CHAPTER 1

INTRODUCTION

In many engineering applications, extended surfaces are used to promote high heat fluxes from small components having a limited heat transfer surface. One of the main objectives of this study is to determine the advantages of DHEs with extended surfaces. For this purpose, radially finned DHEs are modelled and compared with bare ones.

The heat transfer performance is strongly related to the geometrical design. Another objective of this study is to examine the effects of fin parameters such as fin length, fin thickness and the distance between the fins.

1.1 DOWNHOLE HEAT EXCHANGERS

The downhole heat exchangers eliminate the problem of disposal of geothermal fluid since only heat is removed from the well. The basic DHE is a simple device, with some similarities to a shell and tube heat exchanger. Commonly, a simple U shaped unfinned pipe coil is placed in the well and clean water from the city supply is piped through it, heating as it circulates [1-5].

Downhole heat exchanger has a number of advantages in extracting heat from underground. It can eliminate many problems caused by the traditional method of pumping water out of wells. The continually exploitation of geothermal resources without any protection may cause some environment problems, and even earth subsidence. By installing heat exchangers into the well, the disposal problem of the wastewater, and the corrosion and scaling problems of surface equipment are eliminated [6].

1.1.1 Advantages of Downhole Heat Exchangers

- Generally DHEs do not remove geothermal fluid from the reservoir. Only heat is removed from the well. Up to 140 kW of heat had been produced from a well of Rotorua (New Zealand) with a diameter of 4″ and it had been enough to supply the peak demand of eight Rotorua homes, saving 20-80 tonnes per day of fluid withdrawal from the field [7].
- Maintaining a DHE system is simple and inexpensive compared to operating a downhole pump, which must operate within a hot often-corrosive fluid.
- There is no need for a re-injection well. Current environmental restrictions almost require geothermal water to be returned to the aquifer from which it was derived. Therefore, techniques involving removal of water from a well require a second injection well to dispose of the water. This can be a costly addition to a small geothermal heating project [2].
- The required equipment is very simple. In some instances no circulation pump is required and the system can provide heat by thermo-syphoning. However, heat output is very low with this arrangement [5].

1.1.2 Disadvantage of Downhole Heat Exchanger

- The DHE system has one main disadvantage; heat output is limited with DHE compared to downhole pump systems. Whenever a higher heat output is needed at the surface, geothermal fluid is withdrawn by pumping.

1.1.3 How can the DHE systems be financially attractive?

The well usually represents a large cost in geothermal applications, but the heat output of an individual well is usually fairly low with a DHE, typically less than 1 MW [8].

DHEs may be financially attractive in a range of situations [5]:

- When heat loads are very low and widely dispersed, drilling more wells may be cheaper than distributing all the heat available from a single well.
- DHEs may also be attractive where scaling and aggressive reservoir fluids cause expensive or frequent equipment maintenance.
- When unsuccessful or abandoned wells; geothermal wells which are low volume producers or wells with fluids considered too cold or aggressive for extraction, oil wells which are exhausted or dry; are available, they may be suitable for a DHE installation.
- When hot fluids occur at shallow depths, dramatically lowering the cost of drilling.

1.1.4 Types of DHE Systems

(a) U-tube DHE

The most common type DHE is the U-type. It consists of a pipe with U shape which suspends in the well through which clean water is pumped or allowed to circulate by natural convection. The space heating DHE is usually 1-1/2 or 2″ black iron pipe. The domestic water DHE is ¾ or 1″ pipe [3,4].

Figure 1.1 shows a typical installation of a DHE. It consists of a wellbore generally 15 to 36 cm in diameter and an unfinned U-shaped heat exchanger made from bare steel pipe [1].

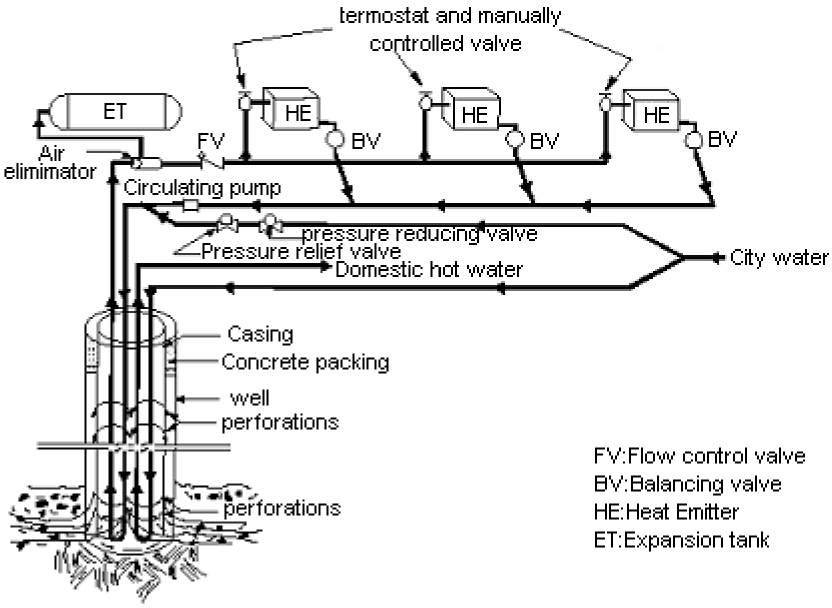


Fig 1.1 Typical downhole heat exchanger system (Klamath Falls, OR) [3].

(b) Annular DHE

An other common type of DHE is the annular type. It consists of two coaxial pipes. Flow down the pipe and up the annulus is said to be in the "forward" direction type. Flow down the annulus and up the central pipe is said to be in the "reverse" direction type(Figure 1.2). Heat output of an annular DHE was predicted to be similar to that of the U-tube in some early modeling and laboratory scale tests. However, full scale testing showed that annular DHE output could be much lower because of interference between the up and down flow becomes important. Interference occurs when heat is lost from the ascending hot fluid to the descending cold fluid [5].

In the Rotorua tests the annular DHE provided just 32 kW at a return temperature of 74°C where the previously installed U-tube DHE had provided 114 kW at 81°C. This reduction was due almost entirely to interference effects, because the inner tube was made from steel (a conductive material) [7].

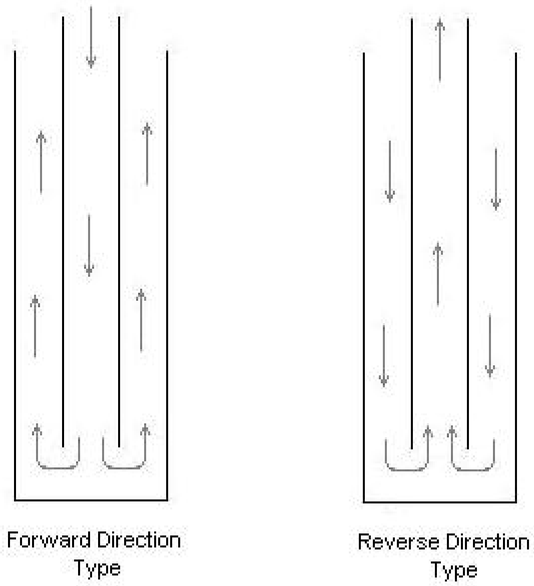


Fig 1.2 Annular DHE

(c) Multi-tube DHE

Multi-tube DHEs are similar to the tube bundle of a shell and tube exchanger. They are capable of high heat transfer rates but can cause a relatively high-pressure drop. They are probably best suited to wells with a high internal circulation rate, and a high heat load capacity, where heat transfer is critical [5].

Fig 1.3 Test project using multiple loops being lowered in a well (Klamath Falls) [8].

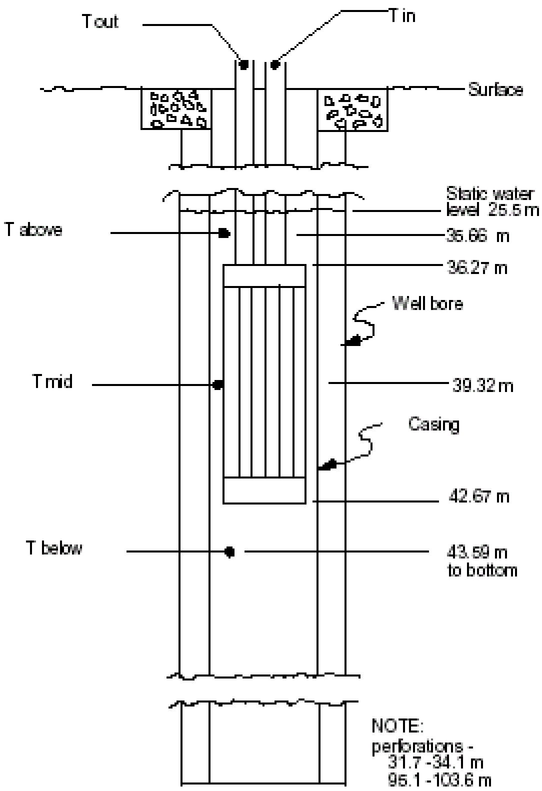


Fig 1.4 Diagram of the multi-tube DHE installation in Klamath Falls [8].

CHAPTER 2

THEORY AND LITERATURE SURVEY

The literature on DHEs is not extensive. Oregon Institute of Technology and Geothermal Institute of the University of Auckland do most of the studies on DHE.

2.1 DOWNHOLE HEAT EXCHANGE UTILIZATION

The first downhole heat exchanger, locally known as a coil, was installed in Klamath Falls about 1930 [3].

DHEs are currently being used in at least four countries: USA, New Zealand, Austria and Switzerland [4,5]. Several DHEs were used in Iceland for several years, but the wells are now pumped [4].

2.1.1 DHE Use in Turkey

Downhole heat exchangers have been extensively used from 1981 to 1990 [8]. One of these installations was part of the geothermal heating system in the city of Balçova near İzmir, on the West Coast of Turkey. DHEs in Balçova, which were some of the largest in the world in terms of energy output, are now all removed.

Fig 2.1 Downhole heat exchangers being removed from a well in Balçova (3-8-2001)

In Seferihisar, İzmir, a DHE was installed and tested, 1986. Heat output was 1.6 MW with 20°C inlet temperature and 4.75 kg/s DHE flow rate, 2.7 MW with 30°C inlet temperature and 10 kg/s DHE flow rate. The well has not been used because of carbonate scaling. The characteristics of the well as follows [9,10]:

Depth : 199.4 m

Bottom hole temp: 145°C

DHE : 3 loop 5 cm (2″) diameter to 168 m.

Fig 2.2 Downhole heat exchanger system (Seferihisar,İzmir)

In Afyon, DHEs were used for heating a spa-hotel and its recreational facilities and 2000 m^2 of greenhouse but now they are not in use. The wells were 120 to 200 m deep and the temperature was 98°C [4].

1.2 IMPROVING DHE PERFORMANCE

Thermo-syphoning is the major mechanism for fluid movement and heat transfer in wells. The well is naturally unstable with hot (low-density) fluid at depth and colder (heavier) fluid above. However, large-scale circulation does not become established, because turbulent mixing breaks down the circulation cells. A fluid path, which maintains the temperature (buoyancy) difference, must be provided.

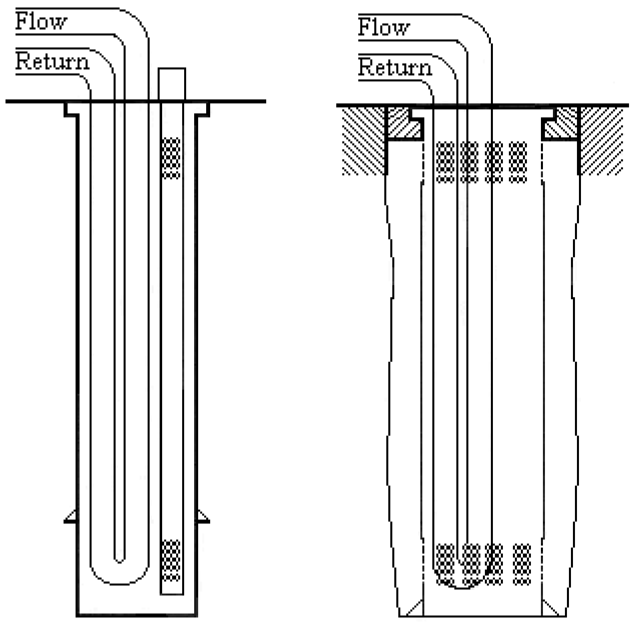


Fig 2.2 a) Promoter pipe system b)Undersized slotted casing [5]

The method of improving well performance involves providing a promoter tube to circulate fluid within the well bore (Fig 2-3a). This method was pioneered in 1945 in Klamath Falls, Oregon, where the technique is to install an undersized casing in a well (Fig 2-3b) [5].

Culver and Reistad [11] presented a detailed study of the U type DHE in a well with a perforated casing. Perforations were below the static water level and in the hot water fed zone. The results showed that there was no vertical fluid flow in the uncased wellbores whereas for a slotted cased well, a convection cell induced the hot water to flow to the upper part of the well. The convection cell was established by the difference in temperature between the hot resource at the bottom and the relatively cooler well walls. For a cased well without a DHE, flow was up the inside and down the outer annulus. For the cased well with a DHE, DHE cooled the fluid on the inside of the casing, and the convection cell was reversed, flowing up in the annulus and down inside the casing.

Vertical temperature profiles from several wells had indicated significant differences between cased and uncased wells. Figure 2.4 shows typical profiles. Casing indicated large vertical water movements, which kept well temperatures nearly isothermal.

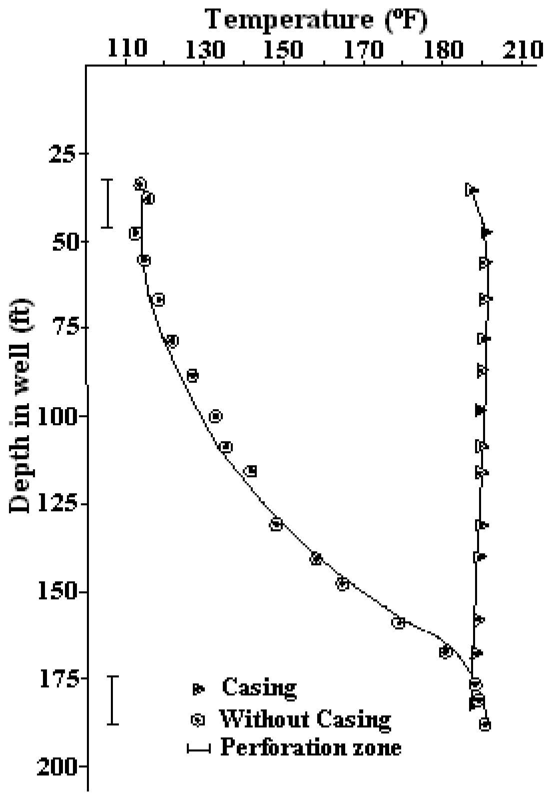


Fig 2.3 Temperature vs. Depth [3].

Velocity measurements showed that velocities in cased wells with no DHE installed, ranged from 9 to 14 cm/sec with the average about 12 cm/sec.

The DHE in the cased well was able to produce a significantly higher output than the uncased well. At the highest output, DHE energy extraction from the cased well was 175 percent of that of the uncased well.

Analytical models of the cased well with and without a DHE were made by Culver and Reistad [11]. The DHE-well-aquifer system was modeled as a network with two types of flow: fluid flow (which also transports thermal energy) and heat flow (conduction). Application of the network modeling to the well tested with the conventional hair-pin DHE showed closer agreement with experimental results. This model was used to design short multi-tube DHEs and testing of these was started in June 1978.

Culver and Reistad also reported the experimental results of work on characterizing flows in wells with and without casing [1]. Before the wells were cased, the velocity was nearly zero, after the casing was installed; the flow in well was approximately 3 kg/s.

R.G. Allis and R. James [12] presented an experimental and theoretical study on inducing a convection cell in the geothermal well. A small-scale model of a well was built in the laboratory in order to clarify the general principles of induced convection within long pipes. 2 m length and 30 mm inside diameter of plastic tube was used for the well model. To optimize the diameter of the convection cell, four different pipes with inside diameters of 8,12,16 and 22 mm, perforated at the top and at the bottom, were used. The results showed that, with the 8 and 12 mm pipes, hot water flowed up the annulus, and returned down the pipe. Tests with the 16 mm pipe showed that the flow could be in either direction, but once established, the direction was stable. With the 22 mm pipe in the well, hot water flowed up the pipe and down the annulus. The direction of flow was directly related to the respective aspect ratios (ie. length to diameter) of the pipe and the annulus. Tests were also made DHE in the annulus beside the 8,12 and 16 mm pipes, and inside the 16 and 22 mm pipes. In all tests, the flow direction in the well was controlled by the location of the DHE. Because the heat extracted by the DHE was greater than that being lost through the well walls, the leg of convection cell containing the DHE was always cooler, and flow was downward around the DHE.

The presence of the pipe improved the heat output of the DHE by 60 to 120 % depending on the diameter of the pipe.

The theoretical results showed that, if a DHE is to be installed in the annulus, then maximum flow will occur with a pipe about 0.5 times the well diameter. Conversely, if the DHE is to be installed inside the pipe, then the pipe should be around 0.7 times the well diameter. These two optimum configurations agreed well with the results from the laboratory model. Optimum heat outputs were obtained with the 16 mm pipe and the DHE in the annulus; and with the 22 mm pipe and DHE inside the pipe.

Horne [13] set up a numerical model to analyze the performance of coaxial (annular) heat exchangers. The calculations were based on conductive heat transfer into the well and were therefore a lower bound on the performance of such system, since in most cases heat will be transferred to the well convectively. The optimum configuration was the one, which had the same velocity (or Reynolds number), in the upward and downward flows. The reverse flow configuration in which fluid flows up the pipe down the annulus resulted in slightly greater heat transfer. It was suggested that in order to maximize heat transfer, the size of the inner pipe should be reduced and the outer tube of the heat exchanger should be as large as the well permits.

Allis [2] investigated four Moana hot water wells in Reno, Nevada. Comparative heat output tests using a DHE, a DHE with convector pipe, and a DHE with a pump had been made. The presence of a convector pipe caused no significant difference in heat output of the DHE. However, the use of a pump significantly improved the heat output of all wells. Analysis of the thermal behavior of the wells during the tests indicated that two factors contributed to the poor performance of the convector pipe.

- Conductive heat losses through the walls of the steel convector pipes that were used greatly reduced the driving force of the induced convection cell.
- The permeability of most wells was insufficient to maintain an adequate cross-flow of water in the hot aquifer.

As a result of considering the natural flow in aquifers of differing permeability together with the thermal effect of a DHE and a convector pipe in a well, the following general conclusions were made by Allis [2].

- The steady-state heat inflow to a non-discharging well with no internal flows is directly dependent on the permeability, the temperature of the aquifer and the vertical cross-sectional area of the wellbore within the aquifer.
- If a DHE is installed in a well which do not have a high permeability, stored heat in the form of hot rock adjacent to the well may provide sufficient heat for days or even weeks. However, in the long-term, the well will cool off.

- In highly permeable wells convector pipe with the DHE is recommended.
- The combination of a DHE and a thermostatically controlled pump is the most efficient means of utilizing the heat in the Moana aquifer.

A DHE program was written by Paul J. Lienau, which calculates the heat output from a DHE in a well where convective steady-state heat transfer is predominant [4]. The program was capable of considering one of two designs: either perforated casing or perforated promoter pipe.

The first experiment for the Downhole Coaxial Heat Exchanger (DCHE) was carried out a well on the island of Hawaii for electricity production [14]. The DCHE had been proposed as a heat extraction method to exploit undeveloped geothermal resources as low productive geothermal reservoirs (ie. Hot Wet Rock), super hot rock adjacent to magma bodies and solidified magma bodies etc.

The experiment was conducted using HGP-A well located in the Kapoha area in Puna. The drilling of the well had been completed in 1976. The bottom hole temperature of the well was 358°C. The depth of the well from the ground surface was 1962 m. The well was completed setting 9 5/8″ casing to a depth of 676 m and 7″ slotted liner to the bottom. In 1979 the top section of the liner was removed and 7″ casing was inserted from the surface down to 890 m. A retrievable bridge plug was set to separate the test section and to avoid the inflow of geothermal brine into the DHE. A total of 74 pieces of 3 1/2″ vacuum type double tube insulated pipes were used as the insulated inner pipe of the DCHE. The bottom end of the insulated inner pipe was 876.5 m in depth.

Analysis indicated that the heat transfer mechanism in the formation during the experiment was almost pure conduction and the thermal conductivity of the formation was estimated to be 1.6 W/m°K. The temperature at the bottom of the DCHE before the experiment was 110°C. The observed highest hot water during the experiment was 98°C, and the maximum thermal output was 540 kW.

Analysis of the experimental results from the DCHE experiments was carried out by these authors to investigate the insulation performance of the inner pipe used in the DCHE and the heat transfer characteristics in the formation [15]. Analysis was carried out by performing numerical simulations.

Major assumptions were employed in the analysis:

- In the formation, heat is transferred to the wellbore only in the radial direction by conduction. Throughout the system, only flowing water in the DCHE transfers heat in the vertical direction.
- Thermal conductivity of the inner pipe is negligibly small when there is flow in the DCHE.

The analysis resulted in very good agreement between theoretical predictions and measured values. The analysis indicated that:

- The thermal conductivity of the inner pipe under the test conditions was estimated to be 0.06 W/m°K.
- The heat transfer mechanism in the formation at the main heat extraction interval was inferred to be almost pure conduction.
- The thermal conductivity of the formation was estimated to be 1.6 W/m°K that presumably represents the thermal conductivity of a low permeability conduction zone of the HGP-A reservoir.

Dunstall [7] carried out an experimental and numerical modeling analysis of the performance characteristics of downhole heat exchangers in small diameter shallow wells.

An old reinjection well (RR520) was used as a monitor before and during subsequent DHE testing. It was located approximately 10 metres North East of the test well. The thermocouple wires were placed in the well to assess the interference effects.

The well chosen for testing (RR679) was 4 in (100 mm) steel cased to a depth of 112 m and has a drilled depth of 123 m. The bottomhole temperature was around 160°C in an undisturbed condition. Firstly, a database of undisturbed temperature profiles were built up, then the well was quenched and its recovery from the quenched condition was monitored. At that time it was noted that well profiles taken with the DHE running show a strong resemblance to the quenched profile with a linear increase in temperature in the cased partition of the well and strong jump in temperature in the open hole region. The similarity was such that further investigation of the quench test was carried out, to establish whether this test could be developed into a technique for predicting DHE behaviour prior to installation. Quench testing at moderate flow rates (around 1 l/s) produced a heat balance quite close to that obtained with a DHE installed and circulating at the same rate.

Three DHE configurations, a conventional U-tube (121 m), a shorter U-tube (65 m) with a full-length convection promoter pipe (Fig 2.5-b) and an annular DHE, were used in the well during the experiments.

The output of the annular DHE was very much less than the U-tube DHE. The author claimed that, the reason was non-uniform temperature distribution in the well.

Heat output with the shorter DHE installed was about 9 kW, irrespective of DHE flow rate. Output from the half length DHE was only 5 % of that found on a full length DHE, and was obtained at much lower temperature. With the perforated promoter the heat output of the DHE increased to 16 kW but it was still very low compared to the full length U-tube DHE.

Another method of increasing the well performance was bleeding the well [7]. A small amount of geofluid was extracted from the well. For this purpose, a small airlift pump was used, with the full length U-tube DHE installed in the well (Fig 2.5-a).

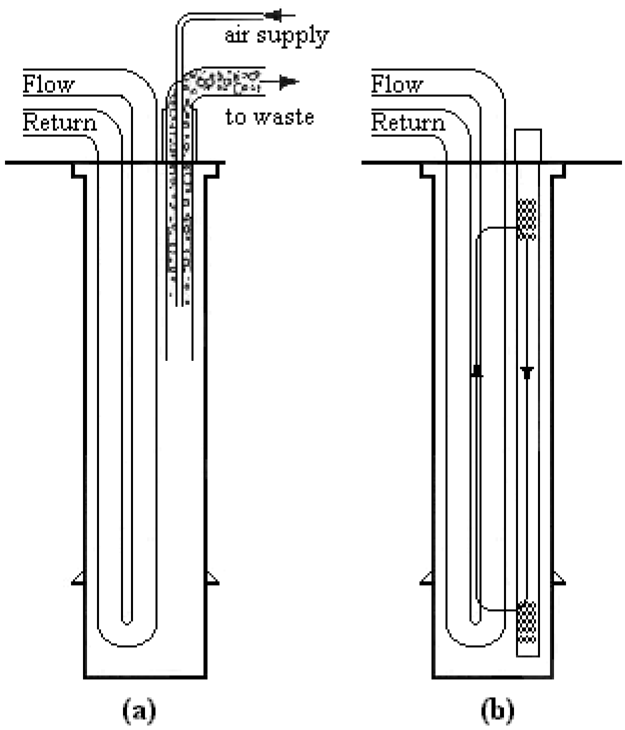


Fig 2.4 a) The airlift system b)The promoter pipe system(with forward flow system) [7]

The well bleeding gave 2-3 kW of additional heat output. However it was highly undesirable to introduce oxygen to the well because of corrosion.

In order to measure the well circulation Rhodamine W.T. dye tests were conducted. Mixing ratios (the proportion of fluid that is recirculated) were determined from dye concentration. The general range was between 0.5 and 0.7.

During the dye tests, it was also revealed that the flow direction did not reverse when the DHE was started flow continues up the annulus. Because the promoter pipe was small, less than two minutes were needed for flow down the pipe to travel 65 m whereas up-flowing fluid requires nearly 30 minutes to flow the same distance. Cooling of the annular fluid requires nearly 30 minutes to flow the same distance. Cooling of the annular fluid exposed to the DHE is therefore very quickly followed by a change in the average promoter fluid temperature, so a density difference is maintained. Flow continued in that manner for several days before finally reversing. After the reversing the temperature at the upper perforations had increased by 5°C.

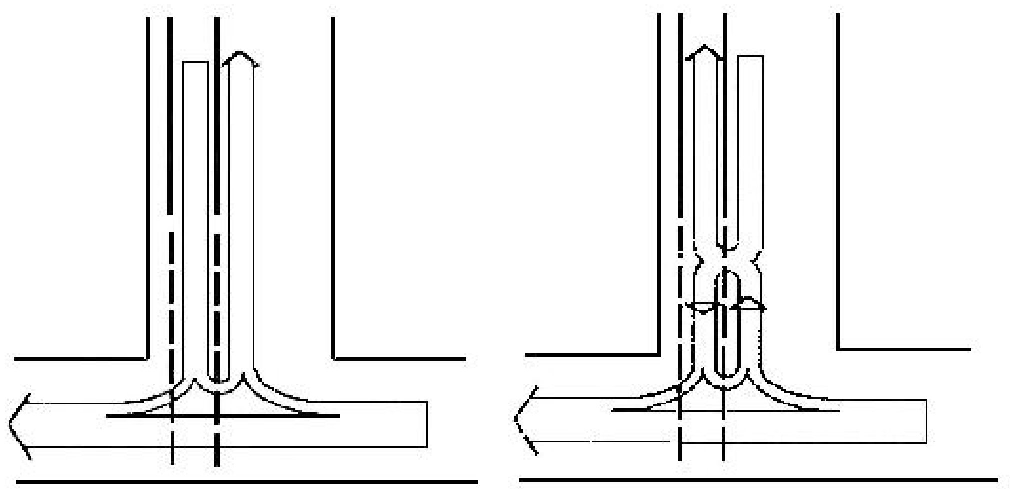


Fig 2.5 a)Well fluid circulation (Forward flow) b)Well fluid circulation (Reverse flow) [7]

DHE performance with two different types of promoter was investigated on a model well at Auckland University, The basic well model was 6 m tall, 75 mm diameter steel pipe. Tests were initially run with a 32 mm ID (1 ¼ in) promoter, and then with a 20 mm ID (3/4 in) promoter. A different type promoter tube was tested in Rotorua well (Fig 2.7). However it was revealed that using larger promoter was more effectual.

A computational fluid dynamics package, PHOENICS, was used to study fluid and heat flow processes in the well and DHE system. Dunstall claimed that localised convection, which might occur in the Rotorua well, had not been successfully modelled using PHOENICS. Flow is highly turbulent on the tube side of the DHE, so a high heat transfer coefficient was specified. The well side relies on conduction and natural convection for heat transfer so a lower coefficient was used there. These coefficients were calculated from the surface area and inlet/outlet conditions from the Rotorua system. The U-tube and annular DHE internal temperature profiles predicted by the numerical model have a very good match to the measured data.

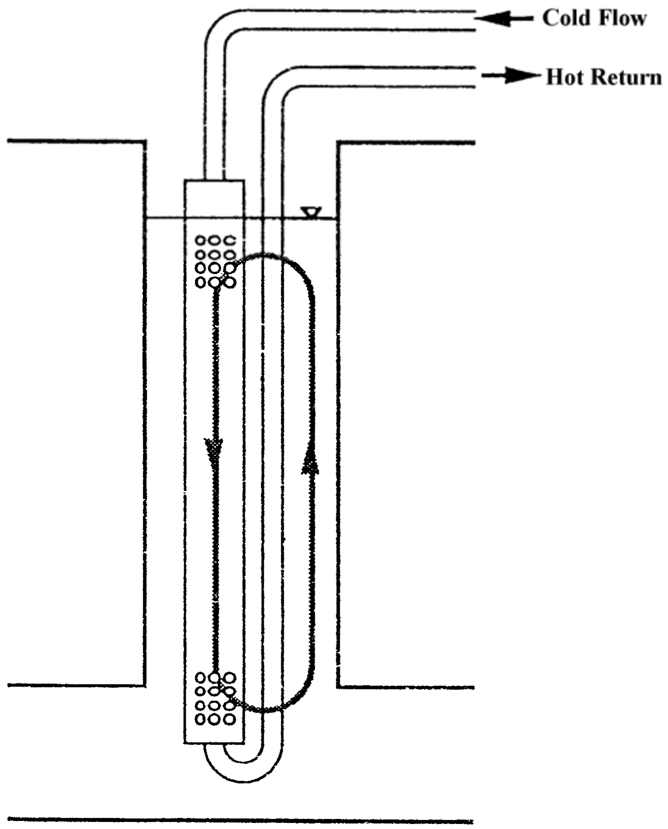


Fig 2.6 An Alternative system proposed for Rotorua Wells [7]

Dai Chuanshan and Liang Jun [6] carried out a mathematical and theoretical modelling of an U-type DHE in a well. Because the ratio of the thickness of the casing to its length, and the ratio of the thickness of DHE tube to its length is small, the conduction heat in vertical direction was ignored. In the well, the heat transferred between one leg and casing and between two legs(flow leg and return leg) were considered to be only in conduction form and in horizontal direction only. A steady state pure conduction model was established for modelling U shape DHEs performance.

The authors concluded that much work should be done on the heat transfer character in DHE system where conduction and convection could be coexistent.

A.Carotenuto, C. Casarosa, M. Dell'Isola and L. Martorana [16], proposed a simplified model to determine the main lumped parameters characterizing the heat and mass transfer between aquifer, well and natural convection promoter.

The numerical simulation and experimental tests carried out on particular type of DHE have allowed the authors to understand that the maximum value of a DHE is a function of the characteristics of the thermal plant, the aquifer and the well configuration and, in particular, of the dimensions and position in the aquifer of the slotted section of the tube casing, and the natural convection promoter.

After they developed the fundamentals of a lumped parameter model to the interaction between aquifer and well of a geothermal plant in which heat transfer occurs only by natural convection, they completely formulated the model by taking into account all the parts of the plant [17]. They have studied natural convection plant distinguishing between plant with a DHE and plant with a geothermal convector (GTC), ie. a special geothermal application of the two-phase thermosyphon. It consists of a sealed vessel partially filled with a working fluid. At the bottom, the working fluid evaporates, the vapour rises to the top where it condenses, and it transfers heat flow to the fluid of the user plant, then the condensate returns by gravity to the evaporation section. Moreover, the model introduces a distinction between plant with a single and double convection loop. In the first case, the geothermal fluid, circulating between the aquifer and the well, crosses through the heat exchanger inserted in the well; in the second case, the plant has a convection promoter. The model, which has formulated in dimensionless terms in order to facilitate a parametric study, illustrates plant performance and allows one to show that, for suitable values of parameters, there are limitations to the maximum heat flow transferred.

A study has been made of the influence of the position of the casing slotted section within on the heat withdrawal rates using DHEs [18]. The study numerically simulated an aquifer using the finite-element method to determine the heat flow that could be withdrawn by the DHE when the slotted section position was varied within a geothermal aquifer (Fig 2.8).

The results obtained have shown that this configuration optimized the heat flow drawn by the DHE from the geothermal aquifer. In case D, compared to other solutions assured a larger withdrawal of geothermal energy from the aquifer.

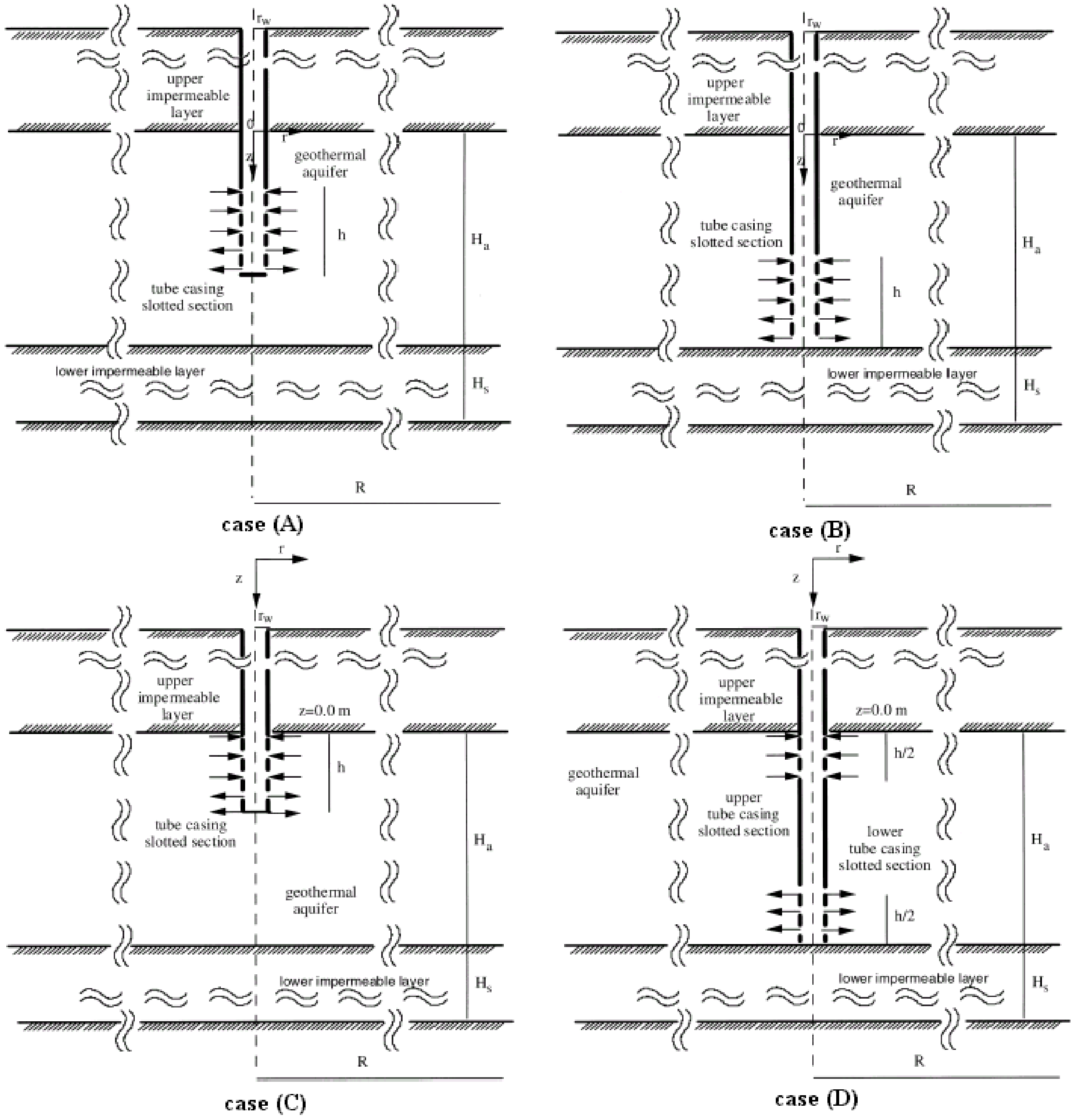


Fig 2.8 Geothermal reservoir layout with the slotted sections located in the 4 different part of the reservoir [18].

CHAPTER 3

NUMERICAL MODELING OF A DHE

A numerical model is developed for a well with a DHE to determine the heat extraction rate for downhole heat exchangers. The numerical problem is approached by an iterative procedure, in order to find the heat transfer rate until the solution converged.

During the calculations, only part of the DHE, which is in the geothermal fluid, is considered and conservation of energy is applied to the very small control volumes both for bare and finned type DHEs.

3.1 THERMAL AND FLUID MODEL

The thermal and fluid dynamic solution of a geothermal aquifer with heat flow withdrawal is carried out by adopting the simplifying hypotheses that.

- The flow is assumed as one phase in order to simplfy the well model.
- Natural convection is the major mechanism in the well.
- Heat transfer coefficient outside the finned tubes is assumed same as outside the plain ones.
- Thermodynamic properties of the geothermal fluid for the applications examined in this study are assumed as pure water.
- Steady-state conditions are valid.

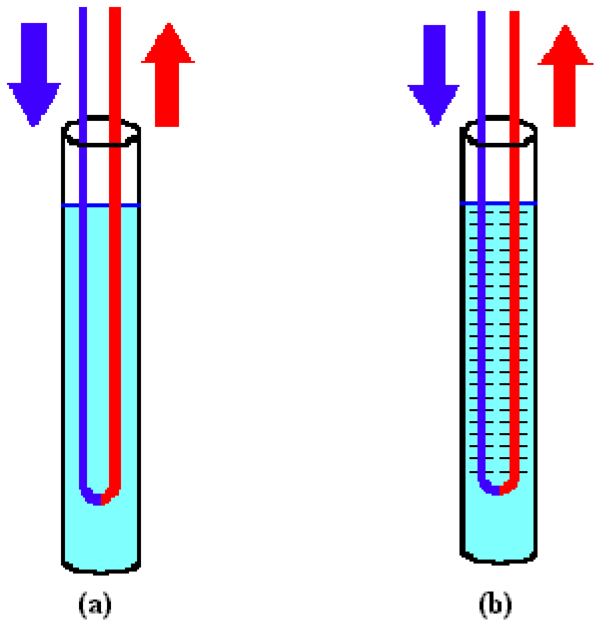


Fig 3.1 (a)Bare type DHE , (b) Finned type DHE

3.1.1 Conservation of Energy for a Bare type DHE

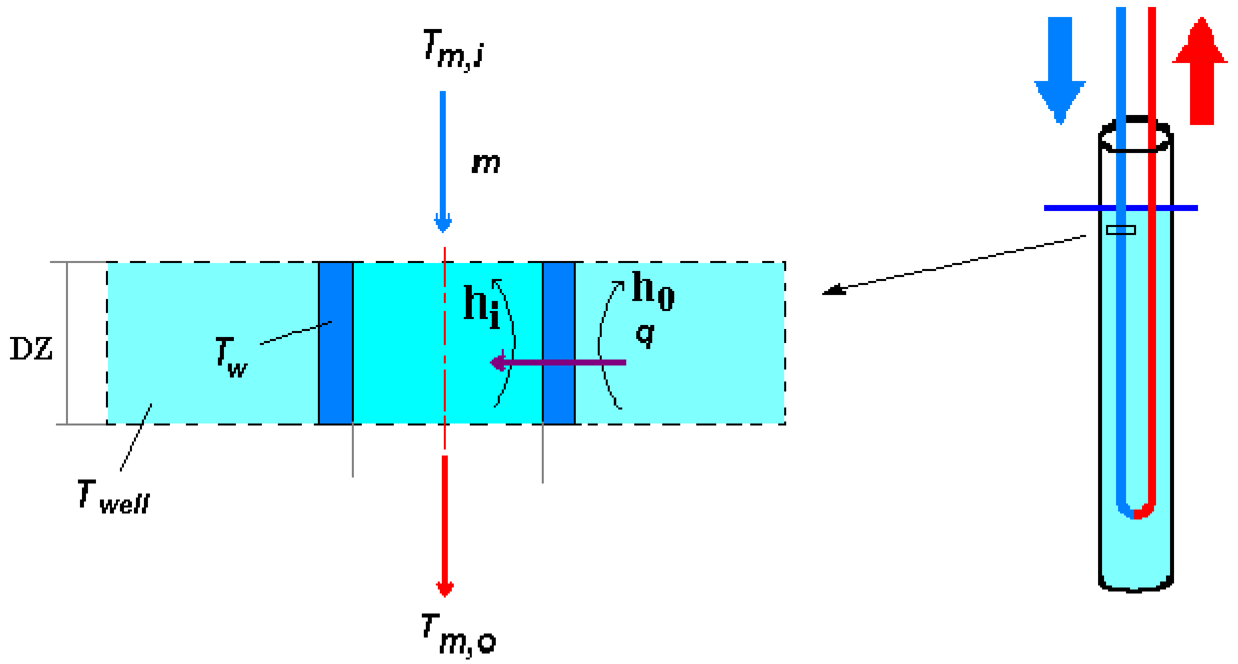


Fig 3.2 Control volume for a bare type DHE

Energy balance may be applied to determine how the mean temperature $T_m(z)$ varies with position along the tube.

Fluid in the DHE moves at a constant flow rate (m), and convective heat transfer occurs at the inner and outer surface of the DHE.

