me.wisc.edu/trnsys/trnlib (free component library)
- TRANSSOLAR libraries: www.transsolar.com
- TESS libraries: www.tess-inc.com

In this study some components have been selected from the Thermal Energy System Specialists (TESS) library in order to get the best efficiency in the system. The components and their detailed descriptions will be explained in next section.

5.2 Modeling of uderfloor heating system using solar energy

For creating the project in TRNSYS simulation studio the desired components should be selected from the list available in the components library. In this study a simple underfloor heating system using solar energy with weather conditions of Larnaca, Cyprus is simulated. The modeling schemes of the systems are designed according to Figure 4.1 as shown in Figures 5.1 and 5.2. In these figures components are connected to each other in the proper way which yields the initial aim described in section 4.1. In Figure 5.1, flat plate collectors are used to utilize solar energy whereas in Figure 5.2 CPC collector replaces flat plate collectors in the system. The components have been chosen from standard and TESS libraries from TRNSYS software which are listed in Table 5.1. Each component has its own properties and some of them have specific mathematical description.

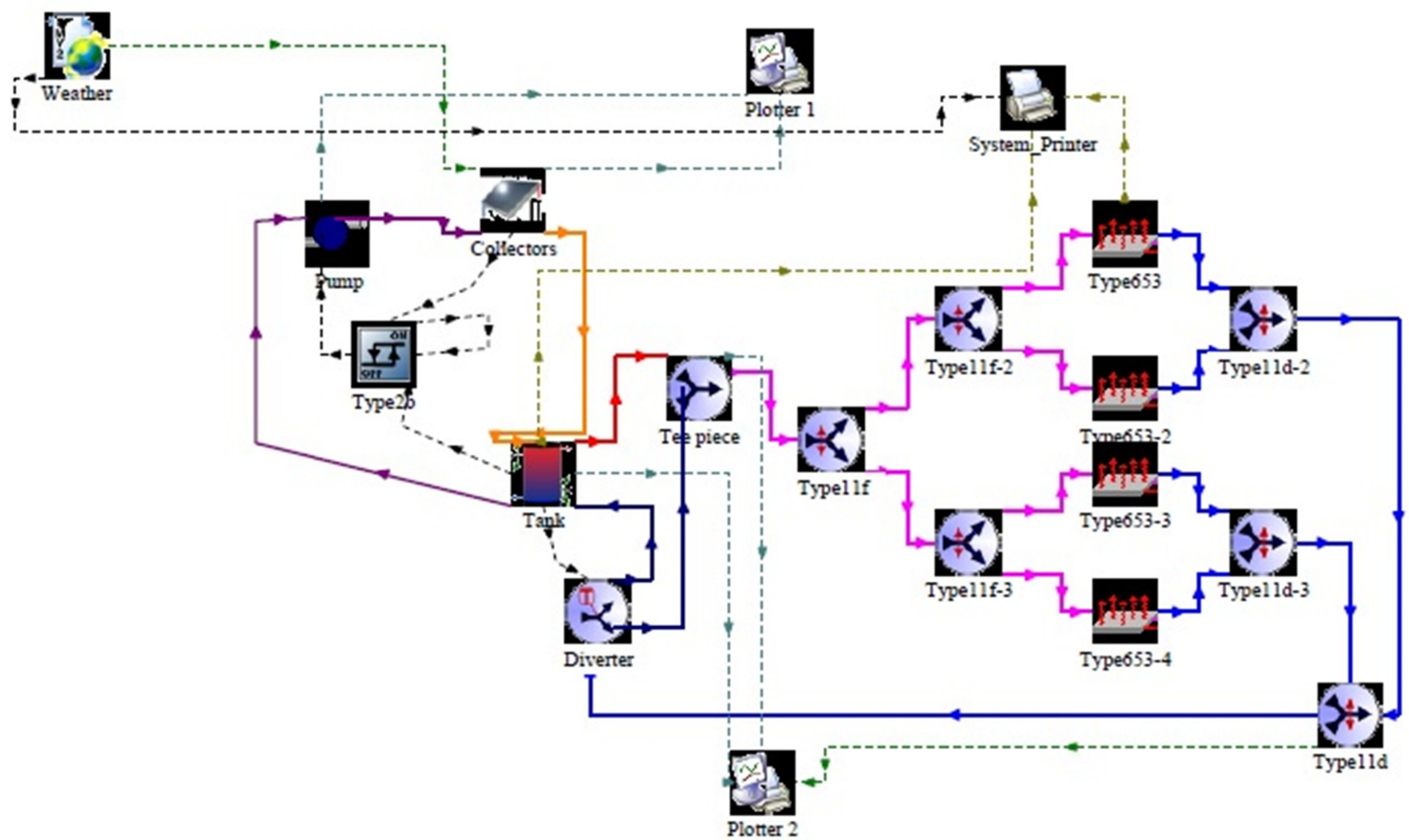

Figure 5.1 Modeling scheme of the system using Flat Plate Collector

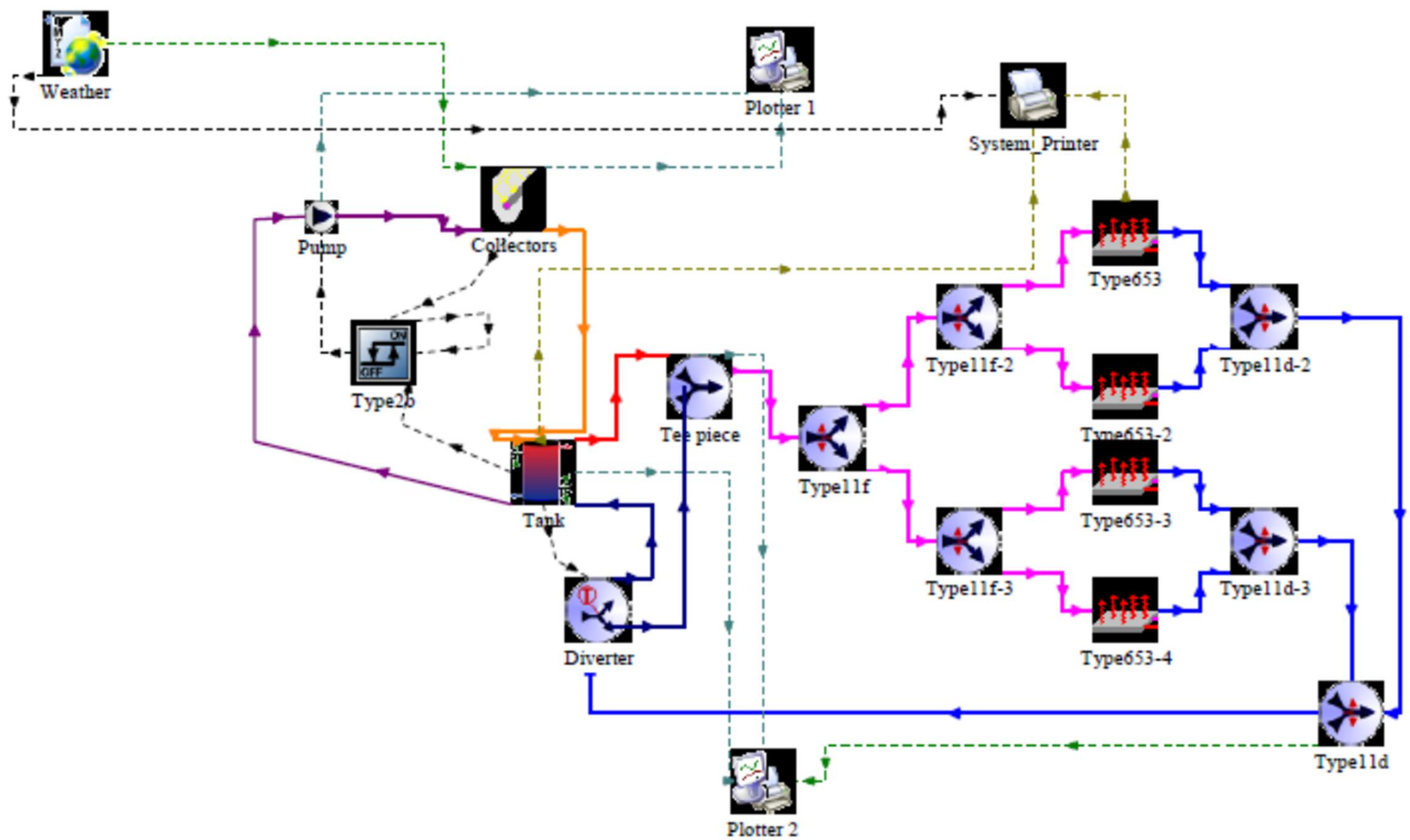

Figure 5.2 Modeling scheme of the system using CPC Collector

Table 5.1 Components used in Simulation Studio [18]

Component (TYPE)	Description
Type109-TMY2	Weather Data Reading and Processing
Type 73	Theoretical Flat-Plate Collector
Type 74	CPC Collector
Type 3d	Single Speed - No Powercoefficients Pump
Type 2b	Differential Controller
Type 4c	Stratified Storage Tank
Type 11b	Tempering Valve
Type 11h	Tee-Piece
Type 11f	Flow Diverter
Type 11d	Flow Mixer
Type 653	Simple Floor Heating System
Type 65a	Online Plotter
Type 25a	Printer

- **See Appendix for the description of each component.**

The system is set up according to Figure 4.1 which is described in section 4.1. In this system, TMY2 is reading the weather information regularly, and checking the solar radiation data to find tilted surface radiation and angle of incidence for an arbitrary number of surfaces. Larnaca climate conditions are used for simulation. The weather data are given on hourly basis. Type 73 and 74 are the models for the thermal performance of a theoretical flat plate collector and CPC Collector, which are shown in

Figures 5.1 and 5.2 respectively. The Hottel-Whillier steady-state model [17] is used for evaluating the thermal performance of both collectors. The parameters of FPC and CPC collectors that are adjusted in the system are shown in Tables 5.2 and 5.3.

Table 5.2 Flat-Plate Collector parameters

Number is series	1
Collector area	8 m^2
Fluid specific heat	4.19 kJ/kg.K
Intercept efficiency	0.80
Incidence angle	45°
