COMPUTER SIMULATION OF SOLAR AIDED HEAT PUMP SYSTEMS WITH UNDERGROUND SPHERICAL THERMAL ENERGY STORES

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By

Recep YUMRUTAŞ

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Approval of the Graduate School of Natural and Applied Sciences.

Prof. Dr. Mazhar ÜNSAL
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of science in Mechanical Engineering Department.

Assoc. Prof. Dr. Sedat BAYSEÇ
Chairman of the Department

We certify that we have read this thesis and that in our opinion. It is fully adequate, in scope and quality, as a thesis for the degree of Master of Science in Mechanical Engineering Department.

Prof. Dr. Mazhar ÜNSAL
Supervisor

Examining Committee in Charge:

Prof. Dr. Ömer T. GÖKSEL

Prof. Dr. Mazhar ÜNSAL

Assist. Prof. Refik KAYALI

Assist. Prof. Şükrü KARATAŞ

Assist. Prof. Ali Rıza TEKİN

ABSTRACT

COMPUTER SIMULATION OF SOLAR AIDED HEAT PUMP SYSTEMS WITH UNDERGROUND SPHERICAL THERMAL ENERGY STORES

YUMRUTAŞ, Recep

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This study contains two computational simulation models for predicting long term performance of solar aided heat pump systems with spherical thermal energy stores.

Two models are developed for prediction of the transient temperature field outside an underground spherical thermal energy store. Solutions of the transient heat transfer problems are obtained by applications of a similarity transformation and a complex finite Fourier transformation. Solutions obtained are used to investigate the long term performance of the systems under consideration. Two interactive computer programs were developed in Fortran 77. The computer programs are utilized to find the transient storage temperature and long term system performance. Results obtained from execution of the programs are presented in graphical form .

Key words : Solar energy, heat pump, thermal storage, solar heating

ÖZET

YERALTI KÜRESEL TANKLARDA ENERJİ DEPOLAMALI GÜNEŞ ENERJİSİ TAKVİYELİ ISI POMPASI SİSTEMLERİNİN BİLGİSAYARDA SİMÜLASYONU

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Bu çalışma güneş enerjisinin yeraltında küresel tanklarda mevsimlik depolanması ve ısı pompası eşliğinde konutların ısıtılmasında sistem yıllık verimini incelemek için iki farklı simülasyonu içermektedir.

Yeraltı küresel ısı deposu sıcaklığını hesaplamak için iki farklı model geliştirilmiştir. Isı geçişi problemine benzetişim ve sonlu Kompleks Fourier Dönüşümü teknikleri uygulayarak çözümler elde edilmiştir. Fortran 77 dilinde etkileşimli proğramlar hazırlanmış ve elde edilen bu çözümler sistemin verimini incelemek için kullanılmıştır. Bilgisayar simülasyonundan elde edilen sonuçlar grafiklerle sunulmuştur.

Anahtar kelimeler : Güneş enerjisi, ısı pompası, ısıl depolama, güneşle ısıtma.

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LIST OF SYMBOLS

A	Surface area of sphere
A_c	Collector area
A_o	Parameter defined on page 32
A_n	Parameter defined on page 32
a	Radius of spherical store
a_n	Parameter defined on page 32
B_n	Parameter defined on page 32
b_o	Incidence angle modifier factor
b_n	Parameter defined on page 32
c	Specific heat of soil
C	$1/(4\pi a k T_\infty)$
C_B	Bond conductance
c_w	Specific heat of water
COP	Coefficient of performance of heat pump
D	Outside tube diameter
D_i	Inside tube diameter
F	Fin efficiency factor
F'	Collector efficiency factor
F_R	Collector heat removal factor
G_S	Solar constant
H	Amplitude of dimensionless house heat load
h	Convective heat transfer coefficient inside collector tubes
$f_{h,i}$	Annual distribution function of house heat load.
$f_{s,i}$	Annual distribution function of solar energy
I	Hourly radiation on a horizontal surface
I_d	Hourly diffuse radiation on a horizontal surface
I_o	Hourly extraterrestrial radiation on a horizontal surface

I_T Hourly radiation on a tilted surface

k Thermal conductivity of soil

k_c Thermal conductivity of collector plate

k_T Hourly clearness index

m Parameter defined on page 36

$\dot{m}$ Total collector mass flowrate

n_d n^{th} day of year

p $\rho_w c_w/(3\rho c)$

Q Net energy charge rate to the store

Q_h Rate of heat loss from house

Q_{hy} Annual dimensionless house heat load

Q_{ls} Annual dimensionless energy loss

Q_{sy} Annual dimensionless solar heat gain

Q_{st} Annual dimensionless stored energy

Q_p Instantaneous energy extracted by heat pump

Q_s Solar heat gain

Q_u Instantaneous useful heat gain of solar system

Q_y Annual dimensionless net heat addition to the thermal store

q $Q/(4\pi akT_{\infty})$

q_i Value of q during i^{th} month

q_h $Q_h/(4\pi akT_{\infty})$ dimensionless solar heat gain rate

q_s $Q_h/(4\pi akT_{\infty})$ dimensionless rate of heat loss from the house

R_b Ratio of beam radiation on a tilted surface to that on a horizontal surface

R' Ratio of radiation on a tilted surface to that on horizontal surface

r radial coordinate

S Amplitude of dimensionless solar energy gain rate

t	Time
t_n	Time at n^{th} hour
T	Temperature of soil surrounding the thermal store.
T_a	Outside air temperature
T_h	Temperature of fluid in load side heat exchanger.
T_i	Inside air temperature
T_o	Collector inlet fluid temperature.
T_w	Temperature of water in the thermal store.
T_∞	Far field deep ground temperature
u	$(UA)_h/(UA)_{he}$
$(UA)_h$	UA- value of the house
$(UA)_{he}$	UA- value of the load side heat exchanger
V_w	Volume of store
w	$W/(UA)_h T_\infty$), dimensionless heat pump power
W	Heat pump power
x	r/a
α	Thermal diffusivity
β_p	Heat pump coefficient
β	Collector slope
ρ	Density of soil
ρ_o	Monthly average reflectivity of earth
ρ_w	Density of water in the store
τ	$\alpha t/a^2$, dimensionless time
$(\tau\alpha)$	Transmittance-absorbtance product
$(\tau\alpha)_n$	Normal transmittance-absorbtance product
ϕ	$(T-T_\infty)/T_\infty$, dimensionless temperature
ϕ_i	$(T_i-T_\infty)/T_\infty$, dimensionless design inside air temperature
ϕ_a	$(T_a-T_\infty)/T_\infty$, dimensionless ambient temperature
ϕ_L	Latitude angle

ϕ_w	$(T_w-T_\infty)/T_\infty$, dimensionless water temperature in the store
η	Parameter defined on page 18
η_c	Collector efficiency
δ	Declination angle
ϕ_L	Latitude angle
δ_t	Thickness of the collector plate
ω_1	Hour angle at time 1
ω_2	Hour angle at time 2
ω_s	Sunset hour angle
Y	α(one year)/a^2, dimensionless time for one year
Ø	Angle of incidence
$Ø_z$	Zenith angle

CHAPTER 1

INTRODUCTION

Energy is an important need for human life. Energy requirement increases with increasing population. 75 percent of energy produced in the world is obtained from fossil fuels which are petroleum and coal and these fuels have negative effects on human health.

Turkey and many other countries spend a great amount to produce fossil fuels. This has negative effects on the economy. Increased use of new energy sources will decrease fossil fuel consumption. Solar energy is an alternative energy source which can be used for domestic space and hot water heating and for industrial process water heating. Increasing interest has been focused on long-term heat storage of solar energy in resent years. Energy storage is useful in compensating the mismatch between energy consumption and production which are out of phase. Availability of excess solar energy with high outdoor air temperature in summer months and existence of solar energy with low outdoor air temperature in the winter season makes for a phase difference between building energy demand and solar energy supply. This situation marks the significance of the storage of solar energy during summer months for use in winter months. There are many examples of physical space for seasonal thermal energy storage. Some examples are boreholes in rock, rock caverns, underground steel tanks, abandoned mines, aquifers, open pits on earth, abandoned hydropower tunnels,duct storage in the ground, underground concrete tanks and excavated bedrock. The geological structure of earth surrounding the store has effects on the system performance and many types of physical space for seasonal thermal energy storage have been under investigation. Investigations of the long-term performance of solar aided heating and thermal energy storage systems increased in number in search for better utiliability of solar energy for space and hot water heating applications. It is important to determine availability as well as technical and economical feasibility of combined heating and storage systems. Many previous researchers focused their studies on this subject. But until now, system simulation models available for predicting the long-term unsteady behavior of seasonal thermal energy storage systems are not sufficiently well developed. The storage of solar energy is important for future success of solar energy utilization.

It appears that much research is required for the development of advanced mathematical models and computer codes for seasonal thermal energy storage systems.

The purpose of this investigation is the determination of the long-term performance of solar aided space heating system with underground spherical thermal energy stores and heat pump systems using a digital computer.

Two computer models are developed in this study. One computer model is based on use of hourly data, while the second model is based on monthly average data for predicting annual performance of a solar aided heating system for buildings in Gaziantep. Flowchart of the computer simulation models is shown in the Appendix. Annual storage systems rely on a large storage tank that uses water as the storage medium. The storage tank is charged by solar heat during summer and the stored heat is used for the winter load. Collection of solar heat continues during the winter.

The fundamental design considerations which effect the performance of the combined system considered in this study are storage volume, collector area, collector slope, type of earth surrounding the store and the number and the heat load of houses. Effects of design considerations on system performance are estimated and discussed in Chapter 5

A literature survey showed that long- term performance of a system have not been studied in our country. In particular, a previous study on the long term performance of solar aided heat pump systems with a spherical thermal energy store was not found. Prediction of performances of solar aided heat pump systems with cylindrical thermal energy stores are available in the literature. There are some simulation programs for predicting of the long-term performance of solar aided heating systems with thermal energy stores. Commonly known simulation computer programs are TRNSYS,NORSOL, KERCONT,SUPERSOL,MINSUN, OPENSOL, etc.

The second chapter consists of a literature survey on the subject under investigation. Third chapter includes the computational simulation model for determining the long-term performance of solar aided heat pump systems with a spherical thermal energy store. Monthly average solar radiation data on a tilted surface and monthly average outdoor air temperature for Gaziantep are utilized in the third chapter. The fourth chapter contains prediction of hourly radiation on a tilted surface and also a computational simulation model for determining performance of the system by using computed hourly radiation on a tilted surface for Gaziantep. The fifth chapter includes results and discussions. The sixth and seventh chapters contain conclusions and recommendations for further study.

The storage is considered as an integral subsystem of a community solar aided heating system. The computer program is applied to simulate the long-term performance of solar aided heating systems following a discussion of the details of the two models.

CHAPTER 2

LITERATURE SURVEY

Seasonal storage of thermal energy in solar heating systems has been under investigation since the mid of the 20th century. Research groups have searched the technical advantages and utizability of large-scale seasonal storage of thermal energy systems. Previous developments about seasonal storage of thermal energy in solar heating systems are summarized in this chapter.

J.E. Braun, S.A. Klein and J.W. Mitchel[1] studied several aspects of seasonal thermal storage for space heating. They considered water as the storage medium. They investigated relationships between collector area storage volume, and system performance using the transient simulation program " TRNSYS". They also investigated the effects of the load heat exchanger size, tank insulation, collector slope, and year to year weather variations on system design. It was shown in their study that the performance of a space heating system depends on both collector area and storage volume. Trade-offs between collector area and the storage volume requirement for a fixed system performance were found to be location dependent. Greater reductions in collector area with increasing storage capacity were found to yield better system performances. They found the optimum collector slope for space heating systems employing seasonal storage to be approximately. equal to the latitude.

P. D. Lund [2] studied optimization of solar heating systems with an electric-driven heat pump and seasonal thermal energy storage. His optimization method comprises thermal, economic and system control analysis. He derived thermal and economic optimal conditions for collector area and storage volume and also investigated effects of different collector types and building load. He used flat plate and concentrating collectors when in his optimization. He developed a numerical computer program,NORSOL,which was designed for predicting the long-term behavior of community solar heating systems. He found that choice of optimal conditions results in reduction in collector and storage cost per house,an increase in life-cycle cost, higher solar fractions for communities with flat-plate collectors, a reduction in collector area and storage volume was observed when concentrating collectors were utilized in place of flat plate collectors because of better thermal collector operational efficiency and also observed that a shift to larger storage sizes per house when moving 50 to 500 unit communities because of rapidly decreasing storage unit costs at large volumes and he improved the collector efficiency as the storage is at a lower temperature.

Jay Shelton[3] studied thermal interaction between underground heat storage and the surrounding ground. An analytic steady-state solution and transient numerical solutions were presented and discussed for an underground heat storage which was of hemispherical geometry. He assumed the ground was homogeneous and an isotopic thermal conductor. Furthermore, he temporarily assumed that temperature and heat flow patterns have only radial dependence. The shape of the storage region was presumed hemispherical with the flat plate face upwards and radial distances were measured from the center of this face. He investigated the performance of both small and large systems for two initial conditions representing a cold start and a hot start with respect to heat loss to the ground. The cold start assumed the system has not previously been in operation so that the ambient ground temperature assumed to be 10 ^{0}C and the hot start assumed the surrounding ground is at its maximum temperature, which would be achieved by maintaining the storage region at its maximum temperature. The largest loss and gain occurred for the system in a rock bed or earth where the ratio of storage dimensions to storage capacity was maximum. With cold start the system was found to loose 21 percent of its collected heat to the ground. With a hot start the storage region gained heat an amount of 10 percent of the collected solar heat from the ground.

P. D. Lund [4] developed an analytical method to investigate the effects of storage operational strategy on the performance of a seasonal thermal storage with a solar heating system and with water storage. He investigated effects of system operating strategy on the thermal performance of a solar heating system with thermal seasonal storage. He derived analytical formulas to account for these effects, prepared a numerical simulation computer program (SUPERSOL) and compared simulation with his analytical model. Result from the computer program showed a yearly solar fraction of 0.8 at optimum storage control strategy.

P. D. Lund and Kangas [5] performed a net energy analysis of district solar heating with seasonal heat storage for Finnish weather conditions. They considered a solar heating system size to meet most of the energy demand for dwellings excavated into rock and they choosed the solar collector area as the main variable in the energy analysis. Holes drilled into rock were used in connection with heat pumps to decrease losses from water storage. They evaluated the yearly energy output of district solar heating system by computer simulations. The computer simulation model was based on numerical solution of energy balance equations. It was used to calculate the temperature distribution in the rock with a finite difference method assuming rotation symmetry. According to their simulation, the gross output of a district solar heating systems both on solar collector area and an heat storage capacity. The annual coefficient of performance was above 3 and increased solar fraction was found to decrease the energy ratio.

P. D. Lund [6] discussed effects of site location on the sizing of main components of a central solar heating system with seasonal storage (CSHPSS). He employed a fast iterative model where the total system performance was described for unconstrained storage conditions and by balance equations. The model described in the study implemented in the FORTRAN program SOLCHIPS. CSHPSS performance was found to vary with geographical location, load parameters and site. The relative storage capacity increased almost linearly with respect to the solar fraction. Optimum normalized storage capacity requirement for the system studied decreased by about 0.6 m^3/m^2 for every degree of latitude when moving northwards. Unit-cost of energy produced by a CSHPSS remains relatively constant up to about 55 ^{0} C North latitude where after strong increase in solar energy cost was found.

P. D. Lund [7] developed a new method for determining the optimum size of storage volume and collector area of solar heating system with a seasonal storage. His solution is based on an iterative approach in which storage volume and collector area are obtained from the yearly system energy balance and the storage balance equations. A basic CSHPSS equation was incorporated in a FORTRAN 77 program (SOLCHIPS) and the program was written on an IBM P.C. compatible computer. He found the storage heat losses to be directly proportional to storage perimeter area and to the average storage temperature. Also there was seen deviation that increases at the higher solar fractions because of two major reasons. First, the solar fraction becomes more sensitive to the availability of heat at higher temperatures. Second, the storage temperature in the numerical simulations rises slightly with increased collector area contrary to the analytical formalism with a constant storage temperature thus increasing storage losses and decreases solar input.

P. D. Lund [8] performed comprehensive numerical computer simulations to investigate the effects of storage control strategies on the thermal performance of a non-heat pump central solar heating plant with seasonal storage(CSHPSS). He studied different operating strategies for the storage loops on the thermal behavior of the seasonal storage. He based the methodology on a new verified numerical simulation computer program SUPERSOL, which is capable of handling a large variety of system control strategies and parameters.

K. G. T. Hollands, J. W. Chinneck and M. Chandrashekar [9] developed a general definition of an effective efficiency of solar collectors in a solar energy system and compared different collectors operating in a particular application. They did a comparison between area required for an actual collector and that for a perfect collector both giving some solar output. They plotted the relation between the yearly solar fraction delivered by a solar energy system as a function of the collector area.

P. D. Lund and M. B. Ostman [10] developed a three dimensional numerical model for seasonal heat exchanger pipes. The model accounts for convective heat flows in the ground. The storage was employed in a district solar heating system with a heat pump. The effects of storage volume, storage medium, collector area and collector type on the system performance were studied. They also gave a brief discussion on economic optimization of the storage and collector installations. They observed that the investment cost in solar collectors is dominating item and a large storage volume reduced the solar collector area requirement and also the behavior of the storage efficiency depend on the volume and on the solar fraction requirement. A large storage volume gave better performance when the collector area and solar fraction requirement were increased.

S. Silman [11] developed a comprehensive computer simulation study on the performance of active solar heating systems with long-term hot water storage and analysed the economical optimization of an annual storage solar heating systems. He observed that the system performance to increase linearly with the storage volume up to the point of unconstrained operations where the storage tank is large enough to store all heat collected in one summer season and it is likely economic optimum. He compared daily and annual storage systems that show only slightly diminishing return as system size increases. He also found the annual storage systems with an intermediate storage size to be more economical.

P. D. Lund and S. S. Peltola [12] compared measured and simulated thermal performance of a full scale seasonal storage solar heating system (CSHPSS) considering one year data. They developed a simulation computer program KERKONT which was used to improve the overall thermal performance of the Kerava Solar Village in Finland. KERKONT consists of submodels for each component and for control logics. The KERKONT needs ground temperature distribution and hourly weather data as outputs. At the end of their study, they obtained only 0.014 difference between measured and simulated solar fractions. Maximum errors in the monthly subsystem energy flows were less than 15 percent even for small absolute energy values. They observed the storage to have three distinctive layers identified as the top, intermediate and bottom layers. The largest deviation at the measured and calculated temperature profiles were found in the winter time in the intermediate section of the storage.

John C. Ward and George O.G. Lof [13] determined the long-term performance of a residential solar heating systems which operated continuously since 1957. They determined the performance of this systems during the 1959-60 heating season and the changes in efficiency occurring during a period of 15 years were recorded.

P. B. Howells and R. H. Marchal [14] developed an iterative simulation code for predicting the long-term performance of a solar heating systems. Their simulation code was based on a modular approach. They demonstrated the application of improved code to the simulation of solar energy systems using two example problems. In the first problem , the emphasis was placed on predicting the temperatures of the fluid within the system and controller actions while in the second problem, the emphasis was on predicting long-term system performance.

E. F. Sowell and R. L. Curry [15] developed a convolution model for calculating output temperature of a rock-bed thermal storage unit. The convolution model developed which was based on the principle of linear superposition, which suggest that the outlet temperature at any instant is the sum of effects of all earlier inlet temperature disturbances. They oriented the Transient Simulation Program (TRNSYS) for solving the differential equations and they compared results of developed model with other models were within 2-4 °C of this solution through the interval, and close agreement was highly dependent upon choice of number of segments and time step for the finite difference models. Their results suggest that finite difference models should be used with caution, especially in the study of temperature-sensitive components such as heat pumps and control elements.

Zalman Lawan and James Thompson [16] studied experimentally the the temperature stratification in hot water storage systems and also effects of inlet and exit port configuration on thermal stratification. Their experimental study showed that even at very large flow rates, thermal stratification could be maintained in cylindrical water tanks.

P. D. Lund [17] studied the effect of solar radiation availability on the performance of different solar heating systems and also investigated different collector orientations and collector types. He generated the solar radiation by a computer simulation program to describe the radiation availability.

G. Cavalleri [18] proposed to heat a city by using an artificial lake as a big storage of heat and proposed to be filled during the spring, summer and with hot water at 98 ^{0}C. He concludes that the estimated cost per person is half of the cost required by a conventional heating systems.

P. D. Lund [19] developed a mathematical and computational simulation model capable of determining the thermal performance and energy flows in a district solar heating system with an annual heat storage excavated in stable bedrock. He used several vertical heat exchanger pipes for thermal storage which were placed in a regular pattern around the tank. He prepared a computer program (NORSOL) which incorporated computational modelling of the subsystems of a district solar heating system with seasonal storage. He reported a comparison between simulated system performance and experimental results for the first charging period in the summer of 1983. He found simulated and measured performances to be in reasonable agreement. He observed that the heat pump increases the system performance significantly.

J. M. Gordon and Y. Zarmi [20] developed a simple analytic method for predicting the long-term performance of solar thermal systems with well-mixed storage and loads that do not vary significantly from day to day. They considered the kind of solar thermal systems which include industrial process heat and domestic hot water ,among others and they commonly followed two paths for predicting solar system performance. One involves the use of large-scale computer simulations. A second approach has been the paremetriaziation of a large number of simulation runs in a form that serves as an easy-to-use calculation tool. They found good agreement between the predictions of the analytic method and corresponding results of Transient Simulation Computer Program "TRNSYS" and ϕ,f-chart method.They also observed that the analytic method was applicable to all collector types and storage fluids and is not restricted to flat plates and hot water storage.

M. J. Brandemuehly and W. A. Beckman [21] developed a method for determining the economic visiability of a solar heating system over conventional heating system. They aimed to determine the technical feasibility of solar energy for domestic water heating and space heating by using the generalized life cycle saving equations in their study. They assumed that the annual load distribution depends only on location and not on the magnitude of the annual load, which was built into many methods for calculating domestic water heating loads by using degree-day method.