Applying conservation of energy to the differential control volume of the DHE [19]:

$$q = m.C_p.(T_{m,o}-T_{m,i}) \tag{3.1}$$

The surface temperature of the grid (T_w) can be assumed constant along this control volume. Then;

$$q = h_i.A.\Delta T_{LM} \tag{3.2}$$

where A is the grid surface area of the tube $A=\pi .D_i.DZ$ and ΔT_{LM} is the log mean temperature difference

$$\Delta T_{LM} = \frac{\Delta T_o - \Delta T_i}{\ln \frac{\Delta T_o}{\Delta T_i}}$$

$$\frac{\Delta T_o}{\Delta T_i} = \frac{T_w - T_{m,o}}{T_w - T_{m,i}}$$

or the heat transfer can also be written as:

$$q = U.A.\Delta T_{LM} \tag{3.3}$$

where;

$$\Delta T_{LM} = \frac{\Delta T_o - \Delta T_i}{\ln \frac{\Delta T_o}{\Delta T_i}}$$

$$\frac{\Delta T_o}{\Delta T_i} = \frac{T_{well} - T_{m,o}}{T_{well} - T_{m,i}}$$

$$U = \frac{1}{\dfrac{1}{h_i} + \dfrac{D_i}{2k_b}\ln\dfrac{D_o}{D_i} + \dfrac{D_i}{D_o.h_o}}$$

3.1.2 Conservation of Energy for a Finned type DHE

Two different types of control volumes are taken into account. Control volume-1 is the bare part, control volume-2 is the finned part of the DHE.

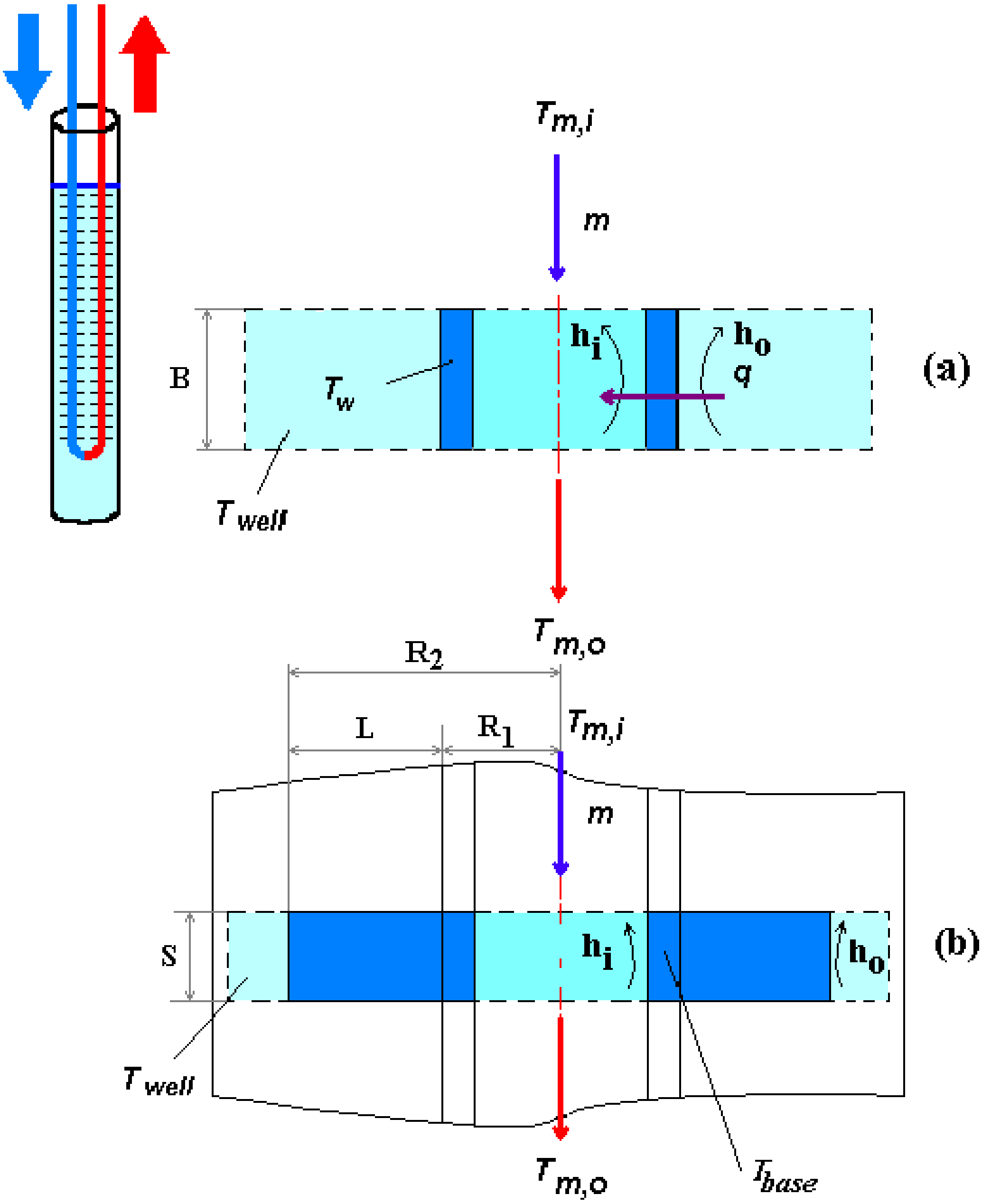


Fig 3.3 Control volumes for a finned type DHE a)Control volume-1,b)Control volume-2

For control volume-1 equations (3.1), (3.2) and (3.3) are used but in this case $A=\pi.Di.B$

Applying conservation of energy to the differential control volume of the fin (control volume-2) [19]:

$$q = m.C_p.(T_{m,o}-T_{m,i}) \tag{3.4}$$

The base temperature of the grid (T_{base}) can be assumed constant. Then;

$$q = h_i.A_K.\Delta T_{LM} \tag{3.5}$$

Where; $A_K=\pi.D_i.S$

$$\Delta T_{LM} = \frac{\Delta T_o - \Delta T_i}{\ln \dfrac{\Delta T_o}{\Delta T_i}}$$

$$\frac{\Delta T_o}{\Delta T_i} = \frac{T_{base} - T_{m,i}}{T_{base} - T_{m,o}}$$

The heat transfer rate of the circular fin with convecting tip is expressed as

$$q = \eta_F.A_F.h_o.(T_{well}-T_{base}) \tag{3.6}$$

where $\eta_F = C_2 \dfrac{K_1(M.R_1)I_1(M.R_{2C}) - I_1(M.R_1)K_1(M.R_{2C})}{I_O(M.R_1)K_1(M.R_{2C}) + K_O(M.R_1)I_1(M.R_{2C})}$

$$C_2 = \frac{(2R_1/M)}{(R_{2C}^2 - R_1^2)}$$

$$R_{2C} = R_2 + S/2$$

$$A_F = 2\pi(R_{2C}^2 - R_1^2)$$

$$M = \sqrt{\frac{2.h_o}{k_b.S}}$$

I_O , K_O , I_1 and K_1 are modified zero and first order Bessel functions of the first and second kinds. The Bessel functions are tabulated in Appendix A.

3.1.3 Heat Transfer Coefficients

(a)Flow in DHE : h_i

- If $\mathrm{Re} \le 2300$, the flow can be assumed as laminar,

For laminar, fully developed conditions with a constant surface temperature (T_w) approximation, the Nusselt number is a constant, independent of Reynolds number [19].

$$\mathrm{Nu}=3.66 \qquad \text{for } \mathrm{Pr} \ge 0.6 \tag{3.7}$$

- If $2300 < \mathrm{Re} < 5.10^6$ then the following correlation is valid [20],

$$Nu = \frac{(f/2)(\mathrm{Re}-1000)\,\mathrm{Pr}}{1+12.7(f/2)^{1/2}(\mathrm{Pr}^{2/3}-1)} \tag{3.8}$$

$$f = (1.58\ln \mathrm{Re} - 3.28)^{-2} \tag{3.9}$$

This correlation is for turbulent fully developed flow and for the interval of Pr 0.5-2000.

$$h_i = \frac{Nu.k}{D_i} \tag{3.10}$$

(b)Flow outside the DHE: h_o

The average Nusselt number for free convection on a vertical cylinder is the same as that for a vertical plate if the curvature effects are negligible.

A vertical cylinder may be treated as a vertical plate when [20],

$$\frac{D}{H} \ge \frac{35}{Gr_H^{1/4}} \tag{3.11}$$

where; D is the diameter, H is the height of the cylinder.

In a case of vertical, slender, circular cylinders, the above criterion is not satisfied; hence a vertical cylinder can no longer be treated as a vertical plate. This matter was handled by Sparrow and Greg [21], Minkowycz and Sparrow [22], and Cebeci [23]. Figure 3.4 shows a plot of the ratio of the local Nusselt number for a vertical cylinder to that for a flat plate as a function of the parameter $\xi = (2\sqrt{2} / Gr_z^{1/4})(z / R)$ for several different values of the Prandtl number. Here R is the radius of the cylinder. Nu_z =h.z/k is the local Nusselt number, and $Gr_z = g\beta(T_w - T_\infty) z^3 / \nu^2$ is the local Grashof number.

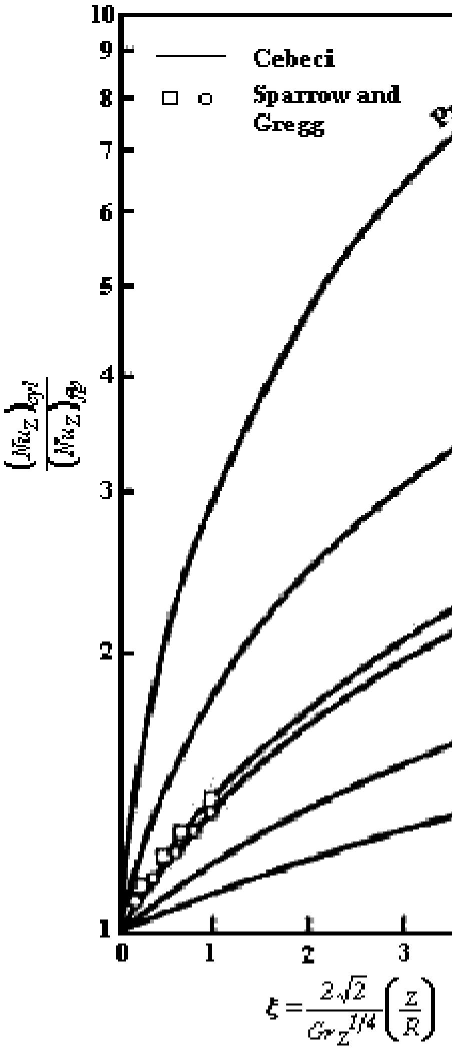


Fig 3.4 The ratio of the Nusselt number for a vertical plate to that for a vertical cylinder [24]

- For laminar free convection on a vertical plate ($Gr_z<10^9$) [25];

$$Nu_z = 0.508 Ra_z^{1/4} \left(\frac{Pr}{0.952 + Pr} \right)^{1/4} \tag{3.12}$$

- For turbulent free convection flow on a vertical plate ($Gr_z > 10^9$) [25];

$$Nu_z = 0.0295(Ra_z)^{2/5} \frac{Pr^{1/15}}{(1+0.494\,Pr^{2/3})^{2/5}} \tag{3.13}$$

Local Nusselt number is found from the above equations for a flat plate. For the flow over a cylinder (DHE), by using the ratio of Nusselt number for a flat plate and a cylinder from Fig 3.4, the Nusselt number over a cylinder can be found (For bare type DHE $R=R_1$, for finned type DHE $R=R_2$).

$$h_o = \frac{Nu_z.k}{z} \tag{3.14}$$

3.1.4 DHE Program

A program is written in Quick Basic language in order to calculate heat output from a DHE in a well. The program is capable of considering one of two designs: either bare or finned type DHE as shown in Figure 3.1. The program is given in Appendix-C.

Program input data:

1. If bare or finned type DHE?
   If bare type DHE, type 1, else type 2:
   This allows the user to select one of two designs: plain or finned type DHE
2. If the well temperature profile is assumed as a polynomial profile?
   If a polynomial profile, type 1, else type 2:
   The temperature distribution through the well changes with depth. If this temperature distribution is known, enter the well temperature profile as $T_{well}(z)=A_6.z^6+A_5.z^5+A_4.z^4+A_3.z^3+A_2.z^2+A_1.z+A_0$ The degree of the polynom is specified by the coefficients (A_6 ,A_5 ,A_4 ,A_3 ,A_2 ,A_1,A_0). (z is the distance from the water level)
   If the temperature distribution through the well is not exactly known, input an appropriate average reservoir temperature for the well.

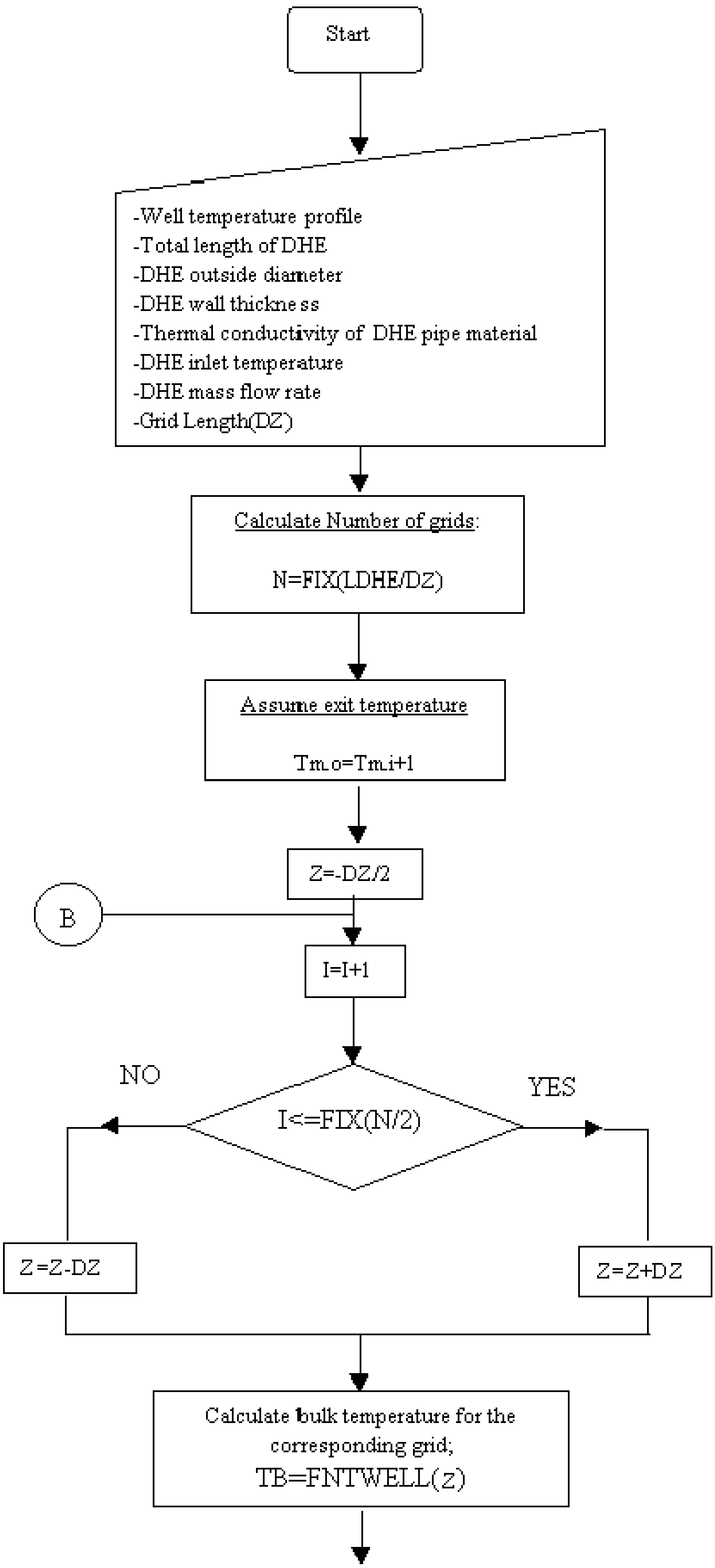
3. Enter total length of DHE installed in the well(m).
4. Enter DHE outside diameter (mm).
5. Enter DHE wall thickness (mm).
6. Enter thermal conductivity for DHE (W/m°C).
7. Enter inlet temperature to DHE (°C)
8. Enter mass flow rate through DHE (kg/s).
9. Enter grid length (DZ) (m)
10. For finned type DHE (Fig 3.1.b):
    Enter fin thickness (mm)
    Enter distance between fins (mm)
    Enter fin length (mm)

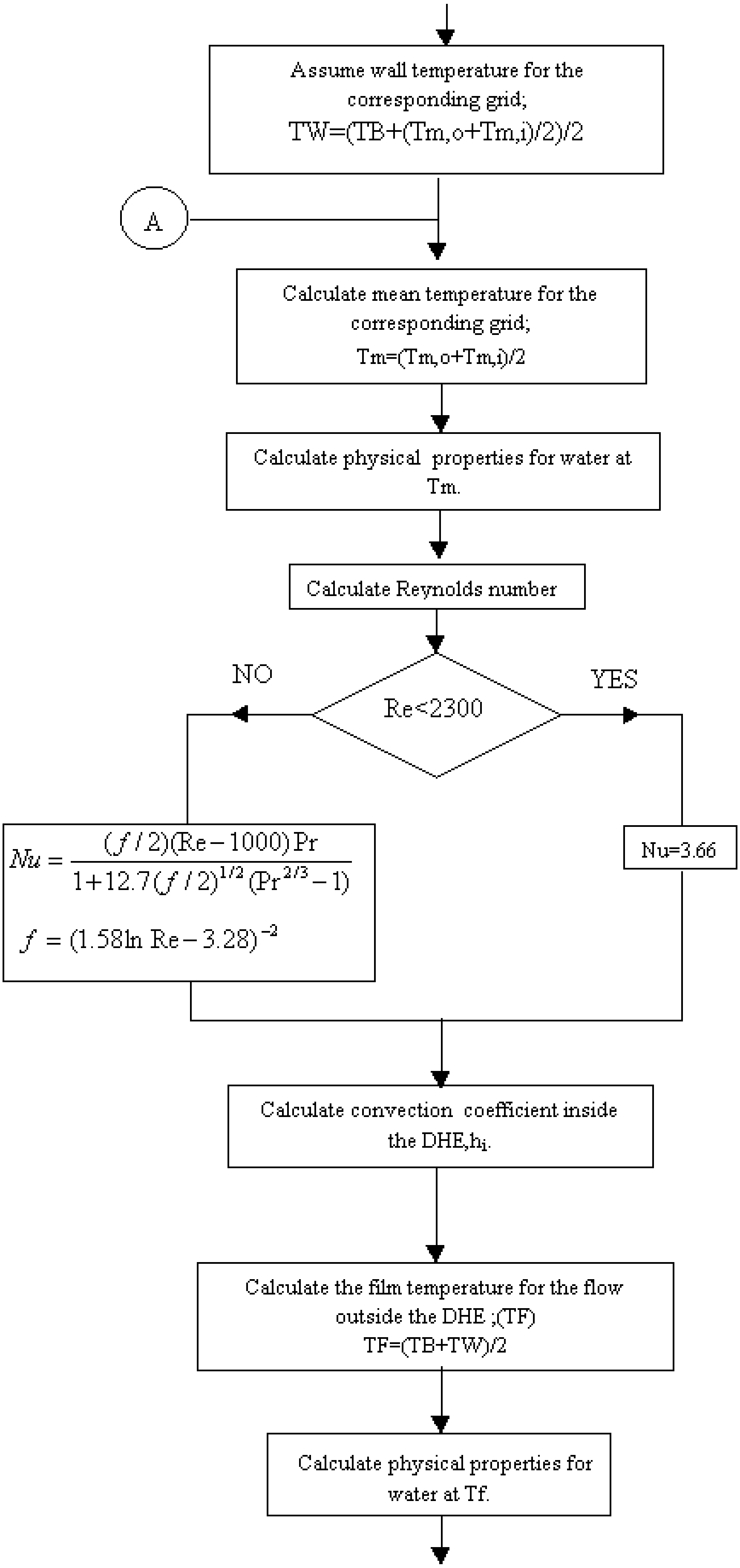
Program output data:

1. DHE exit temperature (°C)
2. Total heat transfer rate DHE (W)
3. Average heat convection coefficient for flow outside the DHE (W/m^2K)
4. Average heat convection coefficient for flow in DHE (W/m^2K)

3.2 SOLUTION ALGORITHM FOR BARE TYPE DHE

By applying conservation of energy to the small control volumes and by solving equations 3.1, 3.2, and 3.3 the temperature distribution through bare type DHE is solved. The method is summarized by the following algorithm;


Start
-Well temperature profile
-Total length of DHE
-DHE outside diameter
-DHE wall thickness
-Thermal conductivity of DHE pipe material
-DHE inlet temperature
-DHE mass flow rate
-Grid Length(DZ)
Calculate Number of grids:
N=FIX(LDHE/DZ)
Assume exit temperature
Tm.o=Tm.i+1
Z=-DZ/2
B
I=I+1
NO
YES
I<=FIX(N/2)
Z=Z-DZ
Z=Z+DZ
Calculate bulk temperature for the corresponding grid;
TB=FNTWELL(z)


Assume wall temperature for the corresponding grid;
TW=(TB+(Tm,o+Tm,i)/2)/2
A
Calculate mean temperature for the corresponding grid;
Tm=(Tm,o+Tm,i)/2
Calculate physical properties for water at Tm.
Calculate Reynolds number
NO
Re<2300
YES
$Nu = \frac{(f/2)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7(f/2)^{1/2}(\mathrm{Pr}^{2/3}-1)}$
$f = (1.58\ln \mathrm{Re} - 3.28)^{-2}$
Nu=3.66
Calculate convection coefficient inside the DHE,h_i.
Calculate the film temperature for the flow outside the DHE ;(TF)
TF=(TB+TW)/2
Calculate physical properties for water at Tf.

Find the ratio of the local Nusselt number for a vertical cylinder to that for a flat plate by using fig 3.4 ($R=D_o/2$)

Calculate local Rayleigh number

$Ra_z < 10^9$

YES

$$Nu_z = 0.508 Ra_z^{1/4}\left(\frac{\Pr}{0.952+\Pr}\right)^{1/4}$$

NO

$$Nu_z = 0.0295 (Ra_z)^{2/5} \frac{\Pr^{1/15}}{(1+0.494\Pr^{2/3})^{2/5}}$$

Find Nusselt number for the flow outside the DHE pipe by using the ratio of Nusselt number for a flat plate and a cylinder from Fig 3.4

Calculate convection coefficient outside the DHE, h_o

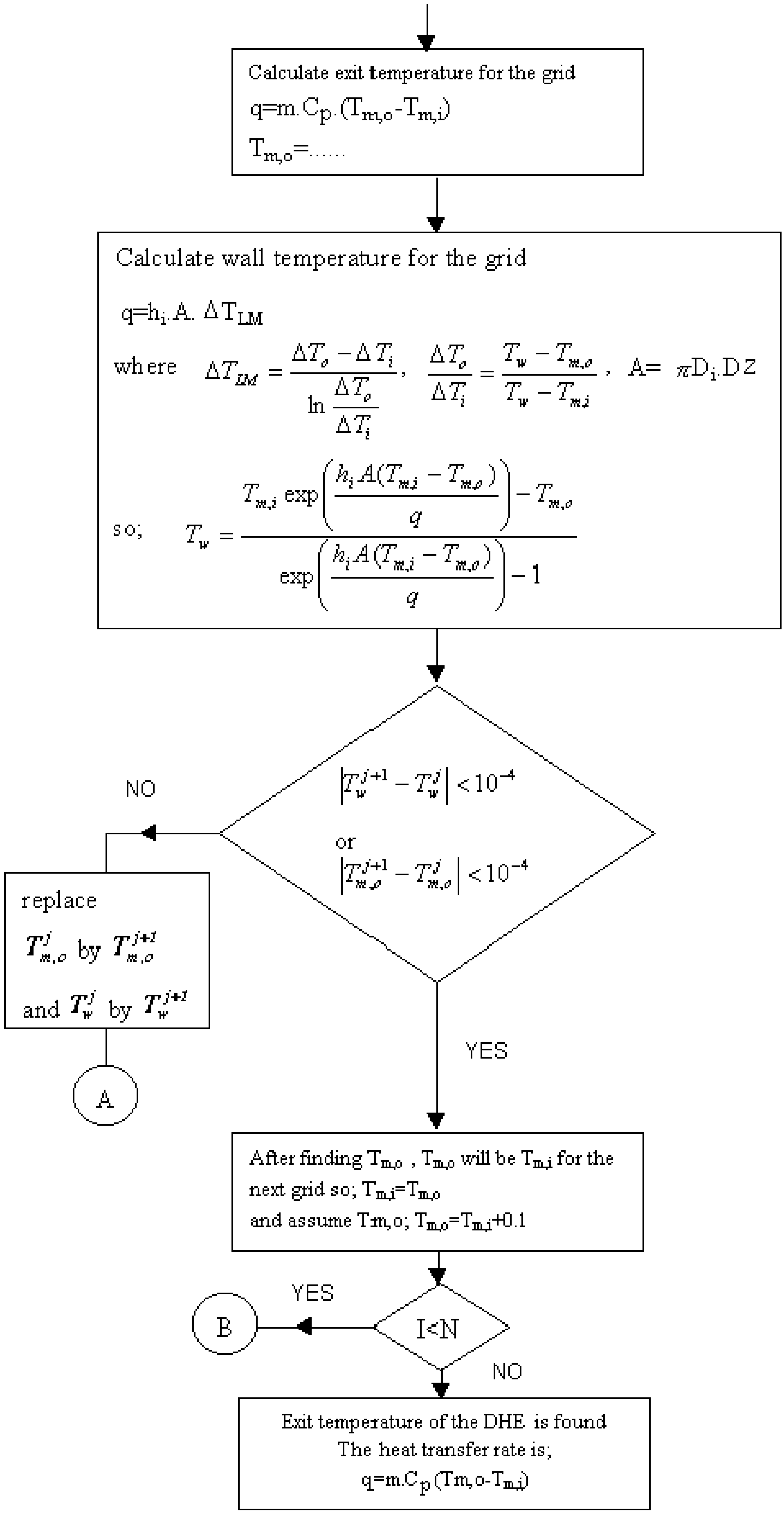
calculate heat transfer rate

$q = U.A.\Delta T_{LM}$

where;

$$\Delta T_{LM} = \frac{\Delta T_o - \Delta T_i}{\ln\dfrac{\Delta T_o}{\Delta T_i}} \quad , \quad \frac{\Delta T_o}{\Delta T_i} = \frac{T_B - T_{m,o}}{T_B - T_{m,i}}$$

$$U = \frac{1}{\dfrac{1}{h_i} + \dfrac{D_i}{2k_b}\ln\dfrac{D_o}{D_i} + \dfrac{D_i}{D_o.h_o}} \quad , \quad A = \pi.D_i.DZ$$


Calculate exit temperature for the grid
q=m.C_p.($T_{m,o}$-$T_{m,i}$)
$T_{m,o}$=……
Calculate wall temperature for the grid
q=h_i.A. ΔT_{LM}
where $\Delta T_{LM} = \frac{\Delta T_o - \Delta T_i}{\ln \frac{\Delta T_o}{\Delta T_i}}$, $\frac{\Delta T_o}{\Delta T_i} = \frac{T_w - T_{m,o}}{T_w - T_{m,i}}$, A= πD_i.DZ
so; $T_w = \frac{T_{m,i} \exp\left(\frac{h_i A (T_{m,i} - T_{m,o})}{q}\right) - T_{m,o}}{\exp\left(\frac{h_i A (T_{m,i} - T_{m,o})}{q}\right) - 1}$
$\left|T_w^{j+1} - T_w^j\right| < 10^{-4}$
or
$\left|T_{m,o}^{j+1} - T_{m,o}^j\right| < 10^{-4}$
NO
replace
$T_{m,o}^j$ by $T_{m,o}^{j+1}$
and T_w^j by T_w^{j+1}
A
YES
After finding $T_{m,o}$, $T_{m,o}$ will be $T_{m,i}$ for the next grid so; $T_{m,i}$=$T_{m,o}$
and assume Tm,o; $T_{m,o}$=$T_{m,i}$+0.1
YES
B
I<N
NO
Exit temperature of the DHE is found
The heat transfer rate is;
q=m.C_p(Tm,o-$T_{m,i}$)

A Typical Solution for Bare Type DHE

******INPUT DATA******

DHE PROGRAM

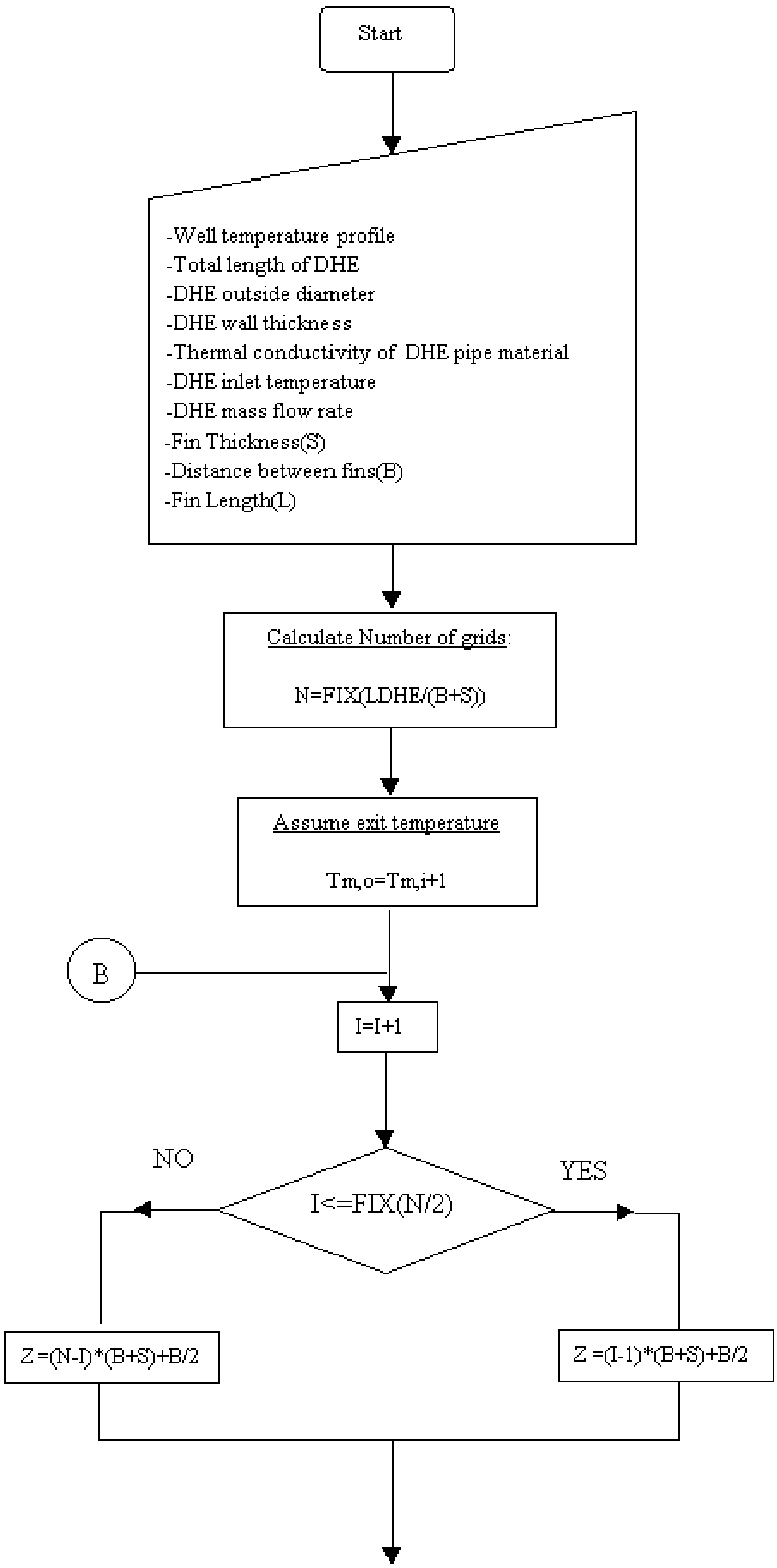
Calculates exit temperature and heat output of a Downhole Heat Exchanger
If bare or finned type DHE
If bare type DHE, type 1,else another number? 1
If the well temperature profile is assumed as a polynomial profile or a constant number
If a polynomial profile, type 1,else another number? 2
Enter average reservoir temperature (deg. C)? 90
Enter total length of DHE installed in the aquifer (m)? 100
Enter DHE outside diameter (mm)? 60
Enter DHE wall thickness (mm)? 4
Enter thermal conductivity of DHE (W/m. C)? 56
Enter inlet temperature to DHE (deg. C)? 30
Enter mass flow rate through DHE (kg/s)? 2
Enter grid length (DZ) (m)? 0.01

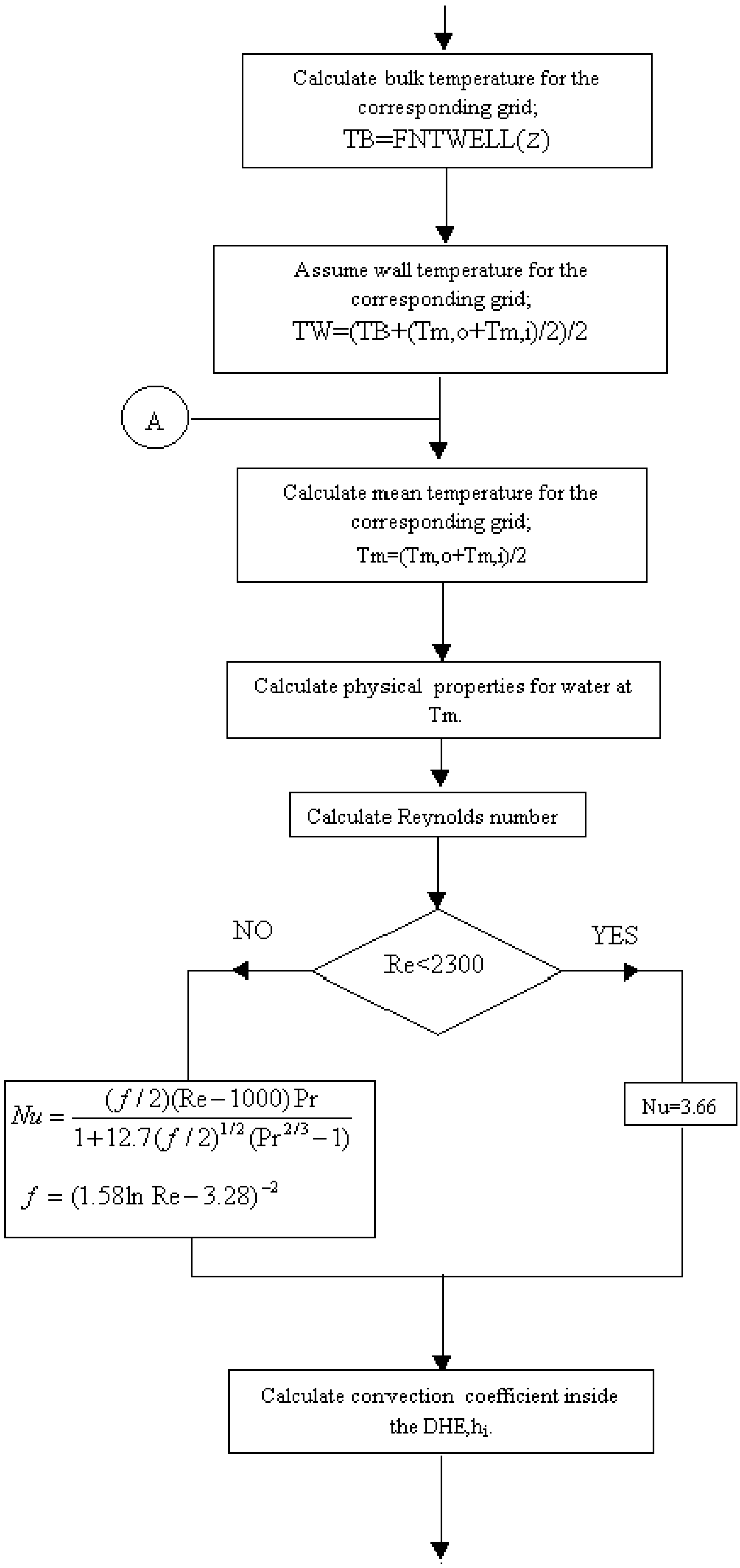
******OUTPUT DATA******

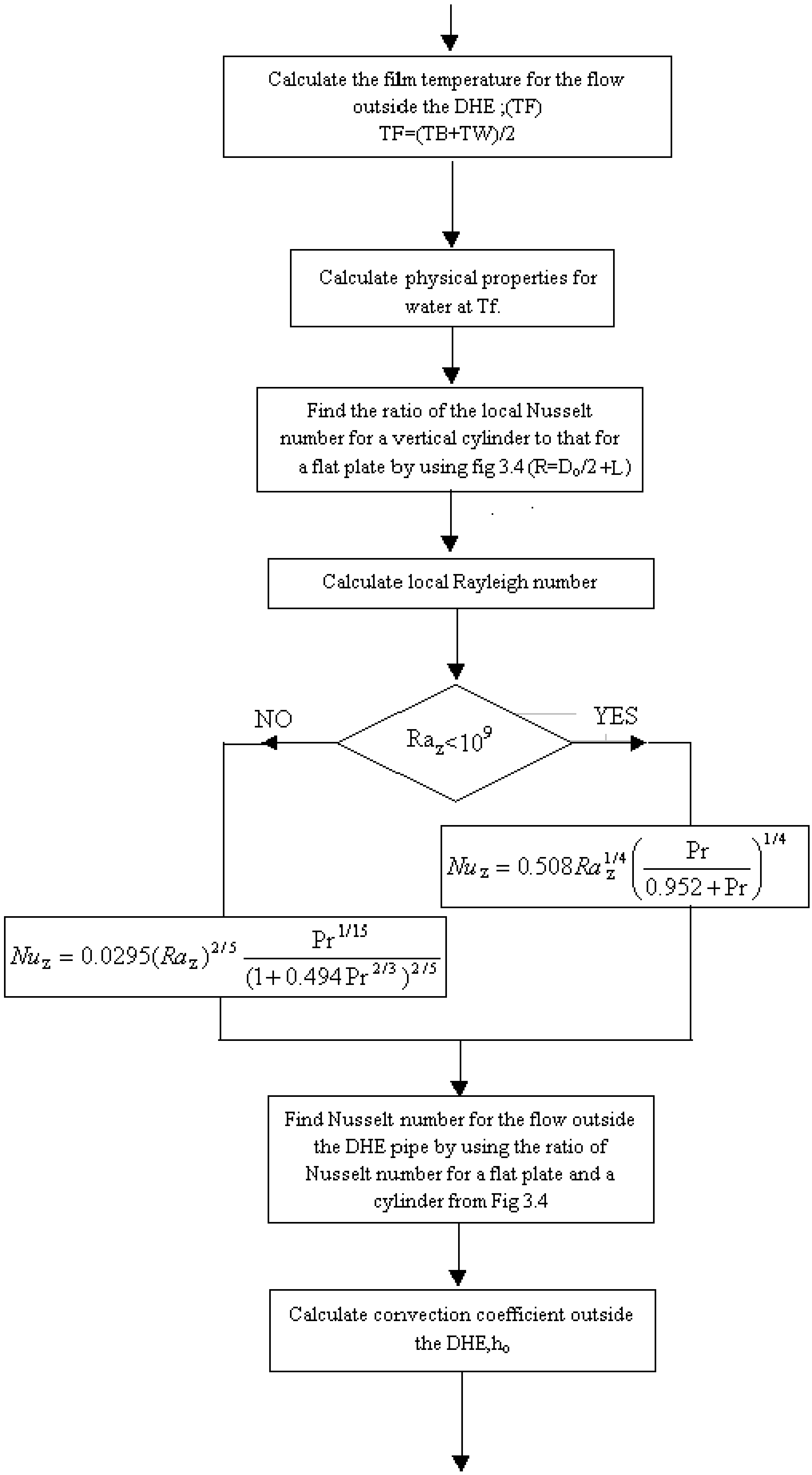
Total heat transfer rate for bare type DHE (W): 475899.7
Exit temperature for bare type DHE (deg. C): 86.8663
Average heat convection coefficient for flow outside the DHE (W/m^2K): 2170.823
Average heat convection coefficient for flow in bare type DHE (W/m^2K): 5630.938

3.3 SOLUTION ALGORITHM FOR FINNED TYPE DHE

Finned type of DHEs consists of two different types of control volumes (Figure 3.3). By applying conservation of energy for these small control volumes and by solving equations (3.1, 3.2, 3.3) for control volume-1 and equations (3.4, 3.5, 3.6) for control volume-2, the temperature distribution through the finned type DHE is solved. The method is summarized by the following algorithm;


Start
-Well temperature profile
-Total length of DHE
-DHE outside diameter
-DHE wall thickness
-Thermal conductivity of DHE pipe material
-DHE inlet temperature
-DHE mass flow rate
-Fin Thickness(S)
-Distance between fins(B)
-Fin Length(L)
Calculate Number of grids:
N=FIX(LDHE/(B+S))
Assume exit temperature
Tm,o=Tm,i+1
B
I=I+1
NO
YES
I<=FIX(N/2)
Z =(N-I)*(B+S)+B/2
Z =(I-1)*(B+S)+B/2


Calculate bulk temperature for the corresponding grid;
TB=FNTWELL(Z)
Assume wall temperature for the corresponding grid;
TW=(TB+(Tm,o+Tm,i)/2)/2
A
Calculate mean temperature for the corresponding grid;
Tm=(Tm,o+Tm,i)/2
Calculate physical properties for water at Tm.
Calculate Reynolds number
Re<2300
NO
YES
$Nu = \frac{(f/2)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7(f/2)^{1/2}(\mathrm{Pr}^{2/3}-1)}$
$f = (1.58\ln \mathrm{Re} - 3.28)^{-2}$
Nu=3.66
Calculate convection coefficient inside the DHE,h_i.