Inlet flowrate	125 kg/hr

Table 5.3 CPC Collector parameters

Number in series	1
Collector area	2 m^2
Fluid specific heat	4.19 kJ/kg.K
Collector fin efficiency factor	0.7
Wall reflectivity	0.9
Half-acceptance angle	45°
Absorptance of absorber plate	0.8
Incidence angle	45°
Axis orientation	Transverse plane 90° from the longitudinal
Inlet flowrate	125 kg/hr

Type 2b is the differential controller component which is monitoring TTOP by comparing the comparing ToColl and TBottom. The input properties of this controller are shown in Table 5.4. When TOColl is greater than TBottom, the controller actuates the pump. If the temperature TTOP reaches 100°C, the pump is stopped.

Table 5.4 Differential Controller input parameters

High limit cut-out	100°C
Upper input temperature Th	TOColl
Lower input temperature Tl	TBottom
Monitoring temperature Tin	TTOP

Type 3d is a single speed pump which is either 'on' or 'off' according to the signal received from Type 2b. When the pump is 'on' the flow rate of water will be 125 kg/hr. Type 4c is the stratified tank which fluid is stored in it during the night time and it's also connected to the type 2b for specifying the Tl and Tin. The tank consists of 6 nodes with equal sizes. The specifications for the stratified tank, which is applied in this system, are shown in Table 5.5.

Table 5.5 The stratified storage tank parameters

Tank Volume	1 m^3
Fluid specific heat	4.19 kJ/kg.K
Fluid density	1000 kg/ m^3
Number of temperature levels (nodes)	6
Height of each node	0.3 m
Boiling point	100 °C

Type 11b is the tempering valve which has one inlet and two outlets. Its performance depends on the outlet fluid temperature of the tank to the load (TTOP), in a case that this temperature reaches the desired temperature the tempering valve will transfer proper portion of the cold water to the Tee-piece. Type 11h is the Tee-piece in which two inlet liquid streams are mixed together into a single liquid outlet stream. The outlet fluid from the Tee-piece needs to be transferred to the floor heating slabs of the house, so the fluid needs to be diverted to each floor. Type 11f is the flow diverter, in which a single inlet liquid stream is split according to a user specified valve setting into two liquid outlet streams. On the other hand, the outlet fluids from the floor heating slabs need to be mixed in order to return to the cycle. Type 11d is the flow mixer, in which two inlet liquid streams are mixed together according to an internally calculated control function so as to maintain the mixed outlet temperature at or below a user specified value. Type 653 is the simple floor heating system that operates under the assumption that the slab can be treated as a single lump of isothermal mass and the fluid to slab energy transfer can be modeled using a heat exchanger effectiveness approach. The simple radiant slab parameters are shown in table 5.6. See the Appendix for the definition of each component described in this section.