CHAPTER 3

MODELLING OF A HEAT PUMP SYSTEM WITH SEASONAL STORAGE

3.1 INTRODUCTION

The system under study consists of solar collectors , a heat pump , an underground spherical thermal energy store and a house. The system considered which is shown in Figure 3.1. An analytical formulation is obtained in this chapter for the transient temperature field around a buried spherical thermal energy store. The solution for the transient heat transfer problem is obtained by the application of a similarity transformation and Duhamel's Superposition Technique.

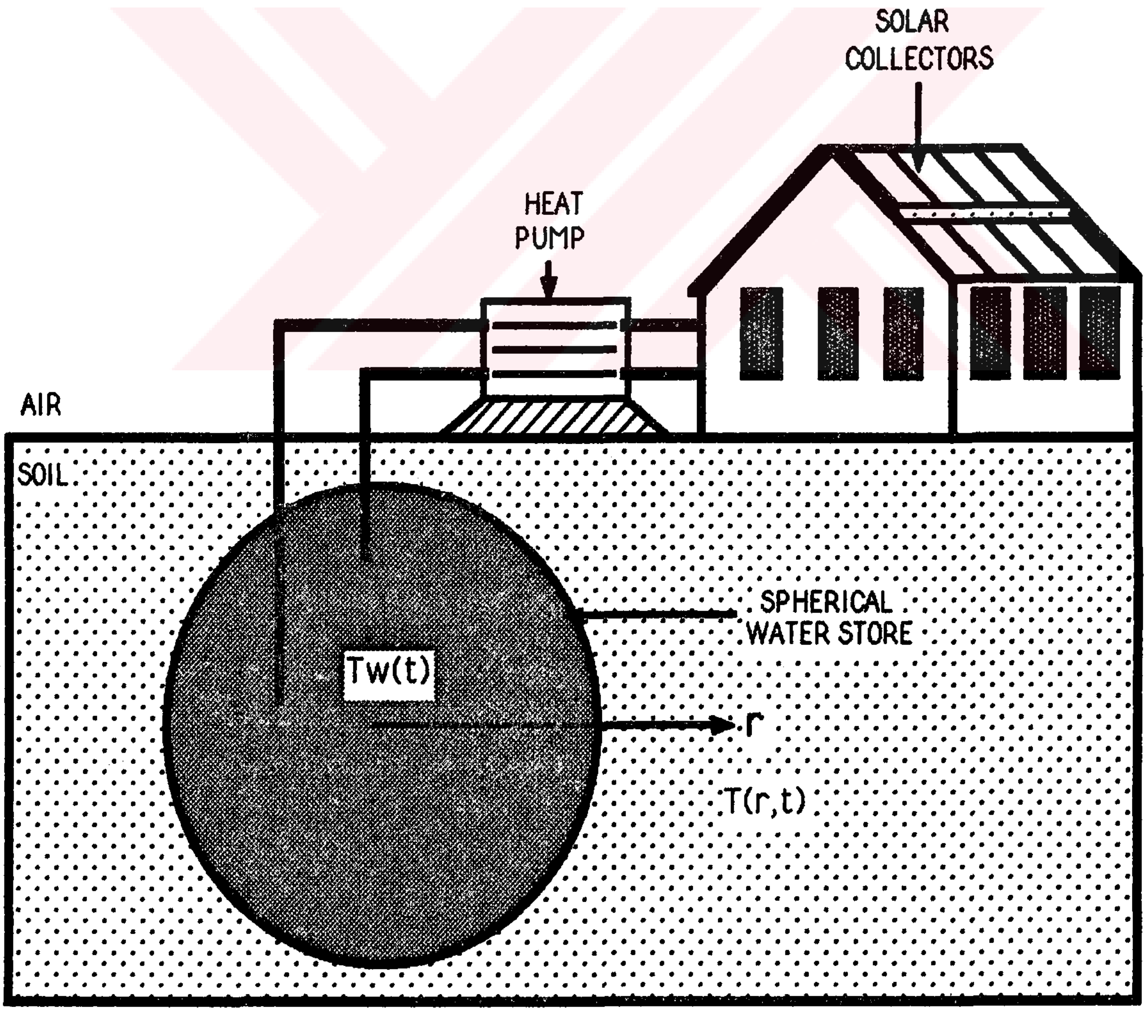

Figure 3.1 Heat pump system with a spherical water thermal store in deep earth

The solution obtained is used to investigate the long-term performance of a heat pump system with an underground energy store. The energy is supplied to the spherical thermal energy store using solar collectors which are mounted on the roof of the house. Heat is extracted from the spherical thermal energy storage for space heating during winter months.

The dimensionless water temperature of the spherical thermal energy store and performance of the heat pump system are calculated using a computer and Fortran 77.

3.2. STRUCTURE OF THE SIMULATION PROGRAM

A simulation program SOLPER1 was developed to evaluate the long term performance of a solar aided heat pump system with a spherical thermal energy store using monthly average solar radiation data. The program is designed to solve a set of time-dependent equations that describe the transient behavior of the system. The overall structure of the SOLPER1 is shown in Figure 3.2 in which a set of control logics is included. SOLPER1 requires the initial state of the system as an input. The flowchart and lists of the program are given in Appendix. The following input and output lists give an idea about the program.

1. Fixed inputs in data files;
   - Annual distribution functions of solar energy, FS
   - Annual distribution functions of house heat load, FH
   - Monthly average values of dimensionless ambient temperature, FA
   - Number of day in each month, IMO

2. Fixed inputs in the program;
   - The specific heat of water, CW
   - The specific heat of soil, CP
   - The density of water, ROW
   - The density of soil, RO
   - The thermal diffusivity of soil, ALFA
   - The ratio of $(UA)_h$ to $(UA)_{he}$, U
   - Heat pump coefficient, BETA
   - Dimensionless inside room temperature, FI
   - Annual average collector efficiency, EF

- Collector area, AC
- Design heat load of the house, QH
- Winter design temperature difference, DELT
- Annual solar energy gain, QYS

3. Variables interactive inputs to be given by user from computer terminal.
- Number of houses, NOH
- Type of soil, ISOIL
- Radius of store, A
- Time increment, ITIME

4. Outputs of SOLPER1;
- Timewise variation of water temperature in the store, FW
- Annual dimensionless solar heat gain, QSY
- Annual dimensionless heat pump work, W
- Annual dimensionless house heating load, QH
- Annual dimensionless increase of internal energy of the store, QST
- Annual dimensionless heat loss from the store, QLT
- Yearly solar energy fraction charged to the system (total energy charged consist of solar and heat pump work), R1
- Yearly heat pump work fraction charged to the system, R2
- Yearly stored energy fraction, R3
- Yearly heat loss fraction charged to the system, R4
- Yearly house heat load fraction, R5
- Coefficient of performance of heat pump, COP

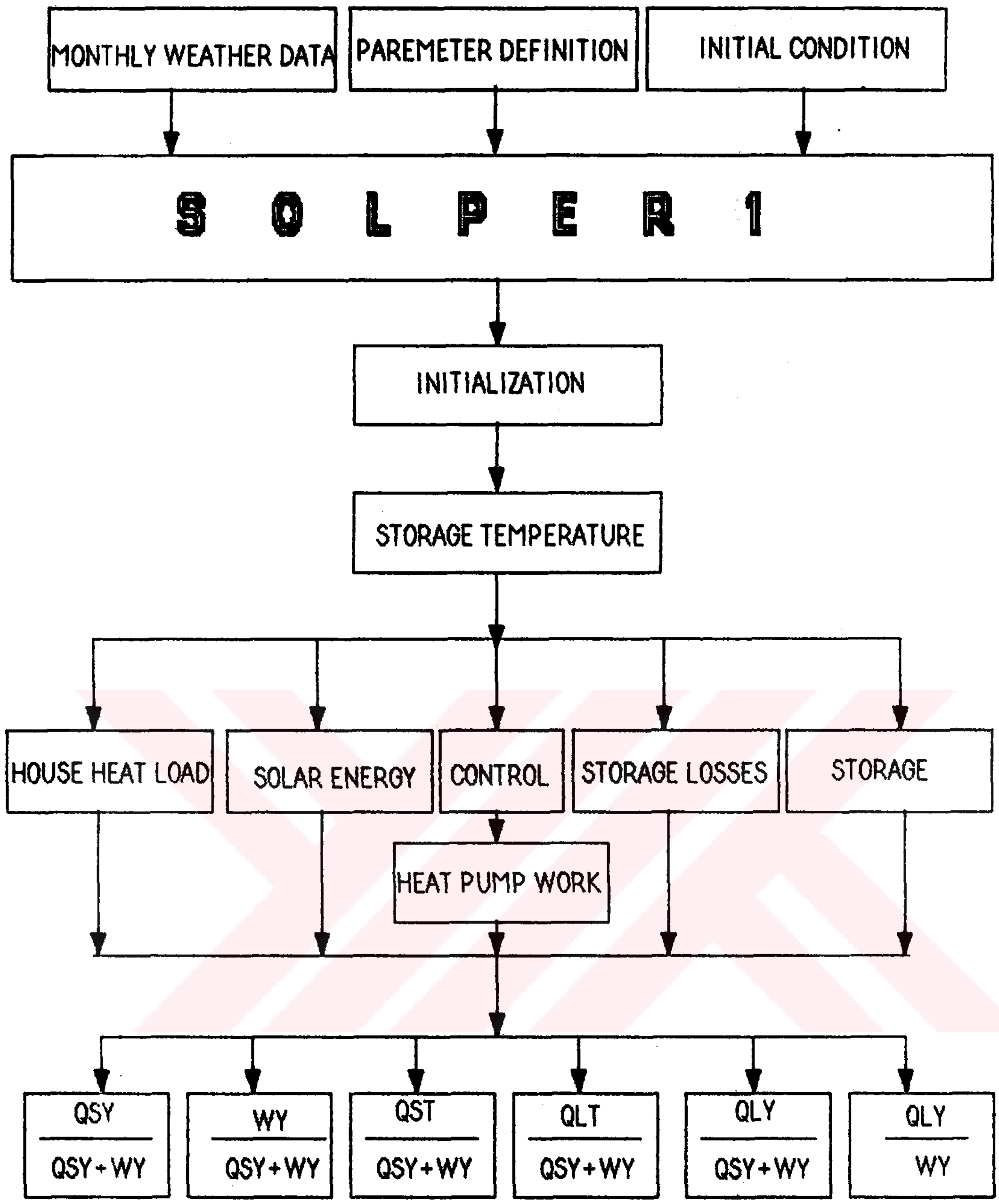

Figure 3.2 Structure of SOLPER1 System Simulation Program

3.3. MODELLING OF THE HEAT PUMP

The heat pump is the heat source to the house. Heat is charged to the underground spherical thermal energy store using solar collectors which are mounted on the roof of the house. Heat is extracted in winter months for space heating by the heat pump. The heat pump is operated only when the temperature of the underground thermal energy store is not sufficient to keep the house at the inside air design temperature.

A formula is derived in this section to calculate the dimensionless heat pump work. Instantaneous energy requirement of the house is expressed by

$$Q_h = (UA)_h(T_i - T_a) \tag{3.3.1}$$

If this energy is supplied by the heat pump to the house, Q_h can also be expressed by

$$Q_h = W(COP) = W\beta_p T_h/(T_h - T_w) \tag{3.3.2}$$

β_p is assumed 0.25 in this formula, whose value depends on the size of heat exchangers and heat pump characteristics.

Also, heat load of a heat exchanger is expressed by

$$Q_h = (UA)_{he}(T_h - T_i) \tag{3.3.3}$$

Equation (3.3.1) and (3.3.3) are combined together and solved for T_h. The expression at the end of the solution is inserted in equation (3.3.2), which yields the following expression for the dimensionless heat pump work.

$$w = \frac{W}{(UA)hT_\infty} = \frac{(\phi_i-\phi_a)(u(\phi_i-\phi_a)+\phi_i-\phi_w)}{\beta_p(u(\phi_i-\phi_a)+\phi_i+1)} \tag{3.3.4}$$

ϕ_i is the design inside dimensionless air temperature of the space and ϕ_a is the dimensionless surrounding air temperature. The dimensionless paremeter u is the ratio of the $(UA)_h$value of the house to the $(UA)_{he}$ value of the load size heat exchanger. This paremeter is represented as;

$$u = (UA)_h/(UA)_{he} = (T_h - T_i)/(T_i - T_a) \tag{3.3.5}$$

u is assumed to be unity

3.4. ANALYSIS OF THE HEAT TRANSFER PROBLEM FOR THE THERMAL ENERGY STORE

The spherical thermal energy store which is located under ground. The farfield ground temperature around the store is assumed constant and equal to the deep ground temperature T_∞. The water in the store is assumed to be at a uniform temperature. In this section, a numerical expression will be estimated for the variation of the dimensionless water temperature in the store with respect to time.

The transient heat transfer problem and its boundary conditions for the spherical thermal energy store are defined in spherical coordinates as follows;

$$\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{3.4.6}$$

$$T(a,t) = T_w(t) \tag{3.4.7}$$

$$T(\infty,t) = T_\infty \tag{3.4.8}$$

$$T(r,0) = T_\infty \tag{3.4.9}$$

The energy balance for the energy store is expressed in the following form.

$$Q = \rho_w V_w c_w \frac{dT_w}{dt} - kA\frac{\partial T}{\partial r}(a,t) \tag{3.4.10}$$

The transient heat transfer problem is transferred to dimensionless form by using following transformation and dimensionless variables which are defined in nomenclature.

$$\psi(x,t) = x\phi(x,\tau) \tag{3.4.11}$$

Dimensionless form of the transient heat transfer problem is expressed as follows;

$$\frac{\partial^2\psi}{\partial x^2} = \frac{\partial\psi}{\partial\tau} \tag{3.4.12}$$

$$\psi(1,\tau) = \phi w(\tau) \tag{3.4.13}$$

$$\psi(\infty,\tau) = 0 \tag{3.4.14}$$

$$\psi(x,0) = 0 \tag{3.4.15}$$

The dimensionless form of the energy balance equation can be written as;

$$q = p\frac{d\phi_w}{d\tau} - \frac{\partial\phi}{\partial x}(1,\tau) \tag{3.4.16}$$

The dimensionless transient heat transfer problem is solved by introducing the following similarity transformation.

$$\eta = \frac{x-1}{2\sqrt{\tau}} \tag{3.4.17}$$

The solution for constant ϕ_0 is:

$$\psi(x,\tau) = \phi_0\left\{1-\mathrm{erf}\left[\frac{x-1}{2\sqrt{\tau}}\right]\right\} \tag{3.4.18}$$

The general solution is found to be the following.

$$\psi(x,\tau) = \phi_w(0)\left\{1-\mathrm{erf}\left[\frac{x-1}{2\sqrt{\tau}}\right]\right\} + \int_0^{\tau}\frac{d\phi_w(\xi)}{d\xi}\left\{1-\mathrm{erf}\left[\frac{x-1}{2\sqrt{\tau-\xi}}\right]\right\}d\xi \tag{3.4.19}$$

If the general solution is differentiated with respect to the dimensionless variables x, the result evaluated at x=1 and substituted into (3.4.16), the following integro-differential equation is obtained.

$$q = p\frac{d\phi_w}{d\tau} + \phi_w(\tau) + \int_0^{\tau} \frac{d\phi_w(\xi)}{d\xi}\frac{d\xi}{\sqrt{\pi(\tau-\xi)}} \qquad (3.4.20)$$

Equation (3.4.20) can be expressed in the following finite difference form.

$$\phi_w(\tau_n) = \frac{q(\tau_n) + \left[\frac{p}{\Delta\tau} + \frac{1}{\sqrt{\pi\Delta\tau}}\right]\phi_w(\tau_{n-1}) - \sum_{i=1}^{n-2}\frac{\phi_w(\tau_{i+1}) - \phi_w(\tau_i)}{\sqrt{\pi\Delta\tau(n-i)}}}{1 + \frac{p}{\Delta\tau} + \frac{1}{\sqrt{\pi\Delta\tau}}} \qquad (3.4.21)$$

The equation (3.4.21) will be used to calculate the dimensionless water temperature of the spherical thermal energy store. The q term in equation (3.4.21) represents the dimensionless net heat input rate to the thermal energy store. The net dimensionless heat input rate to the store is the difference between dimensionless heat collection rate at the solar collectors and the energy extracted by the heat pump to be used by the heat pump system to heat the space.

The net dimensionless heat input rate to the store can be expressed as follows.

$$q(\tau_n) = q_s(\tau_n) - q_h(\tau_n) + \gamma^{-1}w(\tau_n) \qquad (3.4.22)$$

If the monthly values of the annual distribution of solar energy obtained from the sun is f_s and its magnitude is S, then the dimensionless heat gain rate from the sun is expressed by Sf_s. If the monthly value of the annual distribution of the house heating load is f_h and its magnitude H, then the dimensionless heat load of the house will be equal to Hf_h. The net dimensionless heat input rate to the energy store is expressed by

$$q_i = Sf_{s,i} - Hf_{h,i} - \gamma^{-1} w \qquad \text{for} \quad i = 1 \text{ to } 12 \qquad (3.4.23)$$

Values of the distribution function $f_{h,i}$ for a house located in Gaziantep is obtained by application of the degree-day method and are depicted in Table 3.1. The distribution function for solar radiation data, $f_{s,i}$, on this surface is obtained from Reference[24] and is also given in table 3.1. Monthly average dimensionless outside air temperature and the monthly average values of ambient air temperatures for Gaziantep were used during each month. The physical property values of earth are given in Table 3.2 which were used in calculations.

Table 3.1 Distribution functions $f_{s,i}$, $f_{h,i}$ and Monthly Average temperatures.

MONTHS	$f_{s,i}$	$f_{h,i}$	ϕ_a	T_a(°C)
JULY	0.110	0.00	0.0401	26.56
AUGUST	0.110	0.00	0.0443	28.92
SEPTEMBER	0.110	0.00	0.0300	23.64
OCTOBER	0.085	0.04	-0.0026	14.25
NOVEMBER	0.065	0.12	-0.0118	11.58
DECEMBER	0.050	0.19	-0.0365	4.48
JANUARY	0.050	0.22	-0.0369	4.37
FEBRUARY	0.063	0.19	-0.0507	0.37
MARCH	0.081	0.16	-0.0317	5.86
APRIL	0.095	0.08	-0.0038	13.89
MAY	0.091	0.00	0.0175	20.04
JUNE	0.010	0.00	0.0327	24.42

The winter design temperature difference was taken 29 °C. The design heat load of the house was is taken 10 kW. The design inside air temperature is assumed at 20 °C. Calculation of the dimensionless water temperature of the spherical store was started on July 1. System performance was obtained by assuming the annual average collector efficiency to be equal to 0.44.

Table 3.2. Physical Property Values of The Earth

EARTH TYPE	DENSITY (Kg/m^3)	THERMAL CONDUCTIVITY $(W/m\,^{\circ}C)$	THERMAL DIFFUSIVITY (m^2/sec)
COARSE GRAVELLED	2050	0.519	1.39×10^{-7}
CLAY	1500	1.400	1.10×10^{-6}
SAND	1500	0.300	2.50×10^{-7}
GRANITE	2640	3.000	1.40×10^{-6}

A computer program was written in Fortran 77 based on the assumptions mentioned. The program was and executed using a IBM 4331 computer. The results of execution of the computer program are discussed in Chapter 5.

This model wabased on monthly average weather data for Gaziantep. This program required much more execution time using hourly weather data values. The solution technique of the transient heat transfer problem was therefore changed. The other solution technique will be given in the next chapter.

3.5 ANNUAL ENERGY BALANCES OF THE PROBLEM

The annual dimensionless heat pump work can be evaluated from the following integral.

$$w_y = \int_{year} w^+ d\tau \qquad (3.5.1)$$

Noting that $Q_h = (UA)_h(T_i - T_a)$, the dimensionless house heating requirements for a winter season is estimated from.

$$q_{hy} = \int_{year} (\phi_i - \phi_a)^+ d\tau \qquad (3.5.2)$$

The superscript (+) in equations (3.5.1)-(3.5.2) implies that only positive values of the integrand should be accounted for when estimating the integral. Dimensionless annual net heat addition to the store is estimated by integration of q as given in equation (3.4.22).

$$q_v = \int_{year} q(\tau)\, d\tau \qquad (3.5.3)$$

Annual increase in the dimensionless internal energy of the store is given by $p\Delta\phi_w/3$ where $\Delta\phi_w$ is the difference in ϕ_w for a period of one year. One can express this increase by

Annual dimensionless heat loss to the earth surrounding the store can be estimated from

$$q_{ls} = q_v - q_{st} \qquad (3.5.4)$$

CHAPTER 4

ANALYSIS OF THE HEAT TRANSFER PROBLEM OF THE THERMAL ENERGY STORE BY THE COMPLEX FINITE FOURIER TRANSFORM TECHNIQUE

4.1. INTRODUCTION

Formulation was given for finding dimensionless water temperature of an underground thermal energy store in Chapter 3. A computer program (SOLPER1) was written based on this model in Fortran 77. This program was executed and outputs were obtained by using monthly average data. The computer program (SOLPER1) required much more execution time for only one output when using hourly data. For this reason, another solution technique of the transient heat transfer problem was developed. In order to demonstrate the construction of an information flow diagram, consider a simple solar aided house heating system consisting of solar collectors and an auxiliary heater as shown in Figure 4.1.