Calculate the film temperature for the flow outside the DHE ;(TF)
TF=(TB+TW)/2
Calculate physical properties for water at Tf.
Find the ratio of the local Nusselt number for a vertical cylinder to that for a flat plate by using fig 3.4 ($R=D_o/2+L$)
Calculate local Rayleigh number
$Ra_z<10^9$
NO
YES
$Nu_z = 0.508 Ra_z^{1/4}\left(\frac{Pr}{0.952+Pr}\right)^{1/4}$
$Nu_z = 0.0295(Ra_z)^{2/5}\frac{Pr^{1/15}}{(1+0.494 Pr^{2/3})^{2/5}}$
Find Nusselt number for the flow outside the DHE pipe by using the ratio of Nusselt number for a flat plate and a cylinder from Fig 3.4
Calculate convection coefficient outside the DHE, h_o

calculate heat transfer rate

$q = U.A.\Delta T_{LM}$

where;

$$\Delta T_{LM} = \frac{\Delta T_o - \Delta T_i}{\ln \frac{\Delta T_o}{\Delta T_i}} \quad , \quad \frac{\Delta T_o}{\Delta T_i} = \frac{T_B - T_{m,o}}{T_B - T_{m,i}}$$

$$U = \frac{1}{\frac{1}{h_i} + \frac{D_i}{2k_b} \ln \frac{D_o}{D_i} + \frac{D_i}{D_o . h_o}} \quad , \quad A = \pi . D_i . B$$

Calculate exit temperature for the grid

$q = m.C_p.(T_{m,o} - T_{m,i})$

$T_{m,o} = ...$

Calculate wall temperature for the grid

$q = h_i.A.\Delta T_{LM}$

where $\Delta T_{LM} = \frac{\Delta T_o - \Delta T_i}{\ln \frac{\Delta T_o}{\Delta T_i}}, \quad \frac{\Delta T_o}{\Delta T_i} = \frac{T_w - T_{m,o}}{T_w - T_{m,i}} \quad , \quad A = \pi . D_i . B$

so;
$$T_w = \frac{T_{m,i} \exp\left(\frac{h_i A (T_{m,i} - T_{m,o})}{q}\right) - T_{m,o}}{\exp\left(\frac{h_i A (T_{m,i} - T_{m,o})}{q}\right) - 1}$$

$\left| T_w^{j+1} - T_w^j \right| < 10^{-4}$

or

$\left| T_{m,o}^{j+1} - T_{m,o}^j \right| < 10^{-4}$

NO

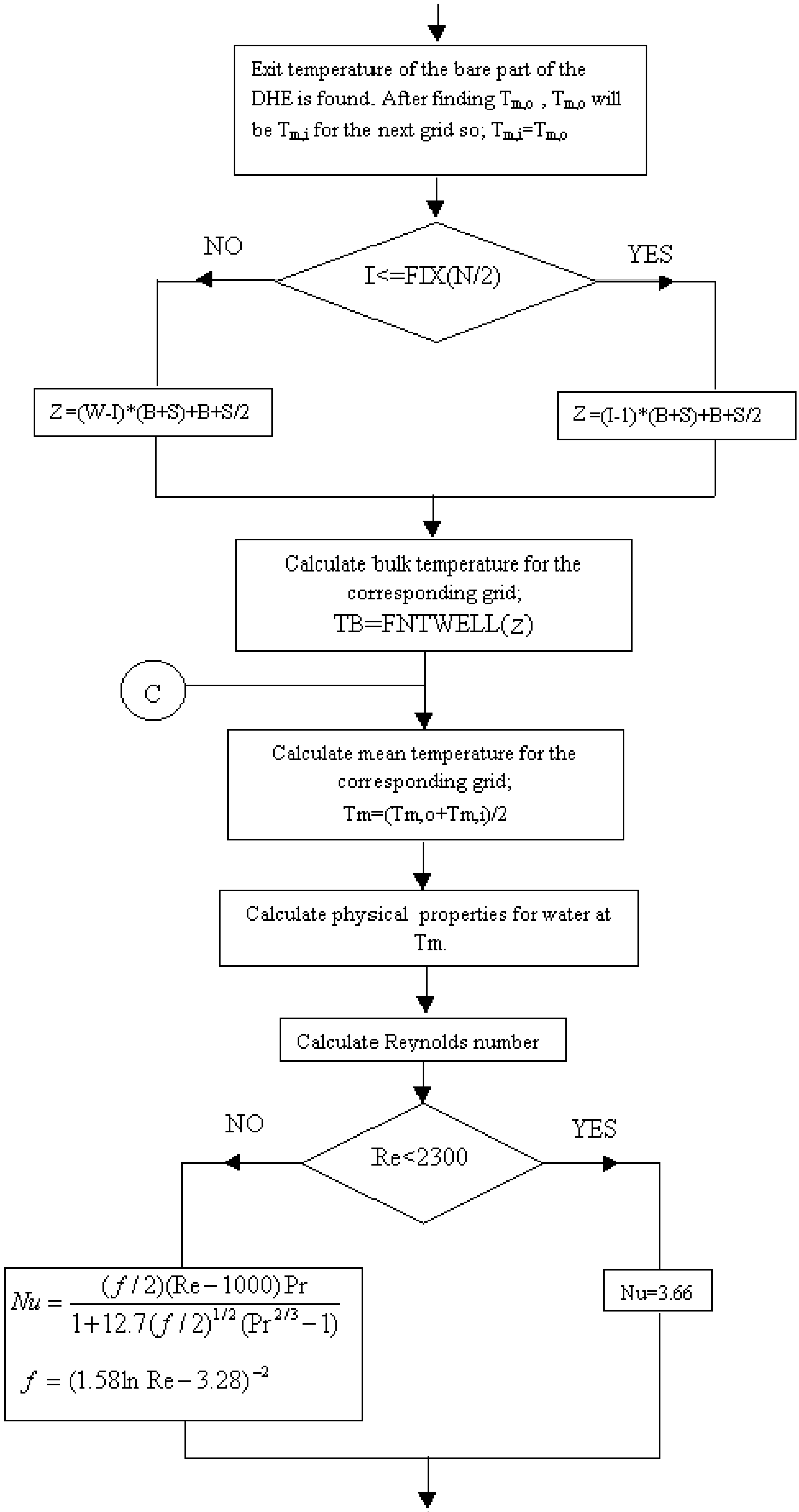
replace

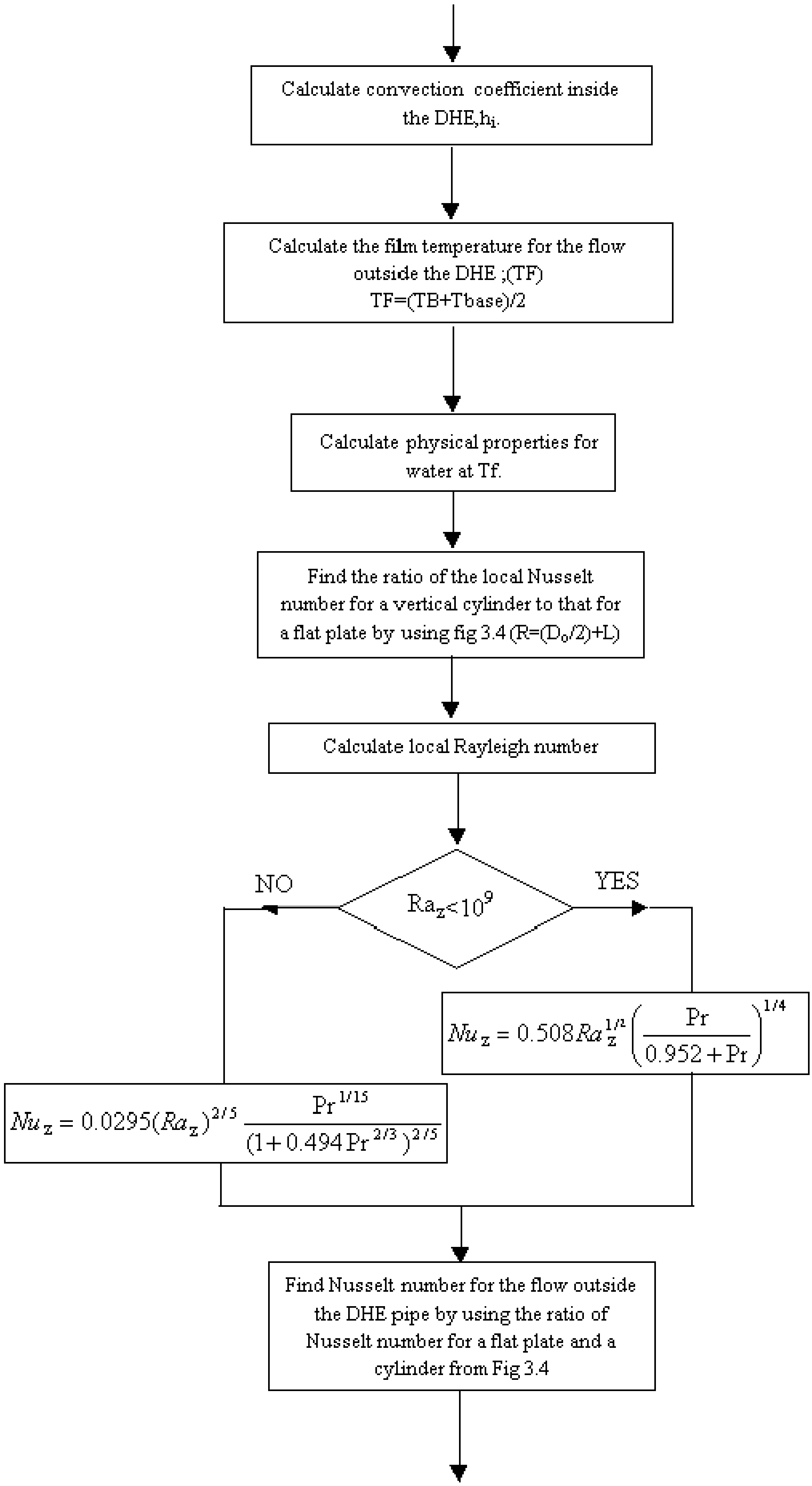
$T_{m,o}^j$ by $T_{m,o}^{j+1}$

and T_w^j by T_w^{j+1}

A

YES


Exit temperature of the bare part of the DHE is found. After finding $T_{m,o}$, $T_{m,o}$ will be $T_{m,i}$ for the next grid so; $T_{m,i}=T_{m,o}$
I<=FIX(N/2)
NO
YES
Z =(W-I)*(B+S)+B+S/2
Z =(I-1)*(B+S)+B+S/2
Calculate bulk temperature for the corresponding grid;
TB=FNTWELL(Z)
C
Calculate mean temperature for the corresponding grid;
Tm=(Tm,o+Tm,i)/2
Calculate physical properties for water at Tm.
Calculate Reynolds number
Re<2300
NO
YES
$Nu = \frac{(f/2)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7(f/2)^{1/2}(\mathrm{Pr}^{2/3}-1)}$
$f = (1.58\ln \mathrm{Re} - 3.28)^{-2}$
Nu=3.66



Calculate convection coefficient inside the DHE,h_i.
Calculate the film temperature for the flow outside the DHE ;(TF) TF=(TB+Tbase)/2
Calculate physical properties for water at Tf.
Find the ratio of the local Nusselt number for a vertical cylinder to that for a flat plate by using fig 3.4 ($R=(D_o/2)+L$)
Calculate local Rayleigh number
NO
$Ra_z<10^9$
YES
$Nu_z = 0.508 Ra_z^{1/2}\left(\frac{Pr}{0.952+Pr}\right)^{1/4}$
$Nu_z = 0.0295 (Ra_z)^{2/5} \frac{Pr^{1/15}}{(1+0.494 Pr^{2/3})^{2/5}}$
Find Nusselt number for the flow outside the DHE pipe by using the ratio of Nusselt number for a flat plate and a cylinder from Fig 3.4

Calculate convection coefficient outside the DHE,h_o

$q=\eta_F . A_F . h_o . (T_B - T_{base})$

where $\eta_F = C_2 \dfrac{K_1(M.R_1)I_1(M.R_{2C}) - I_1(M.R_1)K_1(M.R_{2C})}{I_o(M.R_1)K_1(M.R_{2C}) + K_o(M.R_1)I_1(M.R_{2C})}$

$$C_2 = \frac{(2R_1/M)}{(R_{2C}^2 - R_1^2)}$$

$$R_{2C} = R_2 + S/2$$

$$A_F = 2\pi(R_{2C}^2 - R_1^2)$$

$$M = \sqrt{\frac{2.h_o}{k_b.S}}$$

so calculate η_F

$$q = \eta_f A_f h_o (T_B - T_{base}) = \frac{h_i A_K (T_{base} - T_{m,i}) - (T_{base} - T_{m,o})}{\ln\left(\dfrac{T_{base} - T_{m,i}}{T_{base} - T_{m,o}}\right)}$$

so calculate base temperature of the grid (T_{base})

$$T_{base} = \frac{T_{base} - T_{m,i}}{\exp\left(\dfrac{h_i.A_k(T_{m,o} - T_{m,i})}{\eta_f A_f h_o (T_B - T_{base})}\right)} + T_{m,o}$$

where $A_K = \pi . D_i . S$ and $A_F = 2\pi(R_{2C}^2 - R_1^2)$

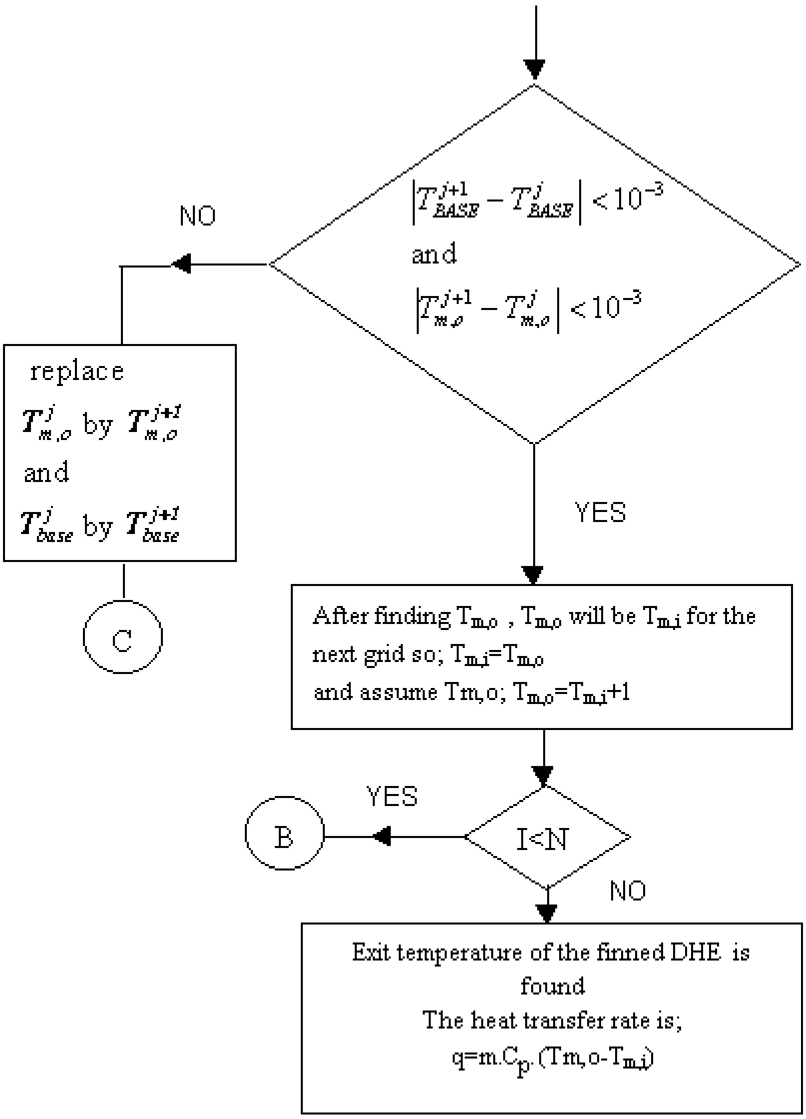
calculate heat transfer rate;

$q = \eta_f A_f h_o (T_B - T_{base})$

Calculate exit temperature for the grid

$q = m.C_p.(T_{m,o} - T_{m,i})$

$T_{m,o}=$……



A Typical Solution for Finned Type DHE

******INPUT DATA******

DHE PROGRAM

Calculates exit temperature and heat output of a Downhole Heat Exchanger

If bare or finned type DHE

If bare type DHE, type 1,else another number? 2

If the well temperature profile is assumed as a polynomial profile or a constant number

If a polynomial profile, type 1,else another number? 2

Enter average reservoir temperature (deg. C)? 90

Enter total length of DHE installed in the aquifer (m)? 100

Enter DHE outside diameter (mm)? 60

Enter DHE wall thickness (mm)? 4

Enter thermal conductivity of DHE (W/m. C)? 56

Enter inlet temperature to DHE (deg. C)? 30

Enter mass flow rate through DHE (kg/s)? 2

Enter fin thickness (mm)? 1

Enter distance between fins (mm)? 5

Enter fin length (mm)? 3

******OUTPUT DATA******

Total heat transfer rate for finned type DHE (W): 486926.5

Exit temperature for finned type DHE (deg. C): 88.18027

Average heat convection coefficient for flow outside the DHE (W/m^2K): 1764.187

Average heat convection coefficient for flow in finned type DHE (W/m^2K): 5706.116

CHAPTER 4

DHE SIMULATION USING A SOFTWARE PACKAGE (FLUENT)

4.1 BACKGROUND

FLUENT is a computer program for modeling fluid flow and heat transfer in complex geometries. FLUENT provides complete mesh flexibility, solving the flow problems with unstructured meshes that can be generated about complex geometries with relative ease. Supported mesh types include 2D triangular/quadrilateral, 3D tetrahedral/hexahedral/pyramid/wedge, and mixed (hybrid) meshes.

FLUENT is written in C computer language and makes full use of the flexibility and power offered by the language.

In this study the geometries are created and meshed using GAMBIT modeling program. The geometries are exported to the FLUENT program. Once a grid has been read into FLUENT all remaining operations are performed within FLUENT. These include setting boundary conditions, defining fluid properties, executing the solution, and viewing and postprocessing the results.

4.2 DEFINITION OF THE PROBLEMS UNDER CONSIDERATION

The wells in Klamath Falls are 25 or 30-cm diameter drilled 20 or more feet (6m) into livewater [3]. Because of having difficulties about the modeling of well and DHE, the minumum well length is chosen.

In order to establish the problem properly geothermal well is modelled with 4 m diameter and 6 m long surrounding rock. Diameter and length of geothermal well are 30 cm and 6 m respectively. The bottom surface temperature of the model is assumed as 100°C and all the other surfaces of the model are assumed insulated.

Two different types of DHE configuration in a well are examined. The schematics of the models developed to analyze the heat extraction rates of the DHEs are given in Figure 4.1 and 4.2

In this work, it is aimed to determine the fluid flow in a well with DHE. The effective DHE design is determined. Also the results are compared with the DHE program developed in this study.

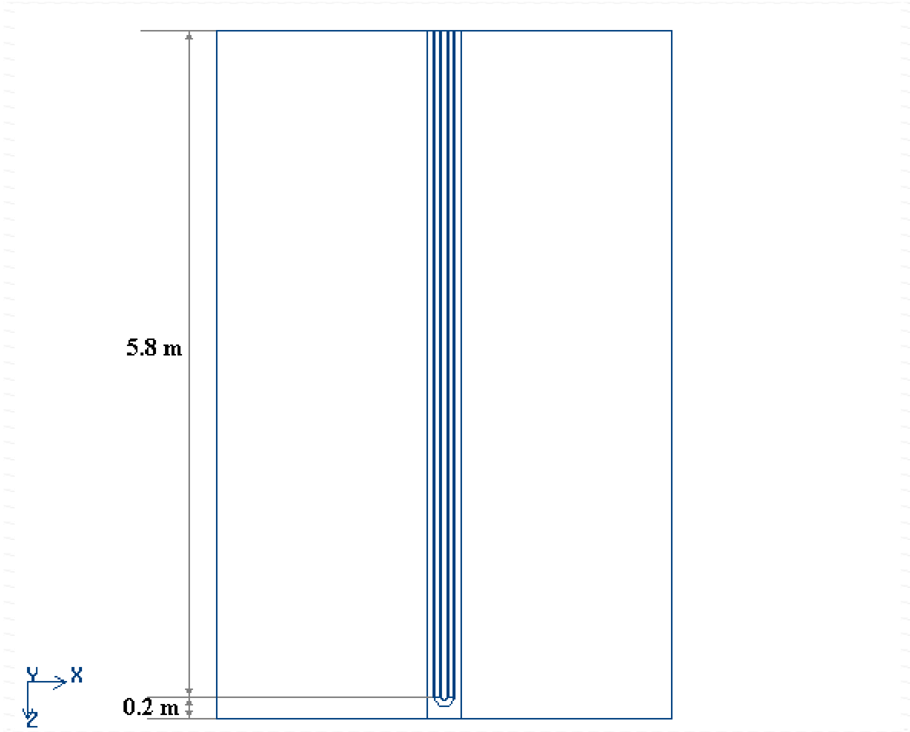


Fig 4.1 Schematics of Model-I (well with bare type DHE, D_o=60 mm, Di=52 mm)

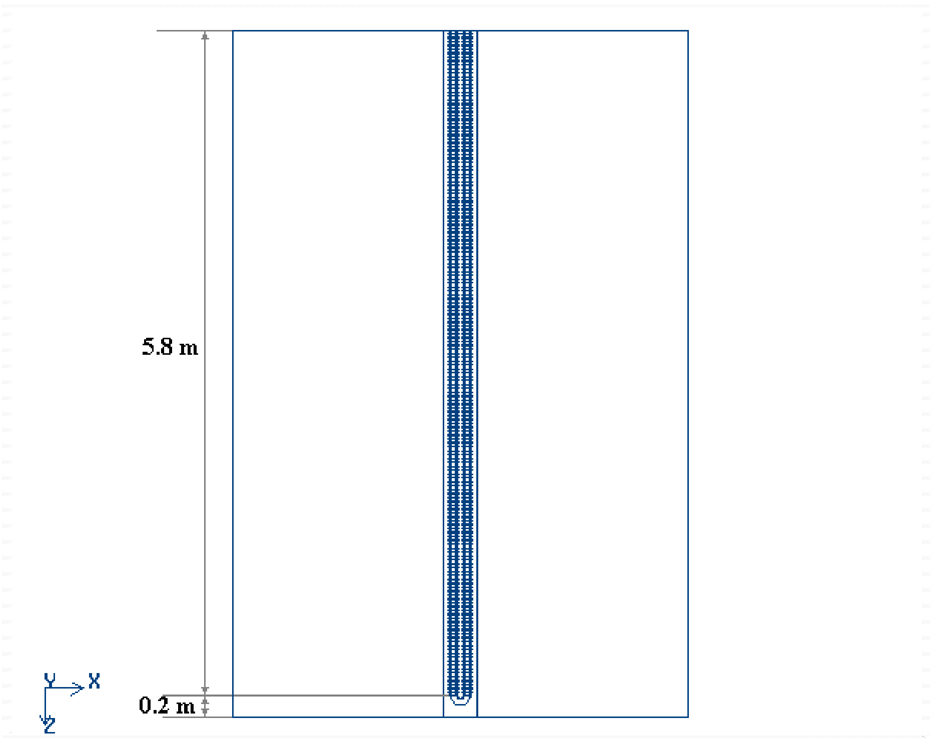


Fig 4.2 Schematics of Model-II (well with finned type DHE, D_o=60 mm, Di=52 mm, S=4 mm, B= 30 mm, L=20mm)

4.3 MODELING THE PROBLEMS

Before solving the problem with FLUENT program, it is necessary to create the model and its volume meshes. The models are created in Gambit Modeling Program.

All the models are consists of 4 volumes; volume 1,the rock; volume 2,the well; volume 3 the DHE; volume 4, the water in the DHE. Volumes 1 and 3 are solid regions and volume 2 and 4 are the fulid regions. All the volumes are meshed with a grid type of Tgrid [26]. Grid informations about the models are as follows:

Model-I (Figure 4.1)

Volume 1 → 480023 volume meshes

Volume 2 → 397947 volume meshes

Volume 3 → 186344 volume meshes

Volume 4 → 290528 volume meshes

Model-II (Figure 4.2)

Volume 1 → 478934 volume meshes

Volume 2 → 402028 volume meshes

Volume 3 → 288236 volume meshes

Volume 4 → 290528 volume meshes

The grid distribution for the models are given from figures 4.5 to 4.13.

4.4 SETTING UP THE PROBLEMS ON THE COMPUTER [27-30]

The computational grid file created is exported to the FLUENT program where problem definition is completed by specifying physical models and boundary conditions for the models.

The problems are set up by following the procedure given below:

1) All the models includes heat transfer so calculation of heat transfer is activated. The physical properties of water such as viscosity, heat capacity, thermal conductivity and density are specified as functions of temperatures. DHE material is taken as steel with constant physical properties. Physical properties of rock are taken from "Downhole Heat Exchangers Performance Analysis" [7].

2) One of the turbulence model of standard k-ε model is chosen for the specification of the flow in the well and DHE. For including the generation of the turbulence due to bouyancy, the gravitational acceleration in +z direction is specified as 9.81 m/s^2.
3) Boundary conditions of the models are specified.
   Mass flow rate for DHE :1 kg/s
   DHE inlet temperature: 300 K
   Bottom surface temperature of the model: 373 K
4) Solution algorithm:Segregated,Implicit
   Segregated: Using this approach, the governing equations are solved sequentially (i.e.,segregated from one another). Because the governing equations are non-linear, several iterations of the solution loop must be performed before a converged solution is obtained. Each iteration consists of the steps illustrated in Figure 4.3.
   Implicit: For a given variable, the unknown value in each cell is computed using a relation that includes both existing and unknown values from neighboring cells. Therefore each unknown appears in more than one equation in the system, and these equations are solved simultaneously to give the unknown quantities such as velocities,pressure and temperature.
5) Steady-state flow:
   The equations representing the conservation of mass and momentum are solved for steady-state flow.
6) Under-Relaxation:
   Because of the nonlinarity of the equation set being solved by FLUENT, the change of unknown values is controlled by under-relaxation factors. In a simple form, the new value of the variable ϕ within a cell depends upon the old value, ϕ_{old}, the computed change in ϕ, $\Delta\phi$, and the under-relaxation factor,α, as follows:

   $$\phi=\phi_{old}+\alpha\Delta\phi \tag{4.1}$$

   During the calculations, under-relaxation factors are as follows:

   Pressure:0.5
   Momentum:0.2

Energy:0.8-1

Turbulence kinetic energy:0.8

Turbulence dissipation rate:0.8

Viscosity:1

Density:1

Body forces:1

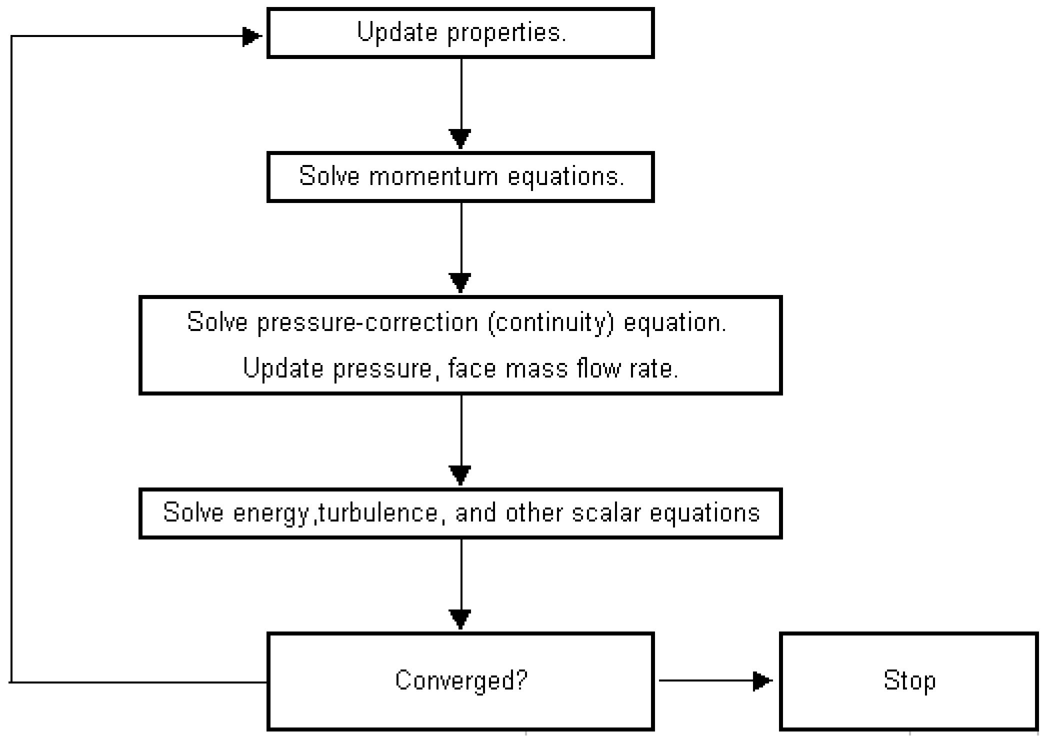


Fig 4.3 Overview of the Segregated Solution Method

After specifying the physical models and boundary conditions. The calculation starts from arbitrary initial conditions (except at the boundries) and converges to the correct solution after performing a number of iterations.