Table 5.6 Simple radiant slab system [21]

Material	Concrete
Capacitance of slab	7500 kJ/K
Specific heat of fluid	4.19 kJ/kg.K
Slab-to-ambient loss coefficient	500 kJ/hr.K
Slab-to-zone heat transfer coefficient	2000 kJ/hr.K

TRNSYS contains two methods for solving differential equations for simple floor heating system [18]. If the differential equation can be written in the form dT/dt=aT+b, (in which both a and b are constants) then the equation can be solved analytically by calling a Differential Equation solving subroutine. If the equation cannot be written in that, then TRNSYS can rely upon its ability to iterate at a given time step until all connected outputs have converged in order to solve the differential equation. In the case of the lumped capacitance slab, the energy balance can be written in the form dT/dt=aT+b. The “a” and “b” terms are given in equations 5.1a and 5.1b respectively.

$$a = \frac{-\varepsilon\, C_{min} - UA_{zone} - UA_{loss}}{m_{slab}\, Cp_{slab}} \tag{5.1a}$$

$$b = \varepsilon\, C_{min}\, \frac{T_{fluid,in}}{m_{slab}\, Cp_{slab}} + UA_{top} \frac{T_{top}}{m_{slab}\, Cp_{slab}} + UA_{back} \frac{T_{back}}{m_{slab}\, Cp_{slab}} \tag{5.1b}$$

During any given iteration, Type 653 passes the temperature of the slab at the beginning of the time step to the TRNSYS Differential Equation solving subroutine [18]. This routine returns the temperature of the slab at the end of the time step. With the slab temperature at the end of the time step, Type653 then calculates the energy transfers. The energy transferred to the slab from the fluid stream is:

$$\dot{Q}_{in} = Cap_{min}\,(T_{fluid,in} - T_{slab}) \tag{5.2}$$

The energy transferred from the slab to the zone is:

$$\dot{Q}_{zone} = UA_{top}(T_{slab} - T_{top}) \tag{5.3}$$

And the energy transferred from the slab to the sink temperature is:

$$\dot{Q}_{loss} = UA_{back}(T_{slab} - T_{back}) \tag{5.4}$$

The temperature of fluid exiting the slab is given by:

$$T_{fluid,out} = T_{fluid,in} - \frac{\dot{Q}_{in}}{\dot{m}_{fluid}\, Cp_{fluid}} \tag{5.5}$$

During the simulation, the results need to be shown in graphs and tables. Type 65a is the online plotter that is used to display selected system variables while the simulation is progressing. This component is highly recommended and widely used since it provides valuable variable information and allows users to immediately see if the system is not performing as desired. After the time that the simulation has been done, the outputs of the components can be accessed by using Type 25a printer. The printer component is used to output (or print) the selected system variables at specified (even) intervals of time.

Chapter 6

RESULTS AND DISCUSSION

In this chapter, the simulation results obtained by TRNSYS software for modeling an underfloor heating system using solar energy are presented. The characteristics of system components are adjusted to obtain the most optimum results. The aim is to model an underfloor heating system for domestic purposes under the Cyprus weather conditions and comparing the performances of Flat-Plate and CPC solar collectors as the absorbers of solar radiation. The simulations have been accomplished for January because it is one of the coldest months in the year. The results are obtained for five days starting from 11th until 15th January.

The hourly ambient temperature (T_a) of the Larnaca airport in Cyprus (the hypothetical location of the model system) and also total radiation on horizontal through January 11th to 15th are shown in Figures 6.1 and 6.2. It is observed that at night time T_a can be as low as 3-4°C, whereas during day time it is between 12 and 17°C. The solar intensity at noon hours is consistently in the vicinity of 2100 kJ/hr.m^3 throughout the 5 days considered except the 4th day on which a cloudy interruption is observed. The area of Flat-Plate Collector is 8m^2 and the area of CPC collector is 2m^2, the incidence angle for both of them is 45° and also the inlet water flowrate is 125 kg/hr. In order to compare the performance of the collectors, all the characteristic of other components of the system are fixed. The temperature variations (in $^{\circ}$C) of inlet and outlet water flow are shown in Figures 6.3 and 6.4.