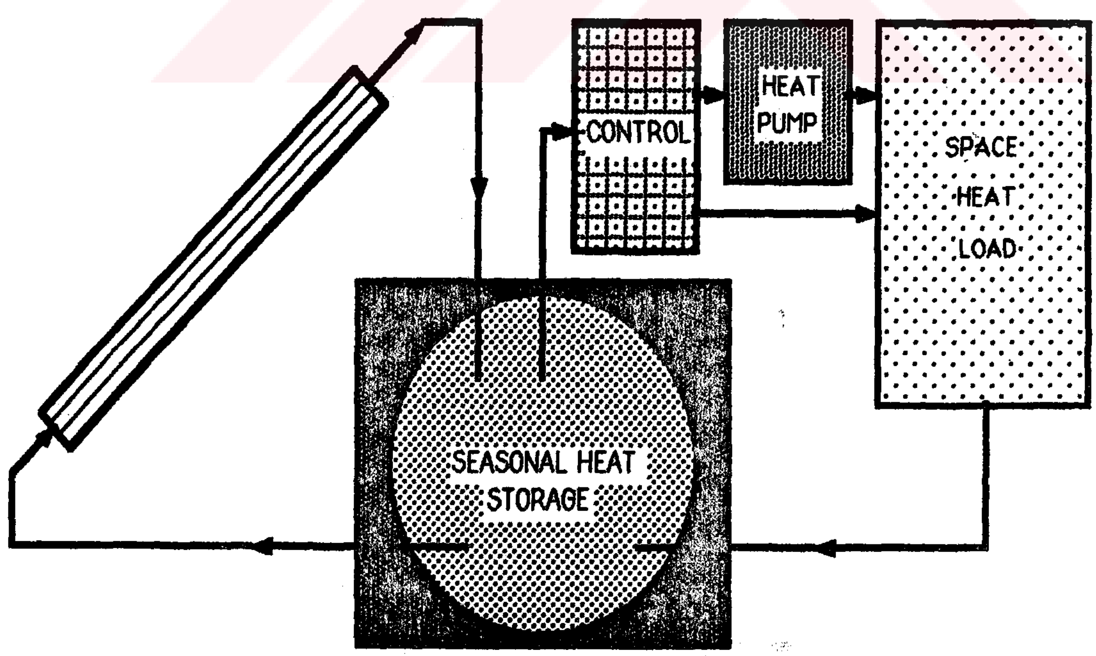

Figure 4.1 Schematic Diagram of the Seasonal Storage Heating System

In this chapter, formulation and solution is given for a of this new analytical model. This technique is applicable for predicting the transient temperature field outside of a spherical seasonal thermal energy storage system during annually periodic operation. Formulated problem is solved by an application of the Complex Finite Fourier Transform Technique. Present analysis leads to a closed form solution for the annual periodic temperature outside the spherical underground seasonal thermal energy store. In this model, dimensionless ground temperature distribution can also be computed from the transient temperature field of the seasonal thermal energy store.

4.2. STRUCTURE OF THE SIMULATION PROGRAM

The basic system equations are incorporated in a FORTRAN 77 code called SOLPER2, a simulation program to predict the long term performance of the system for annually periodic operations. The structure of the program is shown in Figure 4.2. The flowchart and listing of this program are given in the Appendix. Simulation program was based on hour by hour meteorological weather data which are hourly radiation on a horizontal surface and hourly ambient air temperature. SOLPER2 contains two subprograms which are named TLTRAD and STRTMP. TLTRAD subprogram calculates hourly radiation on a tilted surface and transmttance-absorbtance product using hourly radiation on a horizontal surface and normal transmittance-absorbtance product. The calculated values are fed to STRTMP subprogram. The STRTMP subprogram computes annual periodic store temperature and some values that depend on store temperature. An iterative procedure is presented in STRTMP. Monthly components of the dimensionless annual energy gain rate to the store are assumed and the dimensionless hourly store temperatures are computed by using the complex finite Fourier transform technique. The storage temperature computed is then taken as solar collector input temperature and monthly useful energy gain is recalculated. When the monthly average dimensionless useful energy gain is fed as input once again in the iteration procedure, the calculation procedure was found to diverge. A relaxation constant was used to eliminate divergence. The new iteration value for the monthly useful energy gain was taken equal to assumed value minus relaxation constant times the difference between assumed and calculated values. The monthly useful energy gain found was then utilized to recalculate the store temperature. This iterative procedure was repeated until convergence to periodic variation of the store temperature. All other values related to system performance are computed after convergence of the iteration periodic store temperature to a distribution.

Total hourly solar radiation incident on a tilted surface is estimated from data on a horizontal surface using the method described in [23]. SOLPER2 needs as input data the initial state of the system. The meteorological data for hourly radiation on horizontal surface and ambient temperatures for Gaziantep given in Ref[22] were stored in the "SOLAR data" file. Other parameters used in calculations are those given below.

1- Fixed inputs in data files;
- Hourly radiation values on a horizontal surface for one year, II
- Hourly ambient air temperatures for one year, TA
- Numbers of days in a month, IMO
- Names of months, AYLR
- Monthly average reflectivities, RR
- Monthly average dimensionless heat input rates to the store, QD

2- Fixed inputs in the SOLPER2 program
- Design heat load of house, QH
- Winter design temperature difference, DELT
- Heat pump coefficient, BETA
- Latitude of location, FI
- Solar constant,GS
- Specific heat of water, CW
- Specific heat of soil, CP
- Density of water, ROW
- Density of soil, RO
- Convective heat transfer coefficient inside collector tube, H
- Bond conductance, CB
- Thermal diffusivity of soil, ALFA
- Conductivity of soil, CON
- Ratio of $(UA)_h$ to the $(UA)_{he}$, U

3- Variable interactive inputs to be given by user from the computer terminal
- Number of houses, NOH
- Types of soil, ISOIL
- Types of collector, ICOL
- Collector area, AC
- Radius of store, A

4- Outputs of SOLPER2;

- Monthly average useful energy input to the store, QU
- Monthly average radiation on a tilted surface, IT
- Monthly average collector efficiency, EF
- Timewise variation of water temperature in the store, FW
- Annual dimensionless solar heat gain, QSY
- Annual dimensionless heat pump work, W
- Annual dimensionless heating load, QH
- Annual dimensionless increase in the internal energy of the store, QST
- Annual dimensionless heat loss from the store, QLT
- Yearly solar energy fraction charged to the system (total energy charged consist of solar and heat pump work), R1
- Yearly heat pump work fraction charged to the system, R2
- Yearly stored energy fraction, R3
- Yearly heat loss fraction charged to the system, R4
- Yearly house heat load fraction, R5
- Coefficient of performance of heat pump, COP

Modeling of the heat pump is given in Chapter 3.

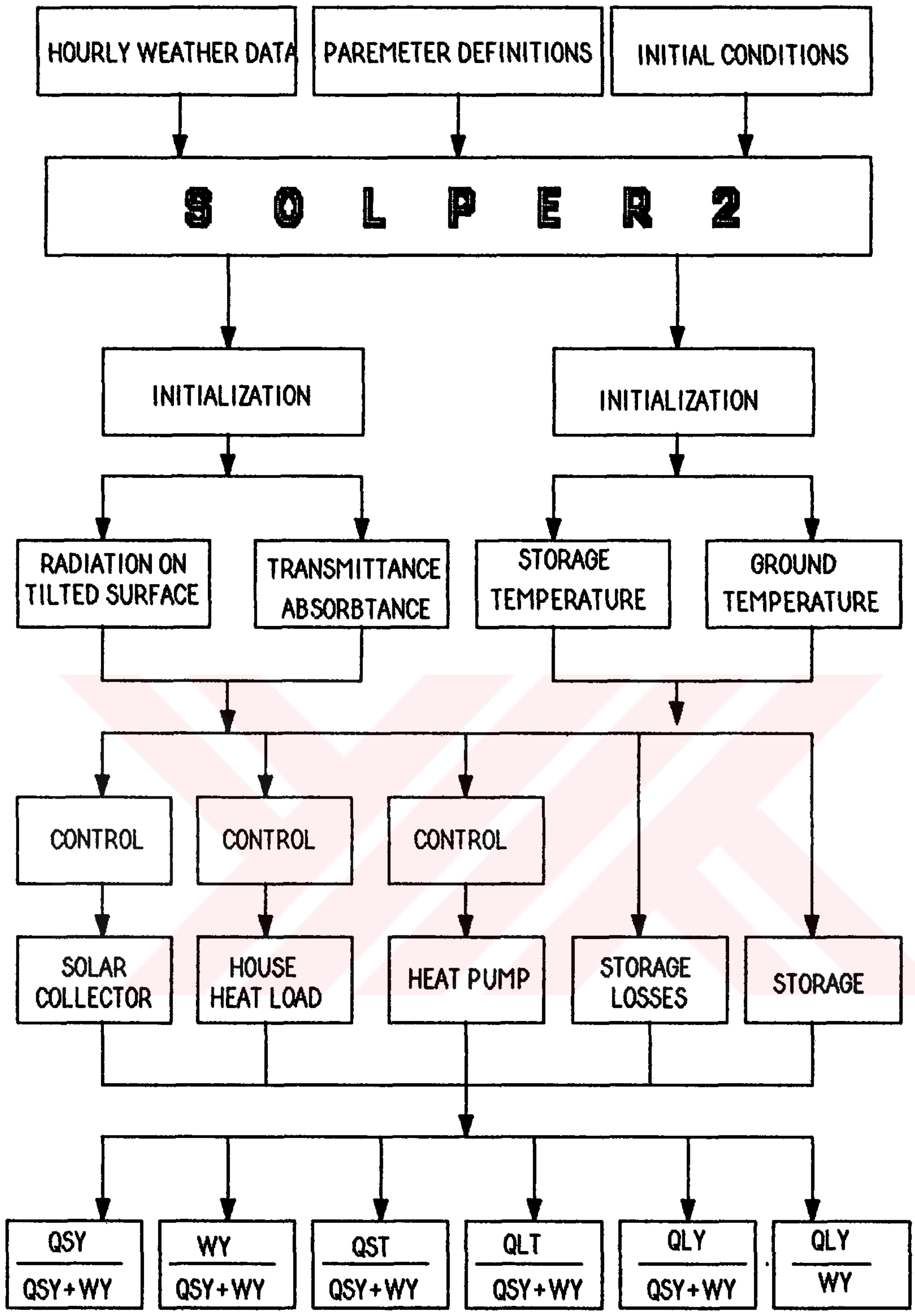

Figure 4.2. Structure of SOLPER2 System Simulation Program

4. 3. FORMULATION AND SOLUTION OF THE TEMPERATURE PROBLEM OUTSIDE A SPHERICAL SEASONAL STORAGE

The system considered is shown in Figure 3.1 and its main components were described in Chapter 3. Temperature around the store is varying with time and simplifying assumptions made in section (3.4) are also valid for this model. Formulation of this problem will be given in this section which is aimed to predict the annually periodic variation of the store temperature, $T_w(t)$. Temperature of seasonal thermal energy store will be periodic if solar energy and heat load are periodic with years. Temperature outside the thermal store is a function of time and distance $T= T(r, t)$. Radiation coordinate, r, is measured from the center of the thermal store.

The transient heat transfer problem for the spherical thermal energy store is formulated in spherical coordinates by the following differential equation, boundary conditions and a periodicity condition.

$$\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (4.3.1)$$

$$T(a, t)= T_w(t) \qquad (4.3.2)$$

$$T(\infty,t) = T_\infty \qquad (4.3.3)$$

$$T(r, 0)= T(r, \text{one year}) \qquad (4.3.4)$$

The energy balance equation for a spherical seasonal thermal energy store is expressed by

$$Q = \rho_w V_w c_w \frac{dT_w}{dt} - kA\frac{\partial T}{\partial r}(a,t) \qquad (4.3.5)$$

The transient heat transfer problem defined in equations (4.3.1)-(4.3.4) is transferred into dimensionless form using the following transformation.

$$\psi(X,\tau) = X\phi(X,\tau) \qquad (3.3.6)$$

Dimensionless heat transfer problem is given by

$$\frac{\partial^2\psi}{\partial x^2}=\frac{\partial\psi}{\partial\tau} \tag{4.3.7}$$

$$\psi(1,\tau)=\phi(\tau) \tag{4.3.8}$$

$$\psi(\infty,\tau)=0 \tag{4.3.9}$$

$$\psi(x,0)=\psi(x,Y) \tag{4.3.10}$$

and the dimensionless energy balance equation becomes.

$$q=p\frac{d\phi_w}{d\tau}-\frac{\partial\psi}{\partial x}(1,\tau)+\psi(1,\tau) \tag{4.3.11}$$

Equations (4.3.7)-(4.3.8) are solved by an application of the following Complex Finite Fourier transform.

$$\psi(x,\tau)=\sum_{n=-\infty}^{+\infty}\psi_n(x)\exp\left\{\frac{i2\pi n\tau}{Y}\right\} \tag{4.3.12}$$

$$\psi_n=\frac{1}{Y}\int_{-Y/2}^{+Y/2}\psi(x,\tau)\exp\left\{-\frac{i2\pi n\tau}{Y}\right\}d\tau \tag{4.3.13}$$

When the transformation given by (4.3.12)-(4.3.13) is applied to the problem given by (4.3.7)-(4.3.10), the following problem is obtained.

$$\frac{d^2\psi_n}{dx^2}-\frac{i2\pi n}{Y}\psi_n=0 \tag{4.3.14}$$

$$\psi_n(1) = \phi_{wn} \tag{4.3.15}$$

$$\psi_n(\infty) = 0 \tag{4.3.16}$$

$$q_n = p\,\frac{12\pi n}{Y}\phi_{wn} - \frac{d\psi_n}{dx}(1) + \psi_n(1) \tag{4.3.17}$$

The solution of the problem defined by (4.3.14)-(4.3.16) is:

$$\psi_n(X) = \phi_{wn}\exp\left\{-(1+i)\frac{\sqrt{n\pi}\,(x-1)}{\sqrt{Y}}\right\} \tag{4.3.18}$$

The following expression is obtained for the dimensionless water temperature of the store by substitution of equation (4.3.18) into equation (4.3.17).

$$\phi_{wn} = \frac{q_n(\eta_1 - i\eta_2)}{\eta_1^2 + \eta_2^2} \tag{4.3.19}$$

where

$$\eta_1 = 1 + \frac{\sqrt{n\pi}}{\sqrt{Y}} \quad \text{and} \quad \eta_2 = \frac{\sqrt{n\pi}}{\sqrt{Y}} + p\frac{2\pi n}{Y} \tag{4.3.20}$$

Equations (4.3.12), (4.3.18), (4.3.19) and (4.3.20) give the dimensionless temperature of the store as a function of the dimensionless heat input, q_n to the store. Ground temperature distribution can be found by using the solution obtained. Ground temperature distribution depends on the dimensionless energy input function, q. This function may be expressed by a Fourier series with a period of one year. Defining g_i to be monthly components of the dimensionless annual energy gain rate to the store, q will be expressed by the following vector.

$$q = (g_1, g_2, g_3, g_4, g_5, g_6, g_7, g_8, g_9, g_{10}, g_{11}, g_{12}) \tag{4.3.21}$$

If the monthly components of the q function are expressed by equation (4.3.21), then the dimensionless heat input rate can be defined by

$$q=\sum_{n=-\infty}^{+\infty} q_n \exp\left\{\frac{i2\pi n\tau}{Y}\right\} \tag{4.3.22}$$

where

$$q_0=\frac{1}{12}\sum_{j=1}^{12} q_j \tag{4.3.23}$$

and

$$q_n=\frac{1}{2\pi n}\sum_{j=1}^{12} q_j\{\eta_{3,j}+i\eta_{4,j}\} \quad \text{for} \quad n\geq 1 \tag{4.3.24}$$

where

$$\eta_{3,j}=\sin(2\pi n r_j)-\sin(2\pi n r_{j-1}) \tag{4.3.25}$$

$$\eta_{4,j}=\cos(2\pi n r_j)-\cos(2\pi n r_{j-1}) \tag{4.3.26}$$

with, $r_j=(j-6)/12$

Solar energy addition to the store over the whole year and energy extraction from the store for the purpose of space heating during winter months are incorporated into the thermal system model via the dimensionless heat input source term, q. Substitution of the complex Fourier coefficients q_n from equations (4.3.23) and (4.3.24) into (4.3.19) gives complex Fourier coefficients of ϕ_W.

Using the equations (4.3.19), (4.3.23) and (4.3.24), the following expressions are obtained.

$$a_0 = \frac{1}{12}\sum_{i=1}^{12} g_i \tag{4.3.27}$$

$$a_n = \frac{1}{\pi n[\eta_1^2 + \eta_2^2]} \sum_{i=1}^{12} g_i\{\eta_1\eta_{3,i} + \eta_2\eta_{4,i}\} \tag{4.3.28}$$

$$b_n = \frac{1}{\pi n[\eta_1^2 + \eta_2^2]} \sum_{i=1}^{12} g_i\{\eta_2\eta_{3,i} - \eta_1\eta_{4,i}\} \tag{4.3.29}$$

where

$$\phi_{wo} = a_0 \text{ and } \phi_{wn} = \frac{(a_n - ib_n)}{2} \qquad \text{when } n>0$$

Ψ can be expressed by

$$\psi(x,\tau) = A_0 + \sum_{n=1}^{\infty}\left[A_n\cos\left(2\pi n\frac{\tau}{Y}\right) + B_n\sin\left(2\pi n\frac{\tau}{Y}\right)\right] \tag{4.3.30}$$

Coefficients in expression (4.3.30) are given by the following relationships;

$$A = a_0 \tag{4.3.31}$$

$$A_n = (a_n\cos\omega_n - b_n\sin\omega_n)\mathrm{Exp}(-\omega_n) \tag{4.3.32}$$

$$B_n = (a_n\sin\omega_n - b_n\cos\omega_n)\mathrm{Exp}(-\omega_n) \tag{4.3.33}$$

where

$$\omega_n = \frac{\sqrt{n\pi}\,(x-1)}{\sqrt{Y}} \tag{4.3.34}$$

Equation (4.3.30) gives the dimensionless ground temperature as a function of distance and time. Dimensionless water temperature of the store can also be determined from equation (4.3.30) by letting x=1.

Monthly components of the dimensionless annual energy gain rate to the store, q, are calculated in the next section using hourly horizontal radiation and hourly outdoor temperatures for Gaziantep.

4.4. PREDICTION OF DIMENSIONLESS MONTHLY USEFUL ENERGY GAIN

Analytical formulations are presented in this section for the prediction of the dimensionless monthly useful energy gain. Formulas given in [23] for the estimation of hourly radiation on a tilted surface are used to estimate monthly useful solar energy gain.

4.4.1. DESCRIPTION OF SOLAR COLLECTORS

A solar collector is a heat exchanger that transforms solar radiant energy into heat. Flat plate solar collectors are the most common device for applications requiring energy delivery at moderate temperatures. The system simulated was modelled with flat plate solar collectors. Heat from collectors is transferred conducted to the storage.

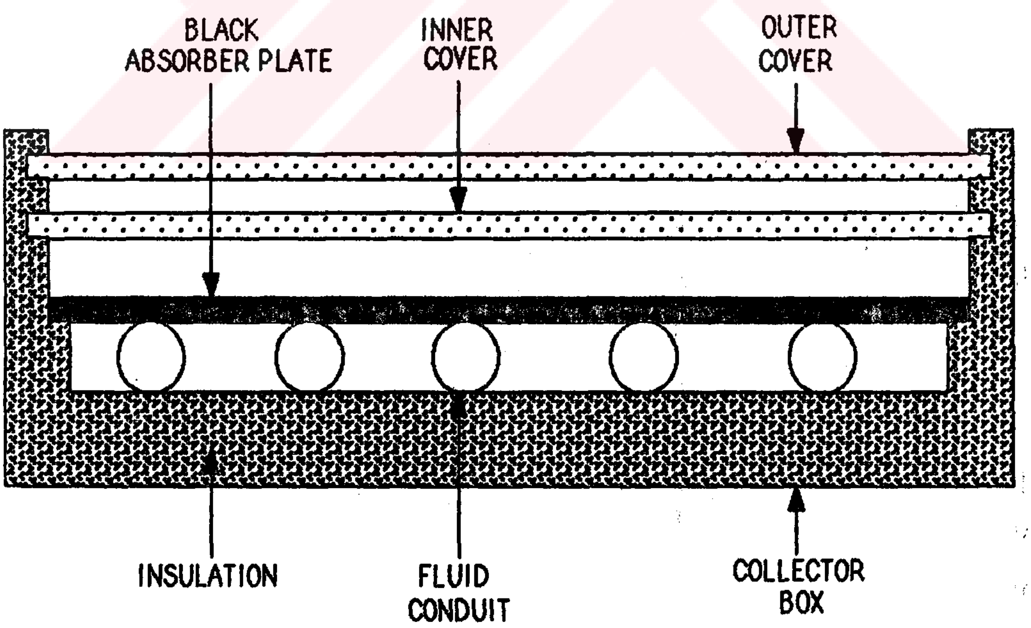

Figure 4.3. Crossection of A Basic Flat Plate Solar Collector.

Crossection of a typical solar collector is shown in Figure 4.3 which consists of a black absorber plate, a transparent glazing, fluid conduits and thermal insulation inside a collector box.

Many studies on solar collector systems and design factors influencing the performance of solar collectors have been reported. The black absorber plate is the "heart" of the collector, which is normally painted black and sometimes covered with a special selective coating to increase the efficiency of solar energy collection. Flat plate solar collectors having two glass covers and a selective surface were used for finding useful solar energy gain in this study.