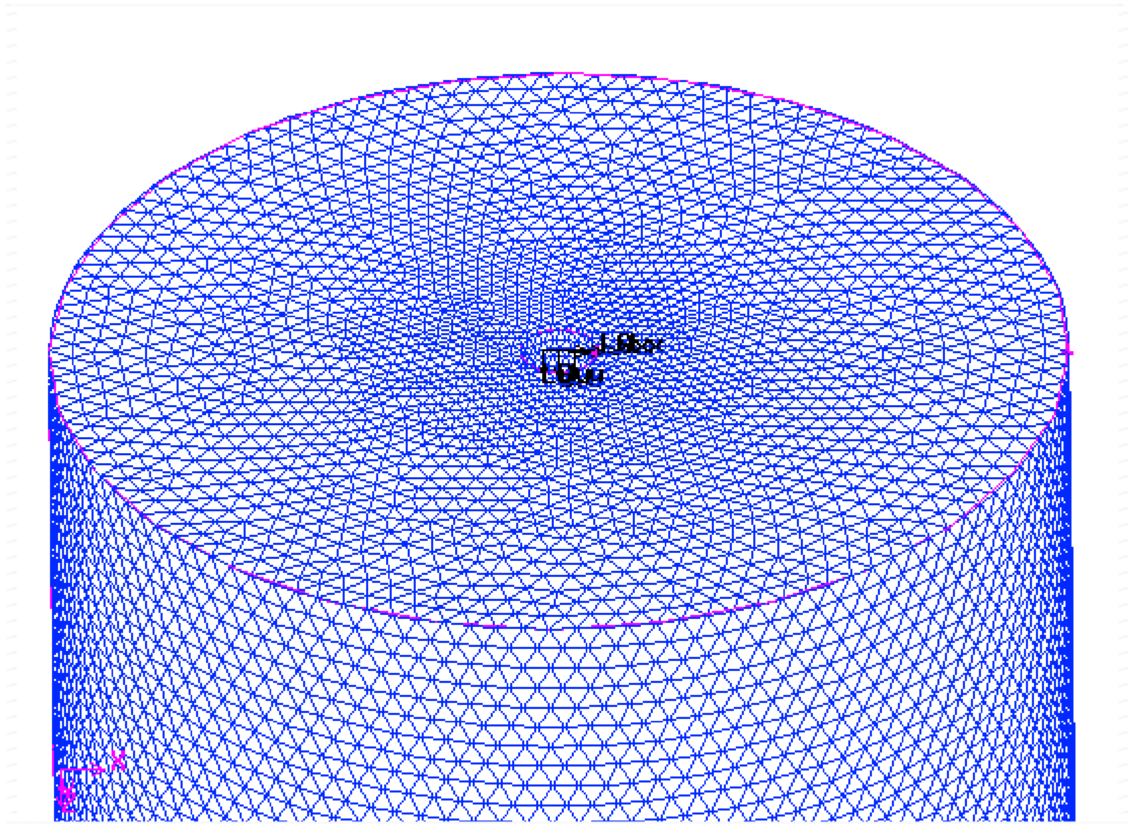


Fig 4.4 Surface grid distribution close to the upper part of the rock

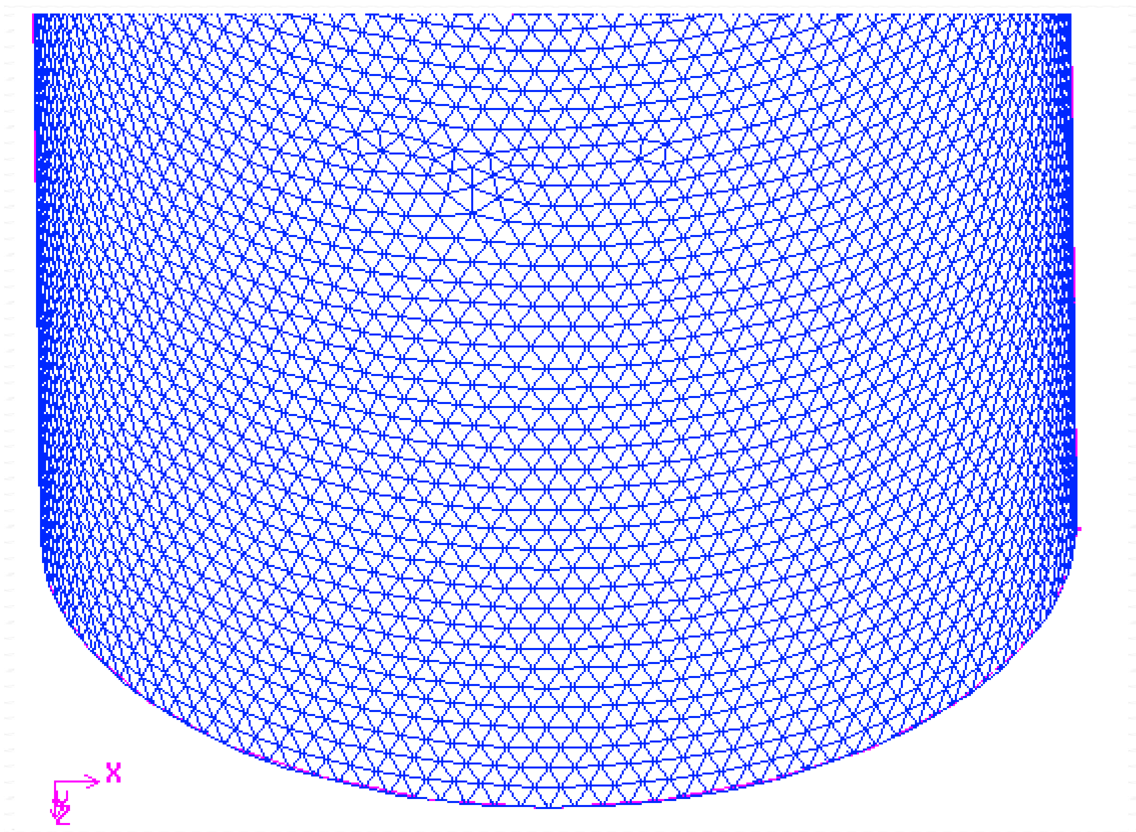


Fig 4.5 Surface grid distribution close to the bottom part of the rock

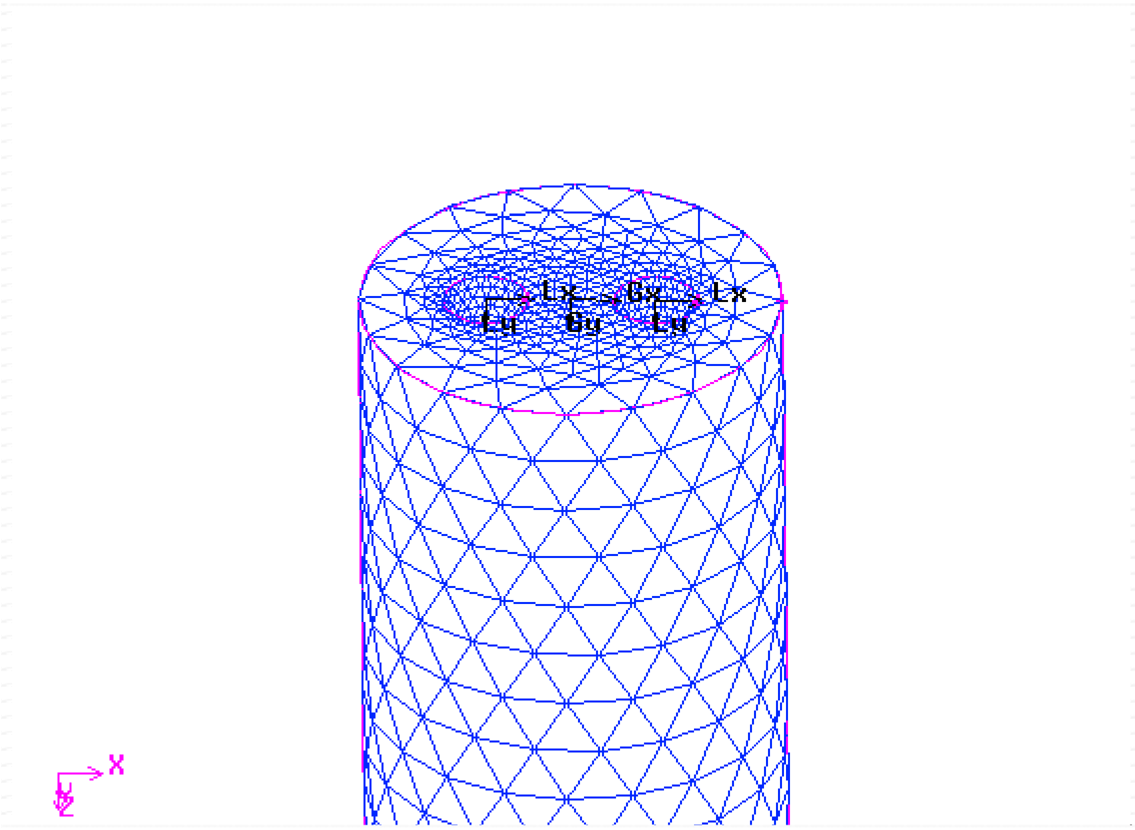


Fig 4.6 Surface grid distribution close to the upper part of the well

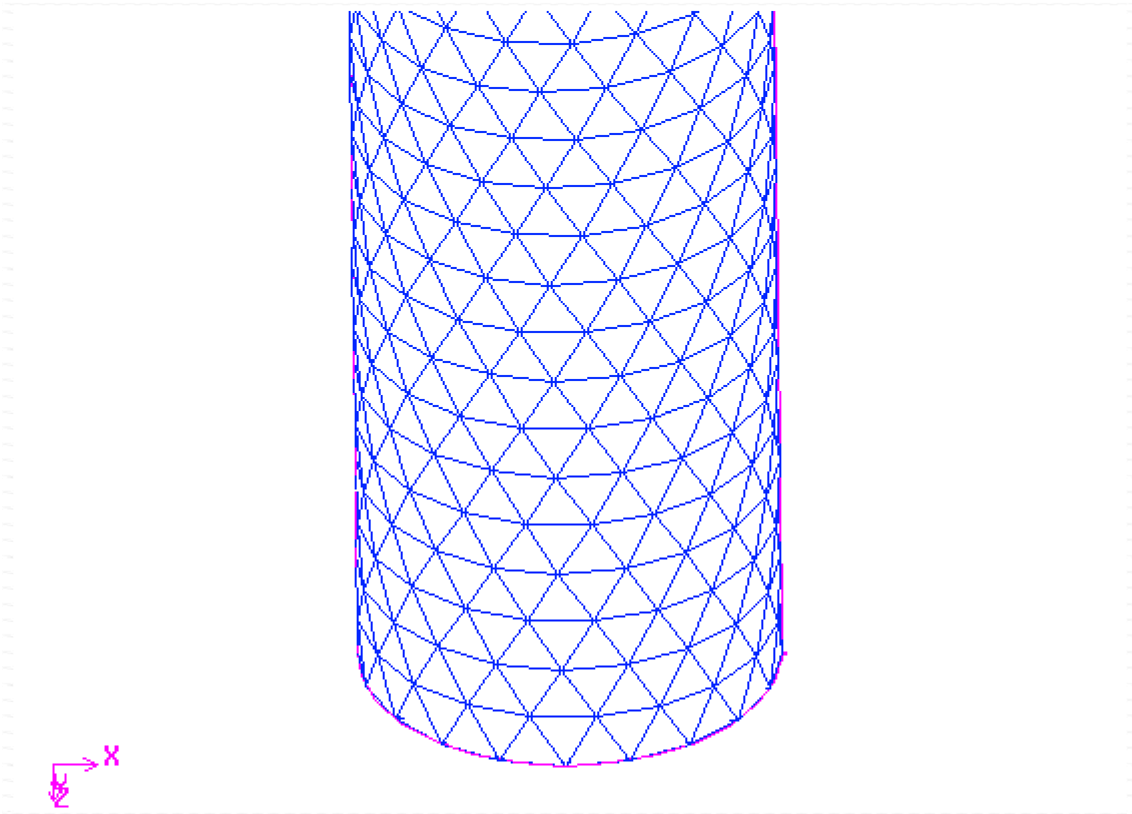


Fig 4.7 Surface grid distribution close to the bottom part of the well

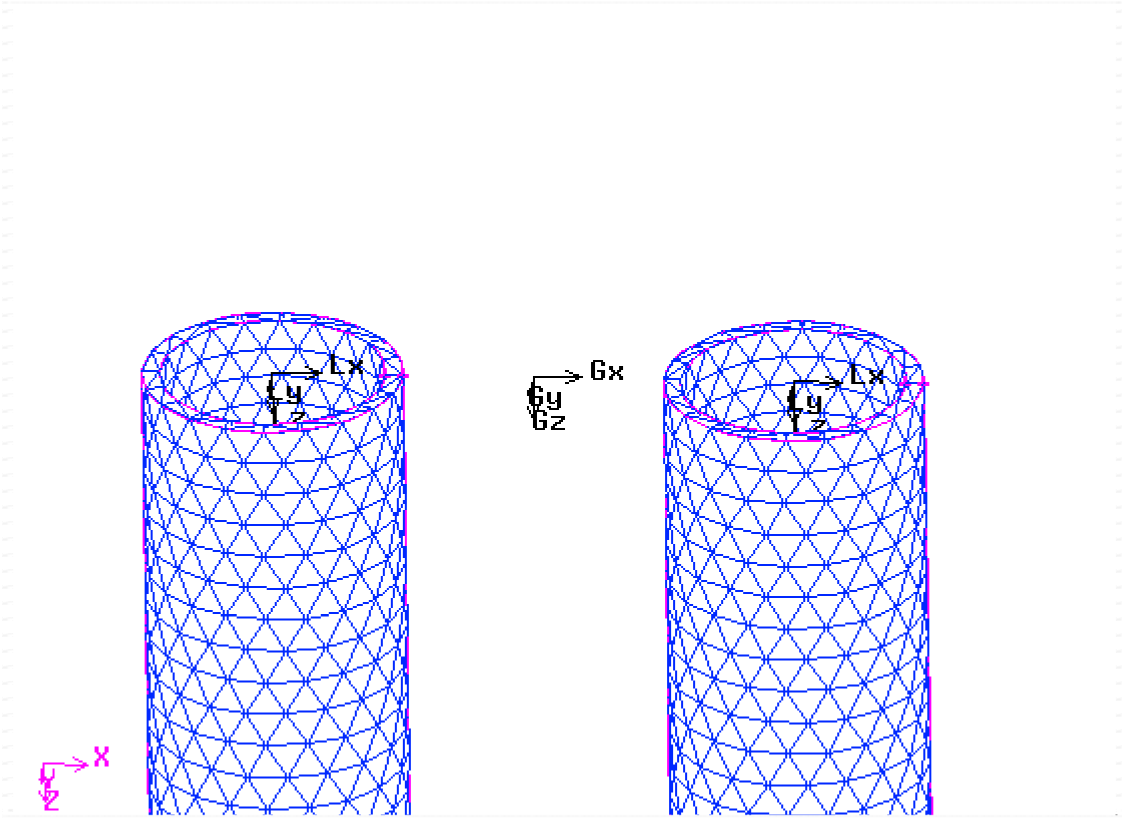


Fig 4.8 Surface grid distribution close to the upper part of the bare type DHE

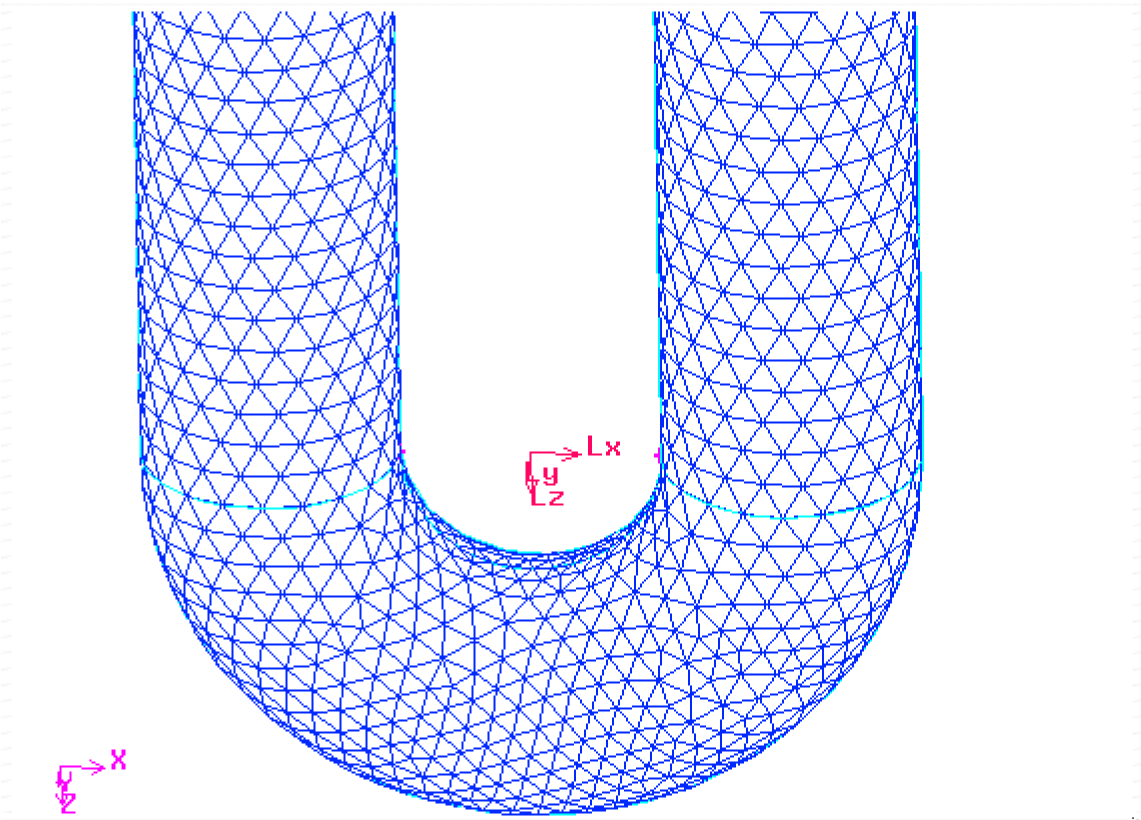


Fig 4.9 Surface grid distribution close to the bottom part of the bare type DHE

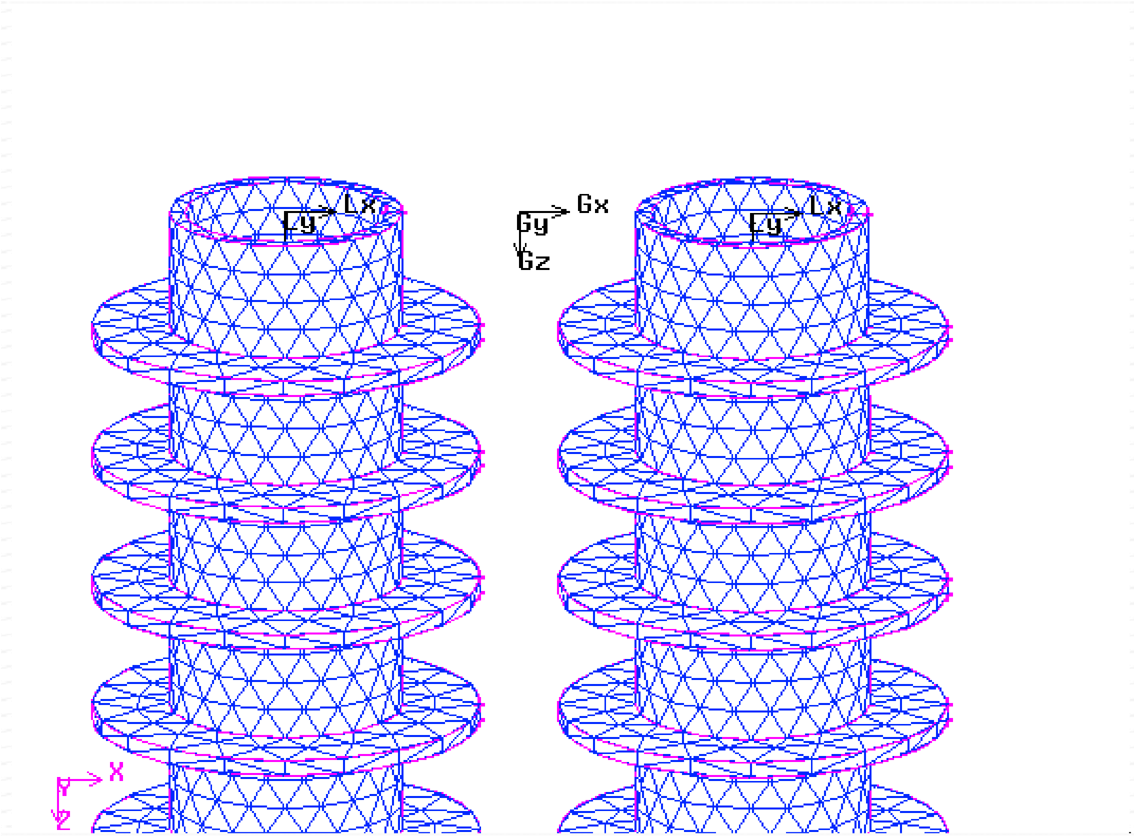


Fig 4.10 Surface grid distribution close to the upper part of the finned type DHE

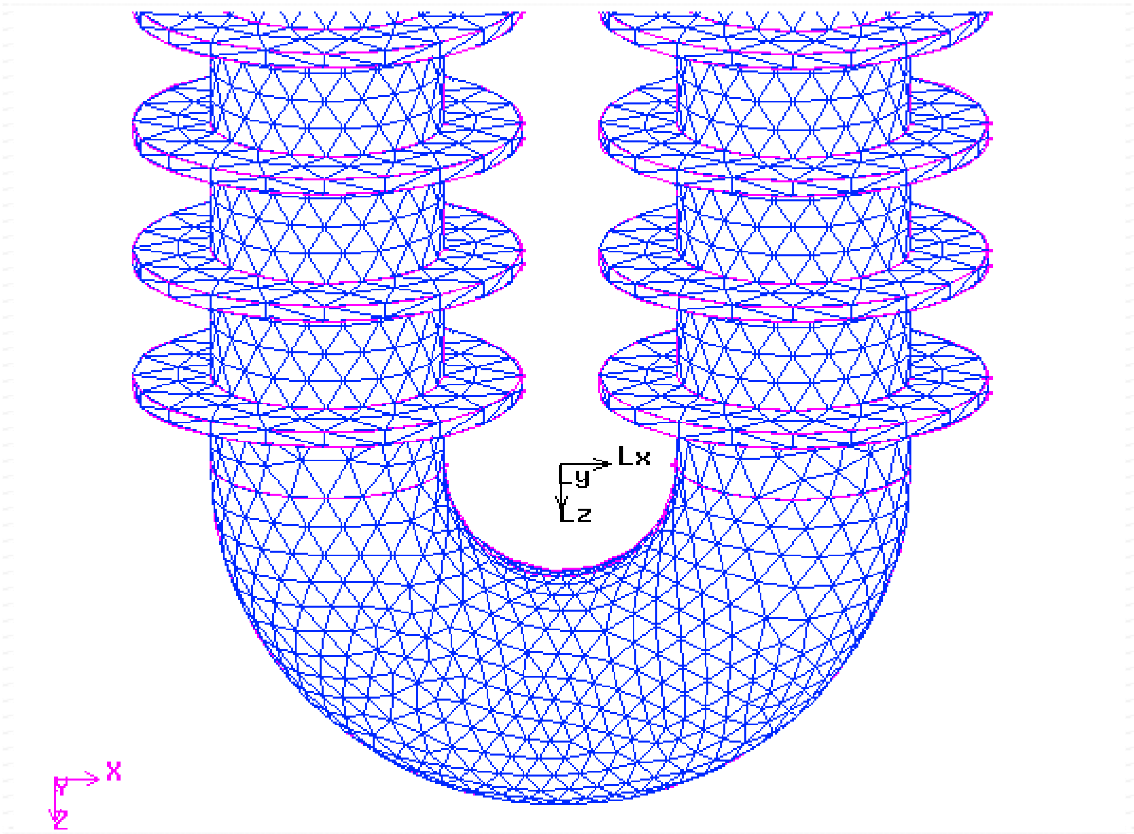


Fig 4.11 Surface grid distribution close to the bottom part of the finned type DHE

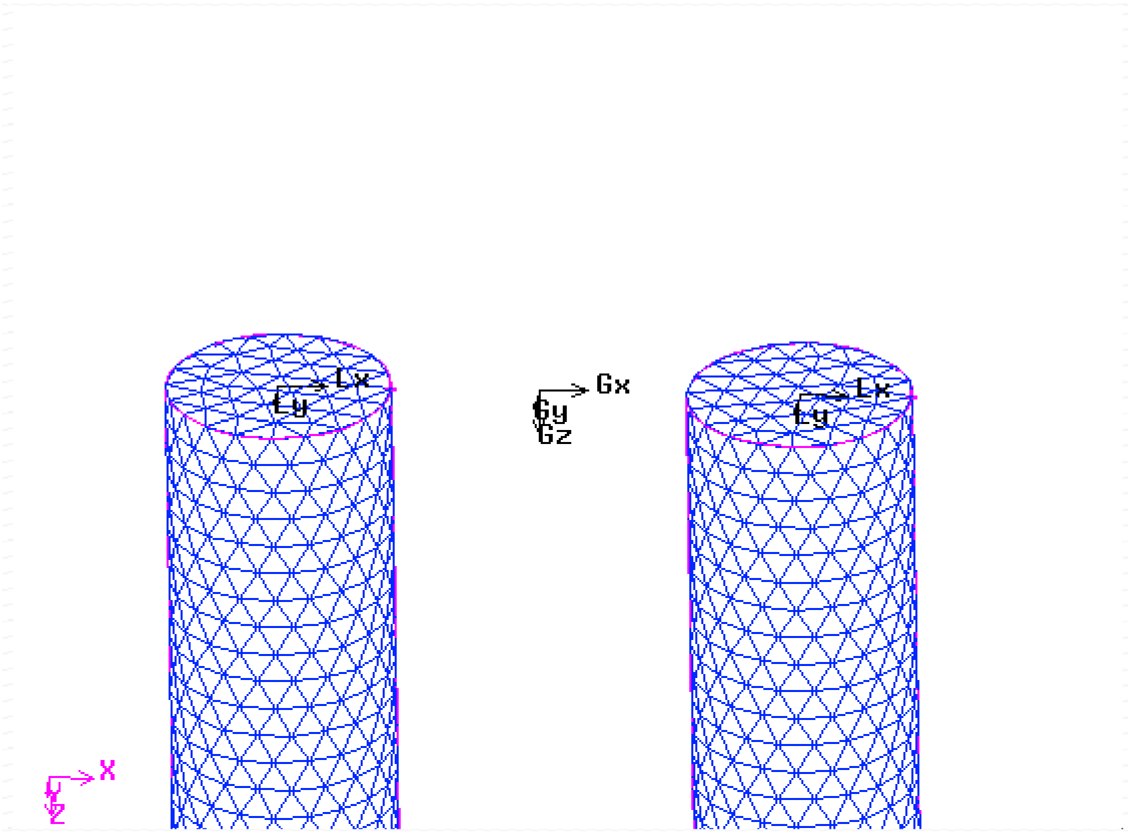


Fig 4.12 Surface grid distribution close to the upper part of the water in the DHE

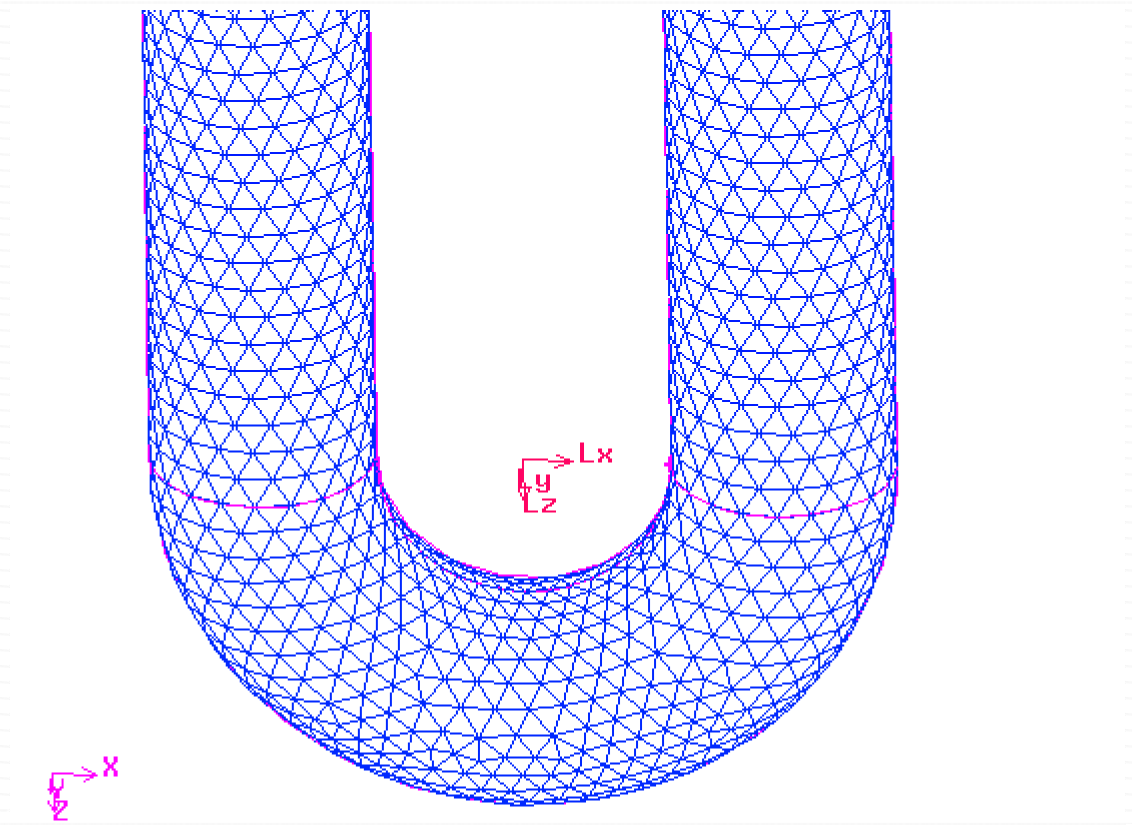


Fig 4.13 Surface grid distribution close to the bottom part of the water in the DHE

CHAPTER 5

RESULTS AND DISCUSSION

3.3 VERIFICATION OF THE DHE PROGRAM

In order to verify the DHE program for bare type DHEs, the experimental results of Dunstall's study are used [7]. However, there is not a study about radial finned type DHEs, so a computational fluid dynamic program, FLUENT, is used to check the accuracy of the program.

5.1.1 Comparing DHE Program with Experimental Results

In Dunstall's study, a DHE was inserted to a 4″ well. During the DHE tests the temperature profiles through the well and DHE were measured.

The U tube, which extended the full length of the well, was 121m long. However, the water level was about 3-4 m below the ground, because the DHE program is written for the DHE, which is in geothermal fluid, the total length of DHE is taken as $(121-4)\times 2=234$ m. The outer diameter of the DHE is 33.7 mm and the thickness of the DHE is 3.2 mm. DHE material is known as mild steel so the thermal conductivity of the material is taken as 56 W/m°C.

The problem is to find temperature distribution through the DHE.

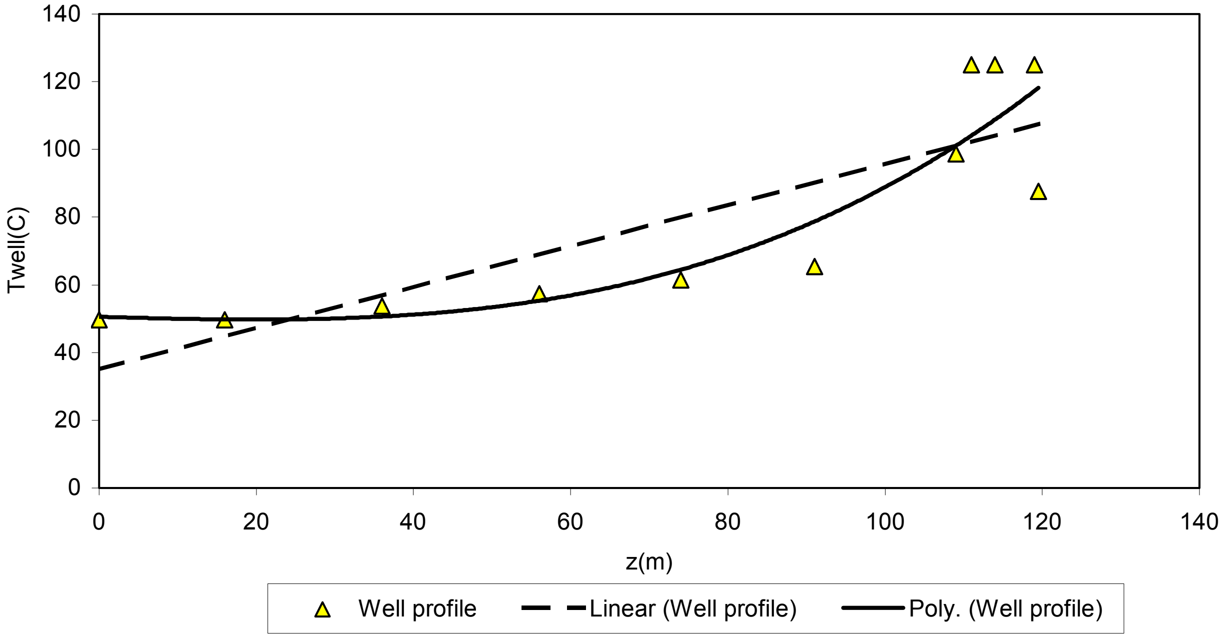


Fig 3.5 Well temperature profile in the geothermal water-DHE running (1.2 l/s)

Figure 5.1 shows the temperature profile of the well while DHE is running with a flow rate of 1.2 l/s. The profile is assumed for two different situations:

- <u>If the well profile is assumed as linear then the following relation can be obtained by using the given data (Fig 5.1):</u>

$$Twell(z)= 0.607890258097225z + 34.9753442526178$$

- <u>If the well profile is assumed as polynomial then the following relation can be obtained by using the given data (Fig 5.1):</u>

$$Twell(z)= 0.000041030371444449z^3 + 0.00036591321904567z^2 – 0.0639456710824788\,0z + 50.5423573907788$$

By using these temperature distributions as input, two different DHE temperature profiles are found (Figure 5.2 and 5.3).

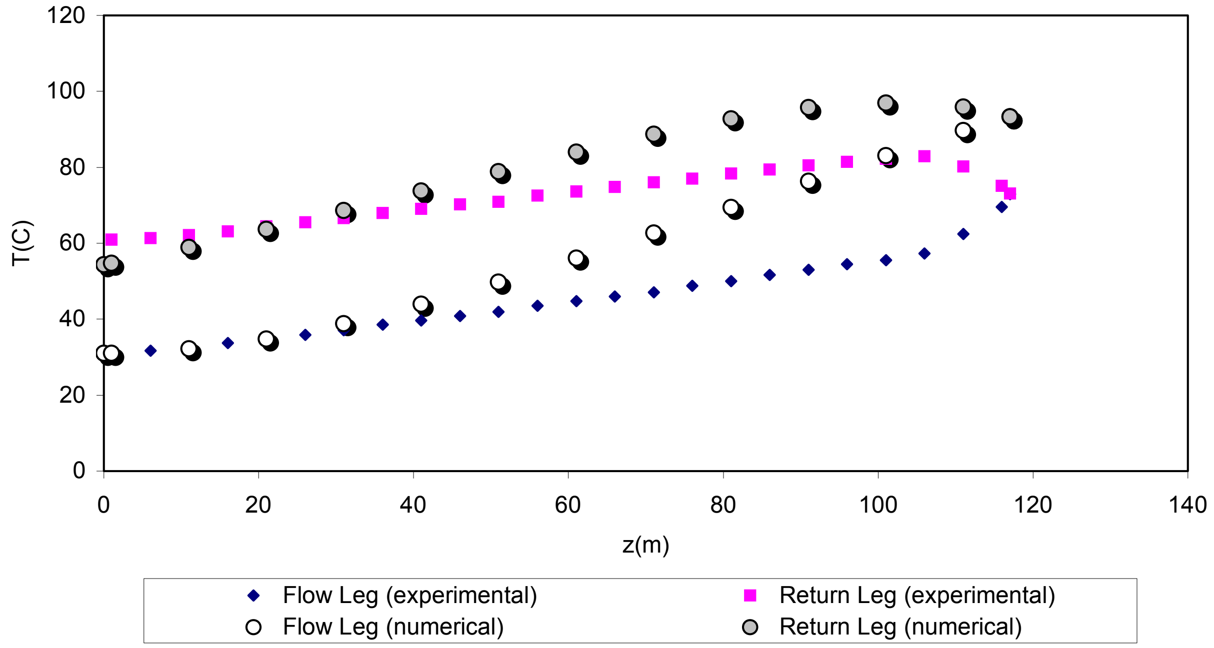


Fig 5.2 DHE internal temperatures with a linear well temperature profile (1.2 l/s)

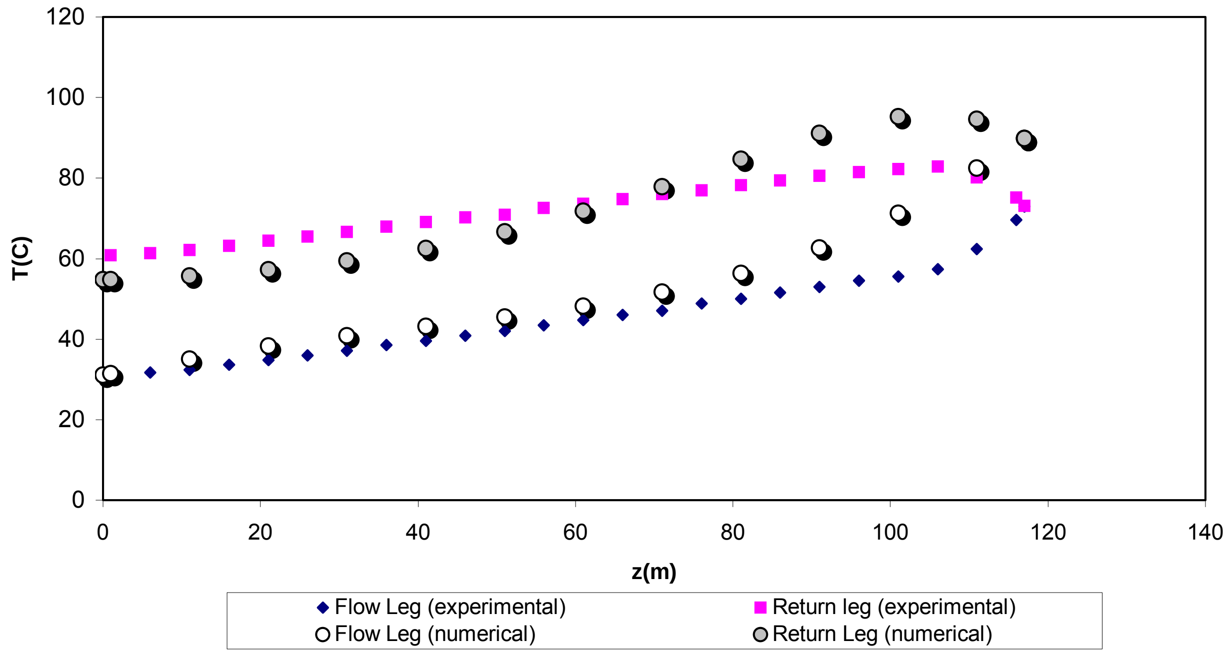


Fig 5.3 DHE internal temperatures with a polynomial well temperature profile (1.2 l/s)

As seen from the figure 5.2 and 5.3 the polynomial profile fits better than the linear temperature profile to specify the more accurate distribution for the DHE. The polynomial temperature profile fits very well between 0-80 m, after 80 m the polynomial profile is not the same as the real ones. As a result, the temperature distribution obtained from the DHE program fits very well between 0-80 m for the flow leg.

5.1.2 Comparing DHE Program with FLUENT

Both bare and finned DHEs are modelled and simulated with FLUENT software. The results are compared with DHE program for same input data such as flow rate, DHE inlet temperature, DHE parameters etc. In addition, the temperature profile through the well used for DHE program as input data is obtained from the results of the FLUENT software by collecting temperature values for different depths and assumed as polynomial function. While the figures 5.8 and 5.9 show the results of both programs for bare type DHE, the results for finned type DHE are presented in figures 5.14 and 5.15. These figures indicate that the results of both programs are in good agreement.

The results of the FLUENT software showed that the temperature distribution through the well is nearly constant with depth, which may be caused by the existence of vertical movements in the well (Figures 5.4 and 5.10). The well circulation is occurred by the existence of temperature differences in the well. Because the temperature of the DHE is lower than the well temperature, flow of the well is down the tube side and up the well side (Fig 5.7). However for finned type DHE, this hot water circulation is affected by the radial fins, which caused the turbulent mixing in the well (Fig 5.12 and 5.13). Although adding radial fins increased the heat transfer area, also decreased the well velocity. The average well velocity is around 0.03 m/s for the well with bare type DHE and 0.02 m/s for the well with finned type DHE for the given situations (Figures 5.6 and 5.12).

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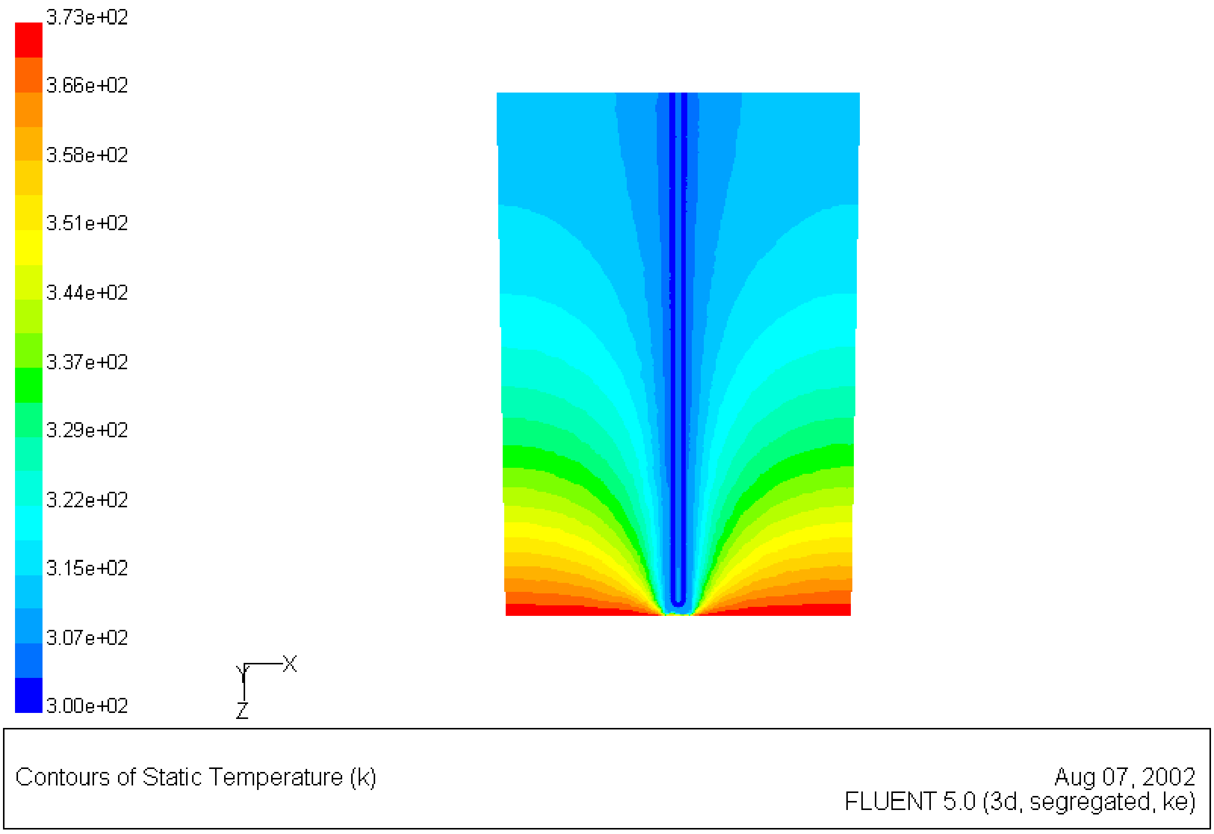

Fig 5.4 Temperature profile for model-I

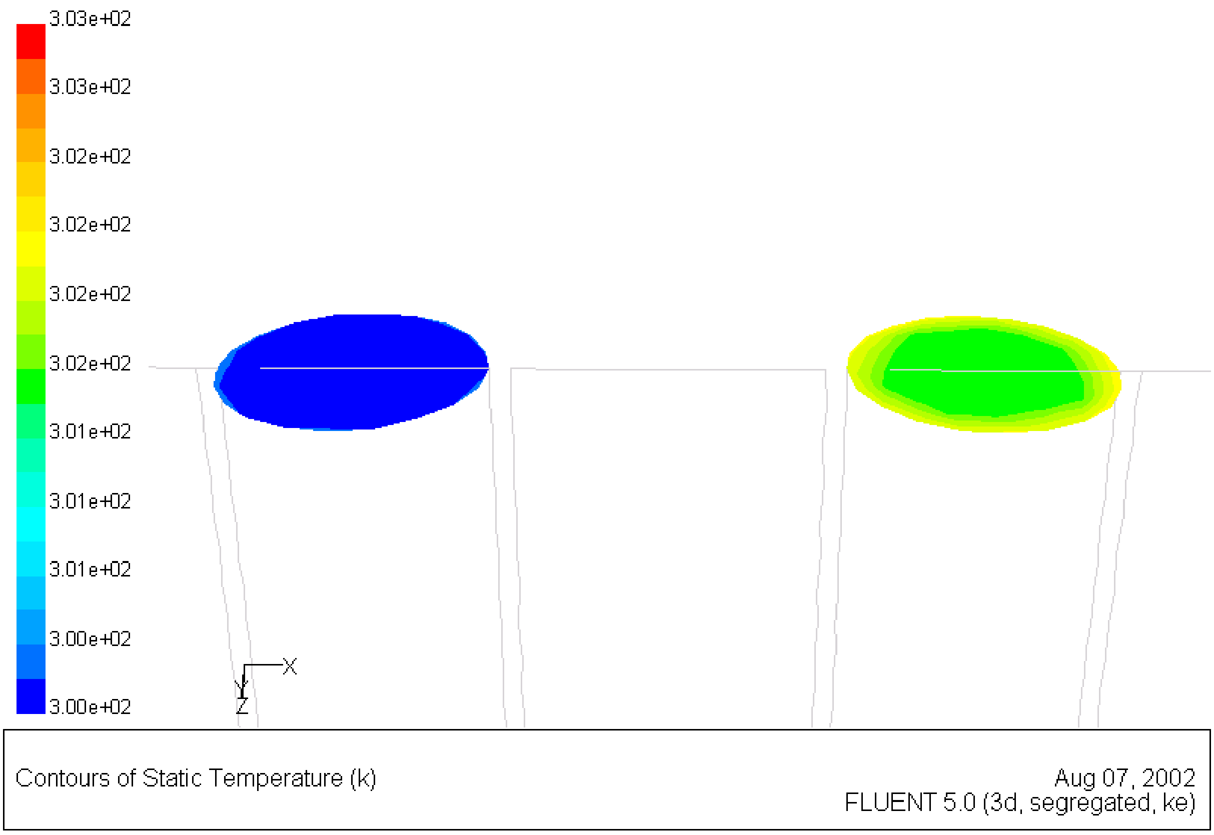

Fig 5.5 Temperature profile at the inlet and exit part of the DHE for model-I

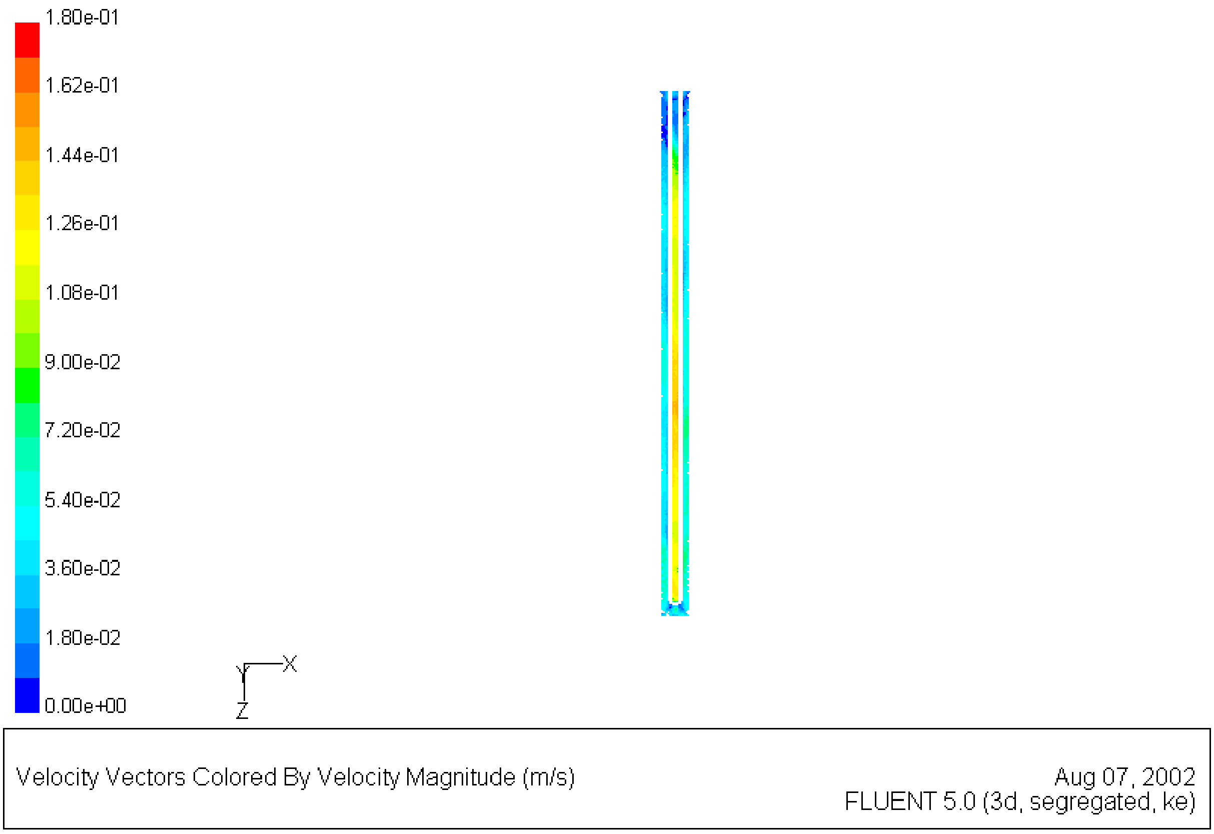

Fig 5.6 Velocity profile for the well with bare type DHE

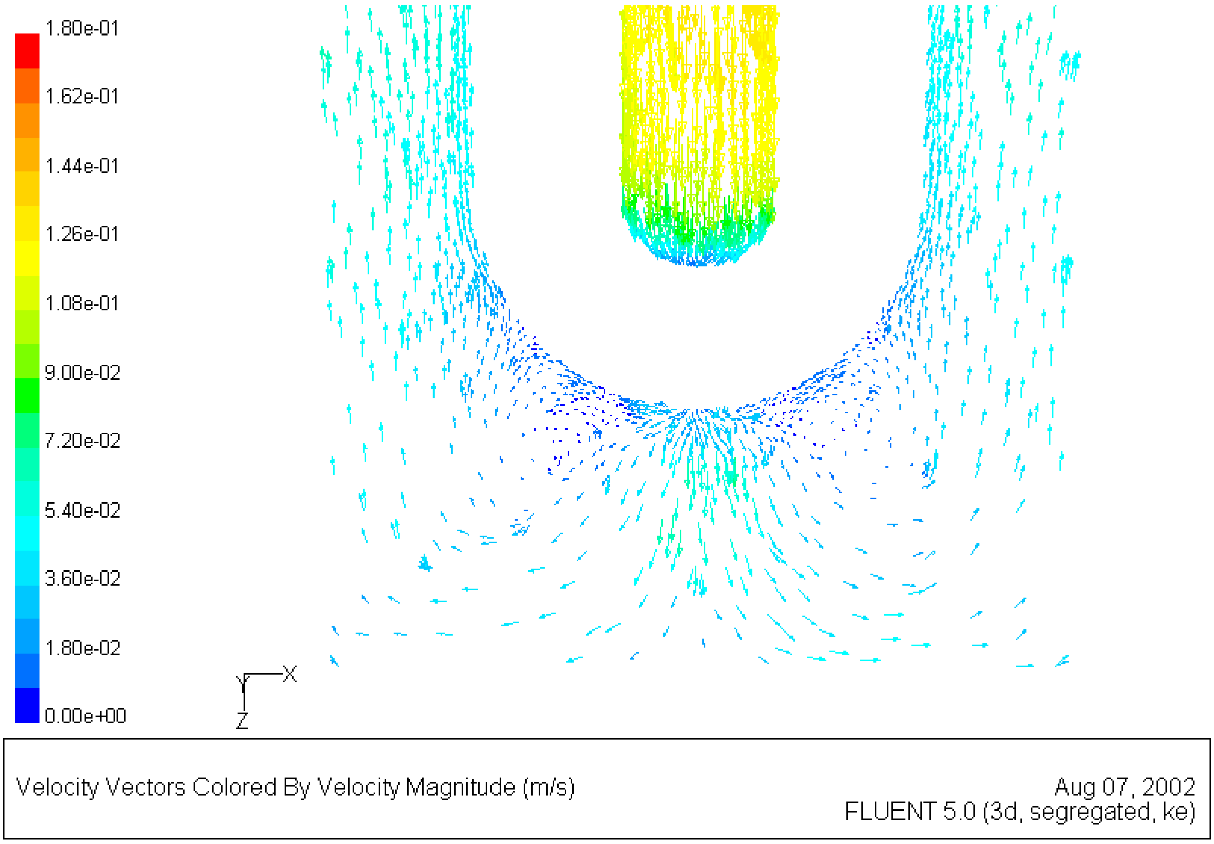

Fig 5.7 Velocity profile for the well with bare type DHE (close to the well bottom)