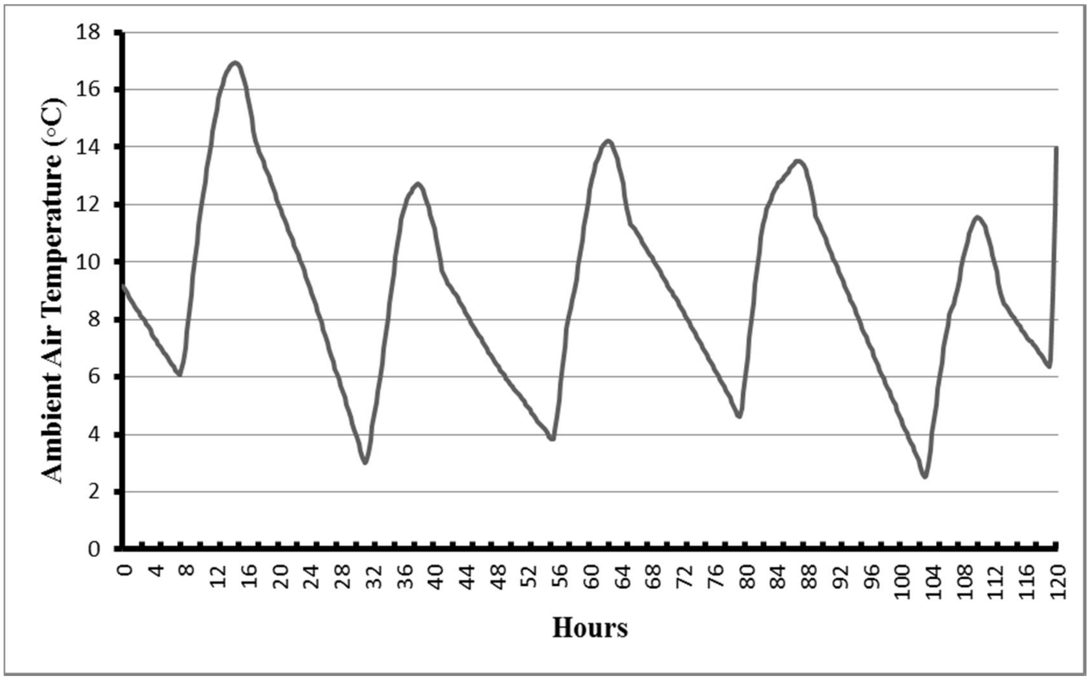

Figure 6.1 Ambient air Temperature variations on January 11th until 15th

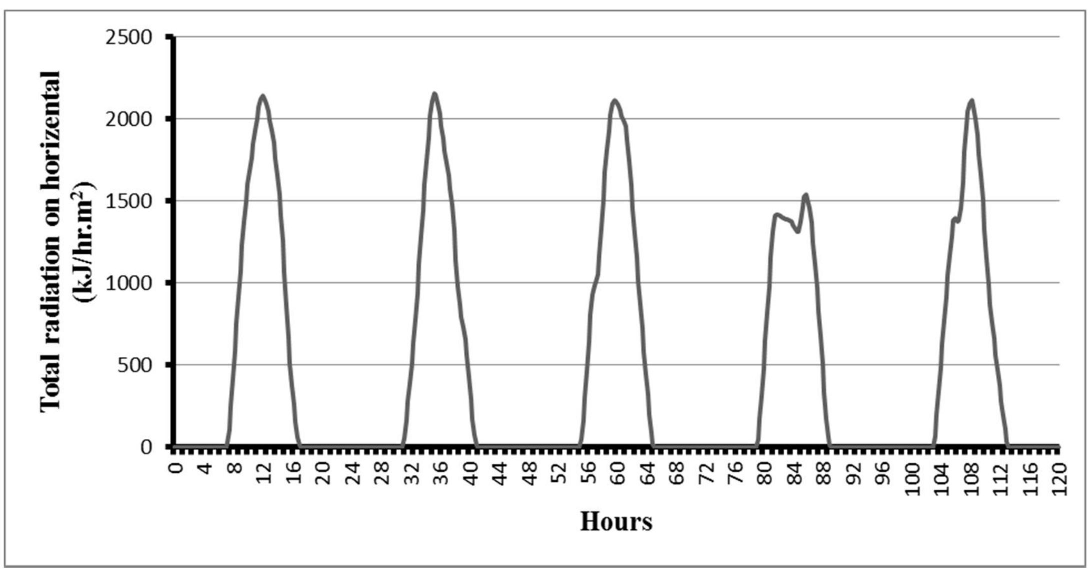

Figure 6.2 Total radiation on horizontal on January 11th until 15th

Figure 6.3 The hourly variation of inlet and outlet water flow temperature-Flat Plate Collector-11th until 15th of January

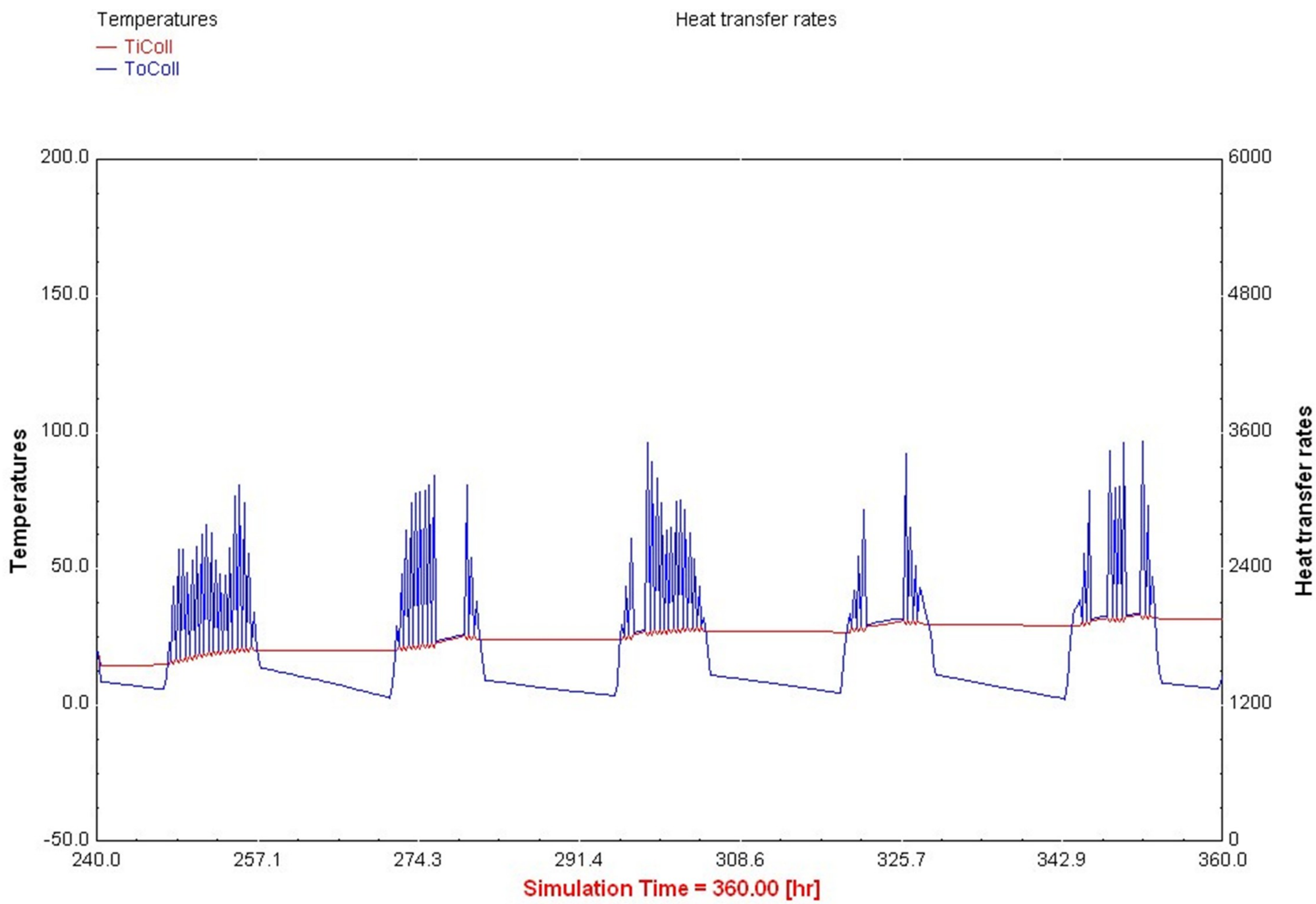

Figure 6.4 The hourly variation of inlet and outlet water flow temperature -CPC Collector-11th until 15th of January

The obtained result showed that during the day time the water flow temperature will increase by absorbing the sun radiation with solar collectors, and the system will stop performing during night time and it's the time that the outlet water from collectors will be stored in storage tank. The outlet fluid temperature of the Flat-Plate collector is between 25-75°C, whereas for CPC collector this range is between 25-95°C. So, concerning the limitation of the desired space that can be used to install the system, it will be more preferable to use CPC collectors.

For better understanding the performance of Flat-Plate and CPC collector, one day has been chosen, i.e. 13th January. In Figure 6.5 the solar radiations on horizontal and on tilted surface are shown, while the obtained results from solar collectors are shown in Figures 6.6 and 6.7.