4.4.2. CALCULATION OF MONTHLY USEFUL SOLAR ENERGY GAIN

The term, q_i is the average monthly dimensionless energy input rate to the store during the i^{th} month. It is equal to dimensionless collected energy coming from solar collectors to the store minus energy extracted from the heat pump;

$$q_i = \frac{\sum_{n=1}^{M} Q(\tau_n)}{M} \qquad M = \text{Number of hours in a month} \qquad (4.4.2.1)$$

$Q(\tau_n)$ represents dimensionless hourly energy input to the store and it is given by

$$Q(\tau_n) = Q_s(\tau_n) - Q_p(\tau_n) \qquad (4.4.2.2)$$

$Q_p(\tau_n)$ is the energy extracted by the heat pump which is equal to the difference between house heating load and heat pump work, and is given by

$$Q_p(\tau_n) = Q_h(\tau_n) - \gamma^{-1} W(\tau_n) \qquad (4.4.2.3)$$

And dimensionless house heating load, $Q_h(\tau_n)$ is calculated from:

$$Q_h(\tau_n)=C(UA)_h[20-T_a(\tau_n)] \quad (4.4.2.4)$$

Where C is a dimensional variables defined in nomenclature. Formula for heat pump work is given in Chapter 3. The term $Q_S(\tau_n)$ in equation (4.4.2.2) is the dimensionless energy absorbed by the solar collectors and is given by

$$Q_s(\tau_n)= CQu(t_n) \quad (4.4.2.5)$$

$Q_U(\tau_n)$ is expressed by

$$Qu(t_n)=\eta_c(t_n)I_T(t_n) \quad (4.4.2.6)$$

where $\eta_c(t_n)$ is given by

$$\eta_c(t_n)=\frac{[F_R(\tau\alpha)I_T(t_n)-U_L(T_0(t_n)-T_a)]}{I_T(t_n)} \quad (4.3.2.7)$$

F_R is calculated from the following formula;

$$F_R=\frac{mc_p}{A_cU_L}[1-EXP(A_cU_LF'/mc_p)] \quad (4.4.2.8)$$

F' is given by the expression

$$F'=\frac{1/U_L}{W\left[\frac{1}{U_L(D+(W-D)F)}+\frac{1}{C_B}-\frac{1}{\pi D_i h_{f,i}}\right]} \quad (4.4.2.9)$$

F is expressed by the following formula

$$F=\frac{[\tanh m(W-D)/2]}{[m(W-D)/2]} \quad (4.4.2.10)$$

where

$$m=[U_L/(k\delta_t)]^{1/2} \quad (4.4.2.11)$$

$(\tau\alpha)$ is given by

$$(\tau\alpha)=(\tau\alpha)_n\left[1+b_o\left(\frac{1}{\cos\varnothing}-1\right)\right] \quad (4.4.2.12)$$

Where $\varnothing$ is expressed by

$$\varnothing=\text{Arccos}(R_b\cos\phi_z) \quad (4.4.2.13)$$

$\cos\phi_z$ is calculated from the following expression

$$\cos\phi_z=\cos\delta\cos\phi\cos w+\sin\delta\sin\phi \quad (4.4.2.14)$$

Where δ is given by

$$\delta=23.45\sin\left[360\frac{284+n_d}{365}\right] \quad (4.4.2.15)$$

Radiation on a tilted surface facing due south ,$I_T(t_n)$, is given by

$$I_T(t_n)=R'I(t_n) \quad (4.4.2.16)$$

Where R' is calculated from;

$$R'=\left[1-\frac{I_d(t_n)}{I(t_n)}\right]R_b(t_n)+\left[\frac{I_d(t_n)}{I(t_n)}\right]\left[\frac{1+\cos\beta}{2}\right]+\rho_o\left[\frac{1-\cos\beta}{2}\right] \quad (4.4.2.17)$$

$I_d(t_n)/I(t_n)$ is calculated from the following correlation.

$$\frac{I_d(t_n)}{I(t_n)}=\begin{cases} 1.0-0.249k_T & \text{for } k_T< 0.35 \\ 1.557-1.84\,k_T & \text{for } 0.35<k_T< 0.75 \\ 0.17 & \text{for } k_T> 0.75 \end{cases} \qquad (4.4.2.18)$$

Where k_T is given by:

$$k_T=\frac{I(t_n)}{I_0(t_n)} \qquad (4.4.2.19)$$

$I_0(t_n)$ and $R_b(t_n)$ are calculated from the following expressions.

$$I_0(t_n)=\frac{\left[43200\frac{Gs}{\pi}\right]\left[1+\frac{0.033\cos(2\pi n)}{365}\right]}{\left[\cos\delta(\sin\omega_2-\sin\omega_1)+(\omega_2-\omega_1)\sin\phi\sin\delta\right]} \qquad (4.4.2.20)$$

$$R_b(t_n)=\frac{\left[\cos(\phi-\beta)\cos\delta\cos\omega_1+\sin(\phi-\beta)\sin\delta\right]}{\left[\cos\phi\cos\delta\cos\omega_1+\sin\phi\sin\delta\right]} \qquad (4.4.2.21)$$

where ω_1 , ω_2 and w_s are given by

$$\omega_1=(t-12)*15 \qquad (4.4.2.22)$$

$$\omega_2=(t-11)*15 \qquad (4.4.2.23)$$

$$w_s=\frac{\omega_1+\omega_2}{2} \qquad (4.4.2.24)$$

CHAPTER 5

RESULTS AND DISCUSSION

5.1. INTRODUCTION

Long term performance of solar aided heat pump systems with spherical stores has been simulated using a digital computer. Results from computations based on monthly average and hourly weather data show the dependence of system performance on load distribution, storage size and type of earth. Results were obtained by the two computer programs developed in this study SOLPER1 and SOLPER2. Results from computations are discussed in the following two sections of this chapter.

5.2. DISCUSSION OF RESULTS FROM SOLPER1 PROGRAM

Monthly average weather data was used in the simulation. The thermal energy store has a central role in the solar assisted heating system. Storage temperature levels greatly affect the COP of the heat pump system. Figures 5.1-5.4 show storage temperature versus months for four types of earth surrounding the store and during the first, fifth, and tenth year of operations.

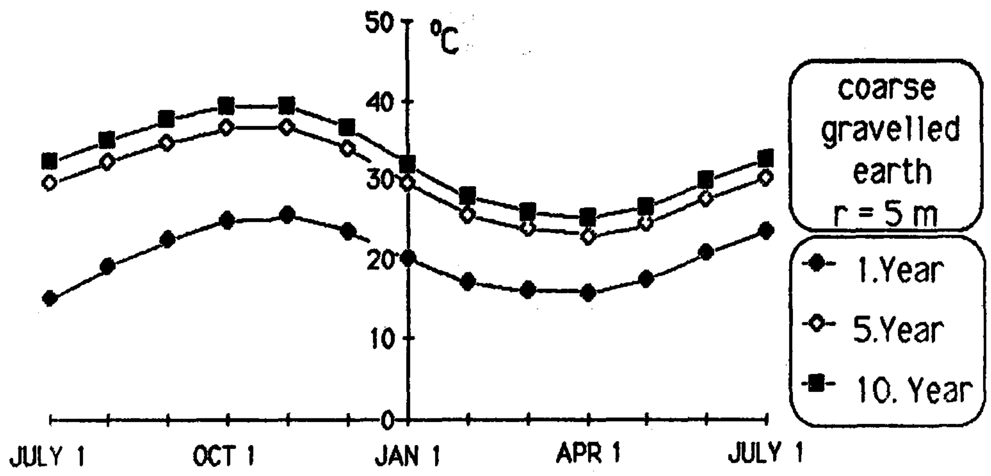

Figure 5.1. Temperature of Thermal Store Embedded in Coarse Gravelled Earth

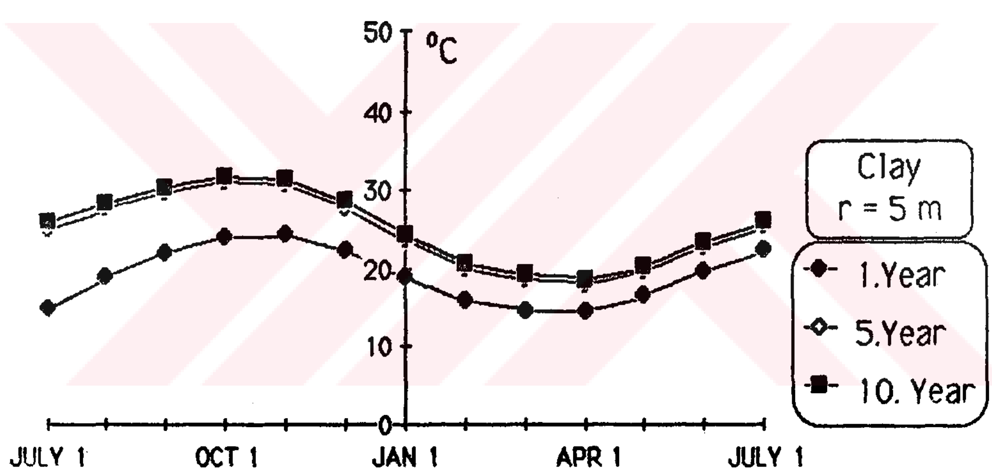

Figure 5.2. Temperature of Thermal Store Embedded in Clay

It is seen from these figures that highest temperatures are observed in the store surrounded with sand which has the lowest thermal conductivity. Lowest temperatures occur in the store surrounded with granite which has the highest thermal conductivity. Difference in the heat pump work, stored energy and lost energy between two consecutive year is greatest for granite. Amplitude of store temperature is also significantly large for granite.

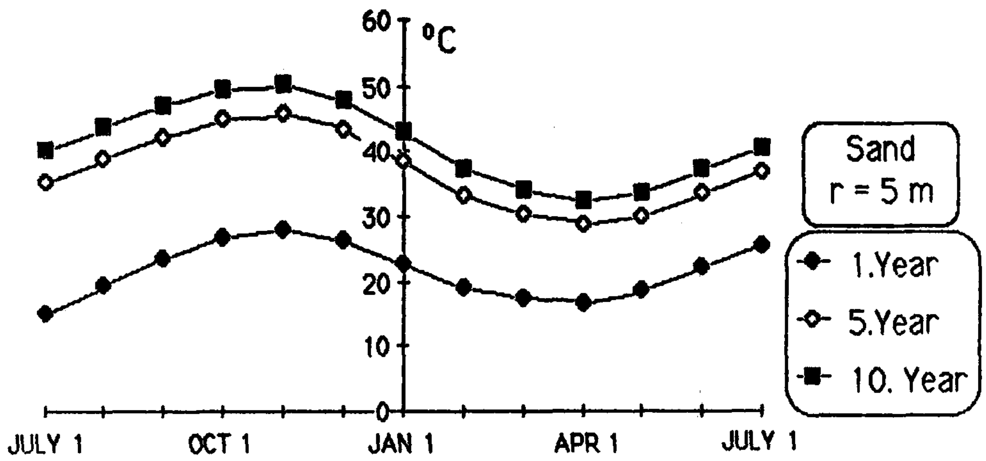

Figure 5.3. Temperature of Thermal Store Embedded in Sand

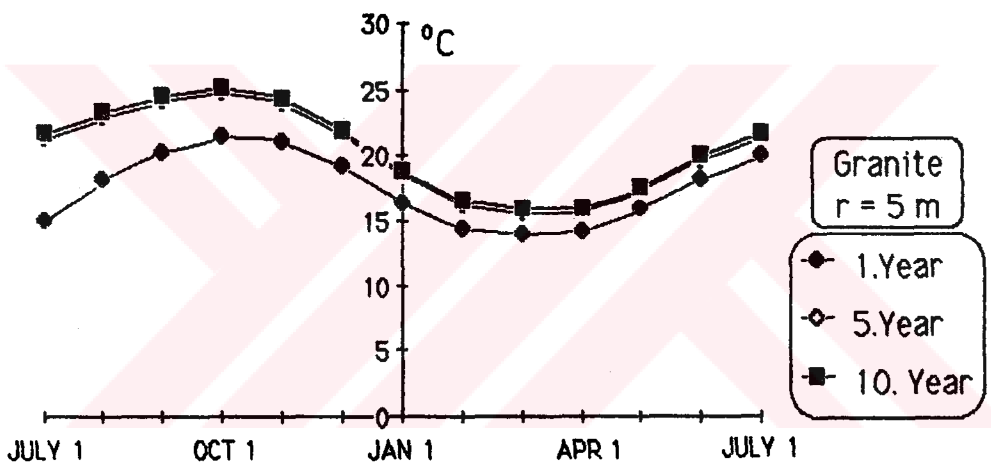

Figure 5.4 Temperature of Thermal Store Embedded in Granite

Figure 5.5 shows variation of store temperature with time during the fifth year of operation for three different store sizes and for stores surrounded by coarse gravelled earth. It is observed that a large store size give low average annual temperatures while small store sizes give high average annual temperatures. Variation of the amplitude of the thermal wave is larger for a store having a small size. It is seen that highest temperatures occur during the summer season while lowest temperatures occur towards the end of the winter month. Figure 5.5 gives a qualitative idea for optimal store size which may yield a better annual system performance.

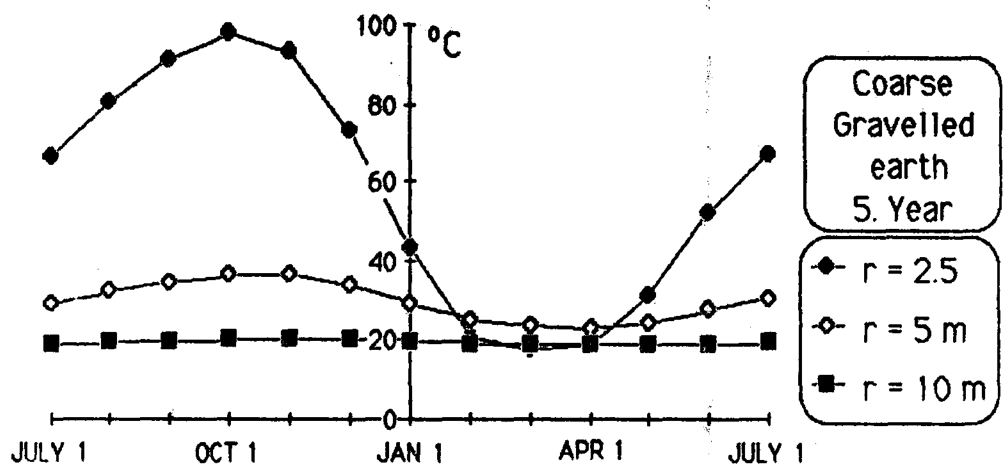

Figure 5.5 Temperature of Thermal Store Embedded in Coarse Gravelled Earth

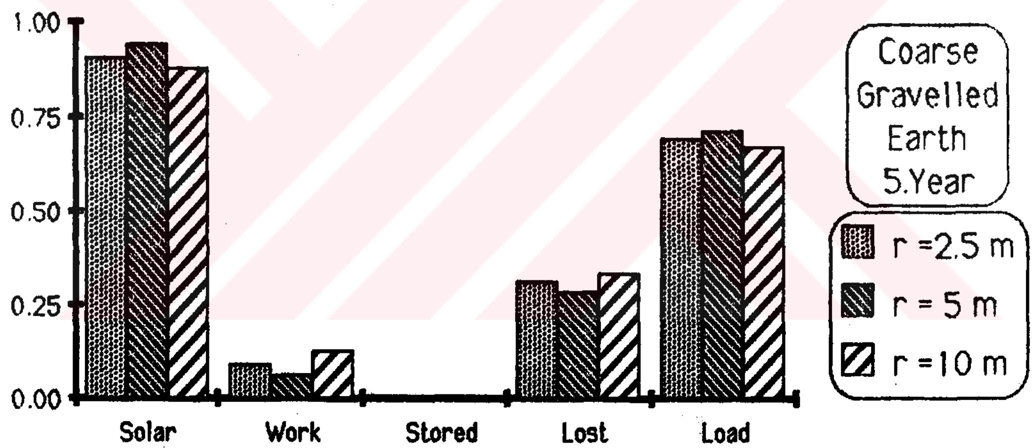

Figure 5.6. Fractions of energy charged to the system (solar energy and heat pump work) compared with fractions stored, lost and utilized at the load.

Total energy supplied to the system during one year is solar energy and heat pump work. Total energy supplied to the system is partially stored in the spherical store, partially lost into the surrounding earth with the remaining part extracted for house heating. Annual energy balance showing annual fractions of energy used in the system are depicted in Figures 5.6-5.9. First two columns of each year are energy supplied to the system and last three columns of each year are energy stored, energy lost and energy utilized at the house.

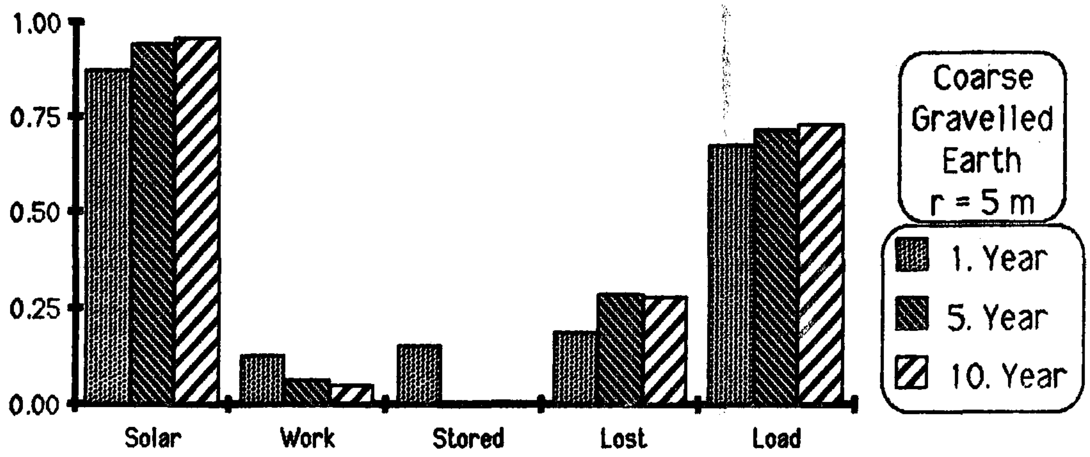

Figure 5.7. Fractions of energy charged to the system (solar energy and heat pump work) compared with fractions stored, lost and utilized at the load.

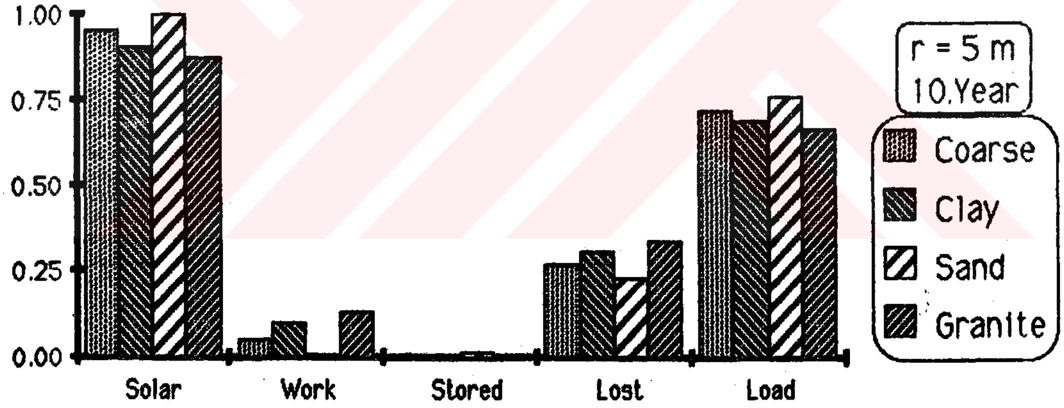

Figure 5.8. Fractions of energy charged to the system (solar energy and heat pump work) compared with fractions stored, lost and utilized at the load.

Figures 5.6-5.8 indicate that nearly two thirds of the energy supplied to the system is used for house heating and about one third is lost into surrounding earth outside the store. Figure 5.9. indicates that nearly two thirds of energy supplied to the system is used for house heating, one sixth is stored and one sixth is lost during the first year operation.

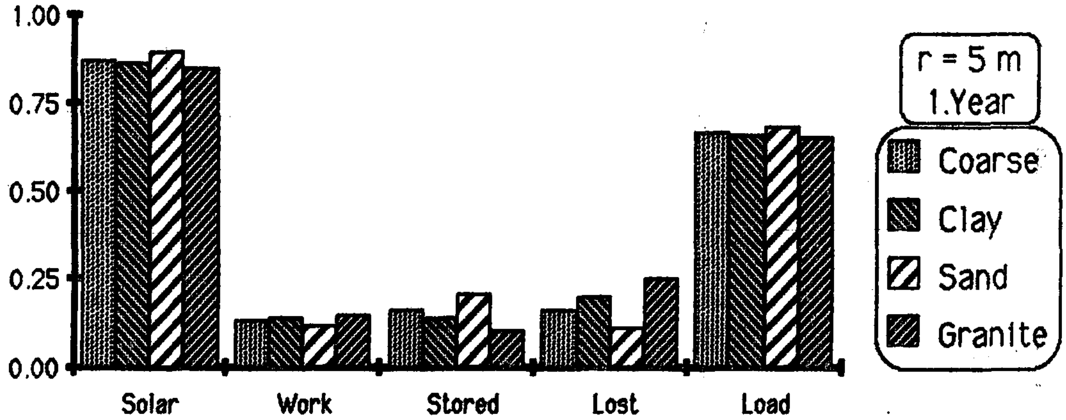

Figure 5.9. Fractions of energy charged to the system (solar energy and heat pump work) compared with fractions stored, lost and utilized at the load.

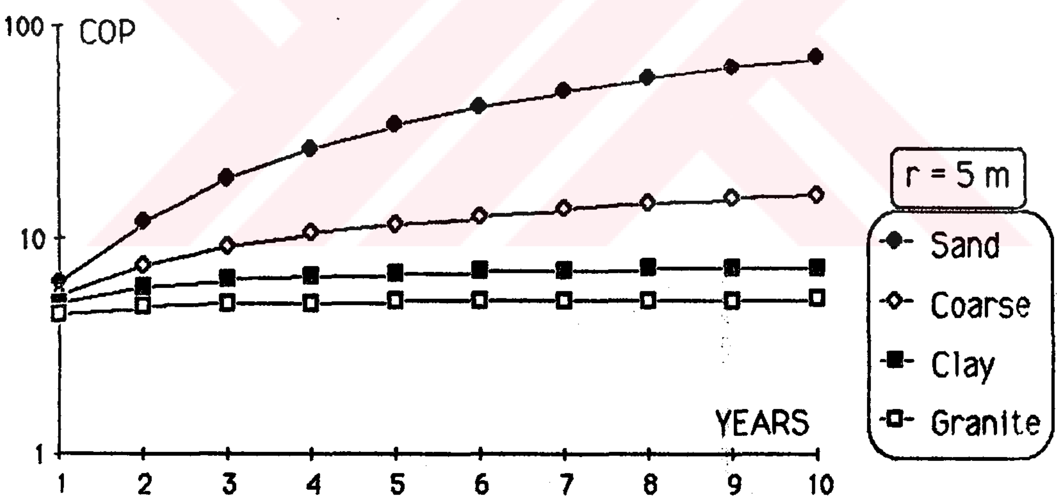

Figure 5.10. Annual coefficient of performance of heat pump.