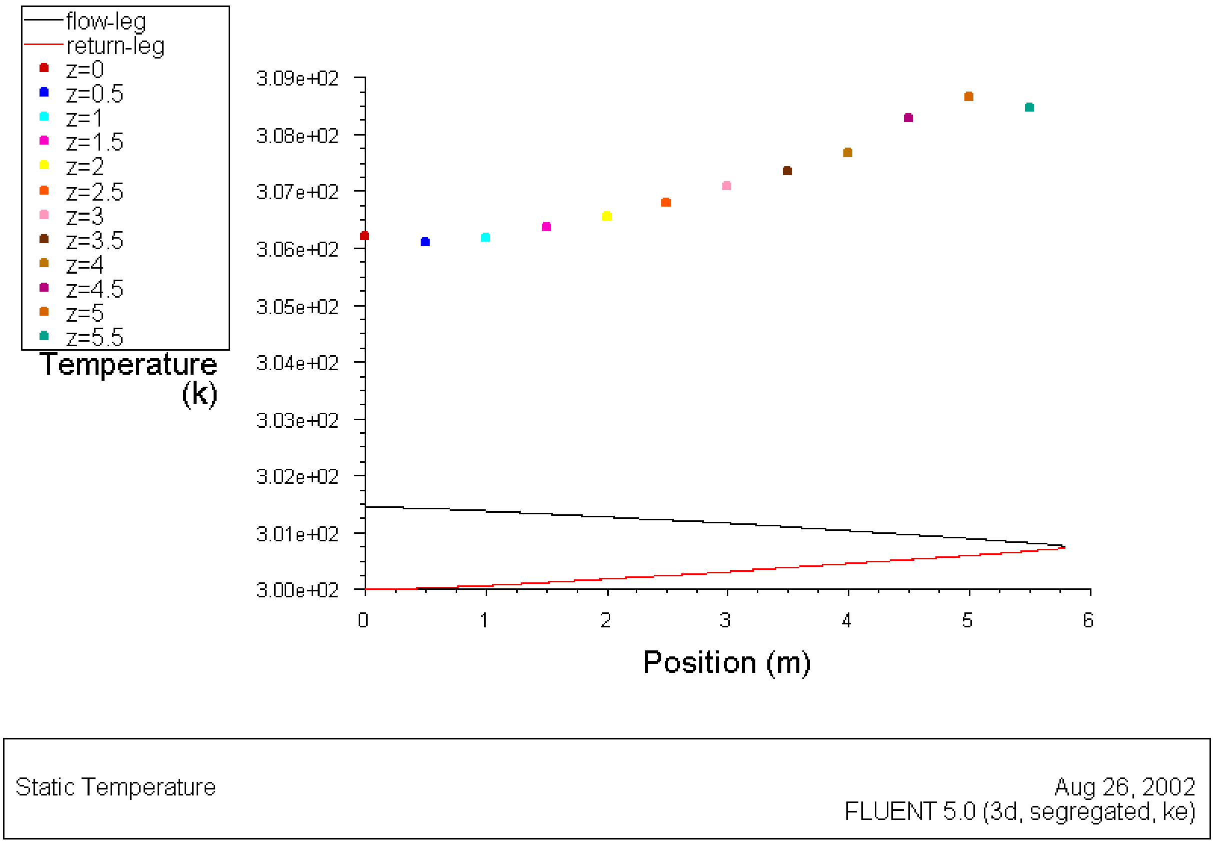

Fig 5.8 Temperature distribution for the well and bare type DHE (FLUENT)

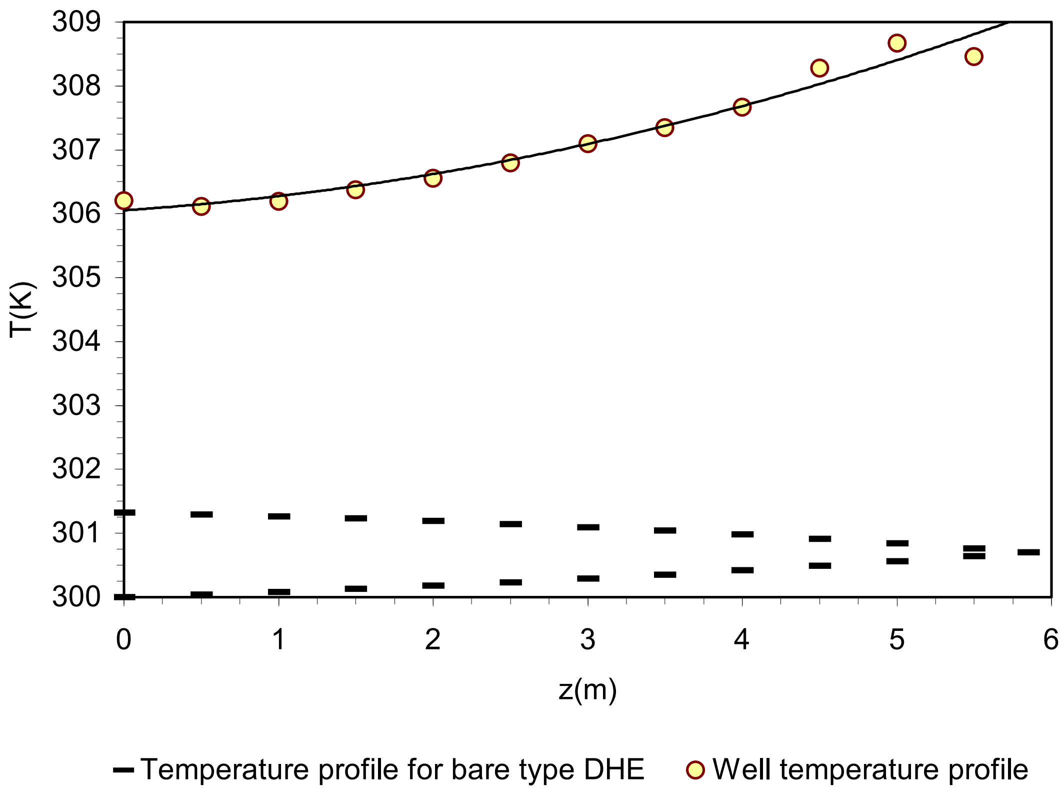

Fig 5.9 Temperature distribution for the well and bare type DHE (DHE Program)

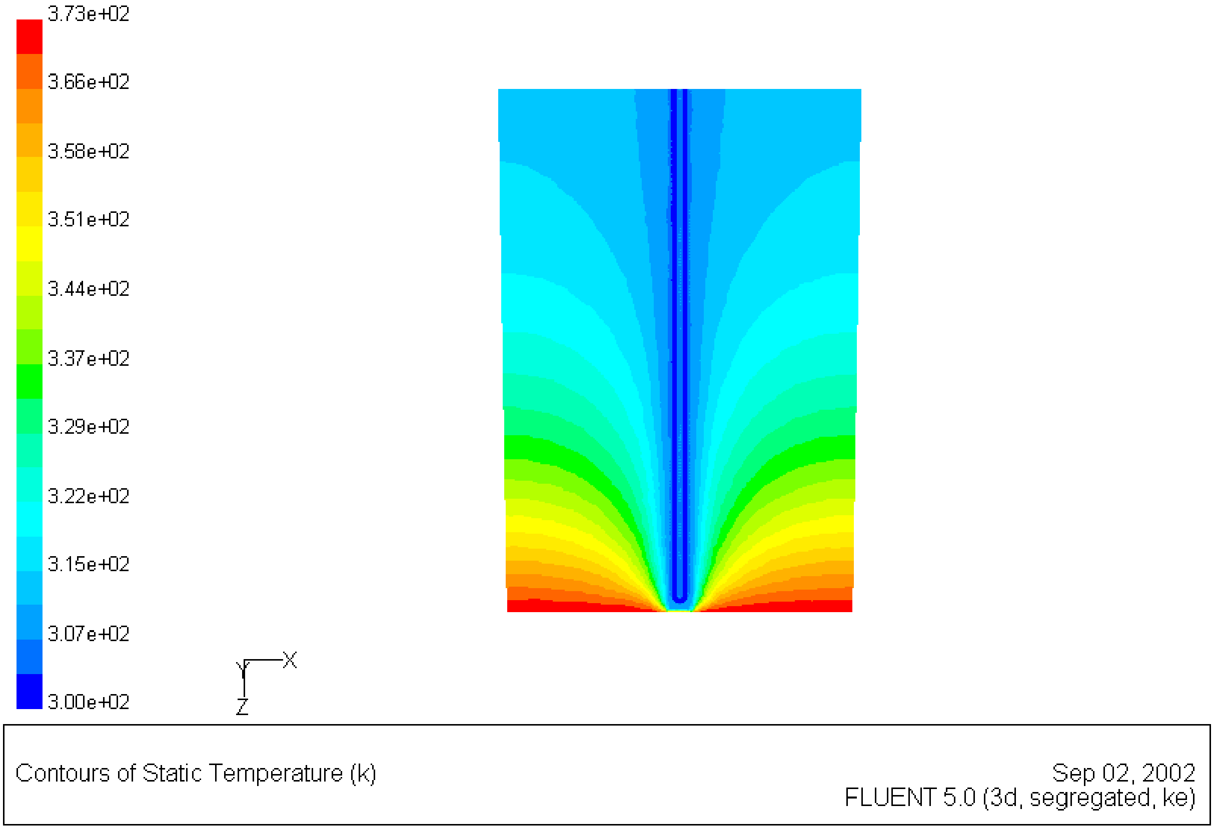

Fig 5.10 Temperature profile for model-II

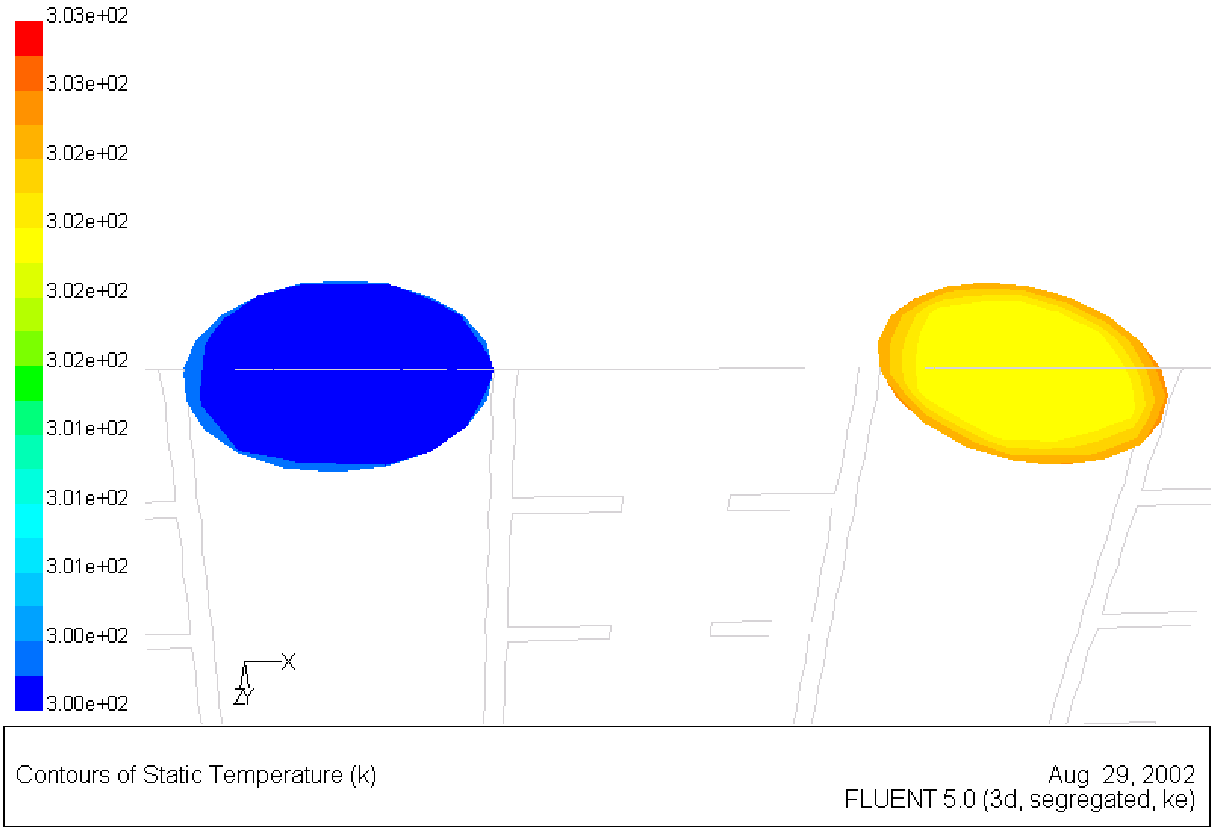

Fig 5.11 Temperature profile at the inlet and exit part of the DHE for model-II

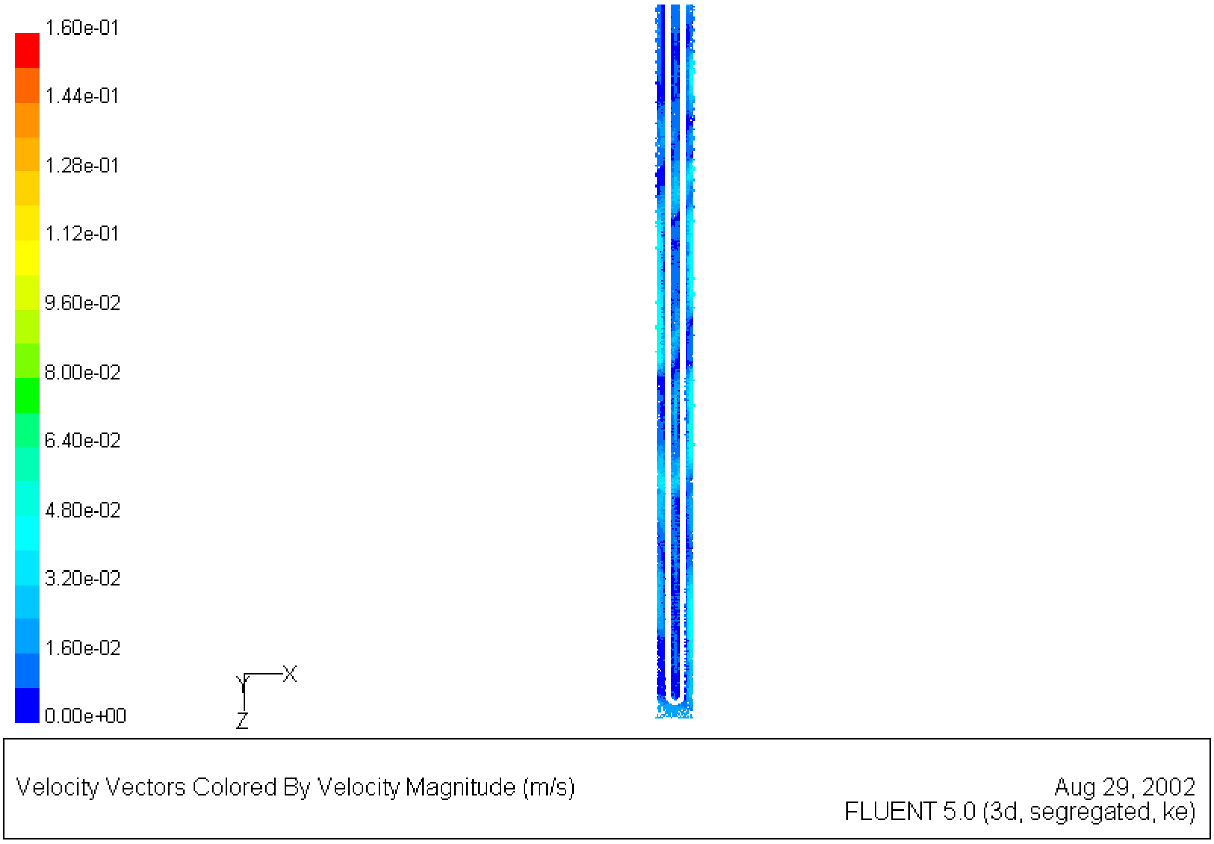

Fig 5.12 Velocity profile for the well with finned type DHE

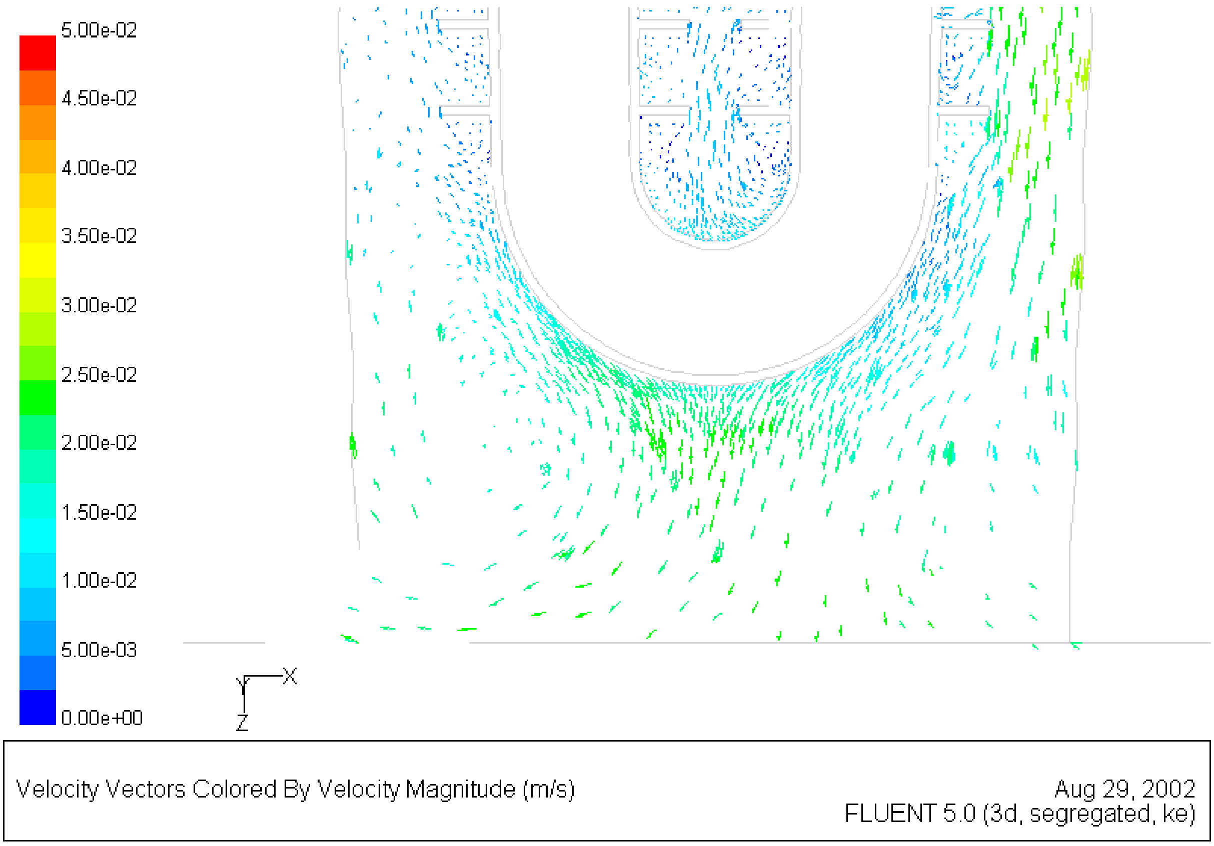

Fig 5.13 Velocity profile for the well with finned type DHE (close to the well bottom)

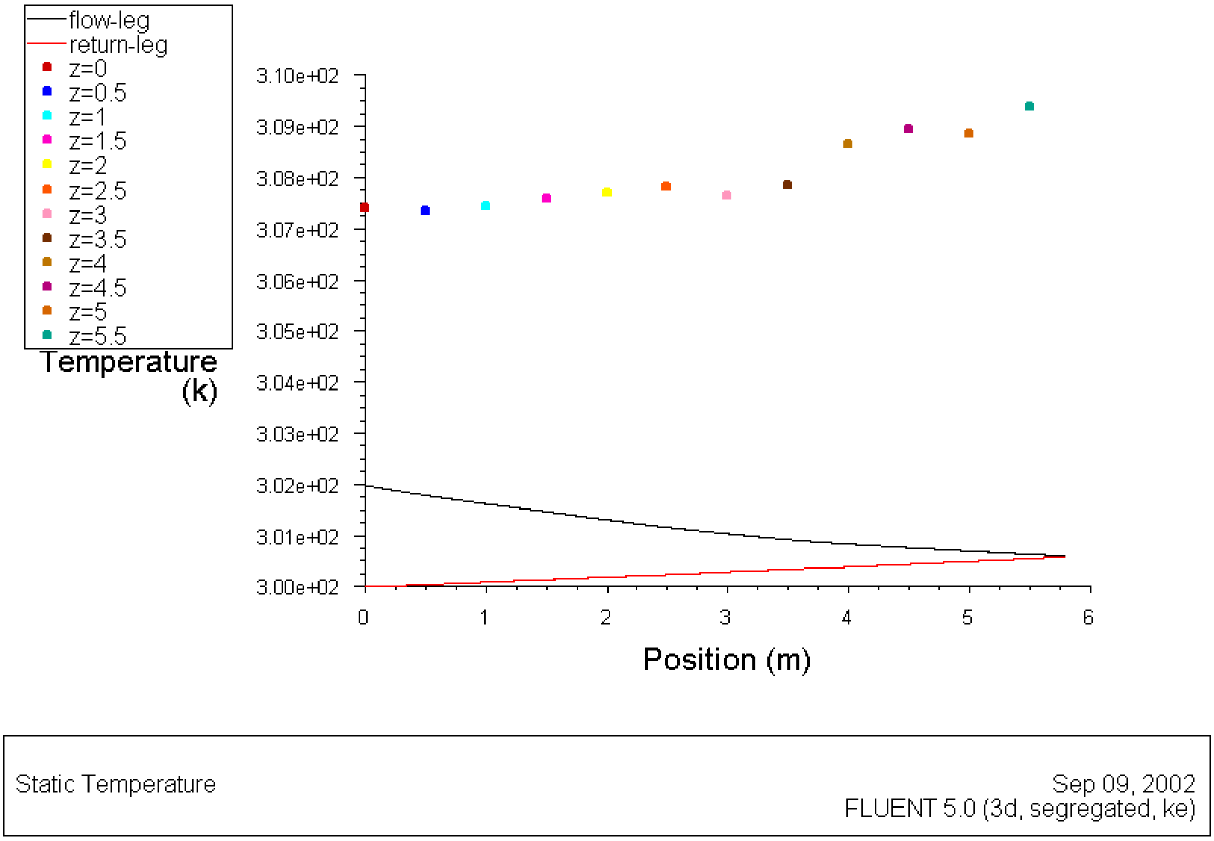

Fig 5.14 Temperature distribution for the well and finned type DHE (FLUENT)

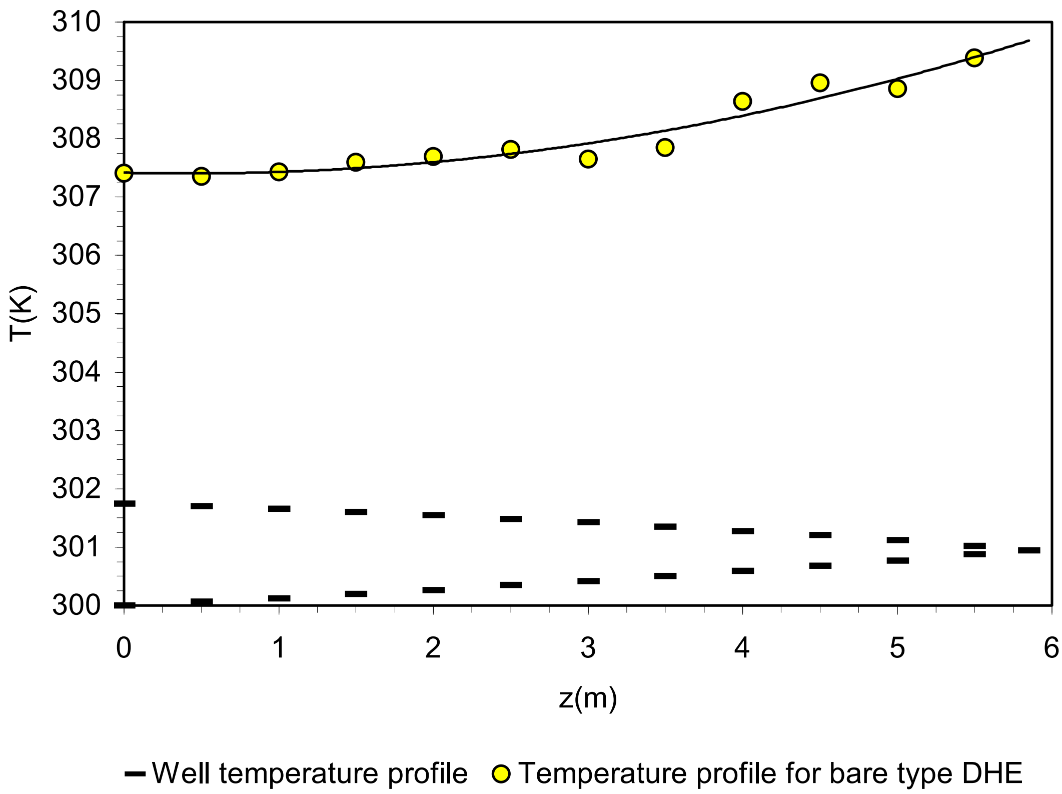

Fig 5.15 Temperature distribution for the well and finned type DHE (DHE Program)

5.2 PARAMETRIC STUDY

With the models proven a parametric study is undertaken for constant and polynomial well profiles and the effects of flow rate, flow temperature and DHE design are investigated. U tube results are presented first, finned type DHEs are presented later.

5.2.1 Polynomial Well Profile

Initially the parametric study for a DHE design is done for the experimental study that was made in New Zealand. Well temperature profile in the experimental study is assumed as a polynomial function and used as input for the DHE Program.

5.2.1.1 Varying the Parameters of Bare type DHE

The effect on DHE flow rate on the heat output is shown in figure 5.17. Flow rate varies from 0.2 kg/s to the maximum of 4 kg/s while the inlet temperature is held at 31°C. As seen from the figures 5.16 to 5.20, increasing the flow rate through the DHE increases the heat output, and also increases the pressure drop and exit temperature. Higher heat loads and temperatures can be obtained by using higher flow rates. For example, the heat output is 33.6 kW for 0.4kg/s DHE flow rate and 51°C outlet temperature, and 95.5 kW for 1 kg/s flow rate and 53.8°C outlet temperature.

If the inlet temperature of a 100-m length of DHE is known the exit temperature and heat output can be determined from figure 5.20 for a particular flow rate. As seen from the figure for 40°C inlet temperature and 4 kg/s flow rate, the outlet temperature is 65°C and heat output is 420 kW.

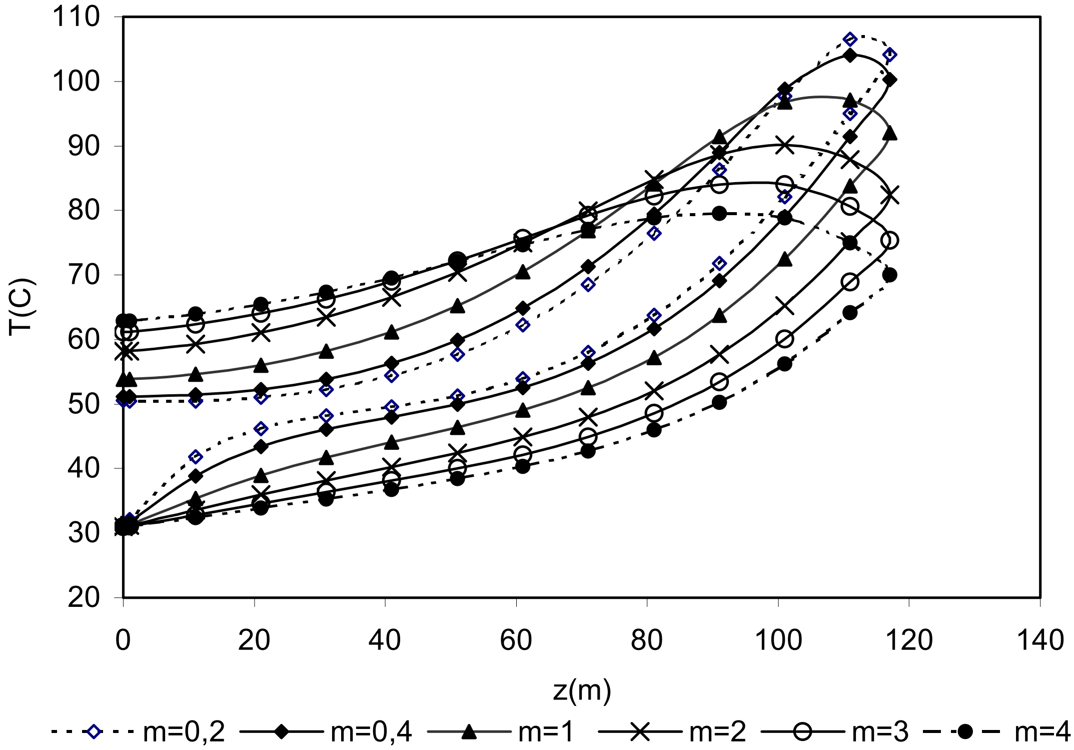

Fig 5.16 DHE internal temperatures for different flow rates

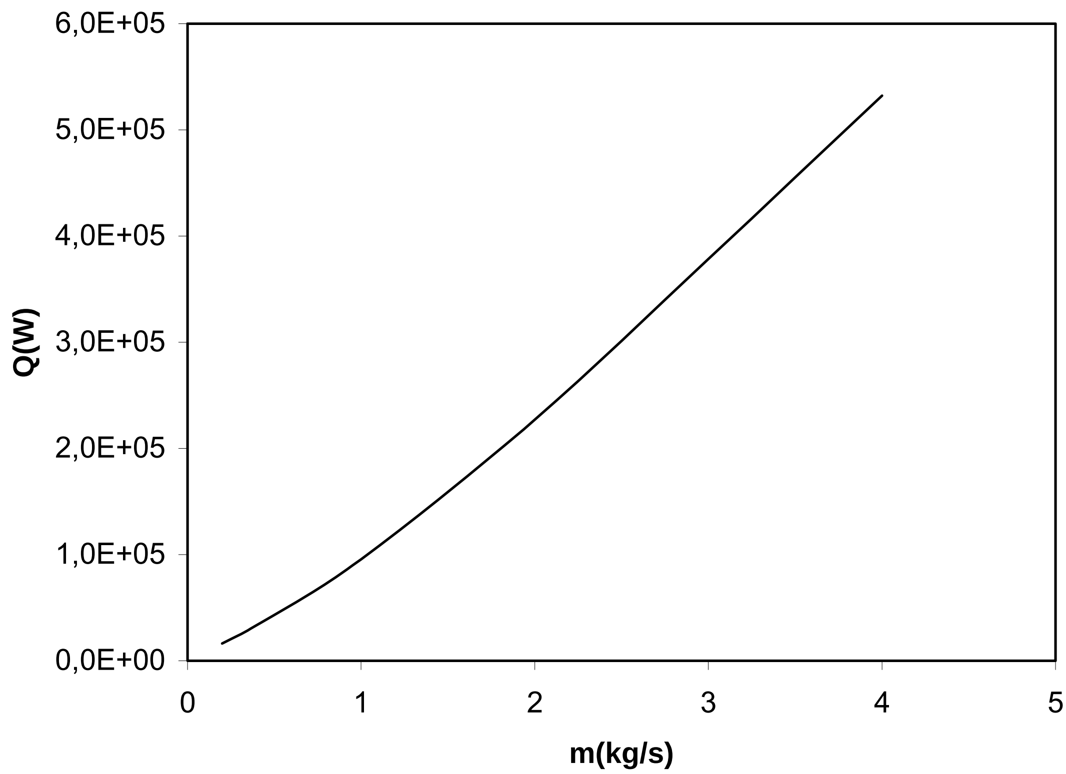

Fig 5.17 DHE heat output for different flow rates

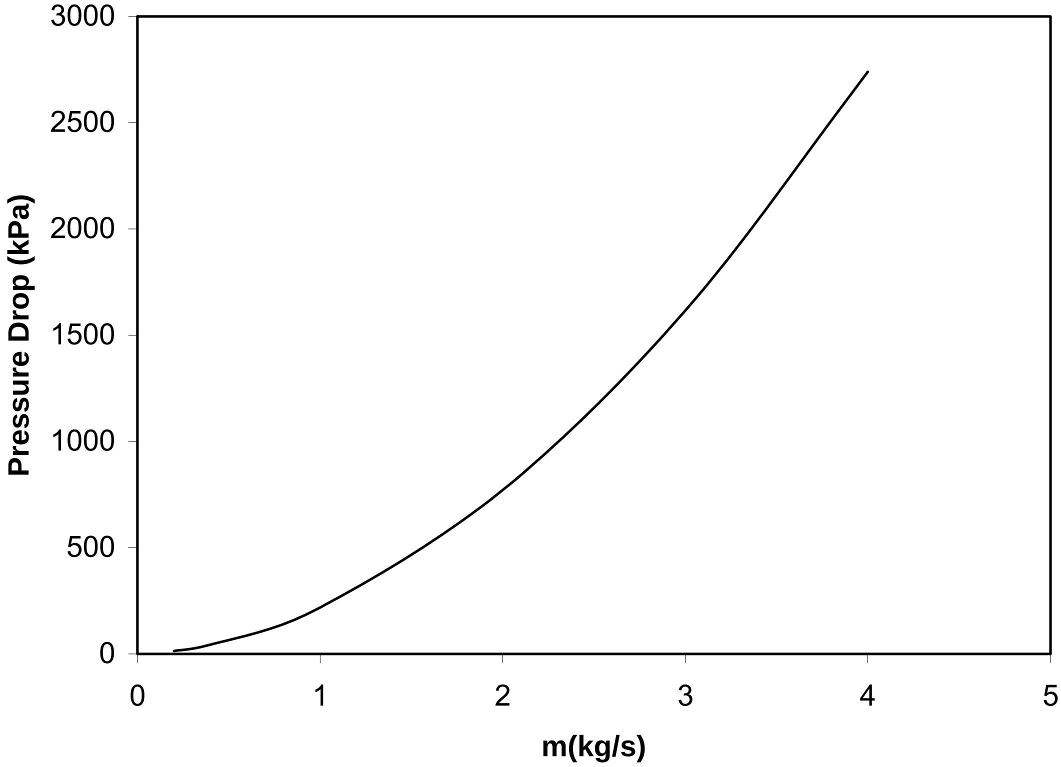

Fig 5.18 Pressure drop in the DHE

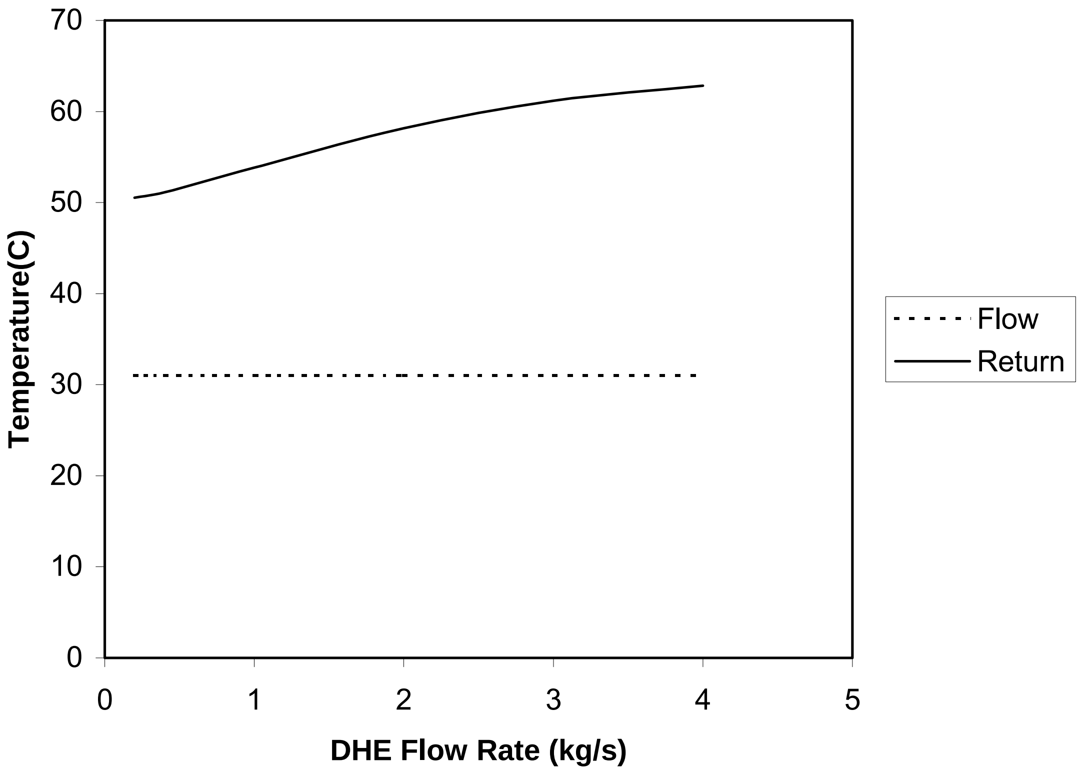

Fig 5.19 Flow/Return temperature vs. flow rate

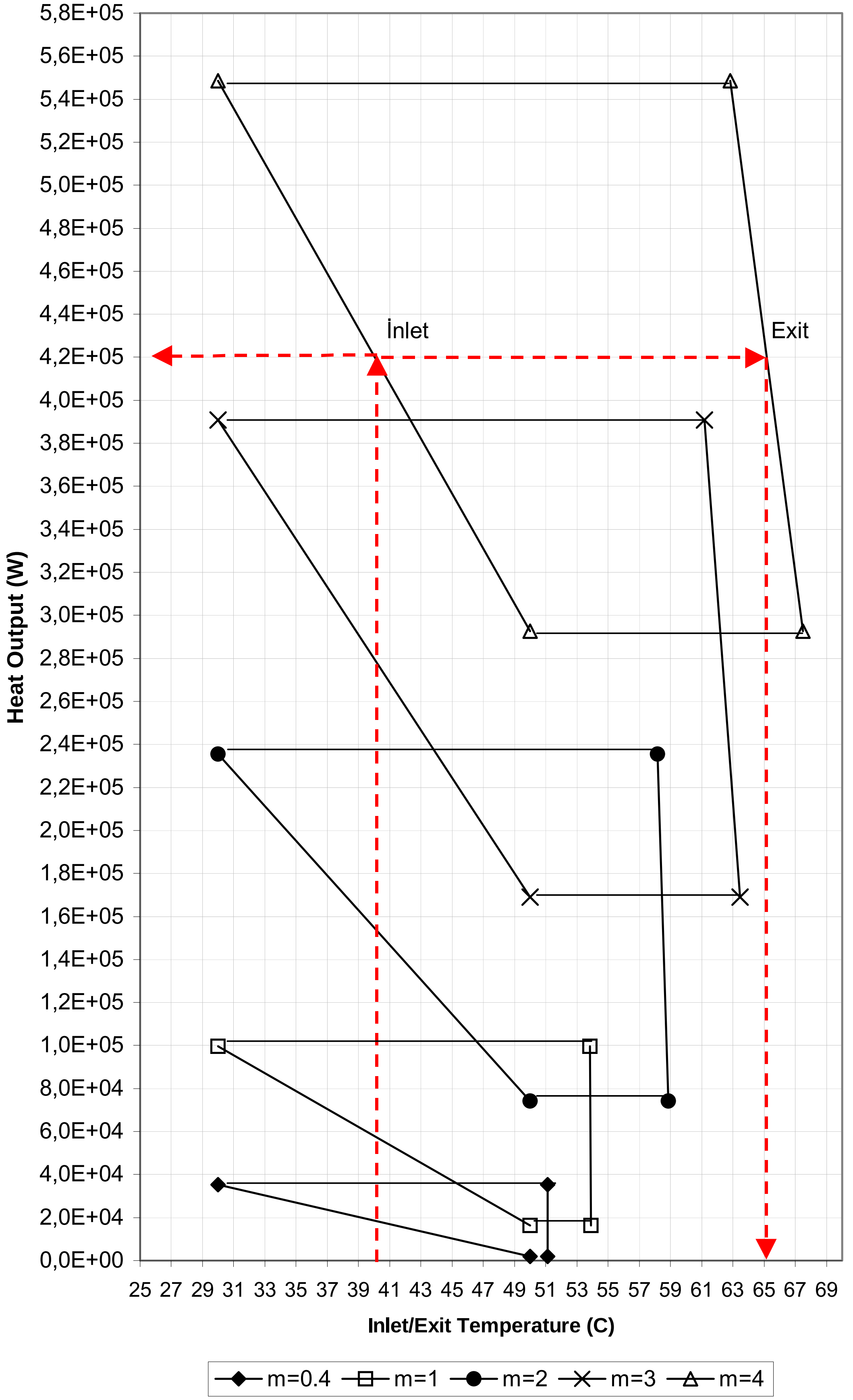

Fig 5.20 Heat output versus inlet/exit temperature

The results for differing flow rates and DHE length at 31°C inlet temperature showed that heat output with the low flow rate (0.4 kg/s) is about 33 kW, irrespective of DHE length. It is understood that much more heat output can be obtained for 234 m DHE length compared to 100m for high flow rates (Fig 5.21).

Figure 5.22 shows how DHE output varies for different pipe materials, for 1.2 kg/s flow rate and 31°C inlet temperature. Because the well fluid is hot at the bottom and cold at the top, increasing the thermal conductivity is not effective after a certain value. Using pipe material with low thermal conductivity is recommended and it is understood that the most effective pipe material is with 2-4 W/mK thermal conductivity. Figure 5.23 shows the DHE internal temperature profiles for different pipe materials.

As seen from the figures 5.16 and 5.23 the temperature of the DHE water increases towards the bottom and decreases towards the top of the well. If the pipe has high thermal conductivity the DHE water at the bottom reaches to 80-95°C and then the temperature decreases to 50-60°C at the exit, depending on the flow rate and pipe material. The water gets hottest at the bottom and gets coldest at the top. The cooling starts approximately at z=101 m at the return leg. This problem can be solved by using a pipe with high thermal conductivity at the flow leg and low thermal conductivity at the return leg between 0-101m (the cooling section). Figure 5.24 shows the results of this kind of pipe. The thermal conductivity of the pipe is 60 W/mK (steel) at the first part and 0.26W/mK (plastic) at the second part (pipe-B). Figure 5.24 also shows the results of pipe with 60 W/mK (pipe-A). When the water in the pipe reaches to 95.6°C at the return leg below the 101 m water level, the exit temperature is 54.74°C with pipe-A and 90.46°C with pipe-B with 179.5 kW energy saving (Table 5.1).