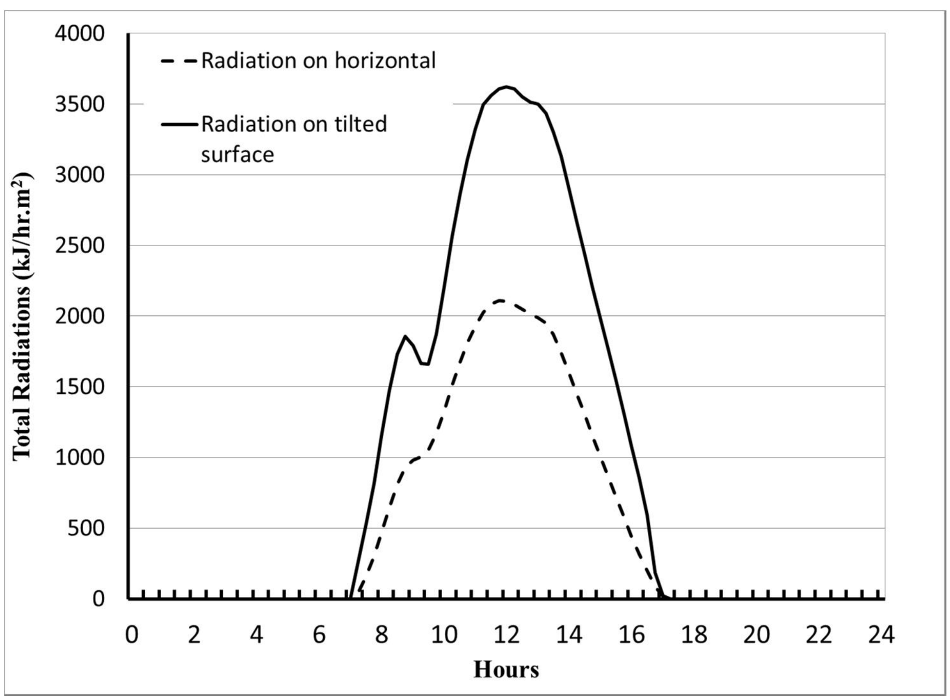

Figure 6.5 The hourly variation of total radiation on horizontal and tilted surface

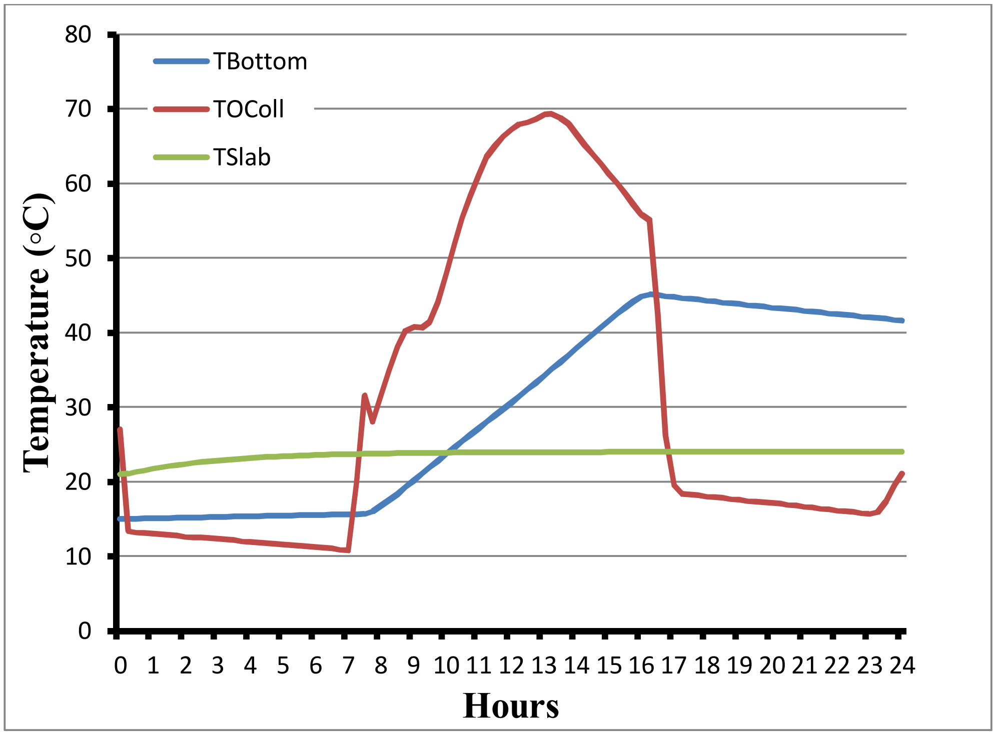

Figure 6.6 The hourly variation of TBottom,TOColl,TTOP and TSlab-Flat-Plate Collector-13th of January

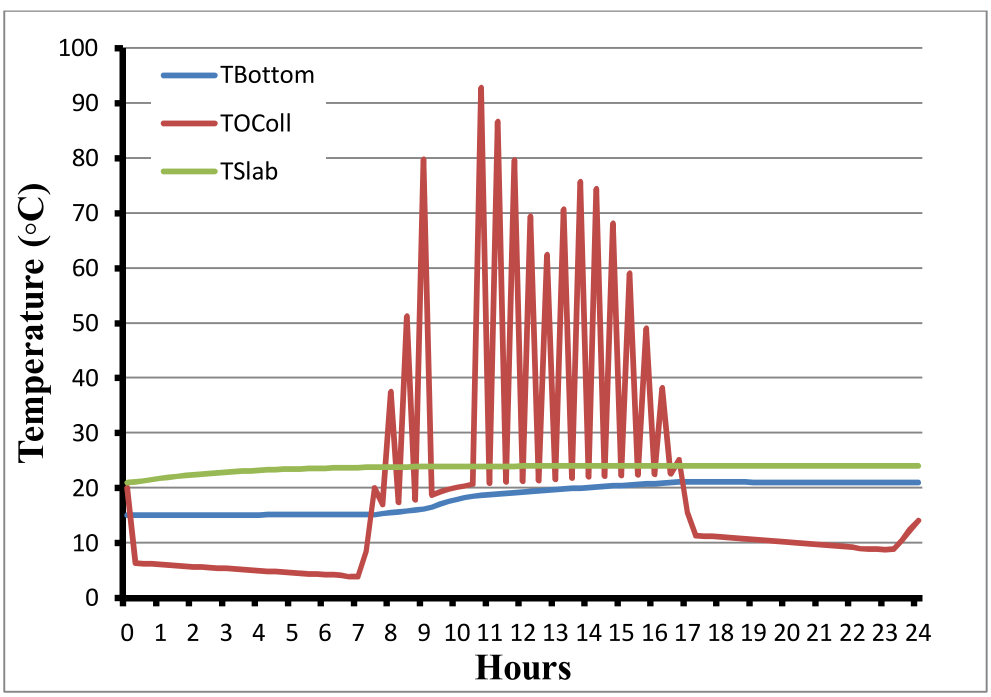

Figure 6.7 The hourly variation of TBottom,TOColl,TTOP and TSlab-CPC Collector-13th of January

The results show that, in the night time when there is no sun radiation, the temperature of the fluid will decrease due to the thermal losses and heat transfer rate. In this time, the tank, which is working 24 hours a day, will provide the desired heat which can yield the proper performance of the underfloor heating system.

The differential controller which is working in this system is monitoring the temperature of outlet fluid from the tank (TTOP). The controller investigates the temperature difference between Th and Tl, and compare it to the upper and lower dead bands. In this regard, the pump will receive the proper signal from the controller in order to perform accordingly.

The temperature of different nodes and the water outlet temperature (in $^{\circ}C$) from the stratified storage tank that will enter to the underfloor heating loop can be seen for both collectors in Figures 6.8 and 6.9 respectively.