Best system performance is obtained for store sizes about 5 meters in radius. The type of earth has small effect on these fractions. Figure 5.10 shows variation of annual COP (Coefficient of Performance of Heat Pump) with time. It is seen that COP increases with years of operation. Highest heat pump COP is obtained when the store is surrounded with sand. The type of earth has a strong effect on the temperature of store and on the COP of heat pump. Earths with small thermal conductivity give larger store temperatures and larger COP.

5.3. DISCUSSION OF RESULTS FROM SOLPER2 PROGRAM

SOLPER2 computer simulation program is based on hourly weather data and hourly calculations for estimation of system performance for annually periodic operation. Annual average collector efficiency was assumed equal to 0.44 in SOLPER1. This assumption is relaxed and collector efficiency is calculated hour by hour in SOLPER2. Results from SOLPER2 are shown in graphical form in this section. All operational conditions used in SOLPER1 were entered as inputs.

Monthly average radiation flux on the tilted surface of solar collectors was used in the calculations and is depicted in Figure 5.11 . Hourly radiation on a tilted surface was obtained by calculation and using radiation data available for a horizontal surface. Effects of variation of collector slope on system performance is not considered in this study. It is mentioned in [1] that the optimum collector tilt angle for space heating systems with seasonal storage is equal to the latitude of the location collector slope was assumed equal to 37.1 degrees in the present study corresponding to the latitude of Gaziantep.

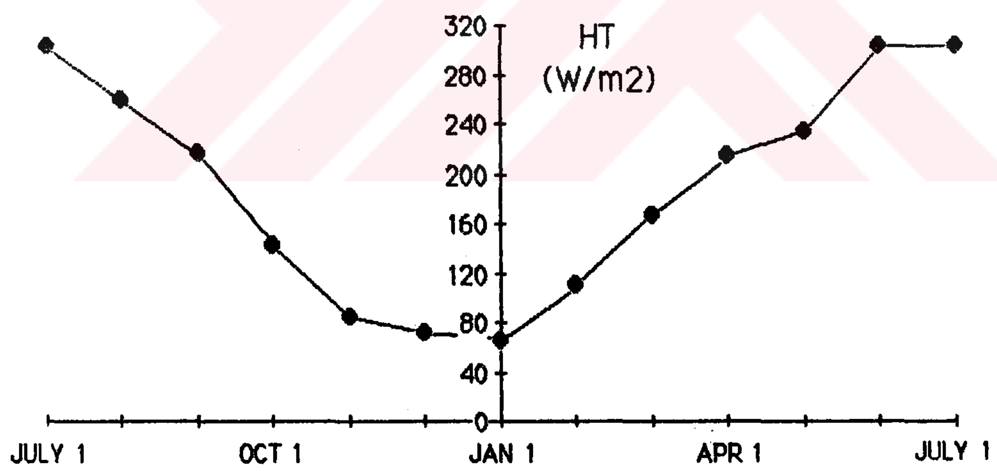

Figure 5.11 Monthly average radiation data on the tilted surface under consideration for Gaziantep ($\Phi_L = \beta = 37.1$ degree)

Figures 5.12-5.15 show simulated storage temperature profiles for different operational conditions. It is seen from Figure 5.12 that highest temperatures occur in the store surrounded with sand while lowest temperatures occur in the store surrounded with granite.

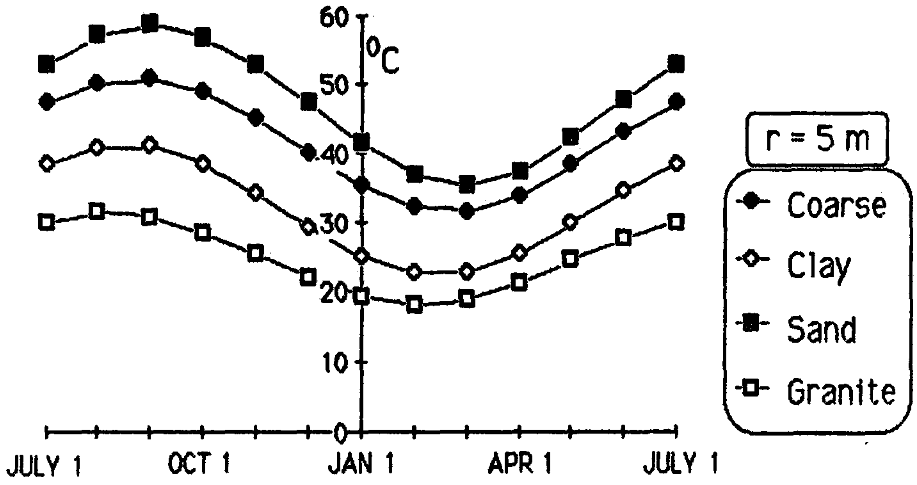

Figure 5.12. Temperatures of Thermal Store Embedded in four types of earth for one house.

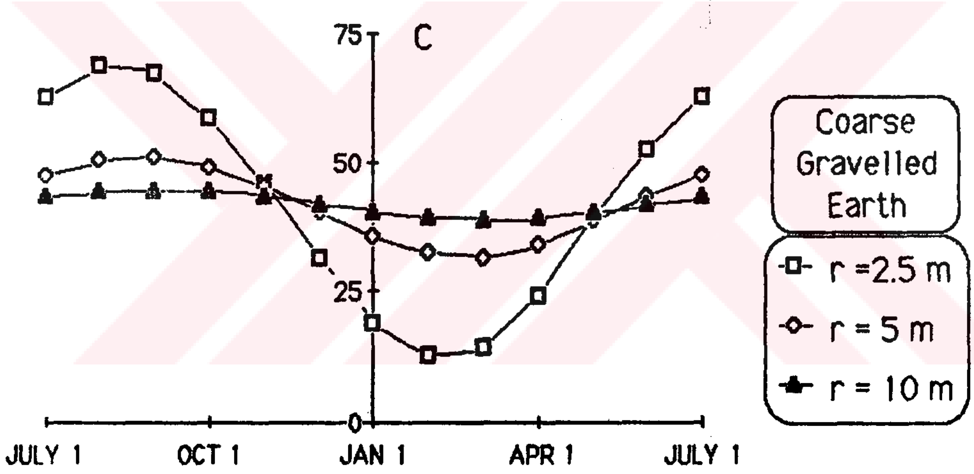

Figure 5.13. Temperature of Thermal Store Embedded in coarse gravelled earth for one house.

Figure 5.13 shows variation of water temperature in the store embedded in coarse gravelled earth for three different storage capacities. Average annual store temperature is lower while amplitude of annual water temperature is higher in the store with a 2.5 meter radius. The store having a radius of 5 meters gives a larger average store temperature than the store with a radius of 2.5 meters.

Results given in Figure 5.14 and 5.15 depict variation of water temperature in the store having a radius of 40 and 60 meters and for 500 houses. It is seen that stores surrounded with granite or clay give larger storage temperatures during summer months while giving low storage temperatures towards the end of the winter season. Sodium chloride (NaCl) can be used to depress the freezing point of water in the store. The lowest lowest temperature obtainable with sodium chloride brine is approximately -21ºC. For this freezing temperature the salt concentration in the solution is approximately 23 percent by mass. The brine temperature of the store surrounded with granite is above the boiling temperature of brine during part of the summer season. This is an unwanted condition for security of the system. To avoid the vaporaziation of the brine, system should be operated under high pressure above the saturation pressure of brine. It is observed that the amplitude of the store temperature surrounded with sand is low. Average annual store temperatures for sandon the other hand, is larger than the others types of earth.

Fractions of energy charged to the system are compared with fractions stored, lost and utilized in Figures 5.16-5.19. These Figures demonstrate that maximum heat supplied to the houses, minimum heat pump work and minimum heat loss from the store occur when the store is surrounded with sand. Also, it is seen from these Figures that system performance increases with store size and with a decreas in the thermal conductivity of earth.

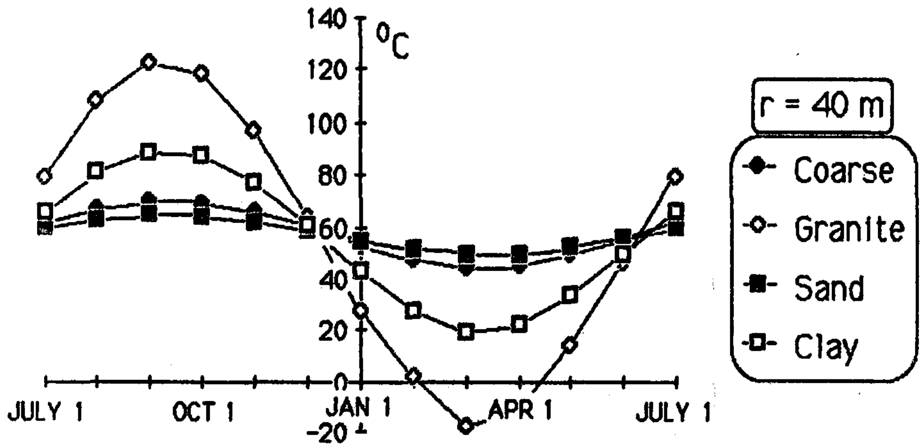

Figure 5.14. Temperature of Thermal Store Embedded in four types of earth for 500 houses.

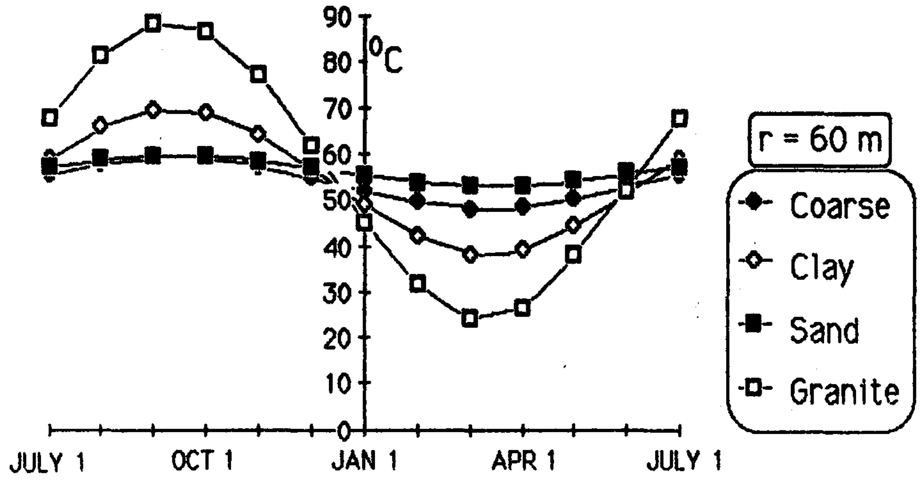

Figure 5.15. Temperature of Thermal Store Embedded in four types of earth for 500 houses.

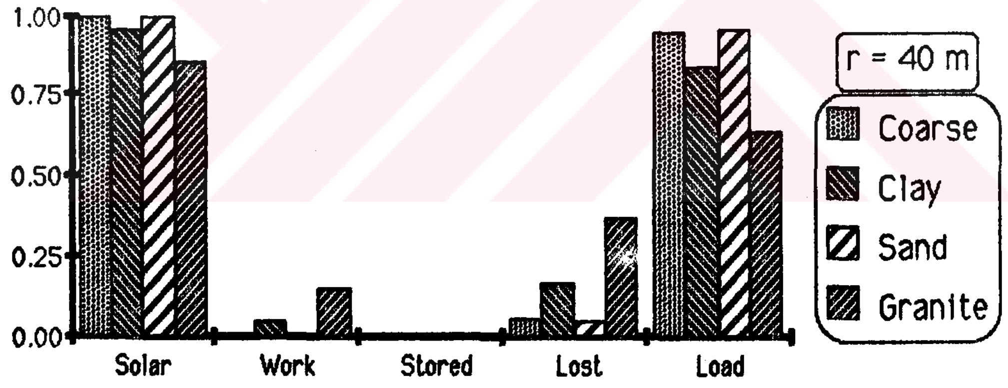

Figure 5.16. Fractions of energy charged to the system (solar energy and heat pump work) compared with fractions stored, lost and utilized at the load. Graph is for 500 houses.

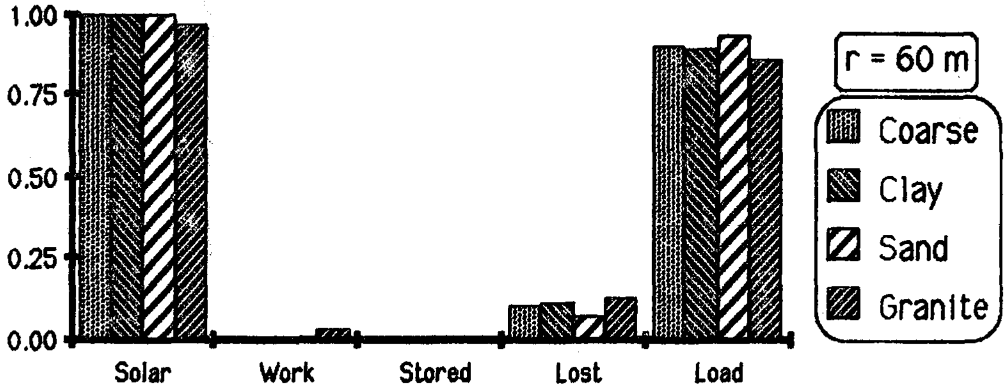

Figure 5.17. Fractions of energy charged to the system (solar energy and heat pump work) compared with fractions stored, lost and utilized at the load. Graph is for 500 houses.

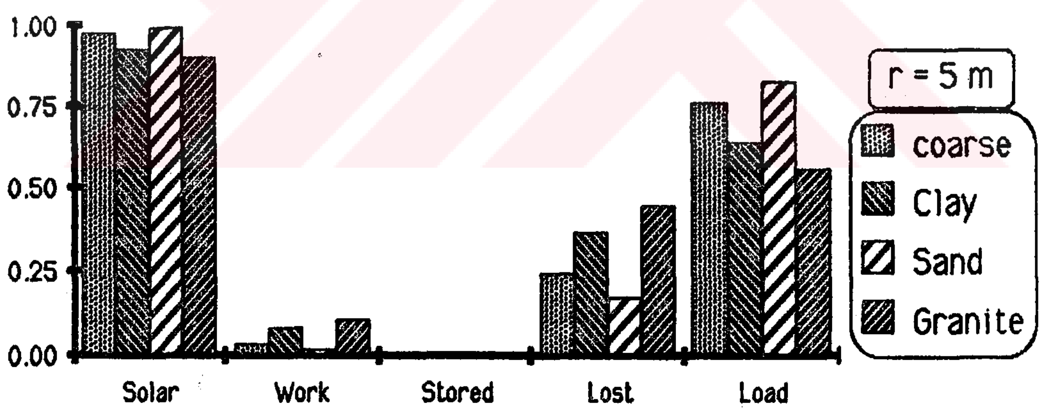

Figure 5.18. Fractions of energy charged to the system (solar energy and heat pump work) compared with fractions stored, lost and utilized at the load. Graph is for one house.

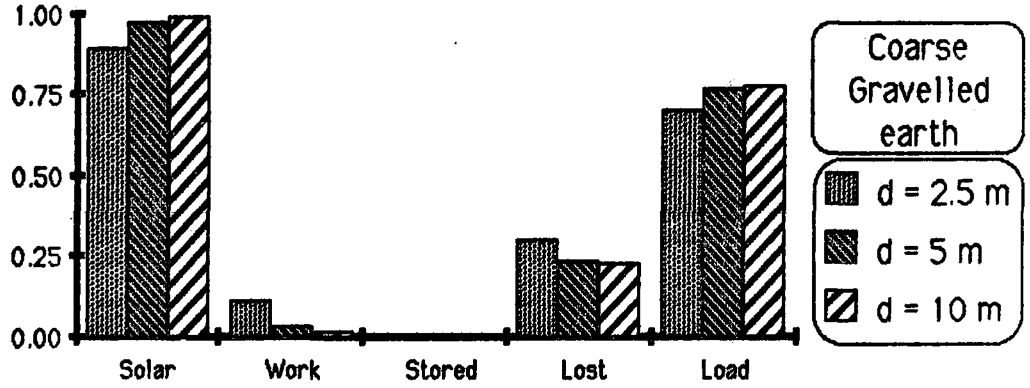

Figure 5.19. Fractions of energy charged to the system (solar energy and heat pump work) compared with fractions stored, lost and utilized at the load. Graph is for one house.

It is seen from Figure 5.19 that a low store size gives a lower solar heat gain fraction, a lower fraction for house heat supply, a high heat loss and a high heat pump work while a large store size gives high solar heat gain fraction, a higher fraction for the house heat supply and lower storage loss fractions. This agrees with results from References [10] and [1] indicating that system performance increases as the storage volume is increased up to a critical point at which the storage tank is large enough to give maximum performance at an thermally optimum condition.

Results for monthly average useful heat gain from the solar system and results for monthly average collector efficiency obtained from simulations are depicted in Figures 5.20-5.25. Collector efficiency depends on temperature of the fluid passing through the solar collector. Figure 5.20 illustrates that maximum collector efficiency results when store is surrounded with granite while minimum collector efficiency results when the store is surrounded with sand. It is understood from Figures 5.20-5.25 that low water temperatures give high collector efficiencies while high water temperatures give low collector efficiencies.

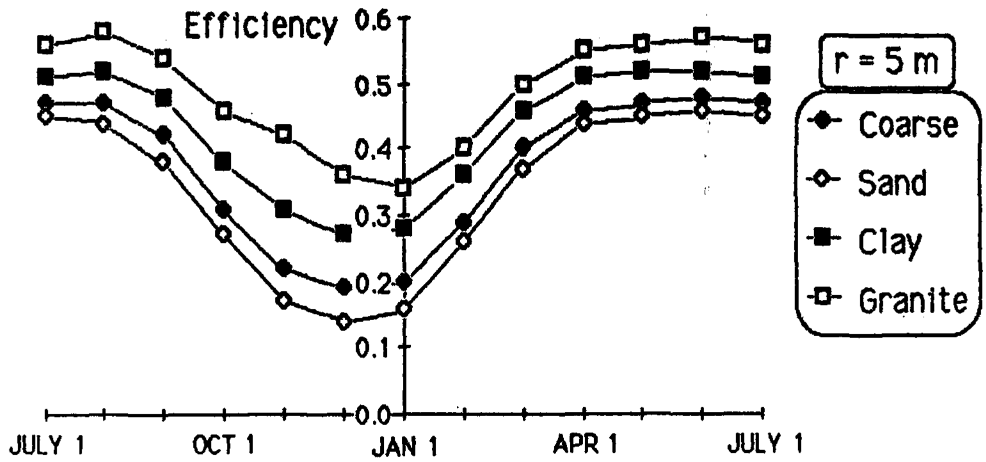

Figure 5.20. Monthly Average Collector Efficiency for one House.

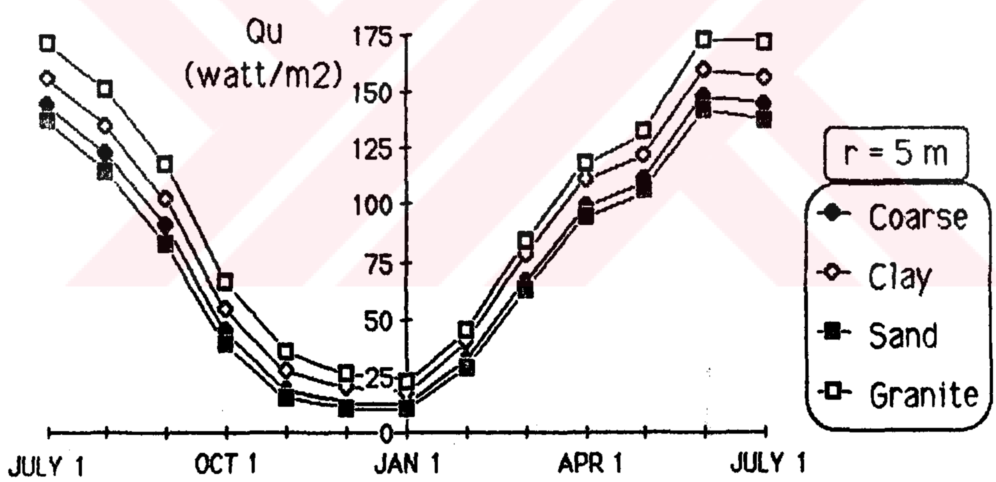

Figure 5.21. Monthly Average Useful Heat Gain of Solar System for one House.

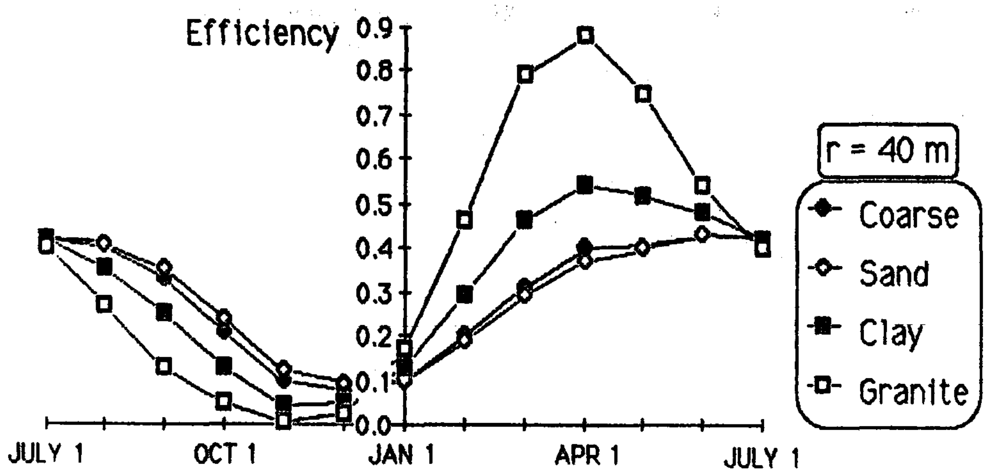

Figure 5.22. Monthly average collector efficiency for 500 house.