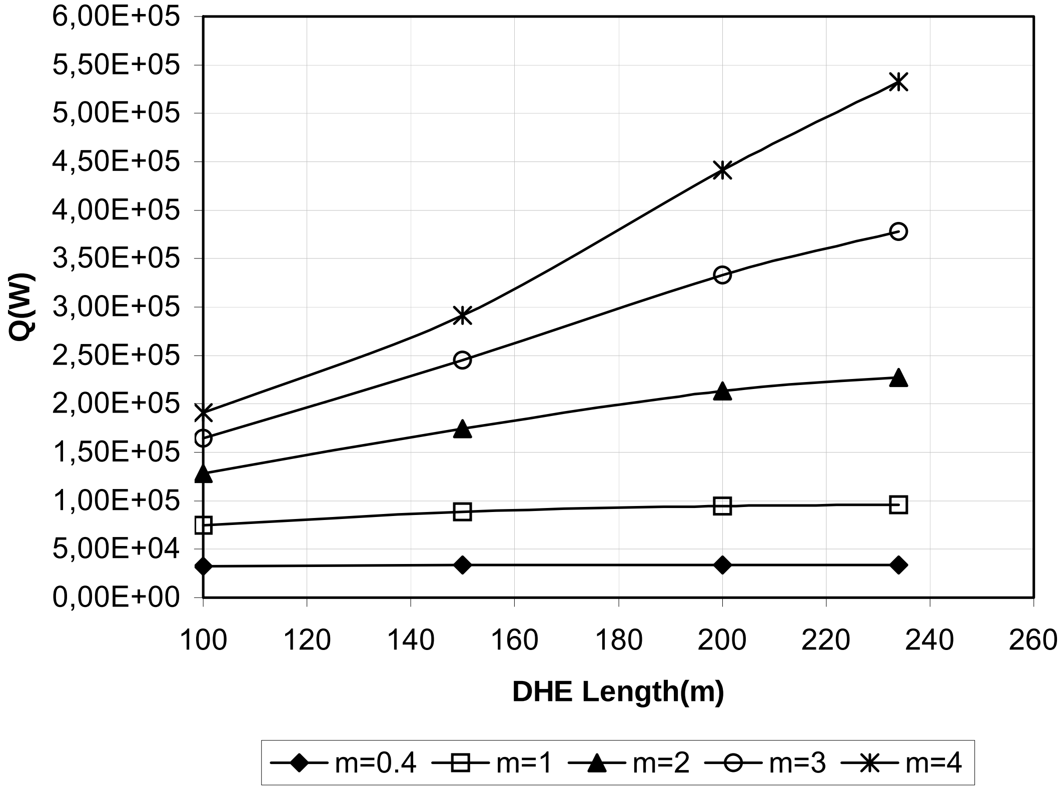

Fig 5.21 DHE heat output versus DHE length

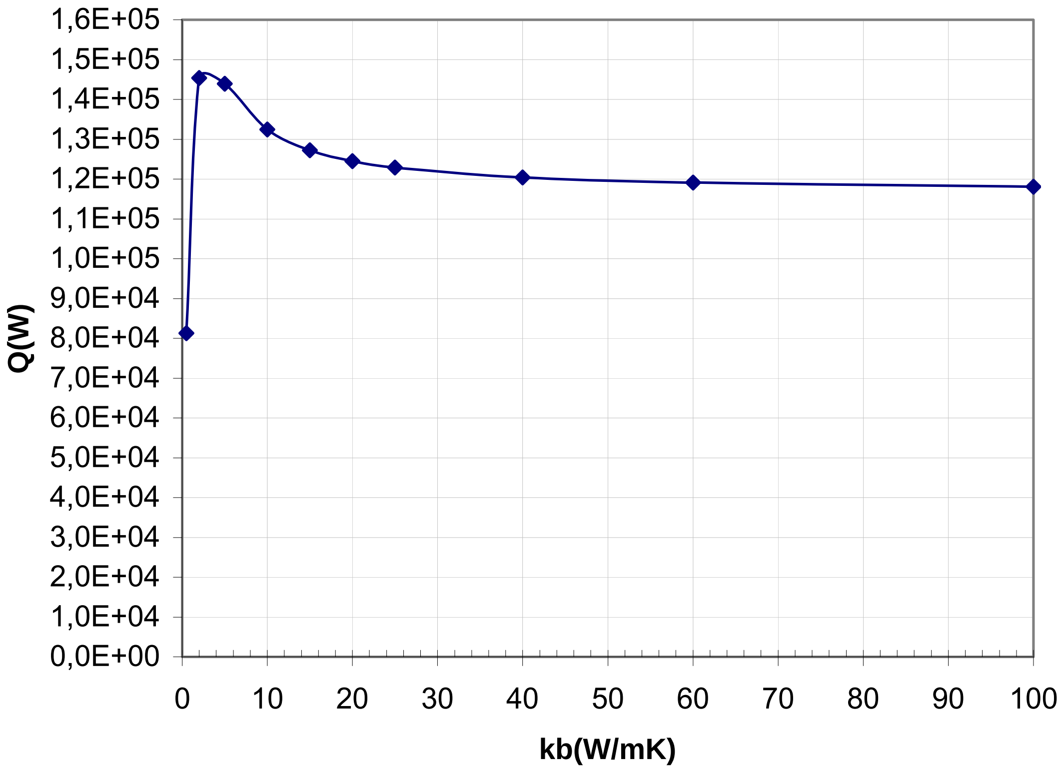

Fig 5.22 DHE heat output versus thermal conductivity of pipe material

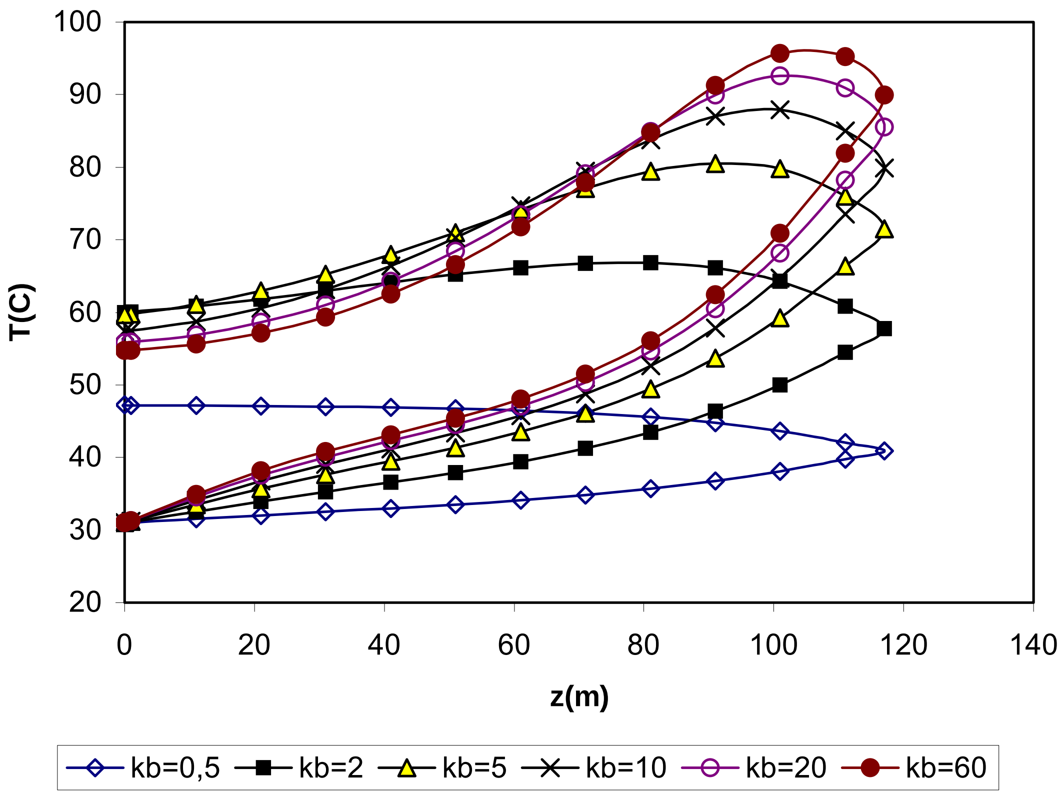

Fig 5.23 DHE internal temperature profiles for different pipe materials

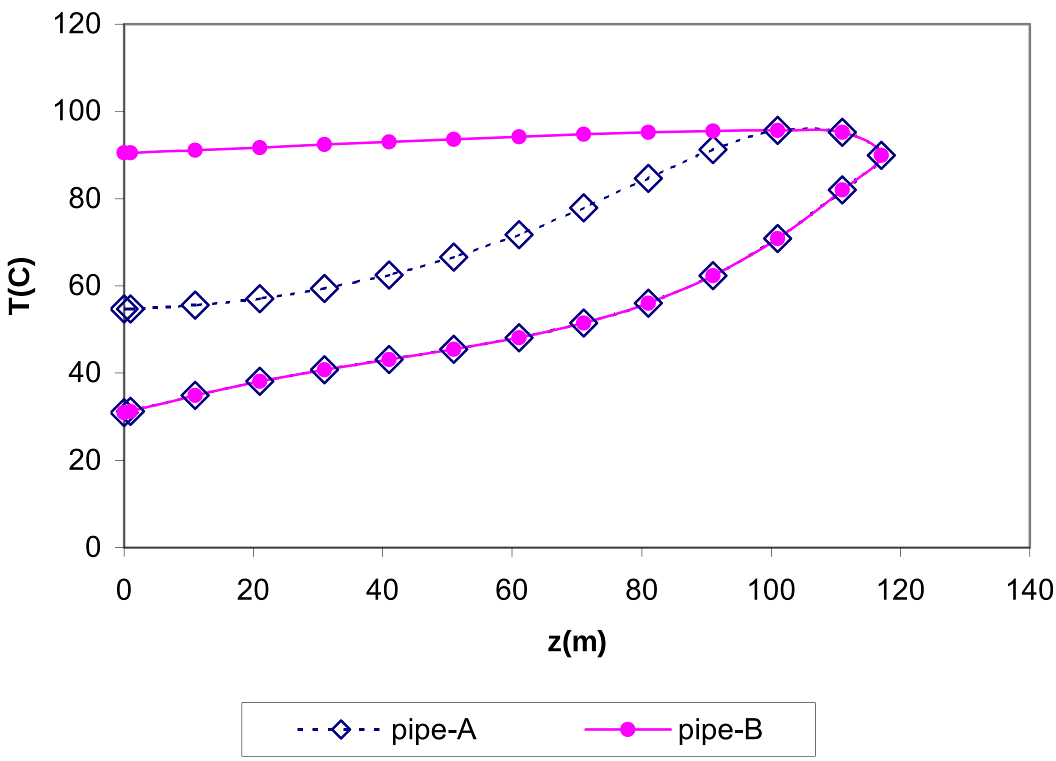

Fig 5.24 DHE internal temperature profiles for pipe-A and pipe-B

Condition	Flow Rate (kg/s)	Inlet (^oC)	Exit (^oC)	Heat Output (kW)
Pipe-A	1,2	31	54,74	119,101
Pipe-B	1,2	31	90,46	298,649

Table 5.1 Heat Output for Pipe-A and Pipe-B

5.2.1.2 Varying the Parameters of Finned type DHE

The effects of fin parameters such as fin length and fin thickness are investigated. As seen from the figures 5.25 and 5.26 internal temperature profiles of the finned DHEs are higher at the bottom and lower at the top of the well. Although adding fins increased the maximum temperature in the pipe, it also decreased the exit temperature and heat output (Fig 5.27). Figures 5.28-5.30 show the heat output and internal temperature profiles of the finned DHEs with various fin lengths. As the fin length increases exit temperature and heat output decreases.

The maximum internal temperature is observed at the return leg, at z=101 m. This temperature is 90°C for bare type DHE and 93°C for finned type DHE. However the exit temperature is 58°C for bare type and 56°C for finned type DHE for 2 kg/s flow rate. The conductive pipe material at the return leg decreases the water temperature, this problem can be solved by using a plastic pipe at the return leg. Figure 5.31 shows the DHE internal temperature profiles with plastic pipe at the return leg, the exit temperature is 87.4°C for bare pipe and 90°C for finned pipe. The DHE with plastic pipe at the return leg produced significantly higher output than the steel pipe. **The presence of plastic pipe at the return leg improved the heat output of the DHE by % 207 for bare type DHE and % 217 for finned type DHE.**

m=2 kg/s , S+B=10 mm

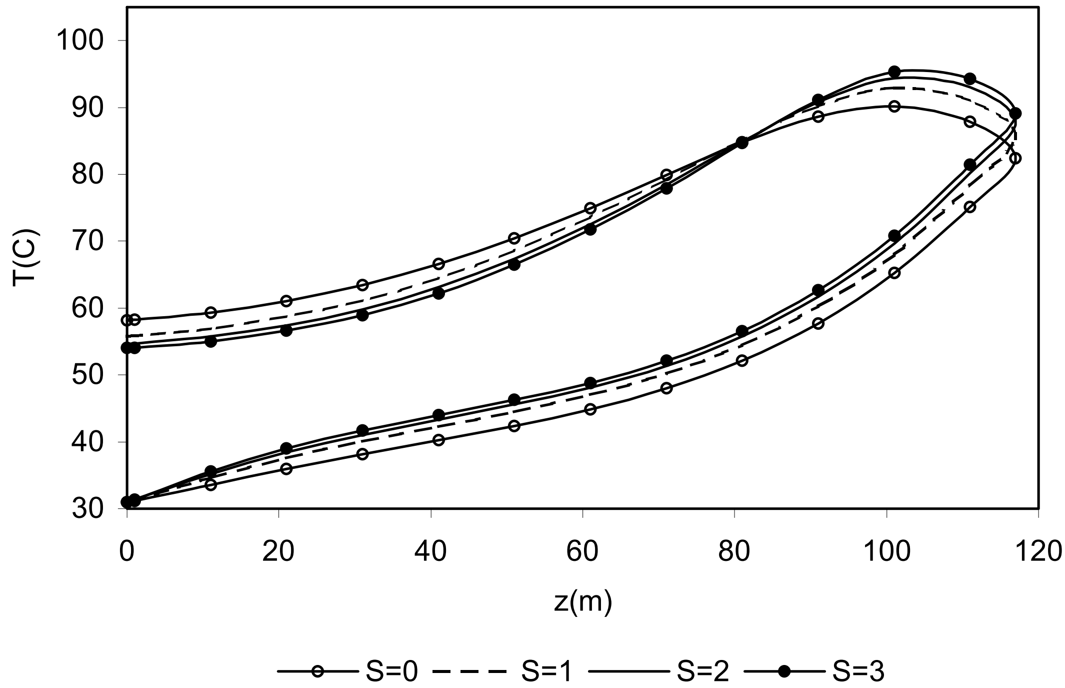

Fig 5.25 DHE internal temperature profiles for differing fin thickness (S+B=10 mm)

m=2 kg/s , S+B=20 mm

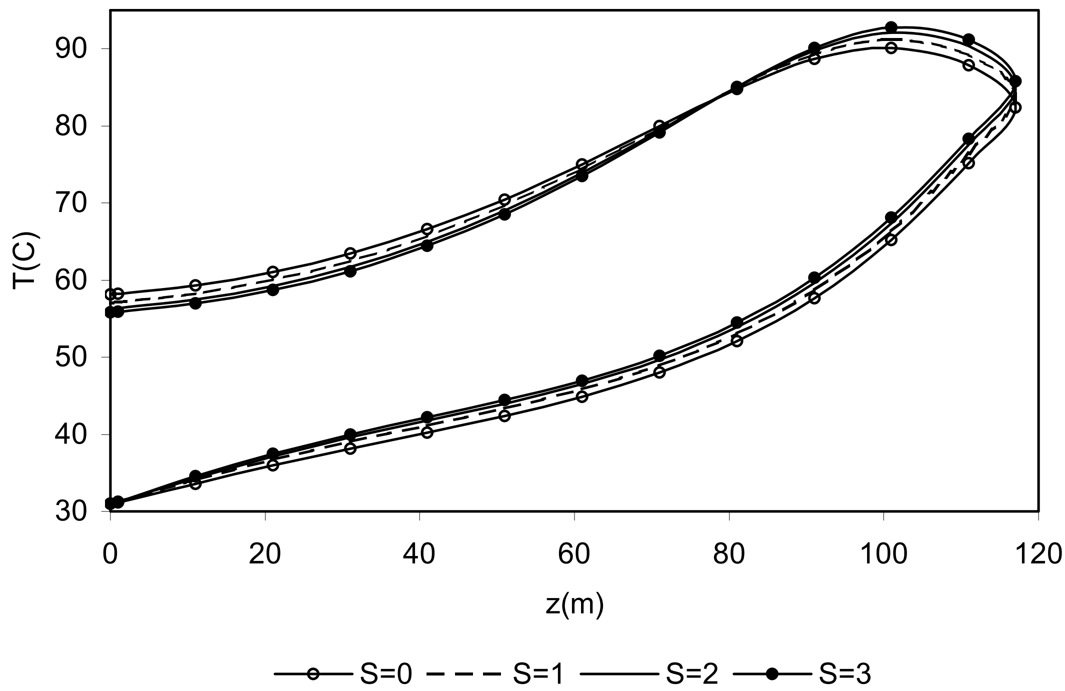

Fig 5.26 DHE internal temperature profiles for differing fin thickness (S+B=20 mm)

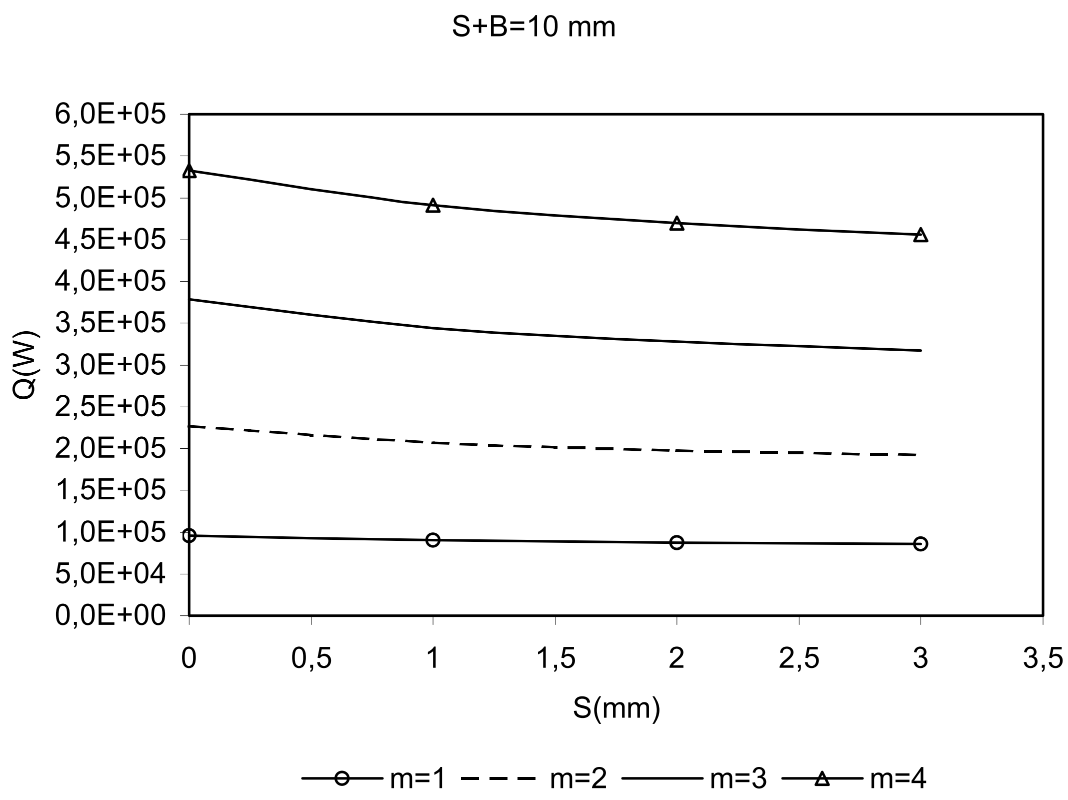

Fig 5.27 Heat output versus fin thickness

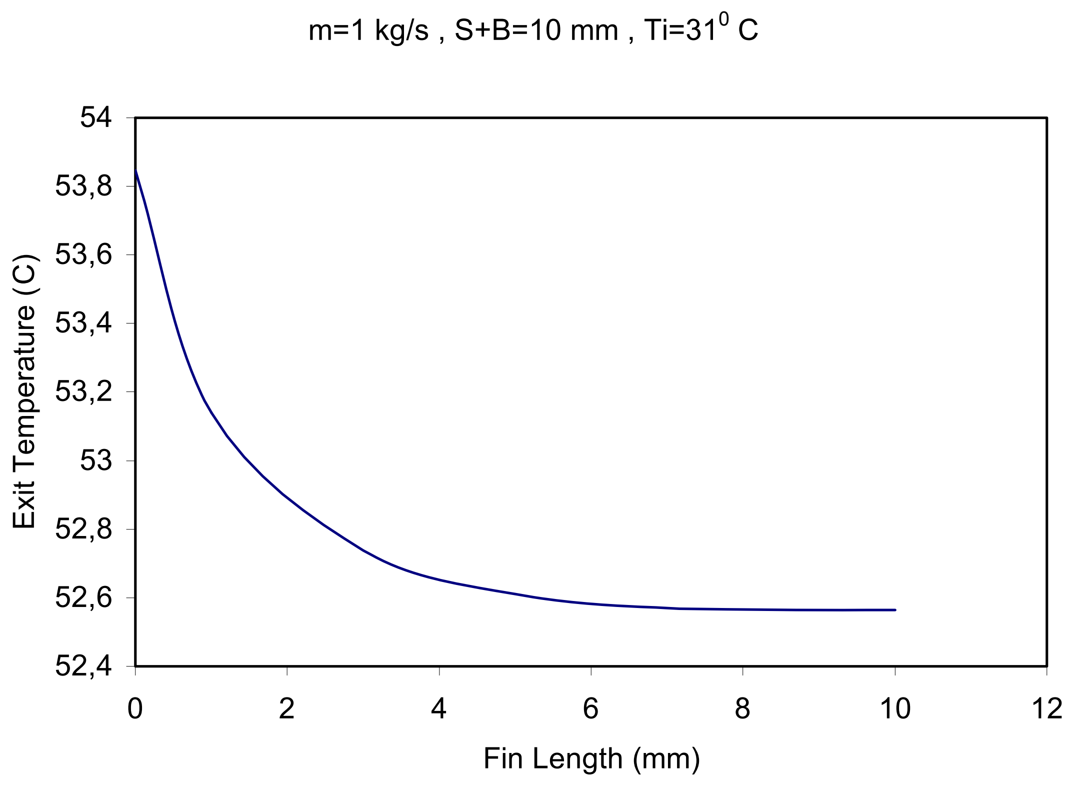

Fig 5.28 DHE exit temperature versus fin length

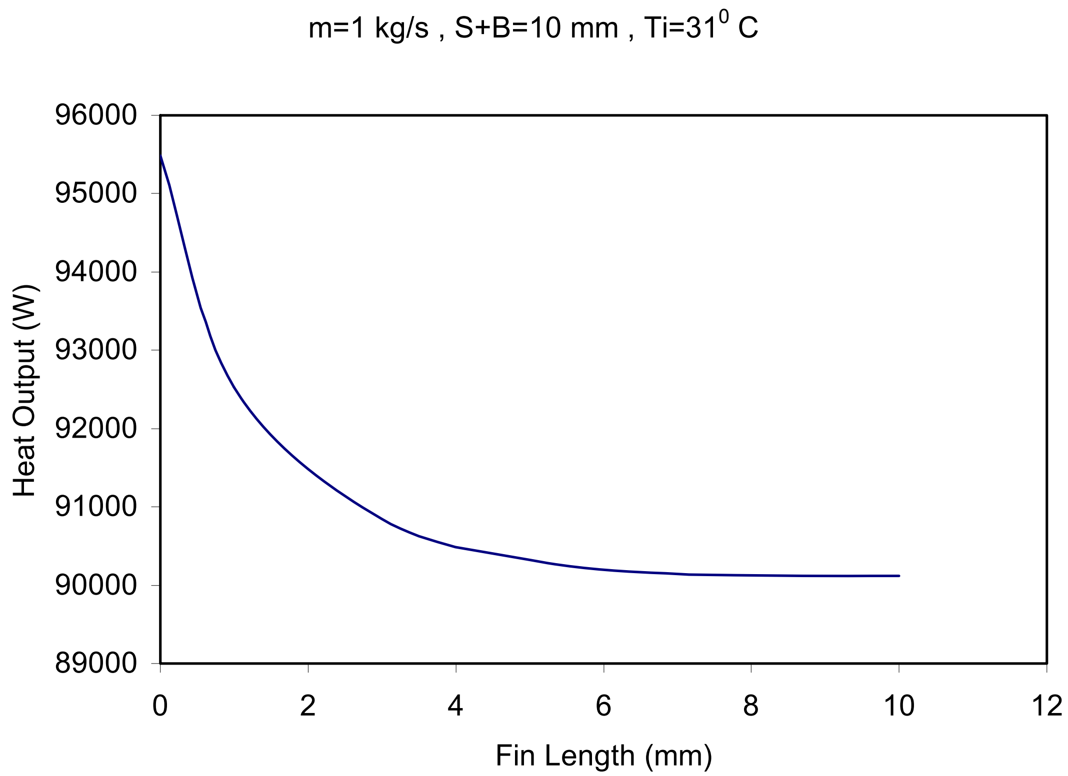

Fig 5.29 Heat output versus fin length

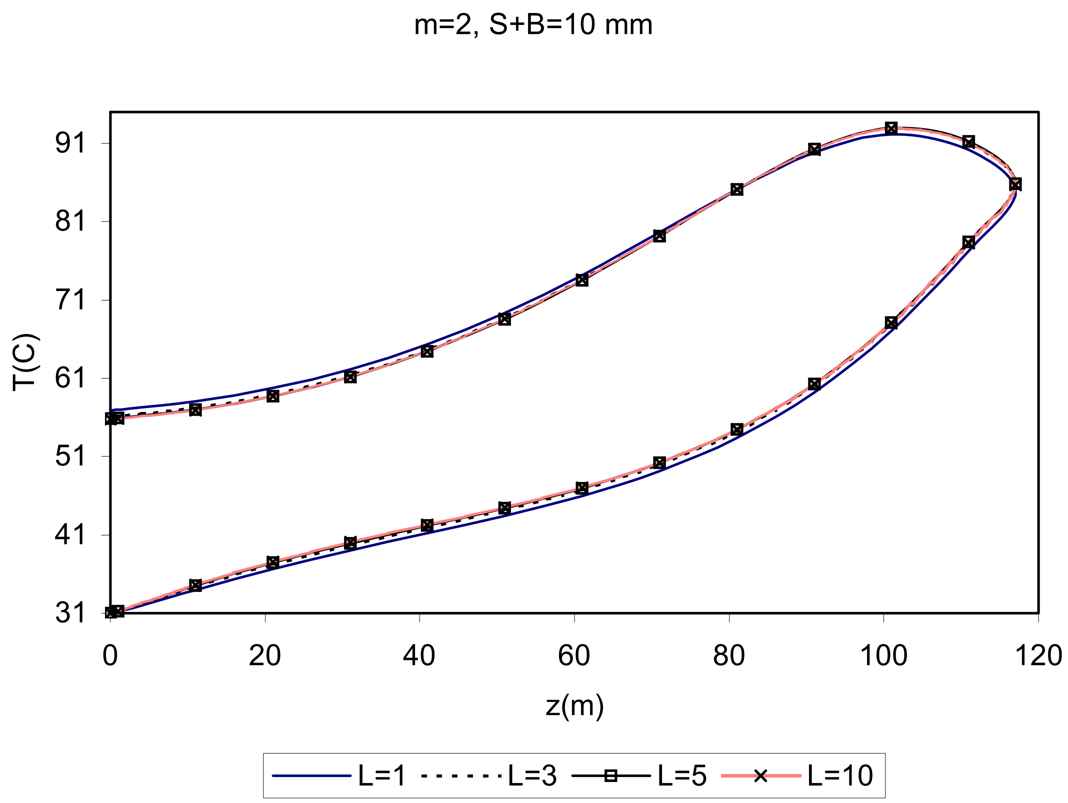

Fig 5.30 DHE internal temperature profiles for differing fin length (S+B=10 mm)

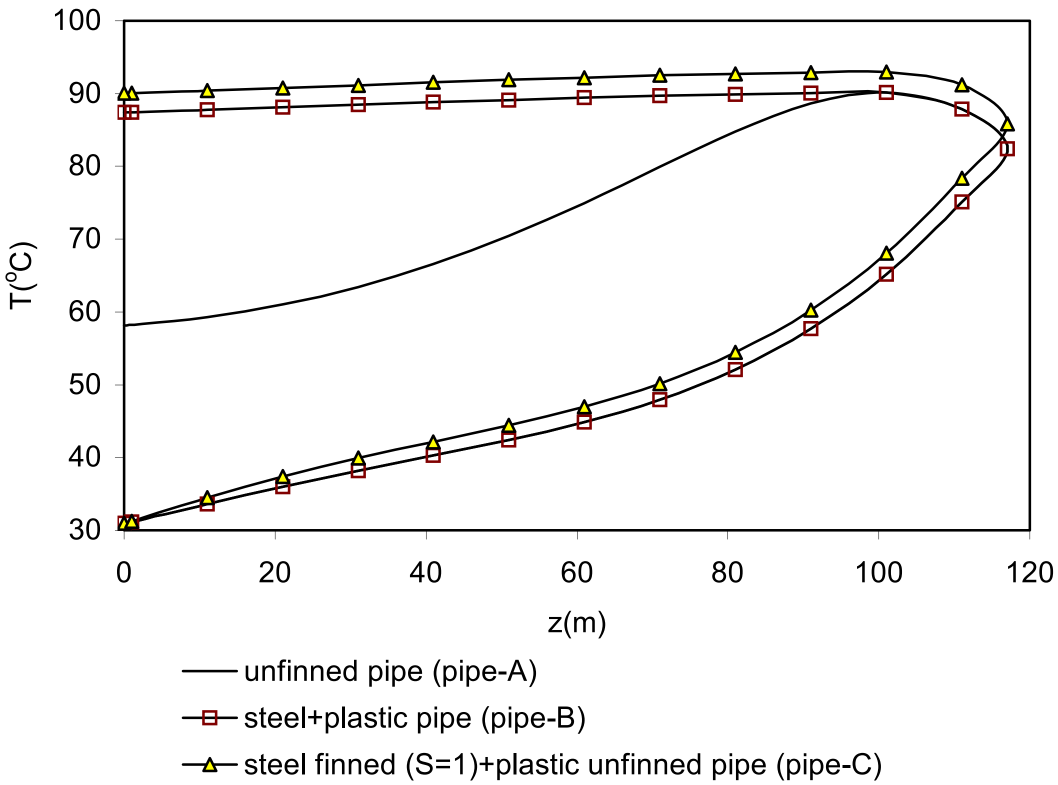

Fig 5.31 DHE internal temperature profiles for different pipe types

5.2.2 Constant Well Profile

After the parametric study performed for the well temperature profile in the experimental study, which is polynomial, also the parametric study for constant well temperature is performed and, the results are represented below.

5.2.2.1 Varying the Parameters of Bare type DHE

Flow rates are varied for a large range up to 5 kg/s. Three inlet temperatures 30,50,70°C and two DHE length 100 m and 300 m are considered. DHE outside diameter and wall thickness are held at 60 and 4 mm, respectively, which are the most frequently used pipe dimensions in DHE applications.

Figure 5.32 shows DHE output varies with flow rate. For comparison the DHE length is taken for two different values 100m and 300m. Average reservoir temperature is assumed as 90°C and thermal conductivity of pipe is taken as 56 W/mK. The results showed that DHE output increases with the increasing flow rate. DHE exit temperatures for these corresponding situations are shown in figure 5.33. Exit temperature is high when the flow velocity is low. In order to see the effects of pipe materials, all the other parameters are assumed constant and heat output of the DHE is calculated for different thermal conductivities of pipe materials (Figure 5.34). Figure 5.34 is for a DHE with 100-m length and 30°C inlet temperature and 90°C reservoir temperature. Because of constant reservoir temperature assumption, heat output increases with the increasing thermal conductivity of pipe materials. As seen from the figure heat output does not change effectively from a certain value of thermal conductivity of pipe material (20W/mK).

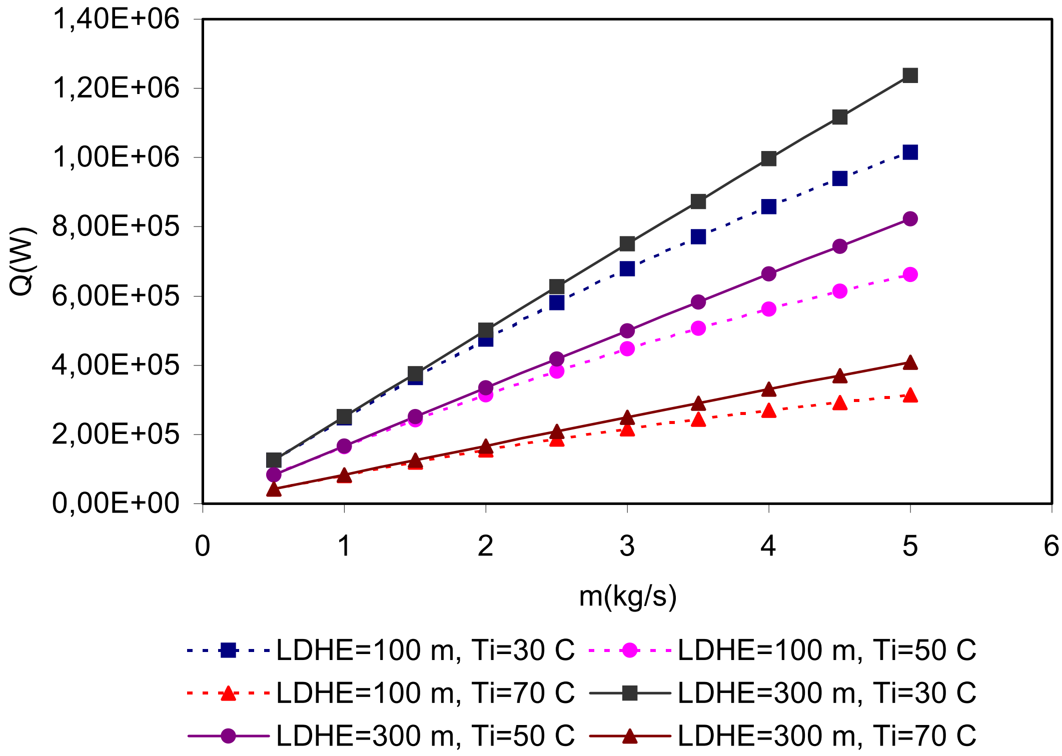

Fig 5.32 DHE heat output versus flow rate for bare type DHE for constant well profile

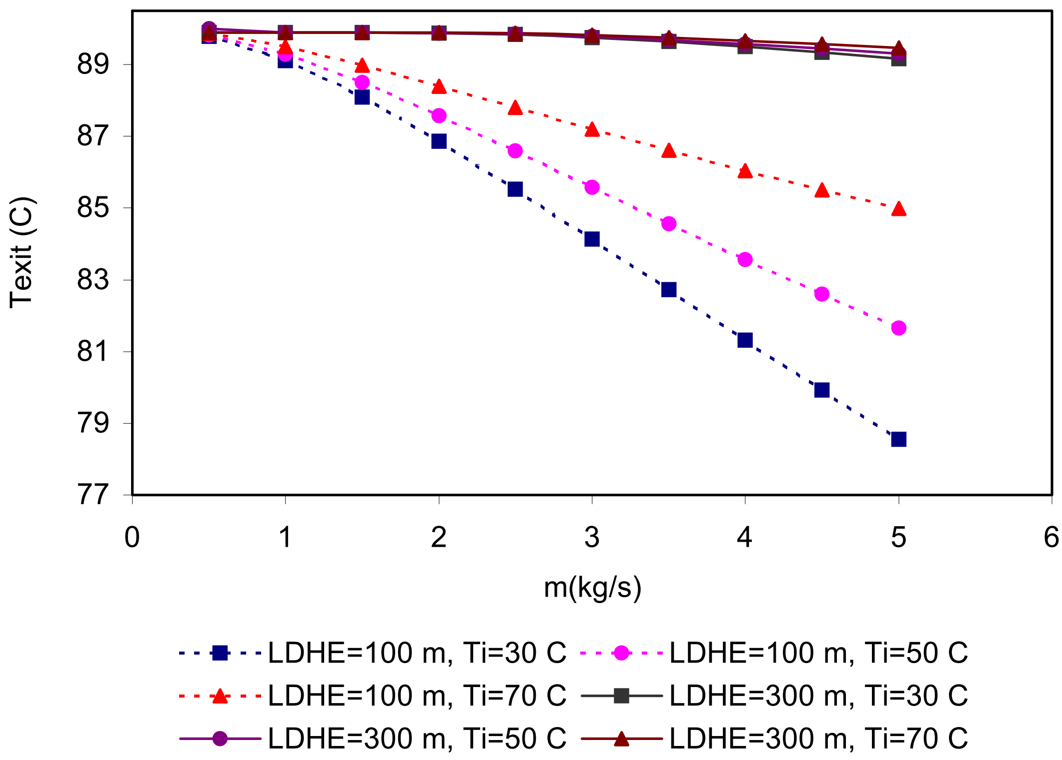

Fig 5.33 DHE exit temperature versus flow rate for constant well profile

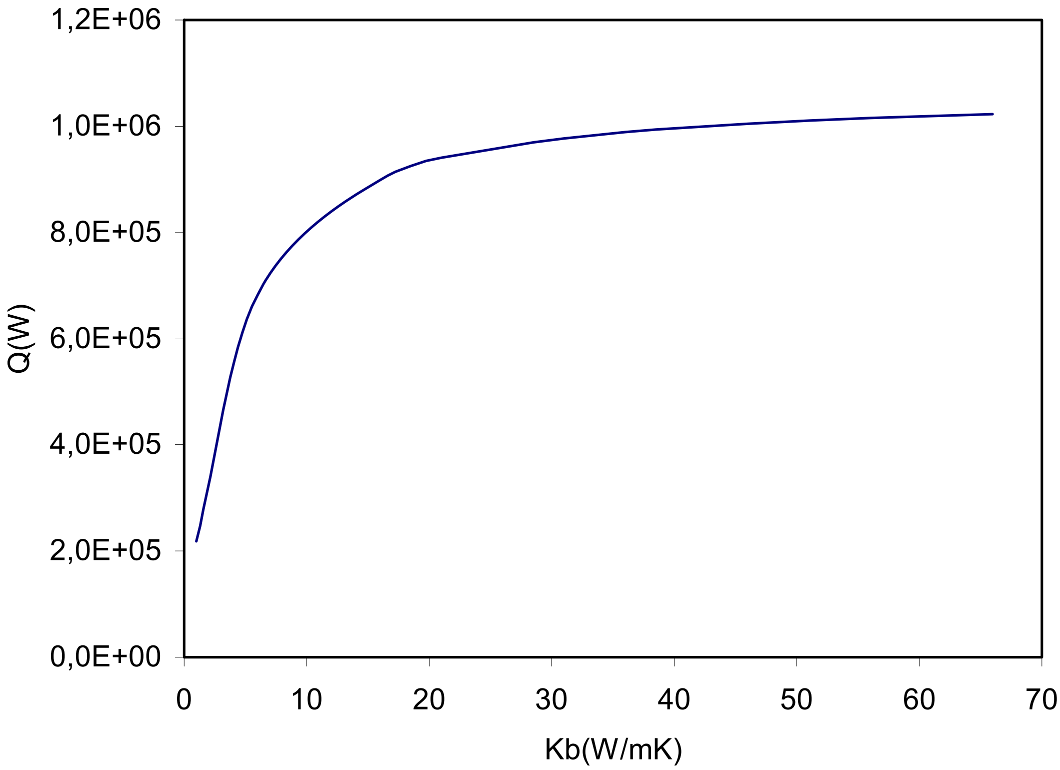

Fig 5.34 DHE heat output versus thermal conductivity of pipe material for constant well profile

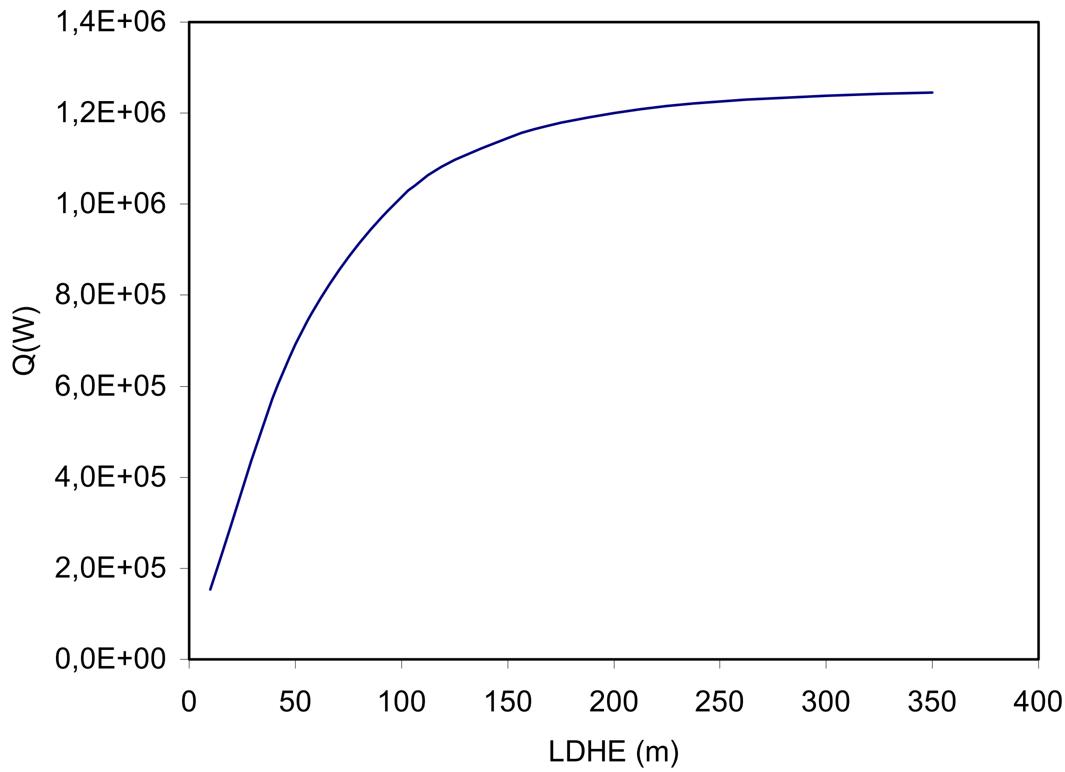

Fig 5.35 DHE heat output versus DHE length for constant well profile

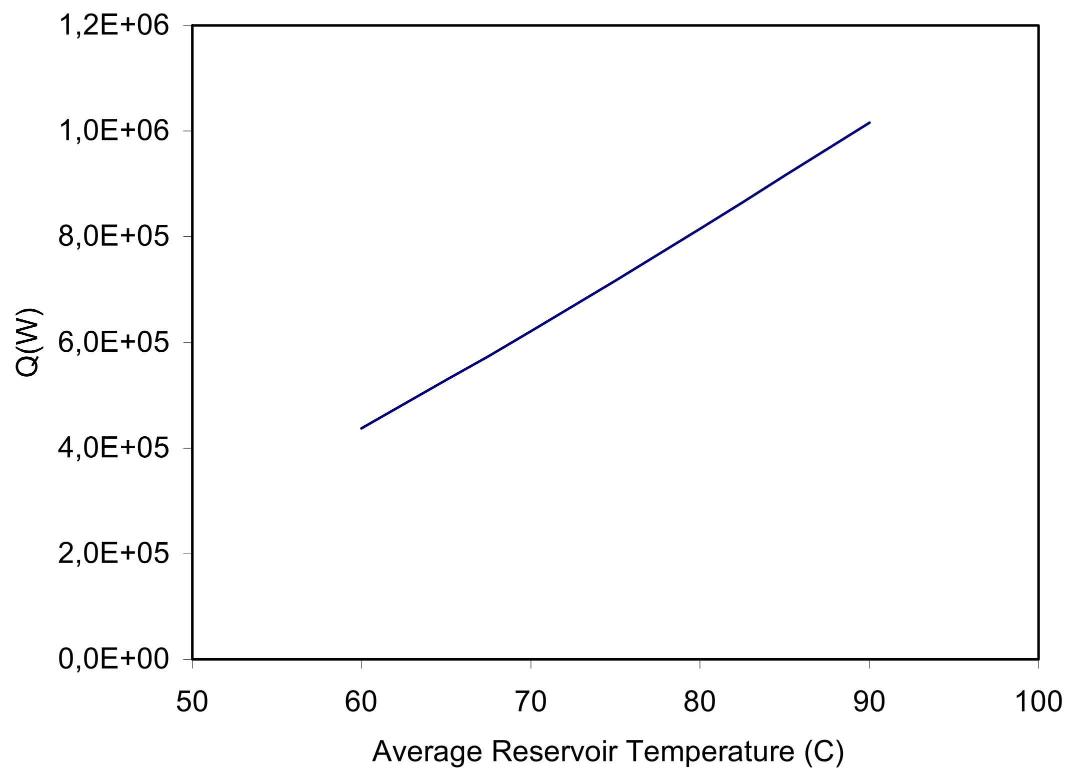

Fig 5.36 DHE heat output versus average reservoir temperature for constant well profile

Figure 5.35 and 5.36 give the effects of DHE length and reservoir temperature on the heat output. It is obvious that heat output increases with increasing temperature. The effects of DHE length on heat output are given in figure 5.35 for 90°C average reservoir temperature, 5 kg/s flow rate and 30°C DHE inlet temperature. There are limitations to the maximum heat flow transferred, so as the DHE length increases heat output increases up to a certain value. The effects of reservoir temperature on heat output are given in figure 5.36 for 100 m DHE length, 5 kg/s flow rate and 30°C DHE inlet temperature. It is clearly seen that heat output increases with increasing reservoir temperature. In both of the analyses the thermal conductivity of pipe material is taken as 56 W/mK.