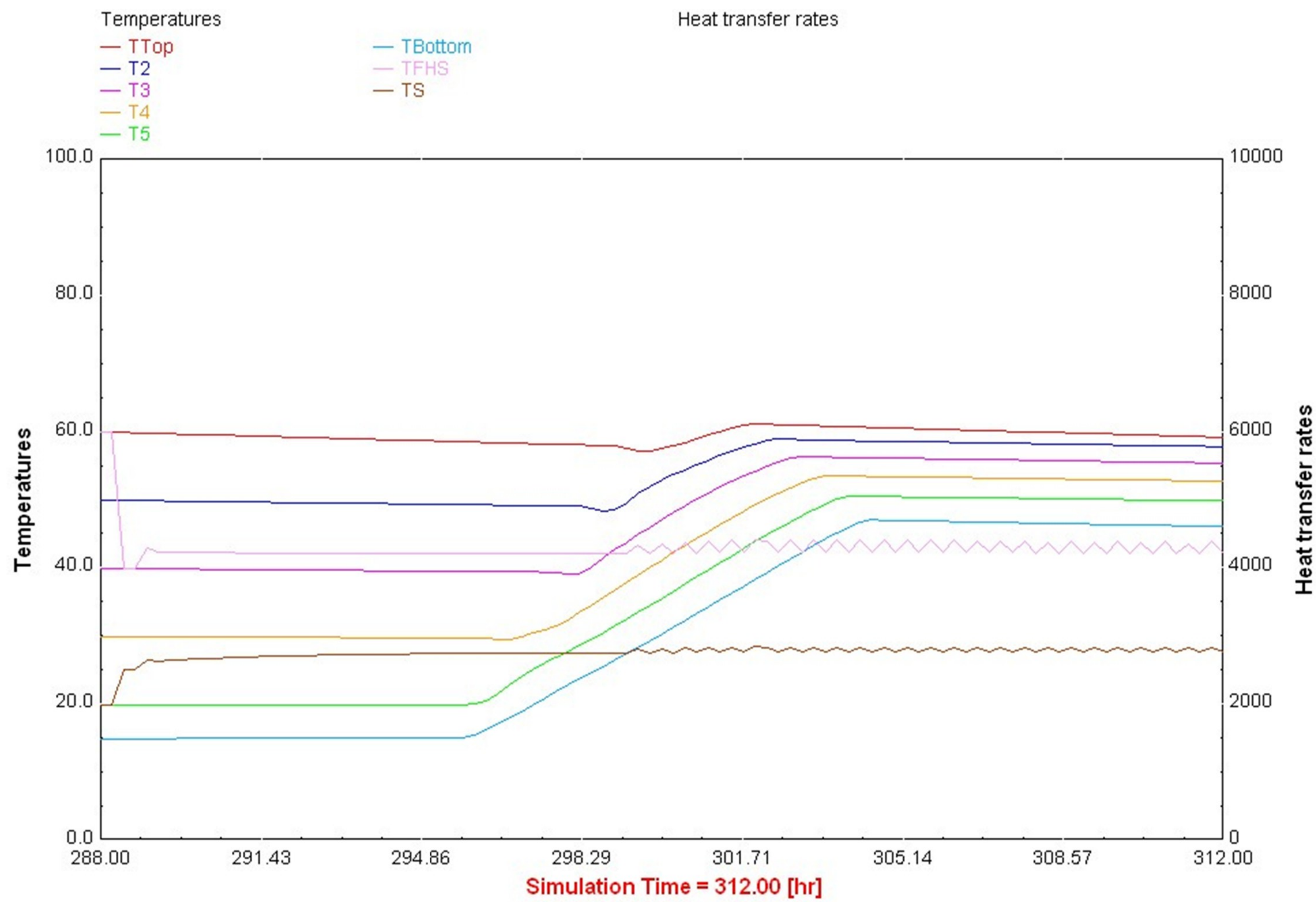

Figure 6.8 The hourly temperature variation of different nodes of the tank for Flat-Plate Collector system-13th January

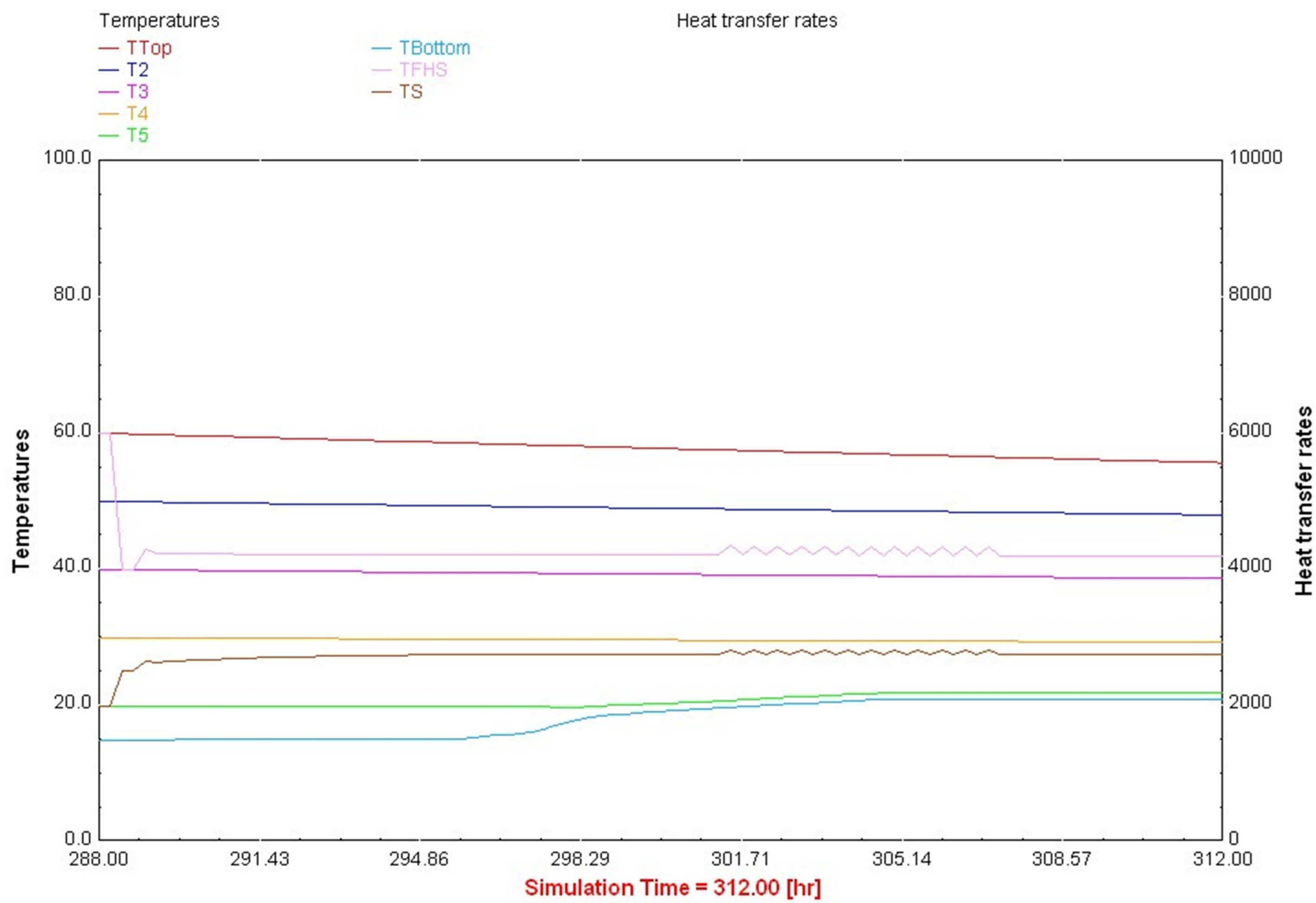

Figure 6.9 The hourly temperature variation of different nodes of the tank for CPC Collector system-13th January