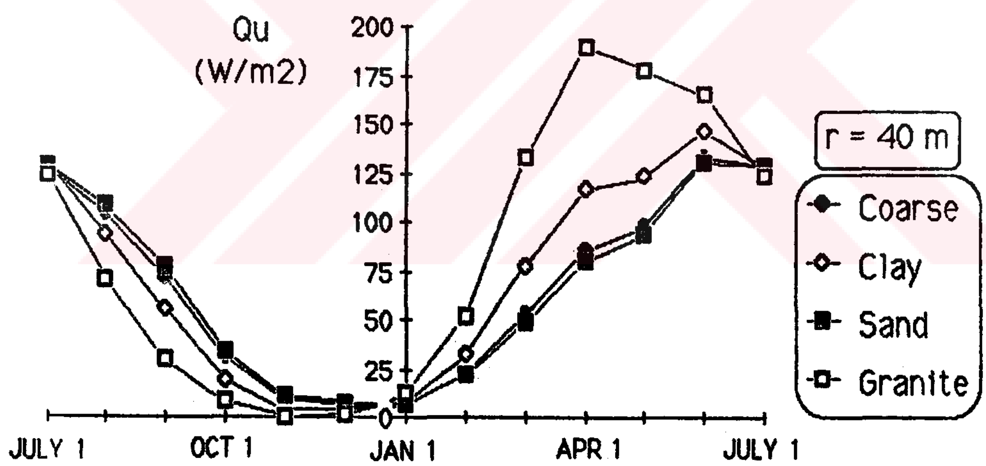

Figure 5.23. Monthly Average Instantaneous Useful Heat Gain of Solar System for 500 Houses.

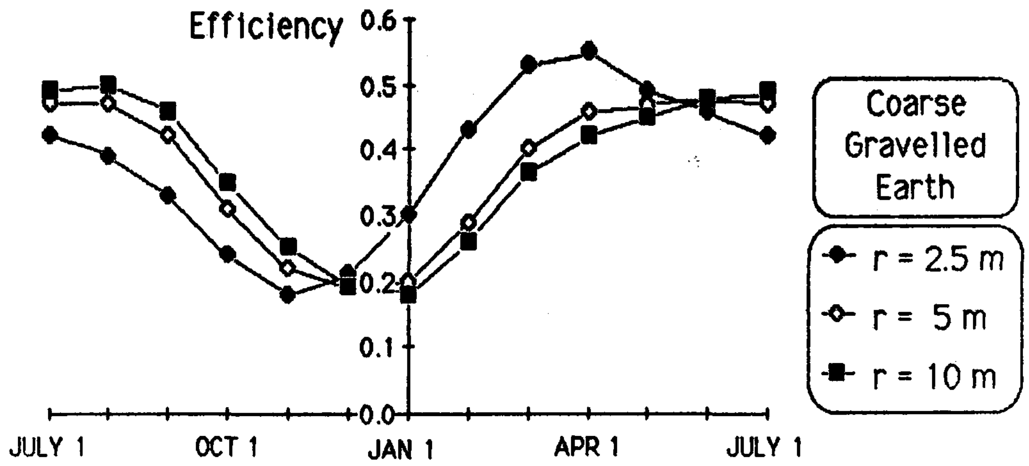

Figure 5.24 Monthly Average Collector Efficiency for one House.

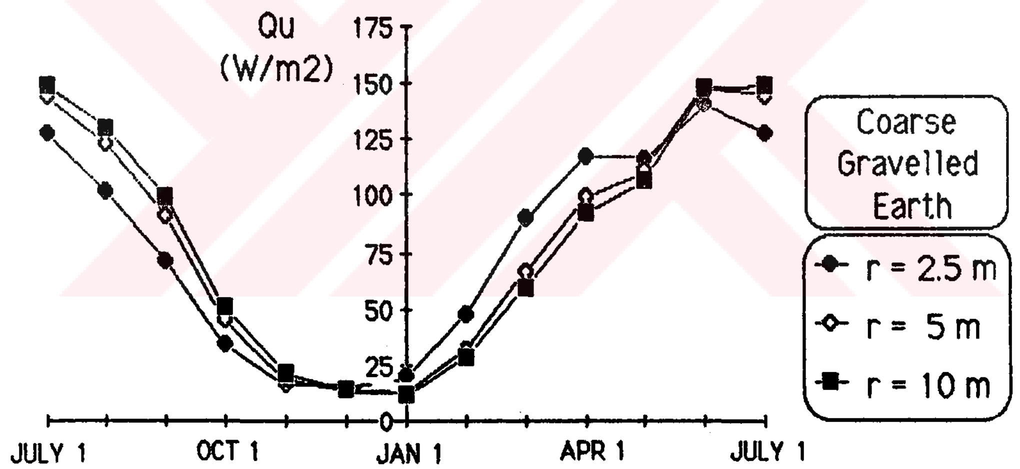

Figure 5.25. Monthly Average Instantaneous Useful Heat Gain of Solar System for one house.

CHAPTER 6

CONCLUSIONS

Two simulation models for prediction of the long term performance of solar aided heat pump systems with a seasonal heat storage were presented. The method of approach is based on computer simulations and the software developed may be applied to obtain optimum parametric values in addition to those of storage volume and system size. The computer program SOLPER2 developed in this study is intended to be run on fast fast computer and is based on hour-by-hour calculations. Simulations showed that a district solar heating system with underground storage can provide a significant solar energy gain. Based on the computer simulations, the major conclusions of this study are the following;

-A shift to larger storage sizes per house when moving from 1 to 500 houses was observed to give better system performance.

- Highest temperatures are attained in a store surrounded with sand which has the lowest thermal conductivity.

- A thermal energy store with a radius of about 5 meters is optimum for stores supplying heat to one house.

- Lowest store temperatures occur in the January and February

- Earth type has a strong effect on the annual store temperature distribution and on the annual heat pump COP. Earth type has also a small effect on the fractions of energy supplied to the system, fractions stored, lost and utilized at the load.

Present study indicates technical feasibility of seasonal energy storage in deep earth. Further efforts are needed on the analytical modelling and experimentation of spherical thermal storages with heat pumps aimed seasonal solar heating systems.

CHAPTER 7

RECOMMENDATIONS FOR FURTHER STUDY

The major objective of this study was the determination of the long term performance of solar aided heating systems with seasonal thermal energy storages.

The hourly solar radiation data and ambient temperatures, reported in Reference [22] were used in the computer simulation. The present study may be extended using hourly weather data for other cities in Turkey.

Variation of collector type, collector side fluid flowrate and collector area per house, which have effects on the system performance, can be further studied. The long term performance of a solar aided heating system should also be studied experimentally for several years of operation. After such an experimental study, one can test validity of the present theoretical study to find out how closely it predicts the results of an experimental study.

Economical analysis was not included in this study. This is quite a separate analysis which is at the moment out of scope of this work and can be the subject of another study.

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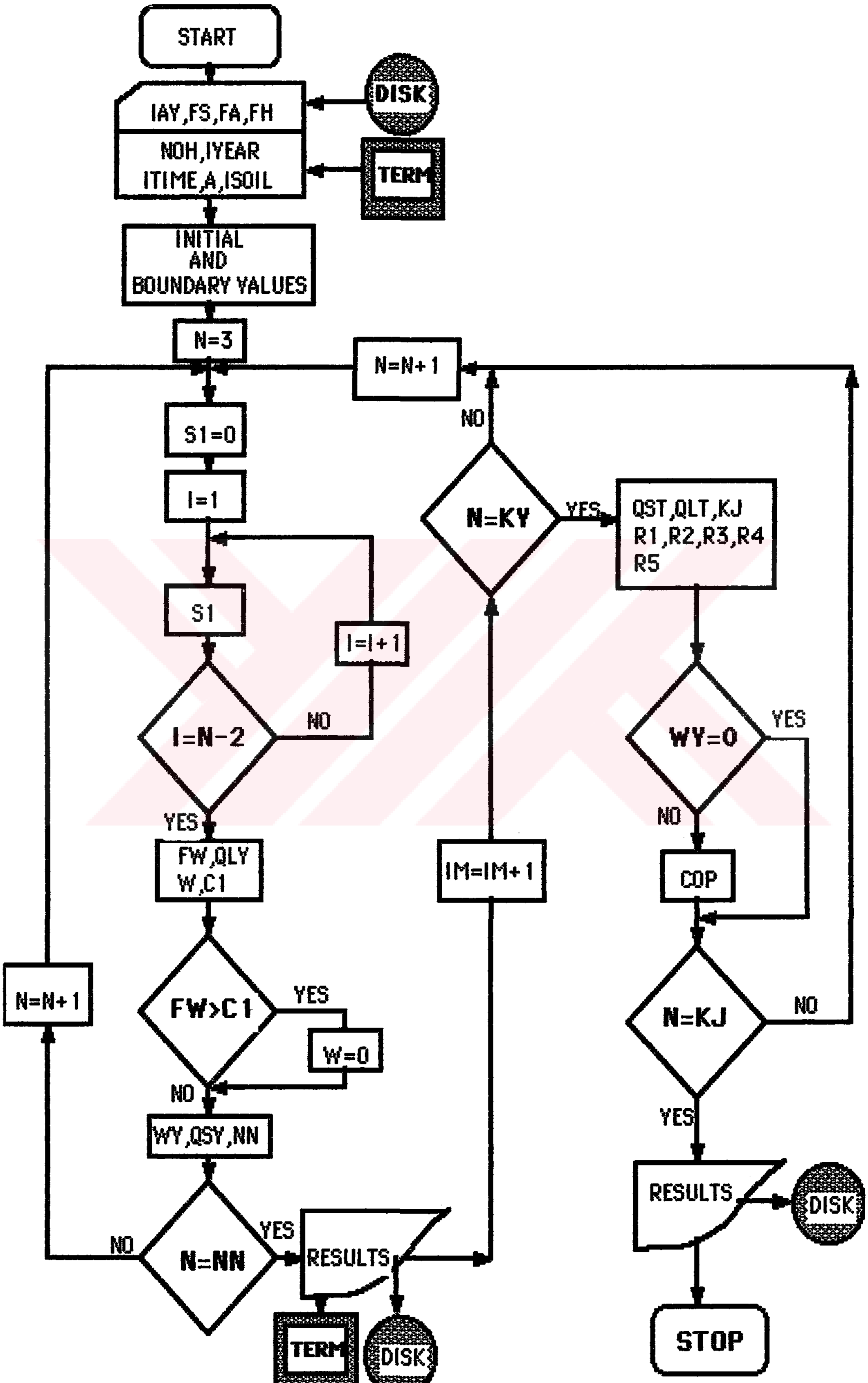
APPENDIX

FLOWCHART OF THE SOLPER1 PROGRAM



LISTING OF SOLPER1 SIMULATION PROGRAM

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C|________________________________________________________________
C|
C|   SOLPER1 SIMULATION PROGRAM
C|
C|________________________________________________________________
      REAL FW(9000),RR(12),FA(12),FI,W(9000),QN(9000),FIW(10,12)
      REAL TKEL(10,12),RT,QLT,QY,QST,QSY,WY,FS(12),FH,(12),S,H
      REAL QHDIM(12),B,MSS,A,P,PI,U,TINF,BETA,ALFA,DT,C1,S1
      INTEGER L,L2,N,IM,N2,MNO,KA,IYEAR,IA,KB,IY,LT(12),IAY(12)
C READING OF NUMBERS OF DAY IN A MONTHS
      READ (8,1) (IAY(J), J=1,12)
1     FORMAT(12I2)
C READING OF THE ANNUAL DISTRIBUTION  OF SOLAR ENERGY AND HOUSE
C HEAT LOAD
      DO 2 I=1,12
      READ(9,3) FS(I),FH(I)
3     FORMAT(F5.3,F4.2)
2     CONTINUE
      FI=0.01736
      DO 4 I=1,12
      READ(7,5) FA(I)
5     FORMAT(F10.5)
4     CONTINUE
      WRITE(6,6)
6     FORMAT(1X,'DISTRIBUTION FUNCTIONS',7X,'DIMENSIONLESS AIR
     *TEMPERATURE',3X,'MONTHS',25('-'),5X,29('-'),3X,6('_'))
      DO 7 I=1,12
      WRITE(6,8) I,FS(I),FH(I),I,FA(I),IAY(I)
8     FORMAT('FS(',I2,')=',F5.3,'FH(',I2,')=',F4.2,13X,'FA(',I2,')=',F8.5,11X,I2)
7     CONTINUE
      QYY=5617.4
      WRITE(6,9)
9     FORMAT(/,
     *'QYY=YEARLY SOLAR ENERGY INCIDENT ON M2          ',/
      *'QSY=ANNUAL DIMENSIONLESS SOLAR HEAT GAIN RATE',/
      *'WY=ANNUAL DIMENSIONLESS HEAT PUMP WORK',/
```

```
     *'QST=ANNUAL INCREASE IN DIMENSIONLES INTERNAL ENERGY',/
     *'QLT=ANNUAL DIMENSIONLESS HEAT LOSS FROM TANK',/
     *'QLY=ANNUAL DIMENSIONLESS HOUSE HEAT LOAD',/
     *'QY=ANNUAL NET HEAT ADDITION TO THE THERMAL STORE',/
     *'R1=FRACTION OF YEARLY SOLAR ENERGY BY ENERGY CHARGED TO THE
     *SYSTEM(SOLAR ENERGY AND HEAT PUMP WORK)',/
     *'R2=FRACTION OF YEARLY HEATPUMP WORK BY ENERGY CHARGED TO
     *THE SYSTEM(SOLAR ENERGY AND HEAT PUMP WORK)',/
     *'R3=FRACTION OF YEARLY STORED ENERGY BY ENERGY CHARGED TO
     *THE SYSTEM(SOLAR ENERGY AND HEAT PUMP WORK)',/
     *'R4=FRACTION OF YEARLY HEAT LOSS BY ENERGY CHARGED TO THE
     *SYSTEM(SOLAR ENERGY AND HEAT PUMP WORK)',/
     *'R5=FRACTION OF YEARLY HOUSE HEAT LOAD BY ENERGY CHARGED TO
     *THE SYSTEM(SOLAR ENERGY AND HEAT PUMP WORK)',/
     *'COP=COEFFICIENT OF PERFORMANCE OF HEAT PUMP')
10    WRITE(4,*) 'ENTER NUMBER OF YEARS THAT WILL BE CALCULATED,
     *IYEAR=?'
      READ(3,*) IYEAR
      WRITE(4,*) 'ENTER RADIUS OF TANK'
      READ(4,*) A
      WRITE(4,*) 'ENTER NUMBER OF HOUSE'
      READ(4,*) NOH
      WRITE(4,*) 'ENTER TIME INCREAMENT'
      READ(4,*) ITIME
      UA=333.34
      EF=0.44
      PI=3.1415
      U=1.0
      BETA=0.25
      TINF=288
      WRITE(6,11) QYY,UA,EF
11    FORMAT('QYY=',F8.2,3X,'UA=',F10.2,3X,'COL. EFFICIENCY=',F5.2)
      WRITE(3,*) 'WHICH ONE OF THE SOL SURROUNDED TO THE STORE'
      WRITE(3,12)
12    FORMAT('IF TYPE OF SOIL IS COARSE  PRINT--------> 1'/,
     *18X,                          'CLAY        , PRINT------>2',/
     *18X,                          'SAND        , PRINT------>3',/
     *18X,                          'GRANITE     , PRINT------>4',/
```

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     *18X,                   'NOT ANY ONE,  PRINT------>ANY NUMBER')
      READ(4,*) ISOIL
13    IF(ISOIL.EQ.1) GO TO 14
      IF(ISOIL.EQ.2) GO TO 15
      IF(ISOIL.EQ.3) GO TO 16
      IF(ISOIL.EQ.4) GO TO 17
      IF(ISOIL.GT.4) GO TO 18
14    RO=2050
      CP=1.842
      CON=0.519
      ALFA=1.39E-7
      WRITE(6,19)
19    FORMAT(128('*'))
      WRITE(6,20)
20    FORMAT('TYPE OF EARTH: COARSE GRAVELLED EARTH')
      GO TO 21
15    RO=1500
      CP=0.88
      CON=1.400
      ALFA=1.1E-6
      WRITE(6,22)
22    FORMAT(128('*'))
      WRITE(6,23)
23    FORMAT('TYPE OF EARTH: CLAY')
      GO TO 21
16    RO=1500
      CP=0.80
      CON=0.3
      ALFA=2.5E-7
      WRITE(6,24)
24    FORMAT(128('*'))
      WRITE(6,25)
25    FORMAT('TYPE OF EARTH: SAND')
      GO TO 21
17    RO=2640
      CP=0.82
      CON=3.0
      ALFA=1.4E-6
```

```
      WRITE(6,26)
26    FORMAT(128('*'))
      WRITE(6,27)
27    FORMAT('TYPE OF EARTH: GRANITE')
21    S=NOH*(EF*QYY*40*E6)/(4*PI*A*CON*TINF*31*24*3600)
      H=UA*NOH*84.7/(4*PI*A*CON*TINF)
      ROW=1000
      CW=4.187
      P=ROW*CW/(3.*RO*CP)
      PI=3.1415
      U=1.0
      BETA=0.25
      TINF=288
      DT=3600*ALFA/(A*A)
      P1=P/DT
      IF(IYEAR.EQ.1) GO TO 28
      KI=(365*24)*IYEAR+2
28    LS=0
      DO 29 J=1,12
      LT(J)=LS+IAY(J)
      LS=LT(J)
29    CONTINUE
      IF(IYEAR.GT.1) GO TO 30
      KI=24*LT(J)/ITIME+2
30    WRITE(6,31)A NOH
31    FORMAT('RADIUS OF TANK=',F5.1,4X,'NUM. OF HOUSE=',I4)
      GAMA=4*PI*A*CON/UA
      WRITE(4,32)S,H,P,GAMA
      WRITE(6,32)S,H,P,GAMA
32    FORMAT('S=',F9.3,3X,'H=',F9.3,3X,'P=',F5.2,3X,'GAMA=',F9.3)
      IM=1
      IY=1
      WRITE(6,33)
      FORMAT(128('- *'),/'!',126X,'!',/,'!',1X,'YEAR',5X,'QSY',7X,'WY',
     *7X,'QST',8X,'QLT',6X,'QLY',8X,'QY',6X,'R1',8X,'R2',8X,'R3',
     *8X,'R4',8X,'R5',7X,'COP',4X,'!',/,'!',1X,4('-'),12(2X,8('-')),1X,'!')
      C1=U*(FI-FA(IM)+FI
C INITIAL BOUNDARY CONDITION OF WATER TEMPERATURE OF
```

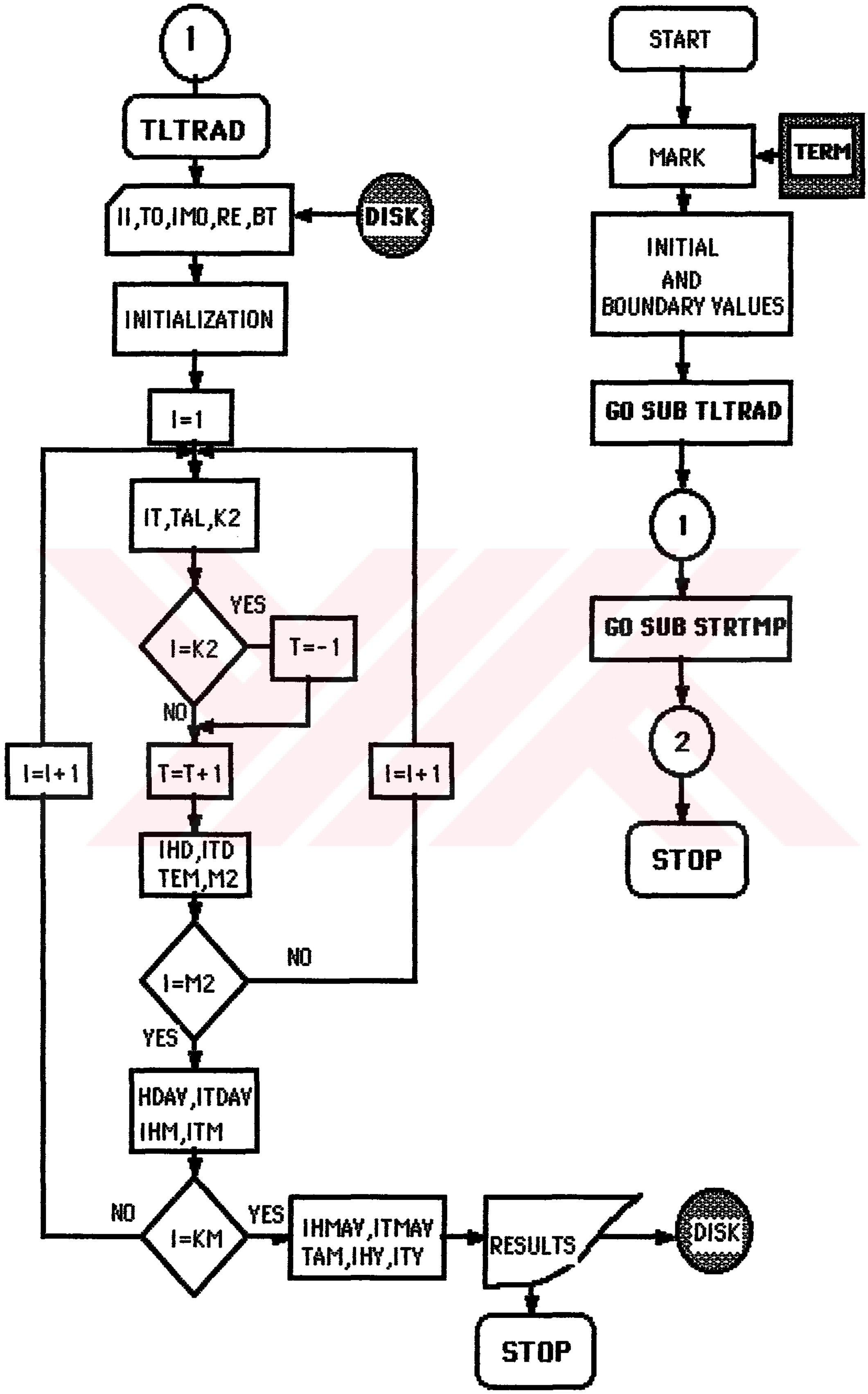
```
C SPHERICAL STORE
      FW(1)=0.0
      QN(1)=S*FS(1)-H*FH(1)
      QM=QN(1)
      RT=SQRT(PI*DT)
      FW(2)=(QN(1)+(P1+1/RT)*FW(1))/(1+(P1+1/RT))
      W(2)=(FI-FA(IM))*(C1-FW(2))/(BETA*(C1+1))
      WRITE(6,34) QN(1),DT,RT,P,P1,FW(2),C1,W(2)
34    FORMAT('QN(1)=',F6.3,' DT='F12.8,' RT='F6.3,' P=',F8.3,' P1=',F12.5,'
     *F12.5,' FW(2)=',F8.6,' C1=',F8.5,' W(2)=',F8.5)
      QY=0.0
      QLY=0.0
      WY=0.0
      QSY=0.0
      JJ=0
      DO 35 N=3,KI
      S1=0.0
      DO 36 I=1,N-2
      S1=S1+(FW(I+1)-FW(I))/SQRT((N-I)/1.)
36    CONTINUE
      QN(N)=S*FS(IM)-H*FH(IM)+(W(N-1)/GAMA)
      QM=QM+QN(N)
      FW(N)=(QN(N)+(P1+1/RT)*FW(N-1)-S1?RT)/(1+(P1+1/RT))
      C1=U*(FI-FA(IM))*(C1-FW(N))/(BETA*(C1+1)
      QLY=QLY+H*FH(IM)*DT
      W(N)=(FI-FA(IM))*(C1-FW(N))/(BETA*(C1+1))
C CONTROL LOGICS WEATHER HEAT PUMP IS USED OR NOT
      IF(FW(N).GE.C1) W(N)=0.0
C SUMMATION OF DIMENSIONLESS HEAT PUMP WORK, SOLAR ENERGY,HOUSE
C HEAT LOAD, AND HEAT INPUT TO THE STORE
      WY=WY+W(N)*DT
      Q(IM)=S*FS(IM)-H*FH(IM)
      QY=QY+(Q(IM)+(W(N)/GAMA))*DT
      QSY=QSY+S*FS(IM)*DT
      LZ+24*LT(IM)
      NN=JJ+LZ
      LJ=LZ-2
      IF(N.NE.LZ)GO TO 35
```