5.2.2.2 Varying the Parameters of Finned type DHE

In the present study, the materials of tube and fin are chosen to be mild steel with thermal conductivity of 56 W/mK. The other parameters are;

DHE inlet temperature: 30°C

Average aquifer temperature: 90°C

DHE outlet diameter: 60mm

DHE wall thickness: 4mm

DHE flow rate. 5 kg/s

The dependence of heat removal on fin length is given in figure 5.37 at a fixed fin thickness (1mm) and spacing between the fins (5mm) for a DHE with a length of 100 m. The exit temperature increases significantly with the increasing fin length up to a certain value which is about 4 mm. As seen from the results it is not necessary to use fins more than 4 mm. length.

The effects of fin spacing and fin thickness are also need to be considered. For this reason, by keeping the fin thickness and fin length constant as 1 mm. and 5 mm. respectively, the effects of fin spacing are investigated. The results show that, as increase in fin spacing, a lower heat transfer rate is obtained (Fig 5.38). Also by keeping the fin length and fin spacing constant as 5 mm, the effects of fin thickness on heat output are investigated. As the fin thickness increases heat transfer rate increases and approaches a limit value because fin spacing is assumed constant and as the fin thickness increases, fin pitch increases and number of fins decreases (Fig 5.39).

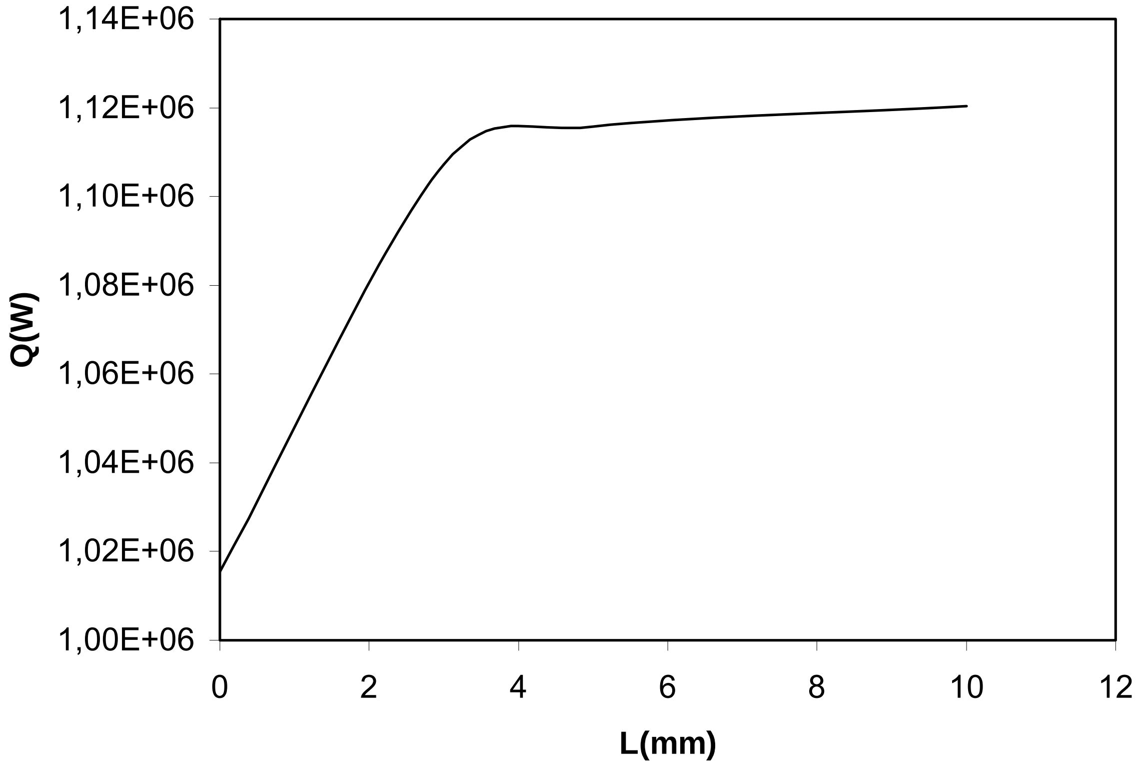

Fig 5.37 DHE heat output versus fin length for constant well profile

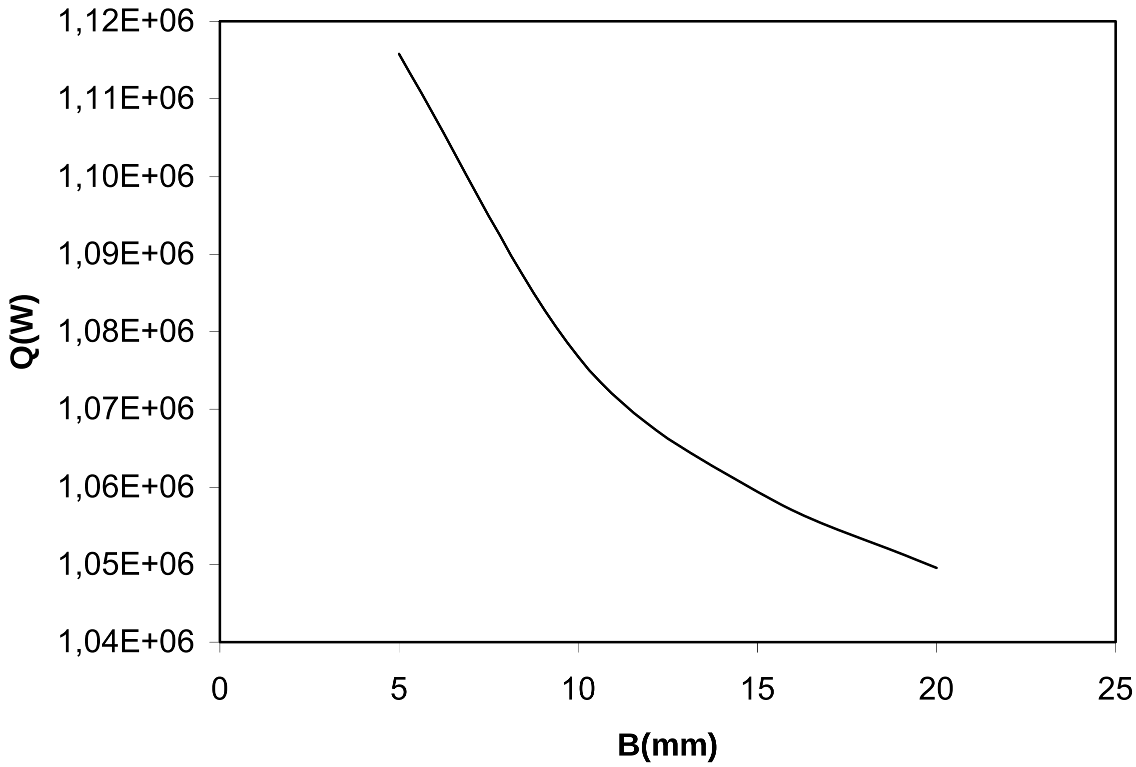

Fig 5.38 DHE heat output versus fin spacing for constant well profile

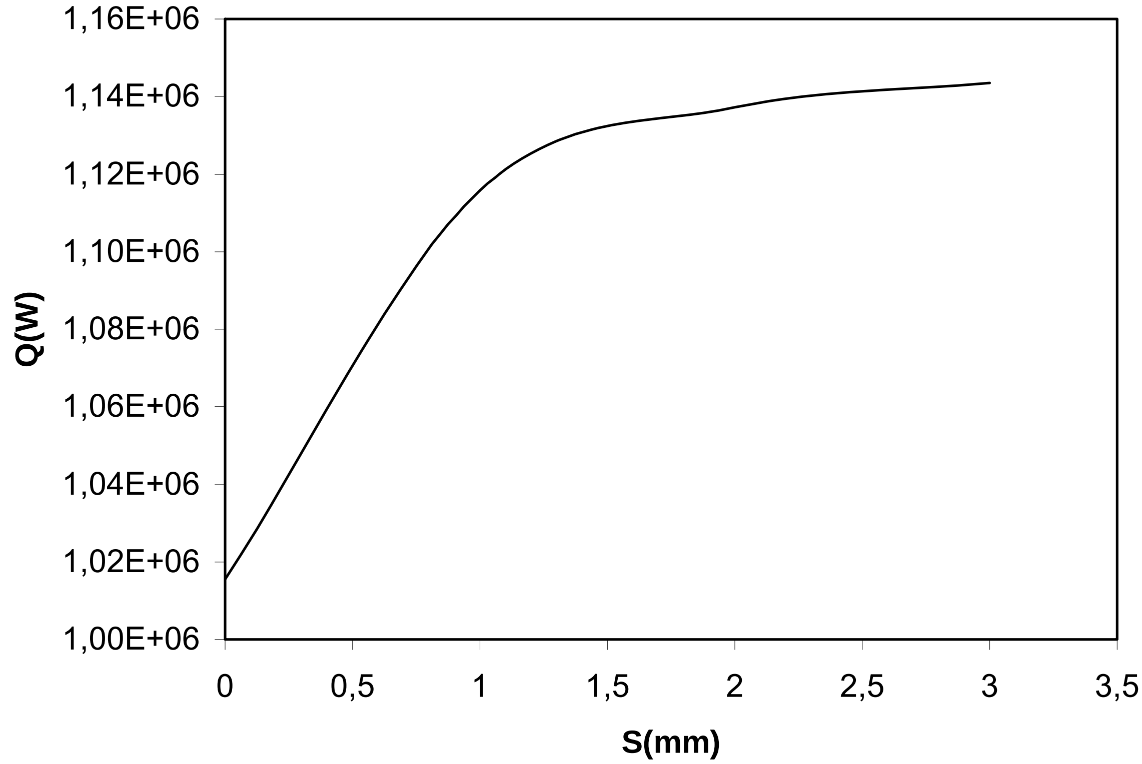

Fig 5.39 DHE heat output versus fin thickness for constant well profile

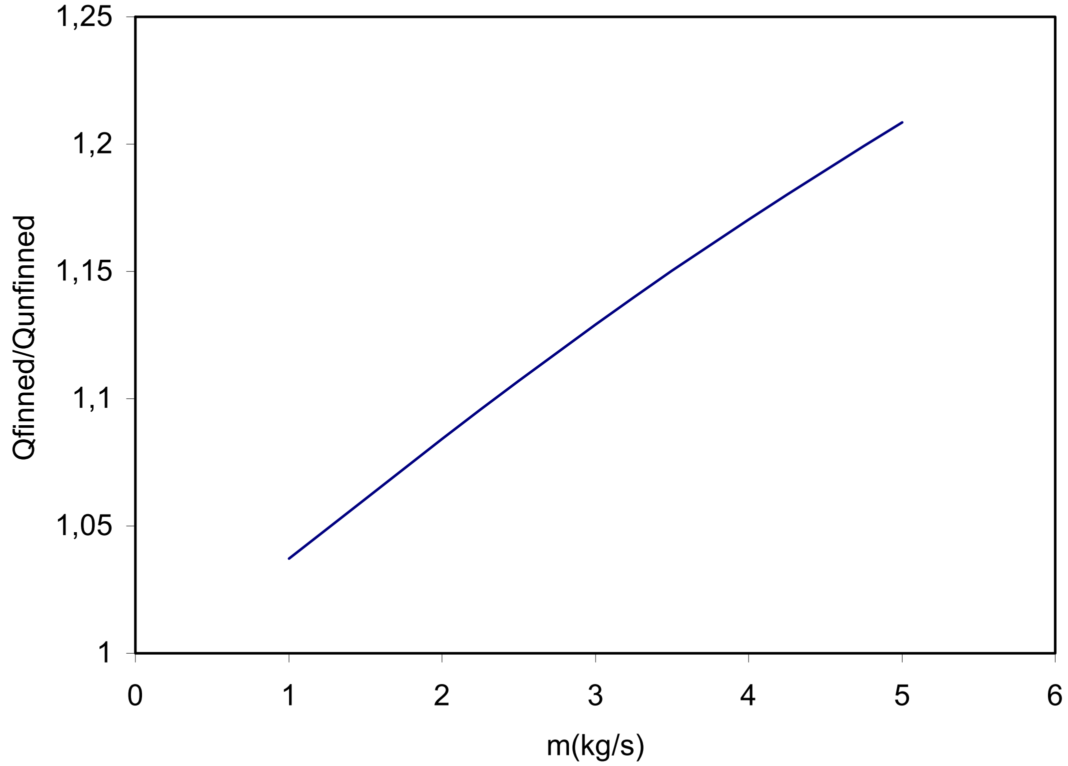

Fig 5.40 Effectiveness of finned DHE versus flow rate for constant well profile

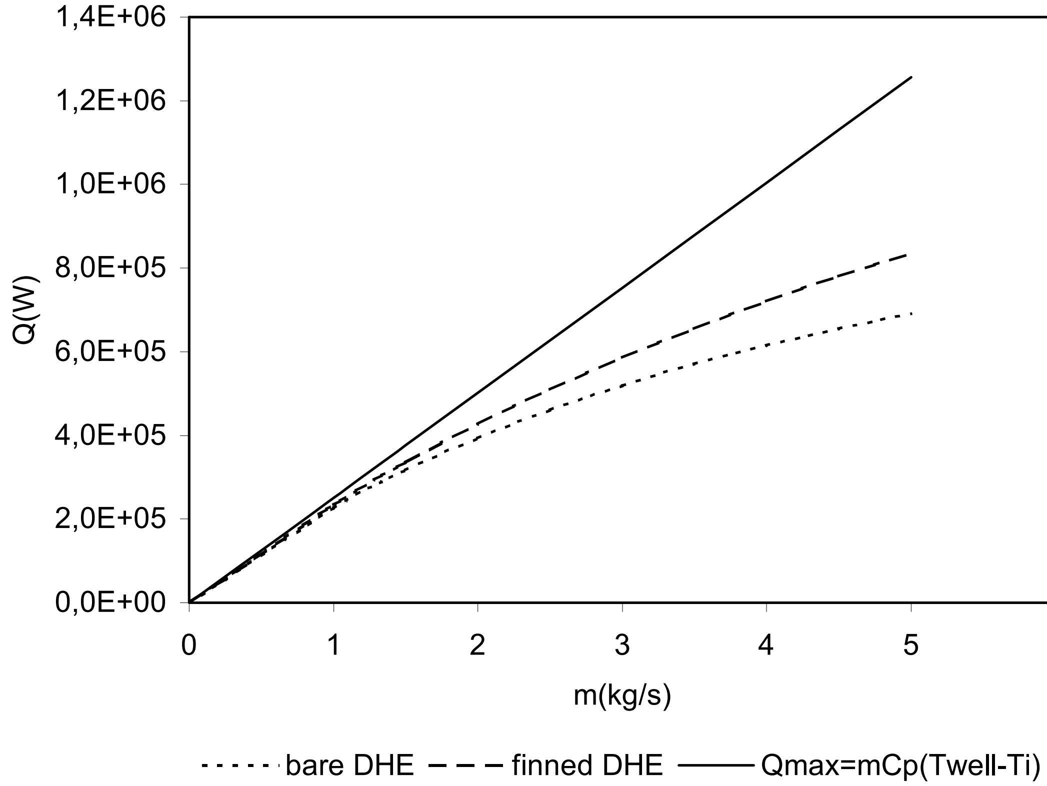

Fig 5.41 Heat output versus flow rate for constant well profile

At a fixed fin spacing (5mm), fin length (5mm) and fin thickness (1mm), effectiveness of finned pipe (ε_f) for different flow rates are given in figure 5.40. Because of constant well temperature assumption, up to 20 % increment of heat output can be obtained for a DHE with a length of 50 m.

$$\varepsilon_f = \frac{Q_{finned}}{Q_{unfinned}} \tag{5.1}$$

Figure 5.41 represents the heat transfer rate of bare and finned type DHEs versus flow rate of water through the DHE pipe. In this figure, Qmax is the maximum heat transfer rate, which can be extracted from the well. It is understood that, 67 % of the Qmax can be obtained with finned type DHE whereas 55 % of Qmax is obtained with bare type DHE for a length of 50 m DHE with 5 kg/s of flow rate.

CHAPTER 6

CONCLUSIONS

In this study, finned and bare types DHEs are analyzed for different situations by utilizing numerical methods. The analyses are performed by DHE program written in BASIC language. In order to check the accuracy of the program, output of the program for bare type DHE were compared with the experimental data from another study performed in New Zealand. This comparison showed that the numerical and experimental results are in agreement. In addition, to understand if the results of the program for finned type DHE are correct, another program, FLUENT software is also used. Because of the difficulties about the modeling well&DHE and meshing the model, 6 m. depth of well is modelled and simulated with FLUENT. It is seen that the results of the DHE program are also in good agreement with FLUENT.

The analyses indicate that the effectiveness of the finned pipe depends on the well temperature profile, If the well temperature distribution through the well is nearly constant with depth, up to 20 % increment of heat output can be obtained. However, If the temperature gradient through the well is quite large, using finned DHE may cause the heat extraction rate to decrease. In addition, higher heat extraction rate can be obtained by using pipes with high thermal conductivity for constant temperature profile through the well, whereas for wells with high temperature gradient, the use of pipes with high thermal conductivity leads to a decrease in heat output. Therefore, for wells with high temperature gradient, plastic pipe can be used at the return leg of the DHE. Figure 5.16 shows that significantly higher output is obtained with this arrangement. **The presence of plastic pipe at the return leg improved the heat output of the DHE by % 207 for bare type DHE and % 217 for finned type DHE.**

The analyses indicate that for the case of constant well temperature profile, heat extraction rate can be increased depending on the fin parameters and flow rate. Heat output increases with the increasing fin length and thickness, but there is a limit on heat extraction rate of finned type DHE for a definite fin length and thickness.

Another conclusion understood from the results, increasing flow rate through the heat exchanger increases the energy extraction rate, but also increases pressure drop and decreases exit temperature, which is not preferred situation for the heating applications. Increased pressure drop will require larger circulation pump and lowered exit temperature will affect process design.

As a conclusion, using finned type DHE can provide higher heat output depending on well temperature profile and fin parameters. Therefore, using finned type DHE may be appropriate for some cases. However, in this study the effects of scaling which may occur between the fins of DHE is not taken into consideration. As a future work, an experimental study can be performed to see the effects of scaling.

As another conclusion obtained from this study, adding radial fins increases the heat transfer area but also decreases the velocity of geothermal fluid in the well. Using longitudinal fins or inclined fins, which will not probably perturb the circulation of geothermal fluid, may provide higher heat output. Thus, these arrangements can be analysed as another future work.

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APPENDICES

APPENDIX-A

Table A-1 Modified Bessel Functions of the First and Second Kinds

z	$e^{-z}I_0(z)$	$e^{-z}I_1(z)$	$e^{z}K_o(z)$	$e^{z}K_1(z)$
0	1	0	∞	∞
0,2	0,8269	0,0823	2,1407	5,8334
0,4	0,6974	0,1368	1,6627	3,2587
0,6	0,5993	0,1722	0,4167	2,3739
0,8	0,5241	0,1945	1,2582	1,9179
1	0,4657	0,2079	1,1445	1,6361
1,2	0,4198	0,2152	1,0575	1,4429
1,4	0,3831	0,2185	0,9881	1,301
1,6	0,3533	0,219	0,9309	1,1919
1,8	0,3289	0,2177	0,8828	1,1048
2	0,3085	0,2153	0,8416	1,0335
2,2	0,2913	0,2121	0,8056	0,9738
2,4	0,2766	0,2085	0,774	0,9229
2,6	0,2639	0,2046	0,7459	0,879
2,8	0,2528	0,2007	0,7206	0,8405
3	0,243	0,1968	0,6978	0,8066
3,2	0,2343	0,193	0,677	0,7763
3,4	0,2264	0,1892	0,6579	0,7491
3,6	0,2193	0,1856	0,6404	0,7245
3,8	0,2129	0,1821	0,6243	0,7021
4	0,207	0,1787	0,6093	0,6816
4,2	0,2016	0,1755	0,5953	0,6627
4,4	0,1966	0,1724	0,5823	0,6453
4,6	0,1919	0,1695	0,5701	0,6292
4,8	0,1876	0,1667	0,5586	0,6142
5	0,1875	0,164	0,5478	0,6003
5,2	0,1797	0,1614	0,5376	0,5872
5,4	0,1762	0,1589	0,5279	0,5749
5,6	0,1728	0,1565	0,5188	0,5633
5,8	0,1696	0,1542	0,5101	0,5525
6	0,1666	0,152	0,5019	0,5422
6,4	0,1611	0,1479	0.5865	0,5232
6,8	0,1561	0,1441	0,4724	0,506
7,2	0,1515	0,1405	0,4595	0,4905
7,6	0,1473	0,1372	0,4476	0,4762
8	0,1434	0,1341	0,4366	0,4631
8,4	0,1434	0,1312	0,4264	0,4511
8,8	0,1365	0,1285	0,4168	0,4399
9,2	0,1334	0,126	0,4079	0,4295
9,6	0,1305	0,1235	0,3995	0,4198
10	0,1278	0,1213	0,3916	0,4108

APPENDIX-B

RESULTS OF THE DHE PROGRAM

Table B-1 Data for Figure 5.16 and 5.17 and 5.19

(D_o=33.7 mm , T=3.2 mm , T_i=31°C , k_b=56 W/mK, L_{DHE}=234 m)

Twell(z)= $0.00004103037144449z^3 + 0.00036591321904567z^2 -$
$0.06394567108247880z + 50.5423573907788$

	Temperature distribution through DHE(°C)					
z(m)	m=0,2	m=0,4	m=1	m=2	m=3	m=4
0	31,01453	31,00903	31,00429	31,00231	31,00158	31,00121
1	32,11952	31,67812	31,31478	31,16744	31,11427	31,08678
11	41,84758	38,90014	35,41584	33,56831	32,81562	32,40543
21	46,21942	43,42185	38,95378	35,97779	34,62743	33,85558
31	48,18143	46,08754	41,73476	38,17513	36,38188	35,30615
41	49,54496	48,00008	44,07496	40,25094	38,12857	36,79351
51	51,25107	49,94961	46,36985	42,39536	39,99646	38,42002
61	53,91008	52,54769	49,03312	44,86604	42,1773	40,3407
71	57,97002	56,31121	52,50401	47,97614	44,92202	42,7691
81	63,80884	61,70842	57,24926	52,09378	48,53995	45,97627
91	71,76308	69,16632	63,7626	57,6818	53,43479	50,31266
101	82,08917	79,00314	72,50787	65,20744	60,05889	56,21452
111	95,00302	91,45536	83,84105	75,14242	68,87701	64,12056
117	104,1104	100,2833	92,02516	82,39515	75,38394	70,0154
111	106,5464	104,0174	97,08688	87,84953	80,6574	75,00726
101	97,69125	98,81656	96,80985	90,12069	84,02197	78,85658
91	86,32574	88,97612	91,40976	88,66385	84,03172	79,54511
81	76,44416	79,39675	84,08533	84,81891	82,24166	78,84921
71	68,4803	71,3073	76,8446	79,93355	79,22518	77,06426
61	62,30593	64,86842	70,49364	74,96655	75,71084	74,66206
51	57,68594	59,9348	65,2906	70,43946	72,20444	72,06373
41	54,39985	56,31538	61,2078	66,58359	69,01353	69,5597
31	52,24658	53,82636	58,16291	63,45554	66,27513	67,31376
21	51,01981	52,2718	56,02306	61,05159	64,05168	65,41848
11	50,48898	51,44182	54,63955	59,31917	62,35776	63,9219
1	50,47913	51,13306	53,88282	58,22715	61,22663	62,88921
0	50,54204	51,12381	53,84644	58,16932	61,16486	62,83192

	m=0,2	m=0,4	m=1	m=2	m=3	m=4
Q(W)	16333,84	33640,67	95486,33	227131	378287	532278,6
$h_{o(average)}$	1579,389	1885,559	2332,443	2644,529	2778,199	2841,758
$h_{i(average)}$	2546,026	4552,783	9740,201	17308,1	24156,29	30561,78

Table B-2 Data for Figure 5.20

(D_o=33.7 mm , T=3.2 mm , k_b=56 W/mK, L_{DHE}=234 m)

Twell(z)= $0.00004103037144449z^3 + 0.00036591321904567z^2 - 0.06394567108247880z + 50.5423573907788$

m	T_i (°C)	Q (W)	T_{exit}(°C)	$h_{o(average)}$	$h_{i(average)}$
0,4	30	35311,51	51,12381	1888,51	4550,01
0,4	50	1880,524	51,12439	1135,614	4676,771
1	30	99663,43	53,84644	2337,092	9730,524
1	50	16315,97	53,90168	1420,299	10168,7
2	30	235476,2	58,16824	2650,584	17282,54
2	50	74227,88	58,87304	1674,292	18423,24
3	30	390729,8	61,15782	2784,797	24111,06
3	50	168954,6	63,46136	1831,046	26185,4
4	30	548635,6	62,81093	2848,449	30494,31
4	50	292629,9	67,48298	1942,504	33621,81

Table B-3 Data for Figure 5.21

(D_o=33.7 mm , T=3.2 mm , k_b=56 W/mK, T_i=31°C, L_{DHE}=234 m)

Twell(z)= $0.00004103037144449z^3 + 0.00036591321904567z^2 - 0.06394567108247880z + 50.5423573907788$

m	L_{DHE}(m)	T_{exit}(°C)	Q(W)	$h_{o(average)}$	$hi_{(average)}$
0,4	100	50,54204	32667,68	901,9507	4082,132
0,4	150	50,99825	33430,68	1229,136	4196,98
0,4	200	51,11545	33626,69	1592,792	4388,37
0,4	234	51,12381	33640,67	1885,559	4552,783
1	100	48,9002	74804,74	1216,873	8660,408
1	150	52,2512	88815,68	1453,609	8971,015
1	200	53,57983	94371,44	1942,452	9394,201
1	234	53,84644	95486,33	2332,443	9740,201
2	100	46,3118	127967,8	1461,783	15217,91
2	150	51,90965	174775	1547,408	15821,1
2	200	56,50533	213211,8	2154,087	16593,69
2	234	58,16932	227131	2644,529	17308,1
3	100	44,13121	164606,8	1570,635	21157,14
3	150	50,54204	245007,6	1548,511	22004,21
3	200	57,56878	333161,1	2226,728	23089,95
3	234	61,16486	378287	2778,199	24156,29
4	100	42,42113	190885,6	1632,634	26764,76
4	150	48,41508	291106,4	1729,216	27784,76
4	200	57,40887	441539,4	2250,83	29106,9
4	234	62,83192	532278,6	2841,758	30561,78

Table B-4 Data for Figure 5.22 and 5.23

(D_o=33.7 mm , T=3.2 mm, T_i=31°C, L_{DHE}=234 m, m=1.2 kg/s)

$Twell(z)= 0.00004103037144449z^3 + 0.00036591321904567z^2 – 0.06394567108247880z + 50.5423573907788$

	Temperature distribution through DHE(°C)				
z(m)	k_b=0,5	k_b=2	k_b=5	k_b=10	k_b=15
0	31	31	31	31	31
1	31,04809	31,12691	31,18864	31,22511	31,24059
11	31,54643	32,56521	33,48995	34,09524	34,36641
21	32,03206	33,94833	35,66314	36,76165	37,24486
31	32,51065	35,25831	37,62744	39,08318	39,70398
41	33,00105	36,54998	39,48263	41,2021	41,91132
51	33,52884	37,90688	41,38367	43,33898	44,12281
61	34,12651	39,43295	43,52271	45,758	46,63787
71	34,83297	41,25213	46,12102	48,75629	49,79111
81	35,69353	43,5053	49,42416	52,66119	53,94994
91	36,75948	46,34904	53,71074	57,8458	59,53095
101	38,08801	49,9585	59,26851	64,67687	66,94238
111	39,74255	54,51525	66,38869	73,52271	76,57318
117	40,92004	57,78202	71,53114	79,91911	83,53596
111	42,07861	60,849	76,01311	85,04434	88,82819
101	43,61866	64,31543	79,80243	87,93329	91,00417
91	44,7533	66,17362	80,4987	87,02274	89,08485
81	45,56455	66,85979	79,40663	83,80462	84,71481
71	46,12523	66,7737	77,10086	79,4114	79,37104
61	46,49839	66,16463	74,157	74,71783	74,01422
51	46,738	65,21671	71,02023	70,26998	69,17467
41	46,88906	64,09657	67,99721	66,36134	65,07764
31	46,98782	62,93501	65,27486	63,11433	61,78909
21	47,06189	61,82798	62,96429	60,56752	59,296
11	47,13085	60,84187	61,11787	58,69498	57,52842
1	47,20552	60,0353	59,78484	57,47507	56,42998
0	47,21286	59,97511	59,69921	57,4053	56,37034

	k_b=0,5	k_b=2	k_b=5	k_b=10	k_b=15
Q(W)	81300,77	145342,5	143957,6	132444	127249,6
$h_{o(average)}$	2920,482	2831,183	2764,458	2642,876	2572,385
$hi_{(average)}$	9787,861	10659,02	11100,57	11245,69	11289,55

	Temperature distribution through DHE(°C)				
z(m)	k_b=20	k_b=25	k_b=40	k_b=60	k_b=100
0	31	31	31	31	31
1	31,24916	31,2546	31,26319	31,26822	31,27239
11	34,51991	34,61865	34,77699	34,87087	34,94925
21	37,51554	37,68848	37,96384	38,12574	38,26015
31	40,04589	40,26194	40,60205	40,79963	40,96227
41	42,29504	42,53485	42,90807	43,12226	43,29712
51	44,54062	44,79938	45,19812	45,42502	45,60872
61	47,1027	47,38905	47,82808	48,07658	48,27721
71	50,33799	50,6751	51,1925	51,48572	51,72279
81	54,63745	55,06397	55,72311	56,09923	56,40498
91	60,44178	61,01165	61,90032	62,41186	62,83018
101	68,18324	68,96507	70,19221	70,90227	71,48497
111	78,25645	79,31995	80,99143	81,95962	82,75375
117	85,54072	86,81054	88,81004	89,96817	90,91647
111	90,87347	92,14326	94,09505	95,19551	96,07993
101	92,58386	93,52751	94,91181	95,65027	96,21732
91	89,98617	90,45901	91,03899	91,27789	91,41801
81	84,93723	84,97209	84,86088	84,70484	84,52793
71	79,09046	78,8237	78,27592	77,89323	77,54755
61	73,42385	72,98815	72,22264	71,74275	71,33371
51	68,43391	67,92943	67,09699	66,60081	66,19001
41	64,29073	63,77818	62,96371	62,49352	62,11163
31	61,02556	60,54276	59,7952	59,37306	59,03468
21	58,59445	58,16001	57,49945	57,13241	56,84108
11	56,90458	56,52421	55,95358	55,64025	55,39323
1	55,88189	55,55082	55,05792	54,78897	54,57775
0	55,82787	55,50031	55,01268	54,74666	54,53783

	k_b=20	k_b=25	k_b=40	k_b=60	k_b=100
Q(W)	124527,1	122883,2	120436,1	119101,1	118053,2
$h_{o(average)}$	2528,088	2497,99	2447,304	2416,018	2389,292
$hi_{(average)}$	11303,94	11310,95	11320,27	11327,78	11334,44

Table B-5 Data for Figure 5.24

(D_o=33.7 mm , T=3.2 mm, T_i=31°C, L_{DHE}=234 m, m=1.2 kg/s)

Twell(z)= $0.00004103037144449z^3 + 0.00036591321904567z^2 - 0.06394567108247880z + 50.5423573907788$

	Temperature distribution through DHE(°C)	
z(m)	pipe-A	Pipe-B
0	31	31
1	31,26822	31,26822
11	34,87087	34,87087
21	38,12574	38,12574
31	40,79963	40,79963
41	43,12226	43,12226
51	45,42502	45,42502
61	48,07658	48,07658
71	51,48572	51,48572
81	56,09923	56,09923
91	62,41186	62,41186
101	70,90227	70,90227
111	81,95962	81,95962
117	89,96817	89,96817
111	95,19551	95,19551
101	95,65027	95,65027
91	91,27789	95,47942
81	84,70484	95,15831
71	77,89323	94,72189
61	71,74275	94,201
51	66,60081	93,62241
41	62,49352	93,00859
31	59,37306	92,3782
21	57,13241	91,74599
11	55,64025	91,12414
1	54,78897	90,52154
0	54,74666	90,46399

	pipe-A	Pipe-B
Q(W)	119101,1	298649,1
$h_{o(average)}$	2416,018	3135,997
$hi_{(average)}$	11327,78	11879,41

Table B-6 Data for Figure 5.25

(D_o=33.7 mm , T=3.2 mm, T_i=31°C, L_{DHE}=234 m, m=2 kg/s ,S+B=10 mm, k_b=56 W/mK)

Twell(z)= $0.00004103037144449z^3 + 0.00036591321904567z^2 - 0.06394567108247880z + 50.5423573907788$

	Temperature distribution through DHE(°C)			
z(m)	S=0 mm	S=1 mm	S=2 mm	S=3 mm
0	31,00231	31,0035	31,00416	31,00463
1	31,16744	31,27342	31,32926	31,36726
11	33,56831	34,57952	3,52E+01	35,55691
21	35,97779	37,54241	38,42067	39,01749
31	38,17513	40,04124	41,058	41,72891
41	40,25094	42,26564	43,33072	44,01474
51	42,39536	44,48641	45,56817	46,24672
61	44,86604	47,01571	48,12201	48,80867
71	47,97614	50,20751	51,37555	52,103
81	52,09378	54,4603	55,74447	56,55708
91	57,6818	60,23901	61,68898	62,62695
101	65,20744	68,02196	69,68428	70,77898
111	75,14242	78,2577	80,14701	81,40678
117	82,39515	85,71169	87,74696	89,11198
111	87,84953	91,04665	93,01126	94,31269
101	90,12069	92,89232	94,37366	95,30088
91	88,66385	90,1867	90,80744	91,10505
81	84,81891	85,07227	84,91543	84,68896
71	79,93355	79,20598	78,49855	77,92494
61	74,96655	73,54829	72,49345	71,71898
51	70,43946	68,57591	67,33049	66,46057
41	66,58359	64,43967	63,10973	62,21682
31	63,45554	61,16235	59,82962	58,96333
21	61,05159	58,69621	57,41068	56,59885
11	59,31917	56,94716	55,73931	55,00243
1	58,22715	55,83839	54,71923	54,0598
0	58,16932	55,77547	54,6634	54,0099

	S=0 mm	S=1 mm	S=2 mm	S=3 mm
Q(W)	227131	207107	197805,5	192339,8
$h_{o(average)}$	2644,529	2040,197	2053,508	2052,237
$h_{i(average)}$	17308,1	17381,18	17411,9	17431,4

Table B-7 Data for Figure 5.26

(D_o=33.7 mm , T=3.2 mm, T_i=31°C, L_{DHE}=234 m, m=2 kg/s ,S+B=20 mm, k_b=56 W/mK)

$Twell(z)= 0.00004103037144449z^3 + 0.00036591321904567z^2 - 0.06394567108247880z + 50.5423573907788$

	Temperature distribution through DHE(°C)			
z(m)	S=0 mm	S=1 mm	S=2 mm	S=3 mm
0	31,00231	31,00513	31,00573	31,00615
1	31,16744	31,21829	31,24626	31,26538
11	33,56831	34,0345	34,33538	34,54897
21	35,97779	36,68995	37,16833	37,50573
31	38,17513	39,01898	39,59595	39,99834
41	40,25094	41,15731	41,78469	42,21658
51	42,39536	43,32946	43,98672	44,43466
61	44,86604	45,81671	46,50286	46,96774
71	47,97614	48,9481	49,67727	50,17278
81	52,09378	53,10533	53,90233	54,44872
91	57,6818	58,75491	59,64303	60,25929
101	65,20744	66,37064	67,37376	68,07863
111	75,14242	76,42335	77,55026	78,34802
117	82,39515	83,75973	84,9644	85,82098
111	87,84953	89,16312	90,34586	91,17238
101	90,12069	91,17186	92,12551	92,76523
91	88,66385	89,2786	89,80064	90,11008
81	84,81891	84,94875	85,02465	85,01368
71	79,93355	79,66902	79,40098	79,15263
61	74,96655	74,41096	73,90484	73,49979
51	70,43946	69,6853	69,03145	68,53542
41	66,58359	65,69385	64,95441	64,4122
31	63,45554	62,48001	61,7057	61,15338
21	61,05159	60,02475	59,25011	58,71
11	59,31917	58,25774	57,5034	56,989
1	58,22715	57,12589	56,399	55,9155
0	58,16932	57,06191	56,3367	55,85676

	S=0 mm	S=1 mm	S=2 mm	S=3 mm
Q(W)	227131	217867,5	211801,3	207786,9
$h_{o(average)}$	2644,529	2154,319	2177,24	2184,22
$h_{i(average)}$	17308,1	17341,72	17365,09	17377,68

Table B-8 Data for Figure 5.27

(D_o=33.7 mm , T=3.2 mm, T_i=31°C, L_{DHE}=234 m, m=2 kg/s ,S+B=20 mm, k_b=56 W/mK)

Twell(z)= $0.00004103037144449z^3 + 0.00036591321904567z^2 - 0.06394567108247880z + 50.5423573907788$

	Heat Output (W)			
m	S=0 mm	S=1 mm	S=2 mm	S=3 mm
1	95486,33	90121,13	87602,58	86178,01
2	227131	207107	197805,5	192339,8
3	378287	344109,3	327589,3	317435,9
4	532278,6	491289,5	469854,1	456003,8

Table B-9 Data for Figure 5.28 and 5.29

(D_o=33.7 mm , T=3.2 mm, T_i=31°C, L_{DHE}=234 m, m=1 kg/s ,S=1mm, B=9 mm, k_b=56 W/mK)

Twell(z)= $0.00004103037144449z^3 + 0.00036591321904567z^2 - 0.06394567108247880z + 50.5423573907788$

L(mm)	T_{exit}(°C)	Q(W)
0	53,84644	95486,33
1	53,13992	92531,88
3	52,73752	90849,23
5	52,61094	90319,94
7	52,56943	90146,34
10	52,5634	90121,13

Table B-10 Data for Figure 5.30

(D_o=33.7 mm , T=3.2 mm, T_i=31°C, L_{DHE}=234 m, m=2 kg/s ,S=1 mm, B=9 mm, k_b=56 W/mK)

Twell(z)= $0.00004103037144449z^3 + 0.00036591321904567z^2 - 0.06394567108247880z + 50.5423573907788$