The outlet flow from the tank is designed to be mixed with the water returning from theslabs. This is achieved by using a diverter before the tank which is connected to a Tee-piece on the supply. The TFHS is specified to be approximately 45°C, so the adjustments of components' characteristics in this part need considerable attention. These adjustments include entering the proper values for the input parameters of storage tank, Tee-piece and tempering valve (diverter). If the temperature TTOP is proper for the system performance the tempering valve will transfer the TS to the tank, otherwise it will transfer the TS to the Tee-piece in order to decrease the temperature TTOP. The flow with the desired temperature will enter the floor heating slabs which it is assumed that the model is a 4 floors house which one slab unit is applied for each of them.

The variations of inlet and outlet water flow temperature into the slabs are shown in Figure 6.10. The outlet flowrate from the slabs then will be transferred to the cycle using a flow mixer and the performance will repeat again.

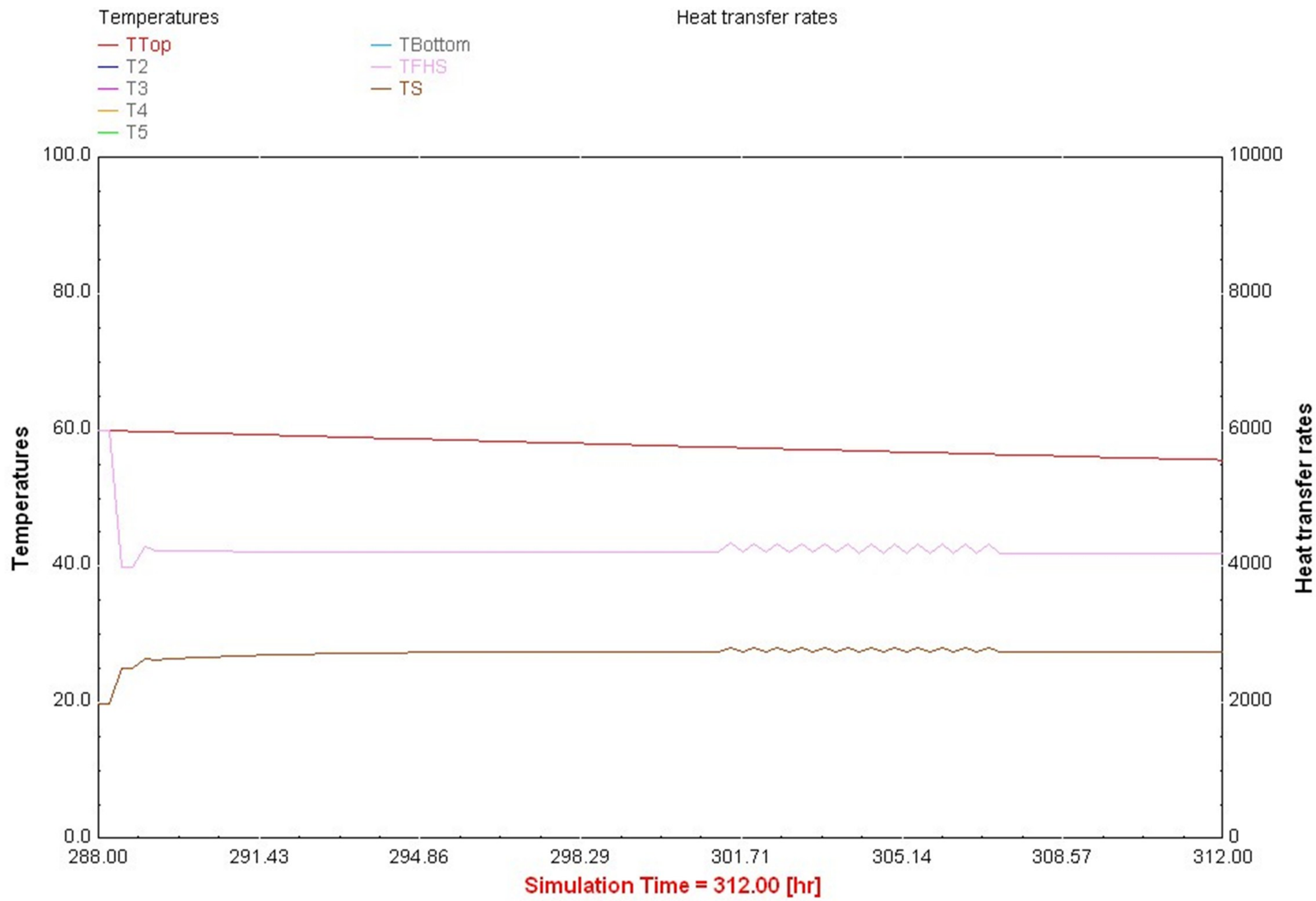

Figure 6.10 The hourly variations of inlet and outlet water flow temperature into the slabs-13th Januarv

Chapter 7

CONCLUSION

The aim of this study was to simulate an underfloor heating system using solar energy in North Cyprus with the use of TRNSYS software. The hourly investigations are performed for five days in January (11^{th} until 15^{th}) which are the coldest days in winter. The performance of two types of collectors, Flat-Pate collector and CPC collector, were compared under the same condition.

It is observed that, using CPC collector increase the fluid temperature between 25 to 95°C, whereas for Flat-Plate collector it's between 25 to 75°C. Although Flat-Plate collectors are more common for domestic applications, but the space requirements also should take into consideration. As these types of collectors are not commonly used in high temperature applications, so the size array should be optimized. The simulations suggest that a 2 m^2 CPC collector can perform satisfactorily to match the job of 8 m^2 Flat-Plate collectors. In order to provide the required temperature that can yield the proper performance of the underfloor heating, the outlet fluid will store in the storage tank. The differential control has a critical role in the solar thermal loop, which is investigating the inlet and outlet temperature of the solar collectors. The on/off signals will control the performance of the system by evaluating the temperature difference between the high and low temperature and compare them with the dead band limitation.