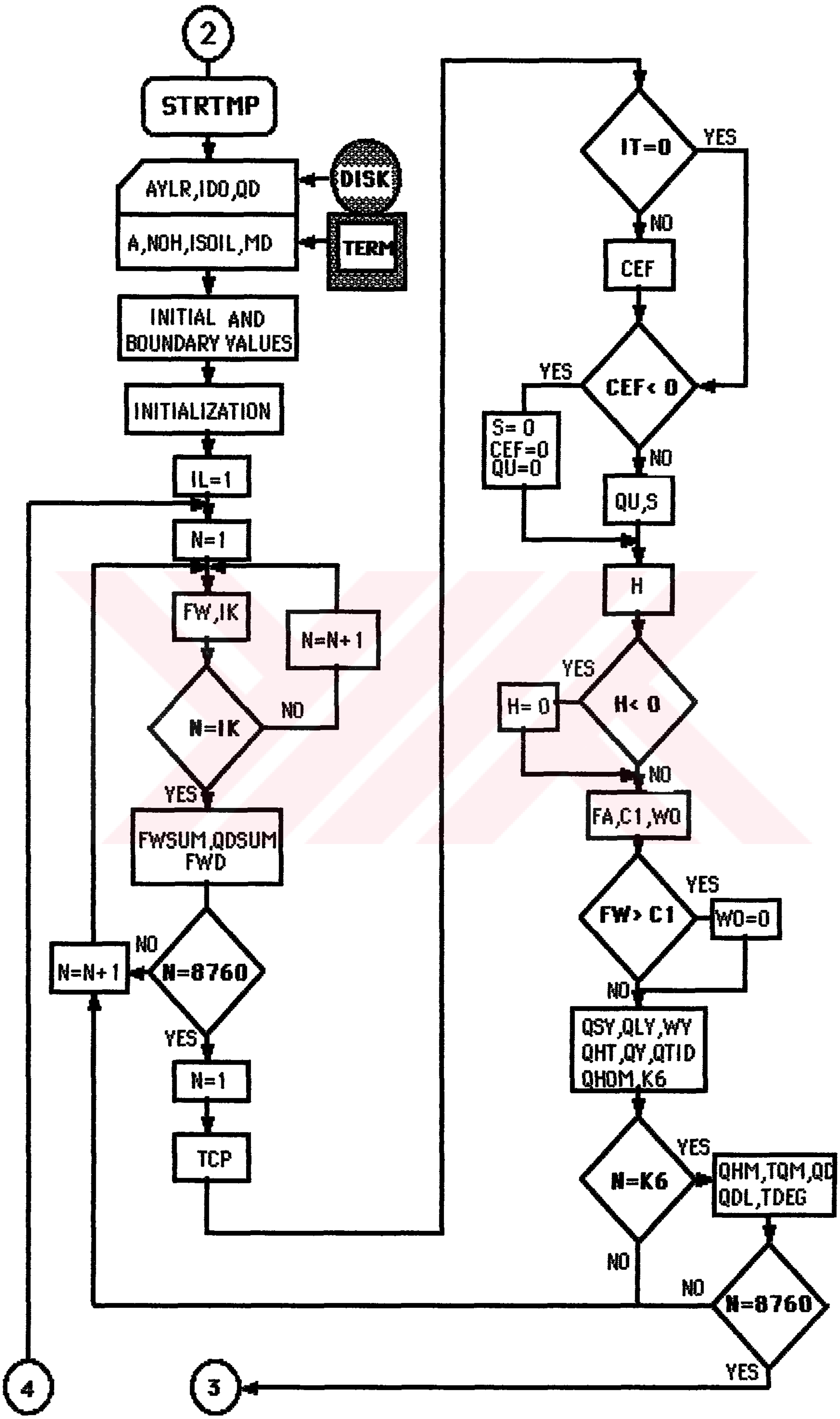
```
      QM=QM/IAY(IM)
      WRITE(4,37) LZ,N,IM,FW(N),QM
      WRITE(6,37) LZ,N,IM,FW(N),QM
37    FORMAT('LZ=',I4,'  N=',I4,'FW(',I2,')',F8.5,'  QM=',F12.6)
      FIW(IY,IM)=FW(N)
      TKEL(IY,IM)=288*(FW(N)+1)-273.
      IM=IM+1
      QM=0.0
35    CONTINUE
      WY=WY/GAMA
      IF(IY.EQ.1.) GO TO 38
      J1=(IY-1)*365*24/ITIME
C COMPUTATION OF ENERGY STORE IN A YEAR
      QST=P*(FW(N)-FW(J1))
      GO TO 39
38    QST=P*FW(N)
C  COMPUTATION OF ENERGY LOST FROM STORAGE
39    QLT=QY-QST
C FRACTIONS OF EACH COMPONENT OF ENERGY TO THE ENERGY INPUT TO THE
C STOREPERFORMANCE OF HEAT PUMP
      R=QSY+WY
      R1=QSY/R
      R2=WY/R
      R3=QST/R
      R4=QLT/R
      R5=QLY/R
      IF(WY.EQ.0.0) GO TO 40
C COMPUTATION OF COEFFICIENT OF PERFORMANCE OF HEAT PUMP
      COP=QLY/WY
      WRITE(6,41) IY,QSY,WY,QST,WY,QST,QLT,QLY,QY,R1,R2,R3,R4,R5,COP
41    FORMAT('!',2X,I2,3X,F8.5,1X,F9.7,2X,F8.5,2X,F8.5,2X,F8.5,6(2X,F8.5),1X
     *F9.1,1X,'!')
      GO TO 43
40    WRITE(6,42) IY,QSY,WY,QST,WY,QST,QLT,QLY,QY,R1,R2,R3,R4,R5,COP
42    FORMAT('!',2X,I2,3X,F8.5,1X,F9.7,2X,F8.5,2X,F8.5,2X,F8.5,6(2X,F8.5),1X
     *F9.1,1X,'!')
43    JJ=IY*365
      WRITE(4,44) ISOIL,A,IY
```

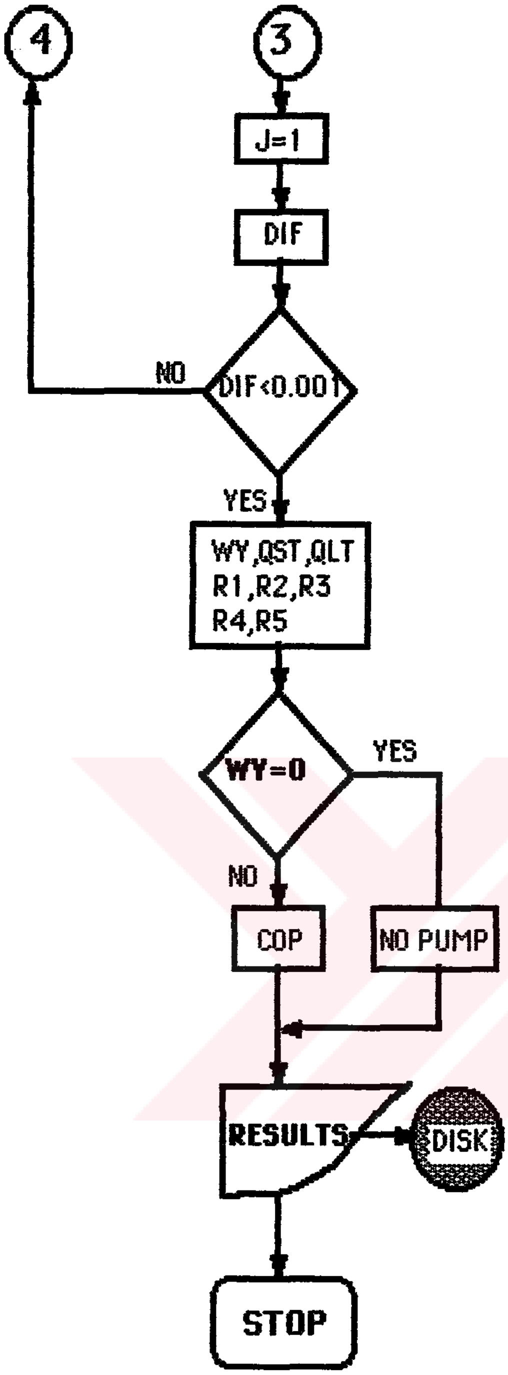
```
44    FORMAT('ISOIL=',I2,2X,'A='F5.2,2X,'YEAR=',I2)
      IY=IY+1
      IM=1
      QSY=0.0
      WY=0.0
      QLY=0.0
      QY=0.0
      WRITE(6,45)
45    FORMAT('!',126('-'),'!'//)
      II=IY-1
      WRITE(6,46)
46    FORMAT(22X,'DIMENSIONLESS WATER TEMPERATURE OF SPHERICAL
      *THERMAL STORE',/22X,59('-'))
      WRITE(6,47)
47    FORMAT(128('-'),/'!',126X,'!',/'!",1X,'YEAR',4X,'JULY',5X,'AUGUST',3X,
     *'SEPTEMBER',3X,'OCTOBER',2X,'NOVEMBER',2X,'DECEMBER',3X
     *,'JANUARY',2X,'FEBRUARY',3X,'MARCH',5X,'APRIL',6X,'MAY'
     *,7X,'JUNE',3X,'!',/'!',1X,4('-'),12(2X,8('-')),1X,'!')
      DO 48 I=1,II
      WRITE(6,49) I,(FIW(I,IM),IM=1,12)
49    FORMAT('!',2X,I2,12(2X,F8.4),2X,'!')
48    CONTINUE
      WRITE(6,50)
      FORMAT(22X,'WATER TEMPERATUREOF SPHERICAL THERMAL STORE(IN
     *DEGRE',/22X,54('-'))
      WRITE(6,51)
51    FORMAT(128('-'),/'!',126X,'!',/'!",1X,'YEAR',4X,'JULY',5X,'AUGUST',3X,
     *'SEPTEMBER',3X,'OCTOBER',2X,'NOVEMBER',2X,'DECEMBER',3X
     *,'JANUARY',2X,'FEBRUARY',3X,'MARCH',5X,'APRIL',6X,'MAY'
     *,7X,'JUNE',3X,'!',/'!',1X,4('-'),12(2X,8('-')),1X,'!')
      DO 53 I=1,II
      WRITE(6,52) I,(TKEL(I,IM),IM=1,12)
52    FORMAT'!',2X,I2,12(2X,F8.2),2X,'!')
53    CONTINUE
      WRITE96,54)
54    FORMAT('!',126('-'),'!')
      IF(ISOIL.EQ.4) GO TO 55
      ISOIL=ISOIL+1
```

```
      GO TO 13
      WRITE(4,56)
56    FORMAT(5X,'DO YOU WANT TO EXACUTE FOR ANOTHER CALCULATIONS'/
     *          5X,   'IF YES,     PRINT      ------>     1     '/
     *          5X,   'IF NOT,     PRINT      ------>ANY NUMBER')
      READ(3,*) NC
      IF(NC.EQ.1 )GO TO 10
55    STOP
      END
```

FLOWCHART OF THE SOLPER2 PROGRAM




2
STRTMP
AYLR,IDO,QD
DISK
A,NOH,ISOIL,MD
TERM
INITIAL AND BOUNDARY VALUES
INITIALIZATION
IL=1
N=1
FW,IK
N=N+1
N=IK
NO
YES
FWSUM,QDSUM FWD
N=8760
NO
N=N+1
YES
N=1
TCP
IT=0
YES
NO
CEF
CEF< 0
YES
S= 0 CEF=0 QU=0
NO
QU,S
H
H< 0
YES
H= 0
NO
FA,C1,WO
FW> C1
YES
WO=0
NO
QSY,QLY,WY QHT,QY,QTID QHOM,K6
N=K6
YES
QHM,TQM,QD QDL,TDEG
NO
N=8760
NO
YES
4
3