	Temperature distribution through DHE(°C)			
z(m)	L=1 mm	L=3 mm	L=5 mm	L=10 mm
0	31	31	31	31
1	31,19678	31,23429	31,25471	31,27342
11	33,95683	34,32464	34,48122	34,57952
21	36,63591	37,2032	37,42508	37,54241
31	39,00626	39,67791	39,92662	40,04124
41	41,19002	41,90881	42,16302	42,26564
51	43,41234	44,15119	44,40092	44,48641
61	45,95988	46,71204	46,95221	47,01571
71	49,17077	49,94261	50,17165	50,20751
81	53,43624	54,24266	54,45918	54,4603
91	59,22913	60,07956	60,27989	60,23901
101	67,02547	67,92885	68,10953	68,02196
111	77,28391	78,23519	78,39124	78,2577
117	84,75365	85,73203	85,87149	85,71169
111	90,15251	91,0833	91,20332	91,04665
101	92,14538	92,87357	92,99367	92,89232
91	89,85997	90,19215	90,24046	90,1867
81	85,15015	85,09695	85,07807	85,07227
71	79,59928	79,25469	79,18088	79,20598
61	74,17719	73,6292	73,50998	73,54829
51	69,37409	68,6951	68,53921	68,57591
41	65,36299	64,60095	64,41492	64,43967
31	62,16986	61,36596	61,15692	61,16235
21	59,76151	58,94295	58,71527	58,69621
11	58,05884	57,23972	56,99546	56,94716
1	57,00591	56,18871	55,92614	55,83839
0	56,95139	56,13419	55,86872	55,77547

	L=1 mm	L=3 mm	L=5 mm	L=10 mm
Q(W)	216943	210107,5	207887	207107
$h_{o(average)}$	2519,494	2323,135	2198,099	2040,197
$h_{i(average)}$	17350,12	17371,65	17378,62	17381,18

Table B-11 Data for Figure 5.31

(D_o=33.7 mm , T=3.2 mm, T_i=31°C, L_{DHE}=234 m, m=2 kg/s ,S=1 mm, B=9 mm)

Twell(z)= $0.00004103037144449z^3 + 0.00036591321904567z^2 - 0.06394567108247880z + 50.5423573907788$

	Temperature distribution through DHE(°C)		
z(m)	pipe-A	pipe-B	pipe-C
0	31	31	31
1	31,16744	31,16744	31,25471
11	33,56831	33,56831	34,48122
21	35,97779	35,97779	37,42508
31	38,17513	38,17513	39,92662
41	40,25094	40,25094	42,16302
51	42,39536	42,39536	44,40092
61	44,86604	44,86604	46,95221
71	47,97614	47,97614	50,17165
81	52,09378	52,09378	54,45918
91	57,6818	57,6818	60,27989
101	65,20744	65,20744	68,10953
111	75,14242	75,14242	78,39124
117	82,39515	82,39515	85,87149
111	87,84953	87,84953	91,2085
101	90,12069	90,12069	92,99277
91	88,66385	90,06744	92,91371
81	84,81891	89,9224	92,74326
71	79,93355	89,70623	92,50184
61	74,96655	89,43705	92,20757
51	70,43946	89,13078	91,87642
41	66,58359	88,80106	91,52237
31	63,45554	88,45895	91,15627
21	61,05159	88,11562	90,78624
11	59,31917	87,77272	90,42003
1	58,22715	87,43946	90,06303
0	58,16932	87,40758	90,0288

	pipe-A	pipe-B	pipe-C
Q(W)	227131	472095,5	494095,3
$h_{o(average)}$	2644,529	3145,683	2930,532
$h_{i(average)}$	17308,1	17975,68	18142,3

Table B-12 Data for Figure 5.32

(D_o=60 mm , T=4 mm, k_b=56 W/mK)

Twell(z)= 90

	Heat Output (W)					
	LDHE=100 m			LDHE=300 m		
m	Ti=30°C	Ti=50°C	Ti=70°C	Ti=30°C	Ti=50°C	Ti=70°C
0,5	125105,3	83435,02	41699,75	125340,1	83800	41759,72
1	247328,6	164577,6	81805,97	250675,7	167175,4	83515,27
1,5	364600,2	241934,7	119464,6	375982,9	250734,2	125246,8
2	475899,7	314868,3	154427,3	501215,3	334228,6	166925,4
2,5	580877,7	383224,5	186725,9	626086,1	417482,9	208479,3
3	679511,3	447108,8	216511,8	750189,9	500072,2	249605,3
3,5	771974,4	506732,7	243980,8	873557,6	582008,8	290166,1
4	858563,3	562358,9	269342,7	996079,4	663250,9	330208,9
4,5	939620,6	614269,5	292793,8	1117633	743709,6	369706,4
5	1015512	662753,9	314519,4	1238102	823306,3	408615,4

Table B-13 Data for Figure 5.33

(D_o=60 mm , T=4 mm, k_b=56 W/mK)

Twell(z)= 90

	Exit Temperature for the DHE (°C)					
	LDHE=100 m			LDHE=300 m		
M	Ti=30°C	Ti=50°C	Ti=70°C	Ti=30°C	Ti=50°C	Ti=70°C
0,5	89,78808	89,82628	89,87146	89,89999	90	90
1	89,10137	89,28069	89,49248	89,89891	89,89896	89,89899
1,5	88,08579	88,49813	88,97804	89,89404	89,89437	89,89486
2	86,8663	87,5803	88,40015	89,88268	89,88441	89,88649
2,5	85,53183	86,59361	87,79986	89,84142	89,85558	89,86961
3	84,13792	85,58077	87,20035	89,75298	89,78361	89,82444
3,5	82,72183	84,56733	86,61456	89,63971	89,68781	89,75376
4	81,30944	83,56909	86,0498	89,50436	89,57465	89,66996
4,5	79,91762	82,59588	85,50945	89,34779	89,4452	89,57596
5	78,55758	81,65395	84,99497	89,17088	89,3006	89,47276

Table B-14 Data for Figure 5.34

(D_o=60 mm , T=4 mm, k_b=56 W/mK, L_{DHE}=100 m)

Twell(z)= 90

k_b	Q(W)	T_{exit} (°C)	$h_{o(average)}$	$h_{i(average)}$
66	1022729	78,90186	2764,624	11509,74
56	1015512	78,55758	2781,13	11487,04
46	1005132	78,06241	2803,848	11454,65
36	988974,4	77,29153	2837,083	11404,85
26	960532,3	75,93445	2890,12	11318,33
16	898474,7	72,97282	2987,08	11135,85
6	682982,1	62,67648	3204,244	10610,45
1	218060,3	40,43839	3371,831	9589,509

Table B-15 Data for Figure 5.35

(D_o=60 mm , T=4 mm, k_b=56 W/mK, m=5 kg/s)

Twell(z)= 90

L_{DHE}	Q(W)	T_{exit} (°C)	$h_{o(average)}$	$h_{i(average)}$
10	152967,7	37,32253	2039,211	9440,949
50	691755	63,09587	2686,995	10627,96
100	1015512	78,55758	2781,13	11487,04
150	1145173	84,74124	2692,207	11942,26
200	1200184	87,36371	2555,191	12224,9
250	1225489	88,56979	2410,63	12413,09
300	1238102	89,17088	2273,13	12544,27
350	1244846	89,49229	2147,267	12642,66

Table B-16 Data for Figure 5.36

(D_o=60 mm , T=4 mm, k_b=56 W/mK, m=5 kg/s, L_{DHE}=100 m)

Twell(°C)	Q(W)	T_{exit} (°C)	$h_{o(average)}$	$h_{i(average)}$
90	1015512	78,55758	2781,13	11487,04
80	815270,2	68,99975	2453,534	11039,37
70	620870,4	59,70692	2115,004	10617,26
60	436931,7	50,91037	1786,871	10225,34

Table B-17 Data for Figure 5.37 ,5.38 and 5.39

(D_o=60 mm , T=4 mm, k_b=56 W/mK, m=5 kg/s, L_{DHE}=100 m,Ti=30°C)

S	B	L	Q(W)	T_{exit} (°C)	$h_{o(average)}$	$h_{i(average)}$	A_o	U_{ave}
0			1015512	78,55758	2781,13	11487,04	18,85	1838,4593
1	5	5	1123300	83,69839	2213,372	11810,84	53,42	882,41839
2	5	5	1141762	84,57864	2249,266	11888,86	48,94	1027,5883
3	5	5	1146431	84,80125	2275,93	11914,43	45,57	1122,8009
0			1015512	78,55758	2781,13	11487,04	18,85	1838,4593
1	5	5	1123300	83,69839	2213,372	11810,84	53,42	882,41839
1	10	5	1080493	81,65706	2369,053	11672,73	37,71	1094,3399
1	15	5	1061558	80,75397	2450,444	11617,16	31,82	1229,1812
1	20	5	1050816	80,24165	2502,45	11583,79	28,73	1322,1875
0			1015512	78,55758	2781,13	11487,04	18,85	1838,4593
1	5	3	1114226	83,26567	2335,275	11783,46	38,97	1173,8738
1	5	5	1123300	83,69839	2213,372	11810,84	53,42	882,41839
1	5	10	1128231	83,93346	2083,979	11825,33	93,24	514,14403

Table B-18 Data for Figure 5.40 and 5.41

(D_o=60 mm , T=4 mm, k_b=56 W/mK, L_{DHE}=50 m, S=1 mm, B=5 mm, L=5 mm)

m	Qunfinned (W)	Qfinned (W)	Qmax=mCp(Twell-Ti) (W)
1	225948,7	234366,1	251100
1,5	316226,3	335385,3	376650
2	393686,8	426789,8	502200
2,5	460552,4	509890,9	627750
3	518800,1	585820,2	753300
3,5	569971,6	655567,9	878850
4	615266,1	720047,3	1004400
4,5	655618,1	779974,9	1129950
5	691755	835980	1255500

APPENDIX-C

DHE PROGRAM

```
CLS
REM "********DHE PROGRAM********"
REM"       by  SELDA ALPAY            "
REM”               GEOCEN              "
COLOR 13
PRINT TAB(30); "DHE PROGRAM": PRINT
PRINT TAB(3); "Calculates exit temperature and heat output of a DHE"
PRINT
COLOR 11
PRINT "If bare or finned type DHE"
INPUT "If bare type DHE, type 1,else type 2"; D1
PRINT
PRINT "If the well temperature profile is assumed as a polynomial profile or a
constant number "
INPUT "If a polynomial profile, type 1,else another number"; P1
IF P1 = 1 THEN 3 ELSE 4
3   PRINT "Well temperature profile is TWELL(Z)=A6*Z^6+A5*Z^5 + A4*Z^4 +
    A3*Z^3 +A2*Z^2 + A1*Z+A0 (deg.C)"
    INPUT "ENTER A6"; A6
    INPUT "Enter A5 "; A5
    INPUT "Enter A4 "; A4
    INPUT "Enter A3 "; A3
    INPUT "Enter A2 "; A2
    INPUT "Enter A1 "; A1
    INPUT "Enter A0 "; T2
    DEF FNTWELL (Z) = A6 * (Z ^ 6) + A5 * (Z ^ 5) + A4 * (Z ^ 4) +
    A3 * (Z ^ 3) + A2 * (Z ^ 2) + A1 * Z + T2

    PRINT
    GOTO 5
4   INPUT "Enter average reservoir temperature (deg.C)"; T2
    PRINT
5   INPUT "Enter total length of DHE installed in the aquifer(m)"; LDHE
    INPUT "Enter DHE outside diameter (mm)"; DD
    INPUT "Enter DHE wall thickness (mm)"; T
    INPUT "Enter thermal conductivity of DHE (W/m.C)"; KB
    INPUT "Enter inlet temperature to DHE (deg.C)"; TI
    INPUT "Enter mass flow rate through DHE (kg/s)"; M
    INPUT “Enter grid length (DZ) (m)”; DZ

    IF D1 = 1 THEN 7
    INPUT "Enter fin thickness (mm)"; TK
    INPUT "Enter distance between fins (mm)"; BB
    INPUT "Enter fin length (mm)"; L
```

```
7     REM "*********CALCULATE AREAS AND DIAMETERS***********"
      DD = DD / 1000
      T = T / 1000
      R1 = DD / 2
      DI = (R1 - T) * 2
      A = (22 / 7) * DI * DZ
      N = FIX(LDHE / DZ)

      REM ""***********PHYSICAL PROPERTIES OF WATER***********"
      DIM T(21), C(21), K(21), G(21), NU(21), PR(21), BE(21), RPR(6)
      T(1) = 20: C(1) = 4182: K(1) = .603: NU(1) = .001008
      G(1) = 1.01E-06: PR(1) = 7: BE(1) = .0002061
      T(2) = 25: C(2) = 4180: K(2) = .61:  NU(2) = .000898
      G(2) = .0000009: PR(2) = 6.15: BE(2) = .0002567
      T(3) = 30: C(3) = 4178: K(3) = .617: NU(3) = .000807
      G(3) = 8.1E-07: PR(3) = 5.45: BE(3) = .0003028
      T(4) = 35: C(4) = 4178: K(4) = .625: NU(4) = .000725
      G(4) = 7.3E-07: PR(4) = 4.85: BE(4) = .0003454
      T(5) = 40: C(5) = 4179: K(5) = .632: NU(5) = .000655
      G(5) = 6.6E-07: PR(5) = 4.34: BE(5) = .000385
      T(6) = 45: C(6) = 4180: K(6) = .638: NU(6) = .000594
      G(6) = .0000006: PR(6) = 3.93: BE(6) = .0004222
      T(7) = 50: C(7) = 4181: K(7) = .643: NU(7) = .000543
      G(7) = 5.5E-07: PR(7) = 3.56: BE(7) = .0004574
      T(8) = 55: C(8) = 4183: K(8) = .648: NU(8) = .000503
      G(8) = 5.1E-07: PR(8) = 3.26: BE(8) = .0004907
      T(9) = 60: C(9) = 4185: K(9) = .654: NU(9) = .000472
      G(9) = 4.8E-07: PR(9) = 2.99: BE(9) = .0005229
      T(10) = 65: C(10) = 4187: K(10) = .658: NU(10) = .000431
      G(10) = 4.4E-07: PR(10) = 2.75: BE(10) = .0005538
      T(11) = 70: C(11) = 4190: K(11) = .663: NU(11) = .000401
      G(11) = 4.1E-07: PR(11) = 2.53: BE(11) = .0005836
      T(12) = 75: C(12) = 4193: K(12) = .667: NU(12) = .00037
      G(12) = 3.8E-07: PR(12) = 2.35: BE(12) = .0006127
      T(13) = 80: C(13) = 4197: K(13) = .67: NU(13) = .00035
      G(13) = 3.6E-07: PR(13) = 2.2: BE(13) = .0006411
      T(14) = 85: C(14) = 4201: K(14) = .673: NU(14) = .000329
      G(14) = 3.4E-07: PR(14) = 2.07: BE(14) = .0006797
      T(15) = 90: C(15) = 4206: K(15) = .676: NU(15) = .000309
      G(15) = 3.2E-07: PR(15) = 1.95: BE(15) = .0007034
      T(16) = 95: C(16) = 4212: K(16) = .678: NU(16) = .000298
      G(16) = 3.1E-07: PR(16) = 1.84: BE(16) = .0007201
      T(17) = 100: C(17) = 4217: K(17) = .68: NU(17) = .000278
      G(17) = 2.9E-07: PR(17) = 1.76: BE(17) = .0007501
      T(18) = 120: C(18) = 4245: K(18) = .686: NU(18) = .000235
      G(18) = 2.485E-07: PR(18) = 1.45: BE(18) = .00086
      T(19) = 140: C(19) = 4287: K(19) = .684: NU(19) = .000199
      G(19) = 2.15E-07: PR(19) = 1.25: BE(19) = .000975
      T(20) = 160: C(20) = 4341: K(20) = .682: NU(20) = .000172
```

```
      G(20) = 1.89E-07: PR(20) = 1.09: BE(20) = .001098
      T(21) = 180: C(21) = 4409: K(21) = .676: NU(21) = .000151
      G(21) = 1.697E-07: PR(21) = .98: BE(21) = .001233
      IF D1 = 2 THEN 311

      REM "*********CALCULATIONS FOR BARE TYPE DHE***********"
      I = 0
      TG = TI
      TC = TI + 1
      LE = -DZ / 2
13    I = I + 1

      REM "______________ITERATIONS FOR A GRID___________________"
      IF I <= FIX(N / 2) THEN LE = LE + DZ ELSE LE = LE - DZ
      TB = FNTWELL(LE)
      TW = (TB + (TG + TC) / 2) / 2
46    TM = (TG + TC) / 2
      TWI = TW: TCI = TC

     REM "___Calculate Reynolds Number and Heat Transfer Coefficients__"

      FOR J = 1 TO 21
      IF TM > T(J) THEN 8
      XS = (TM - T(J - 1)) / (T(J) - T(J - 1))
      C = C(J - 1) + XS * (C(J) - C(J - 1))
      K = K(J - 1) + XS * (K(J) - K(J - 1))
      NU = NU(J - 1) + XS * (NU(J) - NU(J - 1))
      PR = PR(J - 1) + XS * (PR(J) - PR(J - 1))
      GOTO 9
8     NEXT J
9     RE = 4 * M / ((22 / 7) * DI * NU)
       IF RE < 2300 THEN 10 ELSE 11
10     HI = 3.66 * K / DI
      GOTO 17
11    F = (1.58 * LOG(RE) - 3.28) ^ (-2)
      NUS = (F / 2) * (RE - 1000) * PR / (1 + 12.7 * ((F / 2) ^ (1 / 2))
      * (PR ^ (2 / 3) - 1))
      HI = (NUS * K) / DI
17    TF = (TB + TW) / 2
      FOR J = 1 TO 21
      IF TF > T(J) THEN 18
      XS = (TF - T(J - 1)) / (T(J) - T(J - 1))
      K = K(J - 1) + XS * (K(J) - K(J - 1))
      G = G(J - 1) + XS * (G(J) - G(J - 1))
      PR = PR(J - 1) + XS * (PR(J) - PR(J - 1))
      BE = BE(J - 1) + XS * (BE(J) - BE(J - 1))
      GOTO 19
18    NEXT J
19    RPR(0) = 1
      RPR(1) = 1.4444 - ((1.4444 - 1.2555) / 9) * (PR - 1)
```

```
        RPR(2) = 1.7333 - ((1.7333 - 1.4444) / 9) * (PR - 1)
        RPR(3) = 1.9777 - ((1.9777 - 1.6) / 9) * (PR - 1)
        RPR(4) = 2.1666 - ((2.1666 - 1.7333) / 9) * (PR - 1)
        RPR(5) = 2.3111 - ((2.3111 - 1.8444) / 9) * (PR - 1)
        IF LE < 0 THEN LE = DZ / 2
        GRZ = 9.81 * BE * (ABS(TW - TB)) * (LE ^ 3) / (G ^ 2)
        KSI = 2 * (2 ^ (1 / 2)) * LE / ((GRZ ^ (1 / 4)) * (R1))
        FOR RI = 0 TO 5
        IF KSI > RI THEN 43
        XS = (KSI - (RI - 1)) / 1
        R = RPR(RI - 1) + XS * (RPR(RI) - RPR(RI - 1))
        GOTO 44
43      NEXT RI
44      RAZ = GRZ * PR
        IF RAZ > 1E+09 THEN 45
        NUS = .508 * (RAZ ^ (1 / 4)) * ((PR / (.952 + PR)) ^ (1 / 4))
        GOTO 6
45      NUS = .0295 * (RAZ ^ (2 / 5)) * (PR ^ (1 / 15)) /
        ((1 + .494 * (PR ^ (2 / 3))) ^ (2 / 5))
6       NUSCY = NUS * R
        HD = (NUSCY * K) / LE
        U = 1 / (1 / HI + (DI / (2 * KB)) * (LOG(DD / DI)) + DI /
        (2 * R1 * HD))

        REM "__Calculate exit temperature for a grid__"
        D = TB - TG
        B = TB - TC
        IF P1 = 1 THEN 33
        IF TC >= TB THEN 30
        IF TG >= TB THEN 30
        IF (D / B) < 1.000001 AND (D / B) > .99999 THEN 32
        TLM = (D - B) / (LOG(D / B)): GOTO 36
30      TC = TB
        TW = TWI
        GOTO 40
32      TC = TG
        TW = TWI
        GOTO 40
33      IF TC < TB THEN 34
        IF TC = TB THEN 35
        IF TC > TB AND TG < TB THEN 35
34      IF (D / B) < 1.000001 AND (D / B) > .99999 THEN 37
        TLM = (D - B) / (LOG(D / B)): GOTO 36
37      TC = TG
        TW = TWI
        GOTO 40
35       TC = (TB + TG) / 2
36       Q = U * A * TLM
        IF Q = 0 THEN 40
        TC = Q / (M * C) + TG
```

```
      TLM = Q / (HI *A)
      IF TLM = 0 THEN 40
      Y = (TG - TC) / TLM
      IF EXP(Y) = 1 THEN TW = TWI
      IF EXP(Y) = 1 THEN GOTO 40
      TW = (EXP(Y) * TG - TC) / (EXP(Y) - 1)
40     IF ABS(TW - TWI) < .0001 OR ABS(TC - TCI) < .0001 THEN 15
      GOTO 46
15    TWI = TW
      TWTOT = TWTOT + TW
      TG = TC
      TC = TG + .1
      HITOT = HITOT + HI
      HDTOT = HDTOT + HD
      IF I = N THEN 16 ELSE 13
16    TWL = TWTOT / N
      HDAVE = HDTOT / N
      HIAVE = HITOT / N
      HDAVE = HDTOT / N
      SB = TG
      UB = 1 / (1 / HIAVE + (DI / (2 * KB)) * (LOG(DD / DI)) + DI /
      (2 * R1 * HDAVE))
      IF D1 = 1 THEN 100

311   REM"********CALCULATIONS FOR FINNED TYPE DHE**********"

      BB = BB / 1000
      TK = TK / 1000
      L = L / 1000
      R2 = R1 + L + TK / 2
      AK = (22 / 7) * DI * TK
      REM "**MODIFIED BESSEL FUNCTIONS OF THE FIRST AND SECOND
      KINDS** "

      DIM Z(40), IO(40), I1(40), KO(40), K1(40)
      Z(1) = .2: IO(1) = 1.009978: I1(1) = .1005214
      KO(1) = 1.752657: K1(1) = 5.8334 / (EXP(Z(1)))
      Z(2) = .4: IO(2) = 1.040398: I1(2) = .2040816
      KO(2) = 1.114541: K1(2) = 3.2587 / (EXP(Z(2)))
      Z(3) = .6: IO(3) = 1.091996: I1(3) = .3137689
      KO(3) = .7775014: K1(3) = 2.3739 / (EXP(Z(3)))
      Z(4) = .8: IO(4) = 1.166406: I1(4) = .4328677
      KO(4) = .5653457: K1(4) = 1.9179 / (EXP(Z(4)))
      Z(5) = 1!: IO(5) = 1.265904: I1(5) = .5651308
      KO(5) = .421038: K1(5) = 1.6361 / (EXP(Z(5)))
      Z(6) = 1.2: IO(6) = 1.393785: I1(6) = .7144892
      KO(6) = .3185129: K1(6) = 1.4429 / (EXP(Z(6)))
      Z(7) = 1.4: IO(7) = 1.553547: I1(7) = .8860612
      KO(7) = .2436625: K1(7) = 1.301 / (EXP(Z(7)))
      Z(8) = 1.6: IO(8) = 1.749906: I1(8) = 1.084714
```

```
KO(8) = .1879455: K1(8) = 1.1919 / (EXP(Z(8)))
Z(9) = 1.8: IO(9) = 1.989729: I1(9) = 1.317008
KO(9) = .1459259: K1(9) = 1.1048 / (EXP(Z(9)))
Z(10) = 2!: IO(10) = 2.279524: I1(10) = 1.590864
KO(10) = .1138982: K1(10) = 1.0335 / (EXP(Z(10)))
Z(11) = 2.2: IO(11) = 2.628987: I1(11) = 1.914205
KO(11) = .8056 / (EXP(Z(11))): K1(11) = .9738 / (EXP(Z(11)))
Z(12) = 2.4: IO(12) = 3.049011: I1(12) = 2.408564
KO(12) = .774 / (EXP(Z(12))): K1(12) = .9229 / (EXP(Z(12)))
Z(13) = 2.6: IO(13) = 3.55308: I1(13) = 2.754681
KO(13) = .7459 / (EXP(Z(13))): K1(13) = .879 / (EXP(Z(13)))
Z(14) = 2.8: IO(14) = 4.157207: I1(14) = 3.300441
KO(14) = .7206 / (EXP(Z(14))): K1(14) = .8405 / (EXP(Z(14)))
Z(15) = 3!: IO(15) = 4.880785: I1(15) = 3.952834
KO(15) = .6978 / (EXP(Z(15))): K1(15) = .8066 / (EXP(Z(15)))
Z(16) = 3.2: IO(16) = 5.747972: I1(16) = 4.734779
KO(16) = .677 / (EXP(Z(16))): K1(16) = .7763 / (EXP(Z(16)))
Z(17) = 3.4: IO(17) = 6.783873: I1(17) = 5.669208
KO(17) = .6579 / (EXP(Z(17))): K1(17) = .7491 / (EXP(Z(17)))
Z(18) = 3.6: IO(18) = 8.025992: I1(18) = 6.792632
KO(18) = .6404 / (EXP(Z(18))): K1(18) = .7245 / (EXP(Z(18)))
Z(19) = 3.8: IO(19) = 9.516882: I1(19) = 8.140085
KO(19) = .6243 / (EXP(Z(19))): K1(19) = .7021 / (EXP(Z(19)))
Z(20) = 4!: IO(20) = 11.30182: I1(20) = 9.756689
KO(20) = .6093 / (EXP(Z(20))): K1(20) = .6816 / (EXP(Z(20)))
Z(21) = 4.2: IO(21) = 13.44396: I1(21) = 11.70345
KO(21) = .5953 / (EXP(Z(21))): K1(21) = .6627 / (EXP(Z(21)))
Z(22) = 4.4: IO(22) = 16.01324: I1(22) = 14.04213
KO(22) = .5823 / (EXP(Z(22))): K1(22) = .6453 / (EXP(Z(22)))
Z(23) = 4.6: IO(23) = 19.09104: I1(23) = 16.86259
KO(23) = .5701 / (EXP(Z(23))): K1(23) = .6292 / (EXP(Z(23)))
Z(24) = 4.8: IO(24) = 22.79536: I1(24) = 20.25579
KO(24) = .5586 / (EXP(Z(24))): K1(24) = .6142 / (EXP(Z(24)))
Z(25) = 5!: IO(25) = 27.23382: I1(25) = 24.33976
KO(25) = .5478 / (EXP(Z(25))): K1(25) = .6003 / (EXP(Z(25)))
Z(26) = 5.2: IO(26) = 32.57462: I1(26) = 29.25734
KO(26) = .5376 / (EXP(Z(26))): K1(26) = .5872 / (EXP(Z(26)))
Z(27) = 5.4: IO(27) = 39.01181: I1(27) = 35.18148
KO(27) = .5279 / (EXP(Z(27))): K1(27) = .5749 / (EXP(Z(27)))
Z(28) = 5.6: IO(28) = 46.72968: I1(28) = 42.32173
KO(28) = .5188 / (EXP(Z(28))): K1(28) = .5633 / (EXP(Z(28)))
Z(29) = 5.8: IO(29) = 56.01881: I1(29) = 50.9322
KO(29) = .5101 / (EXP(Z(29))): K1(29) = .5525 / (EXP(Z(29)))
Z(30) = 6!: IO(30) = 67.21124: I1(30) = 61.32117
KO(30) = .5019 / (EXP(Z(30))): K1(30) = .5422 / (EXP(Z(30)))
Z(31) = 6.4: IO(31) = 96.95724: I1(31) = 89.01289
KO(31) = .4865 / (EXP(Z(31))): K1(31) = .5232 / (EXP(Z(31)))
Z(32) = 6.8: IO(32) = 140.154: I1(32) = 129.3798
KO(32) = .4724 / (EXP(Z(32))): K1(32) = .506 / (EXP(Z(32)))
Z(33) = 7.2: IO(33) = 202.9237: I1(33) = 188.19
```

```
KO(33) = .4595 / (EXP(Z(33))): K1(33) = .4905 / (EXP(Z(33)))
Z(34) = 7.6: IO(34) = 296.3342: I1(34) = 274.1524
KO(34) = .4476 / (EXP(Z(34))): K1(34) = .4762 / (EXP(Z(34)))
Z(35) = 8!: IO(35) = 427.4694: I1(35) = 399.7465
KO(35) = .4366 / (EXP(Z(35))): K1(35) = .4631 / (EXP(Z(35)))
Z(36) = 8.4: IO(36) = 621.6997: I1(36) = 583.455
KO(36) = .4264 / (EXP(Z(36))): K1(36) = .4511 / (EXP(Z(36)))
Z(37) = 8.8: IO(37) = 905.5745: I1(37) = 852.5005
KO(37) = .4168 / (EXP(Z(37))): K1(37) = .4399 / (EXP(Z(37)))
Z(38) = 9.2: IO(38) = 1320.277: I1(38) = 1247.038
KO(38) = .4079 / (EXP(Z(38))): K1(38) = .4295 / (EXP(Z(38)))
Z(39) = 9.6: IO(39) = 1926.805: I1(39) = 1823.451
KO(39) = .3995 / (EXP(Z(39))): K1(39) = .4198 / (EXP(Z(39)))
Z(40) = 10!: IO(40) = 2814.982: I1(40) = 2671.81
KO(40) = .3916 / (EXP(Z(40))): K1(40) = .4108 / (EXP(Z(40)))


W = FIX(LDHE / (BB + TK))
TG = TI
TC = TI + 1
LE = 0
FOR I = 1 TO W
IF I <= FIX(W / 2) THEN LE = (I - 1) * (BB + TK) + BB / 2 ELSE
LE = (W - I) * (BB + TK) + BB / 2
TB = FNTWELL(LE)

REM "__________ITERATIONS FOR PLAIN PART____________"

REM "__Calculate Reynolds Number and Heat Transfer Coefficients__"
TW = (TB + (TC + TG) / 2) / 2
25  TM = (TG + TC) / 2
TWI = TW: TCI = TC
FOR J = 1 TO 21
IF TM > T(J) THEN 28
XS = (TM - T(J - 1)) / (T(J) - T(J - 1))
C = C(J - 1) + XS * (C(J) - C(J - 1))
K = K(J - 1) + XS * (K(J) - K(J - 1))
NU = NU(J - 1) + XS * (NU(J) - NU(J - 1))
PR = PR(J - 1) + XS * (PR(J) - PR(J - 1))
GOTO 29
28  NEXT J
29  RE = 4 * M / ((22 / 7) * DI * NU)
IF RE < 2300 THEN 23 ELSE 24
23  HI = 3.66 * K / DI
GOTO 27
24  F = (1.58 * LOG(RE) - 3.28) ^ (-2)
NUS = (F / 2) * (RE - 1000) * PR / (1 + 12.7 * ((F / 2) ^ (1 / 2))
* (PR ^ (2 / 3) - 1))
HI = (NUS * K) / DI
27  TF = (TB + TW) / 2
```

```
    FOR J = 1 TO 21
    IF TF > T(J) THEN 38
    XS = (TF - T(J - 1)) / (T(J) - T(J - 1))
    K = K(J - 1) + XS * (K(J) - K(J - 1))
    G = G(J - 1) + XS * (G(J) - G(J - 1))
    PR = PR(J - 1) + XS * (PR(J) - PR(J - 1))
    BE = BE(J - 1) + XS * (BE(J) - BE(J - 1))
    GOTO 39
38  NEXT J
39  RPR(0) = 1
    RPR(1) = 1.4444 - ((1.4444 - 1.2555) / 9) * (PR - 1)
    RPR(2) = 1.7333 - ((1.7333 - 1.4444) / 9) * (PR - 1)
    RPR(3) = 1.9777 - ((1.9777 - 1.6) / 9) * (PR - 1)
    RPR(4) = 2.1666 - ((2.1666 - 1.7333) / 9) * (PR - 1)
    RPR(5) = 2.3111 - ((2.3111 - 1.8444) / 9) * (PR - 1)
    GRZ = 9.81 * BE * (ABS(TW - TB)) * (LE ^ 3) / (G ^ 2)
    KSI = 2 * (2 ^ (1 / 2)) * LE / ((GRZ ^ (1 / 4)) * (R1 + L))
    FOR PI = 0 TO 5
    IF KSI > PI THEN 53
    XS = (KSI - (PI - 1)) / 1
    R = RPR(PI - 1) + XS * (RPR(PI) - RPR(PI - 1))
    GOTO 54
53  NEXT PI
54  RAZ = GRZ * PR
    IF RAZ > 1E+09 THEN 55
    NUS = .508 * (RAZ ^ (1 / 4)) * ((PR / (.952 + PR)) ^ (1 / 4))
    GOTO 56
55  NUS = .0295 * (RAZ ^ (2 / 5)) * (PR ^ (1 / 15)) / ((1 + .494
    * (PR ^ (2 / 3))) ^ (2 / 5))
56  NUSCY = NUS * R
    HD = (NUSCY * K) / (LE)
    U = 1 / (1 / HI + (DI / (2 * KB)) * (LOG(DD / DI)) + DI /
    (2 * R1 * HD))

    REM "__Calculate Exit Temperature for the Plain Part__"
    D = TB - TG
    B = TB - TC
    IF P1 = 1 THEN 83
    IF TC >= TB THEN 80
    IF TG >= TB THEN 80
    IF (D / B) < 1.000001 AND (D / B) > .99999 THEN 82
    TLM = (D - B) / (LOG(D / B)): GOTO 86
80  TC = TB
    TW = TWI
    GOTO 63
82  TC = TG
    TW = TWI
    GOTO 63
83  IF TC < TB THEN 84
    IF TC = TB THEN 85
```

```
    IF TC > TB AND TG < TB THEN 85
84  IF (D / B) < 1.000001 AND (D / B) > .99999 THEN 87
    TLM = (D - B) / (LOG(D / B)): GOTO 86
87  TC = TG
    TW = TWI
    GOTO 63
85  TC = (TB + TG) / 2
86  A = (22 / 7) * DI * BB
    Q = U * A * TLM
    IF Q = 0 THEN 63
    TC = Q / (M * C) + TG
    TLM = Q / (HI * A)
    IF TLM = 0 THEN 63
    Y = (TG - TC) / TLM
    IF EXP(Y) = 1 THEN TW = TWI
    IF EXP(Y) = 1 THEN 63
    TW = (EXP(Y) * TG - TC) / (EXP(Y) - 1)
63  IF ABS(TW - TWI) < .0001 OR ABS(TC - TCI) < .0001 THEN 64
    GOTO 25
64  TG = TC
    TWI = TW
    AB=(22/7)*DD*BB
    ABTOT=ABTOT+AB
    HDTOTF = HDTOTF + HD * AB
    HITOTF = HITOTF + HI * BB

    REM "____________ITERATIONS FOR FINNED PART_______________"

    REM "__Calculate Reynolds Number and Heat Transfer Coefficients__"
    IF I <= FIX(W / 2) THEN LE = (I - 1) * (BB + TK) + BB + TK / 2
    ELSE LE = (W - I) * (BB + TK) + BB + TK / 2
    TB = FNTWELL(LE)
65  TM = (TC + TG) / 2
    FOR J = 1 TO 21
    IF TM > T(J) THEN 68
    XS = (TM - T(J - 1)) / (T(J) - T(J - 1))
    C = C(J - 1) + XS * (C(J) - C(J - 1))
    K = K(J - 1) + XS * (K(J) - K(J - 1))
    NU = NU(J - 1) + XS * (NU(J) - NU(J - 1))
    PR = PR(J - 1) + XS * (PR(J) - PR(J - 1))
    GOTO 69
68  NEXT J
69  RE = 4 * M / ((22 / 7) * DI * NU)
    IF RE < 2300 THEN 73 ELSE 74
73  HI = 3.66 * K / DI: GOTO 77
74  F = (1.58 * LOG(RE) - 3.28) ^ (-2)
    NUS = (F / 2) * (RE - 1000) * PR / (1 + 12.7 * ((F / 2) ^ (1 / 2))
    * (PR ^ (2 / 3) - 1))
    HI = (NUS * K) / DI
77  TF = (TB + TBASE) / 2
```

```
    FOR J = 1 TO 21
    IF TF > T(J) THEN 91
    XS = (TF - T(J - 1)) / (T(J) - T(J - 1))
    K = K(J - 1) + XS * (K(J) - K(J - 1))
    G = G(J - 1) + XS * (G(J) - G(J - 1))
    PR = PR(J - 1) + XS * (PR(J) - PR(J - 1))
    BE = BE(J - 1) + XS * (BE(J) - BE(J - 1))
    GOTO 92
91  NEXT J
92  RPR(0) = 1
    RPR(1) = 1.4444 - ((1.4444 - 1.2555) / 9) * (PR - 1)
    RPR(2) = 1.7333 - ((1.7333 - 1.4444) / 9) * (PR - 1)
    RPR(3) = 1.9777 - ((1.9777 - 1.6) / 9) * (PR - 1)
    RPR(4) = 2.1666 - ((2.1666 - 1.7333) / 9) * (PR - 1)
    RPR(5) = 2.3111 - ((2.3111 - 1.8444) / 9) * (PR - 1)
    GRZ = 9.81 * BE * (ABS(TBASE - TB)) * (LE ^ 3) / (G ^ 2)
    KSI = 2 * (2 ^ (1 / 2)) * LE / ((GRZ ^ (1 / 4)) * (R1 + L))
    FOR SI = 0 TO 5
    IF KSI > SI THEN 93
    XS = (KSI - (SI - 1)) / 1
    R = RPR(SI - 1) + XS * (RPR(SI) - RPR(SI - 1))
    GOTO 94
93  NEXT SI
94  RAZ = GRZ * PR
    IF RAZ > 1E+09 THEN 95
    NUS = .508 * (RAZ ^ (1 / 4)) * ((PR / (.952 + PR)) ^ (1 / 4))
    GOTO 96
95  NUS = .0295 * (RAZ ^ (2 / 5)) * (PR ^ (1 / 15)) / ((1 + .494 *
    (PR ^ (2 / 3))) ^ (2 / 5))
96  NUSCY = NUS * R
    HD = (NUSCY * K) / (LE)
    MK = (2 * HD / (KB * TK)) ^ (1 / 2)
    X1 = MK * R1
    X2 = MK * R2
    FOR J = 1 TO 40
    IF X1 > Z(J) THEN 48
    XS = (X1 - Z(J - 1)) / (Z(J) - Z(J - 1))
    K11 = K1(J - 1) + XS * (K1(J) - K1(J - 1))
    I11 = I1(J - 1) + XS * (I1(J) - I1(J - 1))
    IO1 = IO(J - 1) + XS * (IO(J) - IO(J - 1))
    KO1 = KO(J - 1) + XS * (KO(J) - KO(J - 1))
    GOTO 49
48  NEXT J
49  IF X1 < Z(40) THEN 41 ELSE 47
47  XS = (X1 - Z(39)) / (Z(40) - Z(39))
    K11 = K1(39) + XS * (K1(40) - K1(39))
    I11 = I1(39) + XS * (I1(40) - I1(39))
    IO1 = IO(39) + XS * (IO(40) - IO(39))
    KO1 = KO(39) + XS * (KO(40) - KO(39))
41  FOR J = 1 TO 40
```

```
    IF X2 > Z(J) THEN 58
    XS = (X2 - Z(J - 1)) / (Z(J) - Z(J - 1))
    I12 = I1(J - 1) + XS * (I1(J) - I1(J - 1))
    K12 = K1(J - 1) + XS * (K1(J) - K1(J - 1))
    GOTO 59
58  NEXT J
59  IF X2 < Z(40) THEN 61 ELSE 57
57  XS = (X2 - Z(39)) / (Z(40) - Z(39))
    I12 = I1(39) + XS * (I1(40) - I1(39))
    K12 = K1(39) + XS * (K1(40) - K1(39))
61  Q2 = ((K11 * I12 - I11 * K12) / (KO1 * I12 + IO1 * K12))
    * (4 * (22 / 7) * R1 / MK)
    U = HI

    TBASE = (TBAS - TG) / (EXP(U * AK * (TC - TG) / (Q2 * HD *
    (TB - TBAS)))) + TC
    Q = Q2 * HD * (TB - TBASE)
    TCE = Q / (M * C) + TG
78  IF ABS(TBAS - TBASE) < .0001 AND ABS(TCE - TC) < .0001 THEN 79
    TBAS = TBASE
    TC = TCE
    GOTO 65
79  TBASTOP = TBASTOP + TBAS
    TG = TCE
    TC = TG + 1
    AF=(22/7)*(DD+2*L)*TK+(22/7((DD+2*L)^2)/4-22/7*(DD^2)/4)*2
    AFTOT=AFTOT+AF
    HDTOTF = HDTOTF + HD * AF
    HITOTF = HITOTF + HI * TK
    NEXT I
    TBASEORT = TBASTOP / W
    HDAVEF = HDTOTF / (ABTOT+AFTOT)
    HIAVEF = HITOTF / (LDHE)
    COLOR 11
    TC = TG
    TM = (TG + TI) / 2
    FOR J = 1 TO 21
    IF TM > T(J) THEN 88
    XS = (TM - T(J - 1)) / (T(J) - T(J - 1))
    C = C(J - 1) + XS * (C(J) - C(J - 1))
    GOTO 89
88  NEXT J
89  QFIN = M * C * (TG - TI)
100  TM = (SB + TI) / 2
    FOR J = 1 TO 21
    IF TM > T(J) THEN 98
    XS = (TM - T(J - 1)) / (T(J) - T(J - 1))
    C = C(J - 1) + XS * (C(J) - C(J - 1))
    GOTO 99
98  NEXT J
```

```
99  QBARE = M * C * (SB - TI)
    IF D1 = 2 THEN 313
    PRINT "Total heat transfer rate for bare type DHE (W):"; QBARE
    PRINT "Exit temperature for bare type DHE (deg.C):"; SB
    PRINT "Average heat convection coefficient for flow outside the DHE "
    (W/m2K):"; HDAVE
    PRINT "Average convection coefficient for flow in bare type DHE "
    (W/m2K):"; HIAVE
    IF D1 = 1 THEN 310
313  PRINT
    PRINT "Total heat transfer rate for finned type DHE (W):"; QFIN
    PRINT "Exit temperature for finned type DHE (deg.C):"; TG
    PRINT "Average heat convection coefficient for flow outside the DHE

    (W/m2K):"; HDAVEF
    PRINT "Average convection coefficient for flow in finned type DHE
    (W/m2K):"; HIAVEF
310  END
```