So, when the solar collectors increase the temperatures beyond these limitations, the control signal will stop the pump.

The obtained result show that outlet fluid temperature of the tank also has to be controlled as the inlet fluid temperature of the floor heating system cannot reach more than 45°C. In this case, the tempering valve which in monitoring this temperature will make the required balance. The inlet fluid of the slabs will increase the slab's temperature, which is considered uniform in all parts of it, and the slab then eventually transfer this heat to the environment through heat transfer. Operation temperature of solar heating system makes the usage of a radiant floor to transfer heat into the conditioned spaces appropriate. The estimated slab temperature is approximately 24°C which is compatible with the standards, consequently the fluid outlet temperature is observed to be approximately 25°C. It is concluded that CPC collector which have better performance with smaller required space, can be more effective in this system.

In the future work, it is desired to investigate an economic analysis of the system in North Cyprus. Also, other types of solar collectors can be applied in the system in order to compare their performances to the FPC and CPC collectors as well. The investigation can be expanded to yearly view, so the effectiveness of the collectors can be compared for winter and summer.

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APPENDIX

Appendix: TRNSYS Components' descriptions

- **Type109-TMY2**

The main aim of this component is to read weather information at regular time which is available from a file, inserting it to a desired unit system and checking the solar radiation data to find tilted surface radiation and angle of incidence for an arbitrary number of surfaces. In this version, Type 109 process weather data file in the standard TMY2 format. This format is used by the National Solar Radiation Data Base (USA) but TMY2 files can be provided from many programs, such as Meteonorm.

In this study, Larnaca climate conditions are used for simulation. In the World Meteorological Organization (WMO) the identification number of Larnaca is 176090. The weather data are given on hourly basis.

- **Type 73-Theoretical Flat-Plate Collector**

The main of this component is to provide a model for the thermal performance of a theoretical flat plate collector. This model provides for the theoretical analyses of a flat plate. The Hottel-Whillier steady-state model [17] is used for evaluating the thermal performance.

- **Type 74-CPC Collector**

The main aim of this component is to provide the models for analyzing the thermal performance of a CPC collector. The model provides for the theoretical analysis of compound parabolic concentrators (CPC). The Hottel-Whillier steady-state model [17] is used for evaluating the thermal performance.

- **Type 3d-Single Speed - No Powercoefficients Pump**

This pump model computes a mass flow rate using a variable control function, which must have a value between 1 and 0, and a fixed (user specified) maximum flow capacity. In this instance of Type3, pump power consumption is simply set to the rated value whenever the control signal indicates that the pump is in operation. A userspecified portion of the pump power is converted to fluid thermal energy. NOTE: This component sets the flow rate for the rest of the components in the flow loop by multiplying the maximum flow rate (Parameter 1) by the control signal (Input 3). The mass flow rate input of this component is only for visualization purposes; it is not used except for convergence checking.

- **Type 2b-Differential Controller**

The on/off differential controller generates a control function which can have a value of 1 or 0. The controller is normally used with the input control signal connected to the output control signal, providing a hysteresis effect. However, control signals from different components may be used as the input control signal for this component if a more detailed form of hysteresis is desired.

A high limit cut-out is included with this controller for safety consideration. In this case, the control function will be set to zero if the high limit condition is exceeded. This controller is not restricted to sensing temperatures, even though temperature notation is used. This controller instance uses unit descriptions of degC so that it is readily usable as a thermostatic differential controller. This instance of the Type2 controller is intended for use with the standard TRNSYS SOLVER 0 (Successive Substitution).

- **Type 4c-Stratified Storage Tank**

The thermal performance of a fluid-filled sensible energy storage tank, subject to thermal stratification, can be modelled by assuming that the tank consists of N (N <= 15) fully-mixed equal volume segments. The degree of stratification is determined by the value of N. If N is equal to 1, the storage tank is modelled as a fully-mixed tank and no stratification effects are possible. This instance of Type 4 models a stratified tank having variable inlet positions such that entering fluid may be added to the tank at a temperature as nearly equal to its own temperature as possible. The node sizes in this instance need not be equal. Temperature deadband on heater thermostats are available. This instance further assumes that losses from each tank node are equal and does not compute losses to the gas flue of the auxiliary heater.

- **Type 11b-Tempering Valve**

The use of pipe or duct tee-pieces, mixers, and diverters which are subject to external control is often necessary in thermal systems. This component has ten modes of operation. Modes 1 through 5 are normally used for fluids with only one important property, such as temperature. Modes 6 through 10 are for fluids, such as moist air, with two important properties, such as temperature and humidity. This instance of the Type11 model uses mode 4 or mode 5 to model a temperature controlled liquid flow diverter. In mode 4 the entire flow stream is sent through outlet 1 when Th < Ti. In mode 5, the entire flow stream is sent through outlet 2 under these circumstances.

- **Type 11h- Tee-Piece**

This instance of the Type11 model uses mode 1 to model a tee piece in which two inlet liquid streams are mixed together into a single liquid outlet stream.

- **Type 11f- Flow Diverter**

This instance of the Type11 model uses mode 2 to model a flow diverter, in which a single inlet liquid stream is split according to a user specified valve setting into two liquid outlet streams.

- **Type 11d-Flow Mixer**

This instance of the Type11 model uses mode 3 to model a controlled flow mixer in which two inlet liquid streams are mixed together according to an internally calculated control function so as to maintain the mixed outlet temperature at or below a user specified value.

- **Type 653- Simple Floor Heating System**

This component models a simple radiant slab (floor heating or cooling) system that operates under the assumption that the slab can be treated as a single lump of isothermal mass and the fluid to slab energy transfer can be modeled using a heat exchanger effectiveness approach.

- **Type 65a-Online Plotter**

The online graphics component is used to display selected system variables while the simulation is progressing. This component is highly recommended and widely used since it provides valuable variable information and allows users to immediately see if the system is not performing as desired. The selected variables will be displayed in a separate plot window on the screen. In this instance of the Type65 online plotter, data sent to the online plotter is automatically printed, once per time step to a user defined external file. TRNSYS supplied unit descriptors (kJ/hr, kg/s, degC, etc.), if available, will be printed along with each column of data in the output file.

- **Type 25a-Printer**

The printer component is used to output (or print) selected system variables at specified (even) intervals of time. In this mode, TRNSYS supplied units descriptors (kJ/hr, degC, W, etc.) if available, are printed to the output file along with each column heading. Output can be printed in even time intervals starting relative to the simulation start time or can be printed in absolute time. If relative printing is chosen with a one hour print interval and the simulation starts at time 0.5, values will be printed at times 0.5, 1.5, 2.5, etc. If absolute printing is selected, for the same simulation, values will be printed at times 0.5, 1.0, 2.0, 3.0, etc. Type25 is also able to print simulation information as a header to the output file (name of input file, and time of simulation run). It is further able to append new data to an existing file or can be set to overwrite the existing file.