4
3
J=1
DIF
NO
DIF<0.001
YES
WY,QST,QLT
R1,R2,R3
R4,R5
WY=0
YES
NO
COP
NO PUMP
RESULTS
DISK
STOP

LISTING OF SOLPER2 SIMULATION PROGRAM

```
C|_____________________________________________________________
C|
C|  SOLPER2 SIMULATION PROGRAM
C|
C|_____________________________________________________________
      REAL QSY,WY,QST,QLT,QLY,QY,R,R1,R2,R3,R4,R5.COP,FIW(10.12)
      REAL TDEG(10,12),CEF(12,744),RE(12),RT,WP,FS(12),FH(12),FA(12)
      REAL NC,MD,CAR(12),P,PI,U,TINF,BETA,BK,ALFA,DT,C1,S1
      REAL II(8760),IT(8760),TO(8760),TAL(8760),TA(12,744),QD1(12)
      INTEGER L,L2,N,IM,N2,IYEAR,IY,IAY(12),LT(12),ID0(12),LD(12)
      REAL QD2(12),DELD(12)
C     DEFINITION OF PAREMETERS
1     FORMAT(/
     *'QU=HOURLY USEFUL SOLAR RADIATION',/
     *'II=HOURLY RADIATION ON A HORIZANTAL SURFACE ',/
     *'IT=HOURLY RADIATION ON A TILTED SURFACE ',/
     *'TO=HOURLY AMBIENT TEMPERATURE ',/
     *'QSY=ANNUAL DIMENSIONLESS SOLAR HEAT GAIN RATE ',/
     *'WY=ANNUAL DIMENSIONLESS HEAT PUMP WORK ',/
     *'QST=ANNUAL INCREASE IN DIMENSIONLESS INTERNAL ENERGY ',/
     *'QLY=ANNUAL DIMENSIONLESS HEAT LOSS FROM THERMAL STORE ',/
     *'QY=ANNUAL DIMENSIONLESS NET HEAT ADDITION TO THE STORE ',/
     *'R1=FRACTION OF YEARLY SOLAR ENERGY BY ENERGY CHARGED TO THE
     *SYSTEM(SOLAR ENERGY AND HEAT PUMP WORK)',/
     *'R2=FRACTION OF YEARLY HEATPUMP WORK BY ENERGY CHARGED TO
     *THE SYSTEM(SOLAR ENERGY AND HEAT PUMP WORK)',/
     *'R3=FRACTION OF YEARLY STORED ENERGY BY ENERGY CHARGED TO THE
     *SYSTEM(SOLAR ENERGY AND HEAT PUMP WORK)',/
     *'R4=FRACTION OF YEARLY HEAT LOSS BY ENERGY CHARGED TO THE
     *SYSTEM(SOLAR ENERGY AND HEAT PUMP WORK)',/
     *'R5=FRACTION OF YEARLY HOUSE HEAT LOAD BY ENERGY CHARGED TO
     *THE SYSTEM(SOLAR ENERGY AND HEAT PUMP WORK)',/
     *'COP=COEFFICIENT OF PERFORMANCE OF HEAT PUMP')
C     SELECTION OF SOLAR COLLECTORS THAT WILL BE USED
2     WRITE(6,3)
3     FORMAT(10X,'          TYPES OF COLLECTOR,    PRINT',/
     *'  |-> DEKA OR TEBA(2 GLASS COVER SELECTIVE SURFACE),    3',/
     *'  |-> IRTEK(1 GLAS COVER BLACK PAINT)              ,    5',/
     *'  |-> GURMAK(1 GLAS COVER BLACK PAINT)             ,    7',/
     *'  |-> AKDENIZ(1 GLAS COVER BLACK PAINT)            ,    9',/
     *'  |-> IF YUO ENTER AGAIN                           ,    2',/
     *'  |-> IF YOU WILL STOP                             ,    11')
```

```
      READ(2,*) MARK
      GO TO (3,5,7,9,2) MARK
3     AIC=1.7
      UL=4.5
      TALN=0.76
      CM=6.0
      PK=45.0
      W=0.088
      WRITE(6,4)
4     FORMAT('COLLECTOR TYPE:' 2 GLASS COVER SELECTIVE SURFACE')
      GO TO 10
5     AIC=1.5
      UL=7.4
      TALN=0.89
      CM=5.0
      PK=211.0
      W=0.09
      WRITE(6,6)
6     FORMAT('COLLECTOR TYPE:' IRTEK(1 GLASS COVER BLACK PAINT)')
      GO TO 10
7     AIC=2.0
      UL=7.4
      TALN=0.89
      CM=5.0
      PK=365.0
      W=0.078
      WRITE(6,8)
8     FORMAT('COLLECTOR TYPE:' GURMAK(1 GLASS COVER BLACK PAINT)')
      GO TO 10
9     AIC=1.84
      UL=7.4
      TALN=0.89
      CM=5.0
      PK=211.0
      W=0.09
      WRITE(6,6)
6     FORMAT('COLLECTOR TYPE:' AKDENIZ(1 GLASS COVER BLACK PAINT)')
10    CALL TLTRAD(TALN,IT,TO,TAL)
      CALL STRTMP(IT,TO,TAL,AIC,UL,CM,PK,W)
11    STOP
      END
C*************************************************************
C     SUBROUTINE TLTRAD CALCULATES HOURLY RADIATION ON A TILTED
C     SURFACE AND TRANSMITTANCE ABSORBTANCE PRODUCT
C*************************************************************
      SUBROUTINE TLTRAD(TALN,IT,TO,TAL)
```

```
      REAL DELTA,II(8760),IIO(8760),IDI(8760)KT(8760),RB(8760),RE(12)
      REAL DEL(365),ITT,ITM,ITS,ITY,IHD,ITD,MD,MDC,IHDAV(365)
      REAL ITDAV(365),IHMAV(12),ITMAV(12),TALN,RQ,IHORY,ITILY
      REAL TAM(12)TOR(12),IT(8760),TO(8760),TAL(8760)
      INTEGER IMO(12),LG(12),DAV(10.365)
C     READING OF HOURLY RADIATION ON A HORIZONTAL SURFACE AND
C     AMBIENT AIR TEMPERATURE
      READ(5,1) (II(I),I=1,8760),(TO(I),I=1,8760)
1     FORMAT(5X,12F5.2)
C     READING OF NUMBER OF MONTHS
      READ(9,2) (IMO(J),J=1,12)
2     FORMAT(12I2)
      N=0
      DO  3 I=1,12
      LG(I)=N+IMO(I)
      N=LG(I)
3     CONTINUE
C     READING OF REFLECTIVITY OF THE GROUND
      READ(11,4) (RE(K),K=1,12
4     FORMAT(12F5.1)
      PI=3.1415
      CR1=2.*PI/365.
      CR2=PI/180.
      DO 5 I=1,365
      PIR=CR1*(284+I)
      DELTA=23.45*SIN(PIR)
      DEL(I)=CR2*DELTA
5     CONTINUE
      WRITE(2,6)I,DEL(I)
6     FORMAT(2X,'DEL(',I3,')=',F5.2)
31    WRITE(1,*) 'ENTER THE COLLECTOR ANGLE'
      READ(2,*) BT
C     WRITE(1,*) 'ENTER THE LATITUDE ANGLE'
C     READ(2,*) FI
      FI=37.1
      FII=FI*PI/180.
      BTT=FI*PI/180.
C     INITIAL CONDITIONS
      J1=1
      DEC=2
      IHD=0.0
      ITD=0.0
      IHM=0.0
      ITM=0.0
      IHY=0.0
      ITY=0.0
```

```
      N=182
      T=0.0
      TEM=0.0
      GS=1353.
      DO 19 I=1,8760
      IF(N.EQ.365) N=0
      N=N+1
      L=(I-1)/24+1
      W1=15.*(T-12.)*PI/180
      W2=15.*(T-11.)*PI/180
      W=(W1+W2)/2.
      RIN=2.0*PI*N/365.
      RQ=43200.*GS/PI*(1.+0.033*COS(RIN))*(COS(FII)*COS(DEL(N)*
     *(SIN(W2)-SIN(W1))+(W2-W1)*SIN(FII)*SIN(DEL(N)))
      II0(I)=ABS(RQ)
      KT(I)=II(I)/II0(I)*41870.
      IF(KT(I).LE.0.35) GO TO 7
      IF(KT(I).LE.0.75) GO TO 8
      IF(KT(I).GT.0.75) GO TO 9
7     IDI(I)=1.0-0.249*KT(I)
      GO TO 10
8     IDI(I)=1.557-1.84*KT(I)
      GO TO 10
9     IDI(I)=0.117
10    RBC=(COS(FII-BTT)*COS(DEL(N))*COS(W1)+SIN(FII-BTT)*
     *SIN(DEL(N)))/(COS(FII)*COS(DEL(N))*COS(W1)+SIN(FII)*SIN(DEL(N)))
      BS=ABS((RBC)
      IF(TQ.GE.2.0) GO TO 11
      RB(I)=BS
      GO TO 12
11    AR1=(1.-IDI(I))*RB(I)
12    AR2=IDI(I)*(1.0+COS(BTT))/2.
      AR3=RE(J1)*(1.0-COS(BTT))/2.
      RCF=AR1+AR2+AR3
C  THE RESULT OF CALCULATION OF RADIATION ON A TILTED SURFACE
      IT(I)=RCF*II(I)*41870./3600.
      TEAZ=ACOS(SIN(FII)*SIN(DEL(N))*(COS(FII)*COS(DEL(N))*COS(W))
      TQ=ABS(RB(I)*COS(TETAZ))
      IF(TQ.GT.1.) GO TO 16
      TETA=ACOS(TQ)
      IF(DEC.EQ.1.) GO TO 13
      B0=-0.17
      GO TO 14
13    B0=-0.1
14    AMOD=1.0+B0*(1.0/COS(TETA)-1.0)
      IF(AMOD.LE.0.2) GO TO 15
```

```
      IF(AMOD.GE.1.0) GO TO 16
      TAL(I)=TALN*AMOD
      GO TO 17
15    AMOD=0.9-0.01*TETA*180./PI
      TAL(I)=TALN*AMOD
      GO TO 17
16    TAL(I)=TALN
17    K1=I/24
      K2=24*K1
      IF(I.EQ.K2) T=-1.0
      T=T+1.0
      IHD=IHD+II(I)
      ITD=ITD+IT(I)
      TEM=TEM+TO(I)
      M1=I/24
      M2=24*M1
      WRITE(4,18) I,II(I),IHD,I,TO(I),TEM
      WRITE(6,18) I,II(I),IHD,I,TO(I),TEM
18    FORMAT('II(',I2,')=',F5.2,'  IHD=',F8.2,'  TO(',I2,')=",F5.2,' TEM=',F9.3)
      IF(I.NE.M2) GO TO 19
      IHDAV(L)=IHD/24.*41870./3600.
      ITDAV(L)=ITD/24.
      IHM=IHM+IHD
      ITM=ITM+ITD
      IHD=0.0
      ITD=0.0
      KM=LG(J1)*24
      IF(I.NE.KM) GO TO 19
      IHMAV(J1)=IHM/KL*4187./3600.
      ITMAV(J1)=ITM/KL
      TAM(J1)=TEM/KL
      IHY=IHY+IHM
      TSUM=TSUM+TAM(J1)
      TDIF=20.0-TAM(J1)
      WRITE(4,20) LG(J1),J1,IHMAV(J1),J1,TAM(J1)
      WRITE(6,20) LG(J1),J1,IHMAV(J1),J1,TAM(J1)
20    FORMAT('LG=',I3,' IHMAV(',I2,')=',F10.2,'TAM(',I2,')=',F6.2,' TDIF=',F9.4)
      J=J+1
      IHM=0.0
      ITM=0.0
      TEM=0.0
19    CONTINUE
      TGUN=TEM/24.
      WRITE(4,21) TGUN,L,IHDAV(L),L,ITDAV(L)
      WRITE(6,21) TGUN,L,IHDAV(L),L,ITDAV(L)
21    FORMAT('TGN=',I3,'IHDAV(',I2,')=',F10.2,'ITDAV(',I2,')=',F6.2)
```

```
      TEM=0.0
      K2=24*K1
      DO 23 J=1,12
      TOR(J)=(273.+TAM(J))/288.-1
      WRITE(4,24)J,TOR(J)
      WRITE(6,24)J,TOR(J)
24    FORMAT('TOR(',I2,')='F8.5)
23    CONTINUE
      WRITE(6,*)'HOURLY RADIATIONON ON A TILTED SURFACE(W/M2HOUR)
      WRITE(6,25) (II(I),I=1,24),(IT(I),I=1,24)
25    FORMAT(12F7.2,2X,/12F7.2,2X)
      WRITE(6,*)'DAILY AVERAGE ADIATION ON A TILTED SURFACE
      WRITE(6,26) (ITDAV(J),J=1,30)
26    FORMAT(12F7.2,2X,/12F7.2,2X)
      WRITE(6,*)'MONTHLY AVERAGE ADIATION ON A TILTED SURFACE
      WRITE(6,27) (ITMAV(J),J=1,12)
27    FORMAT(12F6.2,2X)
      IHORY=IHY*41870./(8760*3600)
      WRITE(6,*)'YEARLY AVERAGE ADIATION ON A HORIZANTAL SURFACE
      WRITE(6,28) IHORY
28    FORMAT(F6.2)
      WRITE(6,*)'YEARLY AVERAGE ADIATION ON A TILTED SURFACE
      ITILY=ITY/8760.
      WRITE(6,29) IHORY
29    FORMAT(F6.2)
      WRITE(1,30)
30    FORMAT(2X,'DO YOU WANT TO CALCULATE NEW VALUES',/
     *2X,   IF YOU WANT,      PRINT--->   1',/
     *2X,   IF NOT       ,    PRINT--->   ANY NUMBER')
      READ(2,*) NUM
      IF(NUM.EQ.1) GO TO 31
      RETURN
      STOP


C*********************************************************************
C     SUBROUTINE STRTMP CALCULATES ANNUAL PERIODI STORE
C     TEMPERATURE AND OTHER VALUES WHICH ARE ABOUT THE
C     PERFORMANCE OF THE SYSTEM
C*********************************************************************
      SUBROUTINE STRTMP(IT,TO,TAL,AIC,UL,CM,PK,W)
      REAL QLT,QV,QST,QSY,WY,QY,R1,R2,R3,R4.R5.COPA,P,PI,U,TINF
      REAL BETA,ALFA,DT,C1,NOH.ISOIL,FIW(30,12),FW(30,8760),TDEG(12)
      REAL TDIM(30,12),FWD(12),H(8760),S(8760),QN(8760),CEF(8760)
      REAL QU(8760),WO(8760),II(8760),IT(8760),TAL(8760),TQM(12)
      REAL QIN(12),QD1(12),QD2(12),DELD(12)CEFD(12,31),CEFM(12)
```

```
      REAL RT,WP,MDC,FR,FP,FL,MD,NC,IMO(12),LG(12),QD(50,12),RJ(15)
      REAL T,TAG,ETA3(12),ETA4(12)
      INTEGER IDO(12),LD(12)
      CHARECTER*12 AYLR(12)
C     READIN OF MONTHS
      DO 1 J=1,12
      READ(20,2) AYLR(J)
2     FORMAT(A9)
1     CONTINUE
      CAR(1)=0.0
      CAR(2)=0.0
      CAR(3)=0.0
      CAR(4)=1.0
      CAR(5)=1.0
      CAR(6)=1.0
      CAR(7)=1.0
      CAR(8)=1.0
      CAR(9)=1.0
      CAR(10)=1.0
      CAR(11)=0.0
      CAR(12)=0.0
C READING OF NUMBERS OF DAY IN A MONTHS
      READ (8,4) (IDO(J), J=1,12)
4     FORMAT(12I2)
      LL=0
C READING OF RELAXIATION NUMBER
      READ(21,5) AL
5     FORMAT(F5.3)
      DO 6 J=1,12
      LD(J)=LL+IDO(J)
      LL=LD(J)
6     CONTINUE
      A0=Q0/12.
      WRITE(4,*)'WHAT IS THE RADIUS OF TANK'
      READ(4,*) A
      WRITE(4,*)'HOW MANY HOUSE DO YOU HAVE'
      READ(4,*) NOH
      WRITE(4,*)'WHAT IS THE TYPE OF SOIL'
      READ(4,*) ISOIL
44    WRITE(4,7)
7     FORMAT('    IF TYPE OF SOIL IS        COARSE     PRINT ----> 1'/,
     *18X,                                'CLAY       PRINT ----> 2'/,
     *18X,                                'SAND       PRINT ----> 3'/,
     *18X,                                'GRANITE    PRINT ----> 4'/,
     *18X,              'IF YOU WILL FED AGAIN        PRINT ----> 5'/,
     *18X,              'IF YOU WILL NOT FED AGAIN    PRINT ----> ANY')
```

```
      READ(4,*) ISOIL
8     IF(ISOIL.EQ.1) GO TO 9
      IF(ISOIL.EQ.2) GO TO 11
      IF(ISOIL.EQ.3) GO TO 13
      IF(ISOIL.EQ.4) GO TO 15
      IF(ISOIL.EQ.5) GO TO 7
      GO TO 1
9     RO=2050
      CP=1.842
      CON=0.519
      ALFA=1.39E-7
      WRITE(6,10)
10    FORMAT(80('*'),/' TYPE OF EARTH: COARSE GRAVELLED EARTH')
      GO TO 17
11    RO=1500
      CP=0.88
      CON=1.4
      ALFA=1.1E-6
      WRITE(6,12)
12    FORMAT(80('*'),/' TYPE OF EARTH: CLAY')
      GO TO 17
13    RO=1500
      CP=0.8
      CON=0.3
      ALFA=2.5E-7
      WRITE(6,14)
   14 FORMAT(80('*'),/' TYPE OF EARTH: SAND')
      GO TO 17
15    RO=2640
      CP=0.82
      CON=3.0
      ALFA=1.4E-6
      WRITE(6,10)
12    FORMAT(80('*'),/' TYPE OF EARTH: GRANITE')
17    DO 18 J=1,13
      RJ(J)=(J-7)/12.0
18    CONTINUE
C**********************************************************************
*
C     DEFINITION OF INITIAL VALUES
C     WRITE(2,*)'HOW MANY COLLECTORS WILL BE USED'
C     READ(2,*) NC
C     WRITE(2,*)'HOW MUCH IS THE MASS FLOWRATE OF THE COLLECTOR
C    *SIDE(IN KG/(M2*SEC))'
C     READ(2,*) MD
C DEFINITION INITIAL VALUES OF PAREMETERS
```

```
47    AC=40.0
      MD=0.01
      UA=333.34
      ROW=1000
      CPW=4187.0
      CPC=4187.0
      WRITE(6,19) A,NOH,UA,AC,MD
19    FORMAT(/,
     *'RADIUS OF STORAGE TANK              =',F7.2,/
     *'NUMBERS OF HOUSE                    =',F7.2,/
     *'UA VALUES OF HOUSE                  =',F7.2,/
     *'COLLECTOR AREA                      =',F7.2,/
     *'MASS FLOWRATE                       =',F7.5)
      P=ROW*CPW/(3*RO*CP)
      FI=0.01736
      U=1.0
      BETA=0.25
      DT=ALFA*3600/(A*A)
      Y=ALFA*365*24*3600./(A*A)
      GAMA=4.*PI*A*CON/(NOH*UA)
      DLT=0.0005
      DS=0.01
      CB=300
      HC=300
      MDC=MD*AC
      QM=SQRT(UL/(PK*DLT))
      WDS=W-DS
      FL=TANH(QM*WDS/2.)/(QM*WDS/2.)
      EP=1/(UL*W*(1./(UL*(DS+WDS*FL))+1./CB+1/(PI*DS*HC)))
      FR=MDC*CPC/(AC*UL)*(1.EXP(-1.*AC*UL*FP/(MD*CPC)))
      WRITE(6,20) MDC,QM,FL,FP,FR
20    FORMAT('MDC=',F8.2,2X,'QM=',F8.2,2X,'FL=',F8.4,2X,'FP=',
     *F8.4,2X,'FR=',F8.4)
      PC1=4.*PI*A*CON*288.
      SAB1=NOH*AC/PC1
      SAB2=NOH*UA/PC1
      DO 21 IL=1,40
      IP=IL+1
      SOL=0.0
      QSY=0.0
      QLY=0.0
      WY=0.0
      QY=0.0
      QHT=0.0
      QLD=0.0
      QTID=0.0
```

```
      QHOM=0.0
      QTIM=0.0
      FWSUM=0.0
      QDSUM=0.0
      Q0=0.0
      ID=1
      IM=1
      IJ=1
      L1=1
      K=1
C CALCULATION OF WATER TEMPERATURE OF THE STORE
      DO 22 N=1,876
      TAG=N*3600.*ALFA*/(A*A)
      T=9TAG-Y/2.)/Y
      SUMG=0.0
      DO 24 NI=1,3
      RD=2.*PI*NI
      T2=P*RD/Y
      QR=SQRT(NI*PI/Y)
      ETA1=1.+QR
      ETA2=QR+T2
      SQ1=ETA1*ETA1
      SQ2=ETA2*ETA2
      ACNS=1./(PI*NI*(SQ1+SQ2))
      SUMA=0.0
      SUMB=0.0
      DO 23 J=1,12
      D1=RD*RJ(J+1)
      D2=RD*RJ(J)
      ETA3(J)=SIN(D1)-SIND2(D2)
      ETA4(J)=COS(D1)-COS(D2)
      SUMA=SUMA+QD(IL,J)*(ETA1*ETA3(J)+ETA2*ETA4(J))
      SUMB=SUMB+QD(IL,J)*(ETA2*ETA3(J)+ETA1*ETA4(J))
23    CONTINUE
      E1=RD*T
      SUMG=SUMG+ACNS*(COS(E1)*SUMA+SIN(E1)*SUMB)
24    CONTINUE
      FW(IL,N)=A0+SUMG
      IK=LD(K)*24
      IF(N.LT.IK) GO TO 21
      FWSUM=FWSUM+FW(IL,N)
      QDSUM=QDSUM+QD(IL,K)
      FIW(IL,IJ)=FW(IL,N)
      WRITE(4,25) IJ,QD(IL,IJ),IL,IJ,FWD(IJ),A,ISOIL
      WRITE(6,25) IJ,QD(IL,IJ),IL,IJ,FWD(IJ),A,ISOIL
25    FORMAT('QD(',I2,')=',F8.4,' ITR=',I2,' FWD(',I2,')=',F10.4,
```

```
     *' A=',F4.0,'            ISOIL=',F2.0)
      IJ=IJ+1
      K=K+1
21    CONTINUE
      K=1
C CALCULATION OF DIMENSIONLES ENERGY INPUT TO THE STORE
      DO 26 N=1,8760
      TCP(N)=(FW(IL,N)+1.)*288.-273.
      IF(IT(N).EQ.0.0) GO TO 27
      CEF(N)=FR*TAL(N)+FR*UL*(TO(N)-TCP(N))/IT(N)
      IF(CEF(N).LT.0.0) GO TO 27
      QU(N)=CEF(N)*IT(N)
      S(N)=QU(N)*SAB1
      GO TO 28
27    S(N)=0.0
      CEF(N)=0.0
      QU(N)=0.0
28    H(N)=CAR(K)*SAB2*(20.-TO(N))
      IF(FIW(IL,N).LT.0.0) H(N)=0.0
      FA=((TO(N)+273.)/288.-1.)
      C1=CAR(K)*U*(FI-FA)+FI
      WO(N)=CAR(K)*(FI-FA)*(C1-FW(IL,N))/(BETA*(C1+1))
      IF(FW(IL,N).GE.C1) WO(N)=0.0
      QSY=QSY+S(N)*DT
      QLY=QLY+H(N)*DT
      WY=WY+WO(N)*DT
      QN(N)=S(N)-H(N)+WO(N)/GAMA
      QHT=QHT+QN(N)
      QY=QY+QN(N)*DT
      QLD=QLD+QU(N)
      QTID=QTID+IT(N)
      N1=N/24
      N2=24*N1
      QHOM=QHOM+QU(N)
      QTIM=QTIM+IT(N)
      IF(N.NE.N2) GO TO 25
      CEFD(IM,ID)=QLD/QTID
      QLD=0.0
      QTID=0.0
      ID=ID+1
      KL=LD(K)*24
      IF(N.NE.KL) GO TO 25
      HQM(IM)=QHOM/(IDO(K)*24.)
      TQM(IM)=QTIM/(IDO(K)*24.)
      RFS(IM)=TQM(IM)
      QRC=QRC+TQM(IM)
```

```
      TDIM(IL,IM)=FW(IL,N)
      TDEG(IM)(FW(IL,N)+1.)*288.-273
      CEFM(IM)=QHOM/QTIM
      QHOM=0.0
      QTIM=0.0
      IM=IM+1
      ID=1
      QD2(K)=QHT/(IDO(K)*24.)
      DELD(K)=QD(IL,K)-QD2(K)
      Q0=Q0+QD(IP,K)
      K=K+1
      L1=L1+1
      QHT=0.0
21    CONTINUE
      A0=Q0/12
C     WHETHER THE STORE TEMPERATURE IS CONVERGE OR NOT IS CHECKED
      DO 29 J=1,12
      IS=IL-1
      IF(IL.LT.2) GO TO 25
      FRK=FIW(IL,J)-FIW(IS,J)
      DIF=ABS(FRK)
      IF(DIF.GT.0.001) GO TO 25
29    CONTINUE
      WRITE(2,*)'TEMPERATURE OF THERMAL STORE IS NOT CONVERGE'
      GO TO 30
25    CONTINUE
30    WRITE(2,*)'TEMPERATURE OF THERMAL STORE IS CONVERGE'
      WY=WY/GAMA
      QST=P*(FW(IL,1)-FW(IL,8760))
      QLT=QY-QST
      R=QSY+WY
      R1=QSY/R
      R2=WY/R
      R3=QST/R
      R4=QLT/R
      R5=QLY/R
      WRITE(4,31) IL,IP,FWSUM,QDSUM
      WRITE(6,31) IL,IP,FWSUM,QDSUM
31    FORMAT('IL=',I2,' IP=',I2,' FWSUM=',F7.4,' QDSUM=',F7.4)
      WRITE(6,32)
32    FORMAT(98('-'),/'|',3X,'MONTHS',4X,'WATER TEMPERATURE',6X,
     *'MONTHLY AVERAGE',4X,'MONTHLY AVERAGE',6X,'MONTHLY AVERAGE',
     *4X,'|',/,'|',11X,'OF SPHERICAL THERMAL',2X,'USEFUL ENERGY
     *STORE(IN  DEG)',6X,'(IN WATT/M2)',7X,'(IN WATT/M2)',28X,'|')
      WRITE(6,33)
33    FORMAT('|',1X,9('-'),2X,20('-'),2X,18('-'),2X,19('-'),2X,20('-'),1X,'|')
```

```
      DO 34 J=1,12
      WRITE(6,35) AYLR(J),TDEG(J),HQM(J),TQM(J),CEFM(J)
35    FORMAT('|',1X,A9,5X,F8.4,16X,F8.4,14X,F8.4,9X,F8.4,10X,'|')
34    CONTINUE
      WRITE(6,36)
36    FORMAT('|',96X,'|',/,98(''),/'|',96X,'|',/'|',3X,'QSY',5X,'WY',
     *7X,'QST',5X,'QLT',5X,'QLY',5X,'QY',6X,'R1',6X,'R2',6X,
     *'R3',6X,'R4', 6X,'R5'.5X,'COP',2X,'|',/'|',1X,6('-'),2X,7('-'),2X,
     *6('-'),8(2X,6('-')),2X,5('- '),1X,'|')
      IF(WY.EQ.0.0) GO TO 36
      COP=QLY/WY
      WRITE(6,37) QSY,WY,QST,QLT,QLY,QY,R1,R2,R3,R4,R5,COP
37    FORMAT('|',1X,F6.3,2X,F7.5,2X,F6.4,2X,F6.3,2X,F6.3,6(2X,F6.3)
     *,1X,F6.1,1X,'|',/"|',96X,"|',/,96('_'),'|')
      GO TO 38
36    WRITE(6,39) QSY,WY,QST,QLT,QLY,QY,R1,R2,R3,R4,R5,COP
39    FORMAT('|',1X,F6.3,2X,F7.5,2X,F6.4,2X,F6.3,2X,F6.3,6(2X,F6.3)
     *,1X,'NO PUMP','|',/"|',96X,"|',/,96('_'),'|')
38    WRITE(1,40) ISOIL,A,NOH
40    FORMAT(' ISOIL=',F5.2,' A=',F5.2,' NOH=',F5.2)
      DO 41 M=1,12
      FS(M)=RFS(M)/QRC
      WRITE(1,42) M,FS(M),QRC,M,QIN(M)
40    FORMAT(' FS(',I2,')=',F8.4,' QRC=',F12.3,'QIN(',I2,')=',F8.4)
41    CONTINUE
      IF(ISOIL.EQ.4) GO TO 43
      ISOIL=ISOIL+1
      GO TO 44
43    WRITE(6,45) L
45    FORMAT('NUMBER OFITERATION=',I4)
      WRITE(2,*) 'WILL YOU CALCULATE ANOTHER CALCULATION'
      WRITE(2,*) 'IF      YES    PRINT ---->        1'
      WRITE(2,*) 'IF NOT         PRINT ---->        ANY NUMBER'
      READ(2,*)LL
      IF(LL.NE.1) GO TO 48
      WRITE(2,*) 'WHAT IS THE STORE RADIUS'
      READ(2,*) A
      WRITE(2,*) 'WHAT IS THE TYPE OF SOIL'
      READ(2,*) ISOIL
      GO TO 44
48    RETURN
      END
```