8

Geothermal Energy

(Energy from the Earth)

8.1. Introduction

Energy present as heat (*i.e.* thermal energy) in the earth's crust ; the more readily accessible heat in the upper most (10 km) or so, of the crust constitutes a potentially useful and almost inexhaustible source of energy. This heat is apparent from the increase in temperature of the earth with increasing depth below the surface. Although higher and lower temperatures occur, the average temperature at a depth of 10 km is about 200°C.

U.S. Geological survey defines geothermal source as "all of the heat stored in the earth's crust above 15°C to a depth of 10 km." It occurs when the immense heat energy in the core of earth rises closer to the surface of the earth due to cracks or faults as accounted by the "Plate Techonics Theory", in the crust and heats the surrounded rock. These hot spots can be liquid dominated, vapour dominated, petro-thermal or geo-pressure system, depending upon several geological and hydrological factors. These inturn are tapped artificially to use the vast stored heat energy, for power generation and several other uses, depending upon the temperature of occurrence and other parameters.

Hot molten (or partially molten) rock, called "Magma" is commonly present at depths greater than 24 to 40 km. In some places, however, anomalous geologic conditions cause the magma to be pushed up toward the surface, in an active volcano, the magma actually reaches the surface, where heat of the magma is being conducted upward through an overlying rock layer.

Fig. (8.1.1) shows a typical geothermal field. The hot magma (molten mass) near the surface (A) solidifies into igneous rock (B). Igneous is Latin word, igneous meaning "of fire" specially formed by volcanic action or great heat. (Igneous rock found at the surface is called volcanic action rock). The heat of the magma is conducted upward to this igneous rock. Ground water that finds its way down to this rock

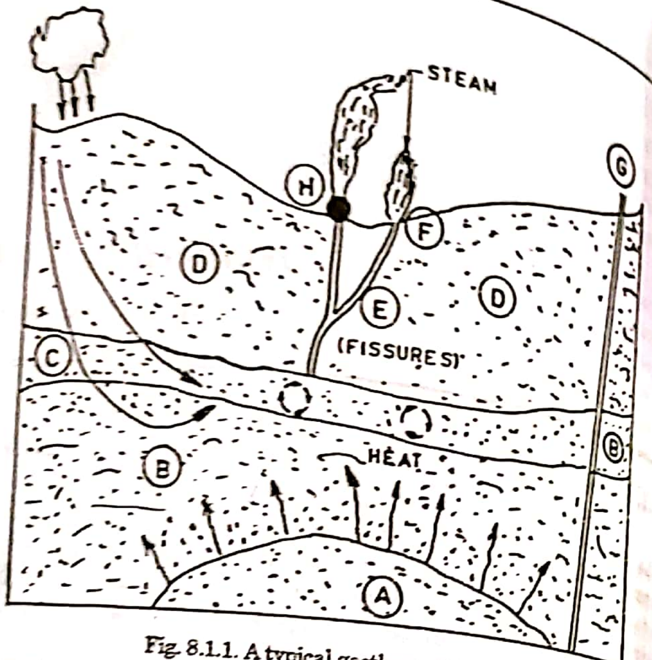


Fig. 8.1.1. A typical geothermal field.

through fissures in it, will be heated by the heat of the rock or by mixing with hot gases and steam emanating from the magma. The heated water will then rise convectively upward and into a porous and permeable reservoir (C) above the igneous rock. The reservoir is capped by a layer of impermeable solid rock (D) that traps the hot water in the reservoir. The solid rock, however, has fissures (E) that act as vents of the giant underground boiler. The vents show up at the surface as geysers fumarols (F) (steam is continuously vented through fissures in the ground, these vents are called fumarols) or hot spring (G). A well (H) taps steam from the fissures for use in a geothermal power plant.

It can be seen that geothermal steam is of two kinds that originating from the magma itself, called *magmetic steam*, and that from ground water heated by the magma called *meteoritic steam*. The latter is the largest source of geothermal steam. Not all geothermal sources produce steam as described above. Some are lower in temperature so that there is only hot water. Some receive no ground water at all and contain only hot rock. Geothermal sources are therefore of three basic kinds : (1) *hydrothermal* (2) *geopressured* and (3) *petrothermal*. These will be explained later.

The total amount of energy in the outer 10 km of the earth's crust exceeds greatly that obtainable by the combustion of coal, oil and natural gas. At present, however, only the relatively small proportion of the geothermal energy in wet reservoirs (a geothermal reservoir is

defined as a region where there is a concentration of extractable heat), may be regarded as economically useful. Nevertheless, this amount is large enough to make a significant contribution to the energy resources. With advances in technology, a portion of the much larger dry geothermal energy resources may also become available.

Historically, the first applications of geothermal energy were for space heating, cooking, and medicinal purposes. The earliest record of space heating dates back to 1300 in iceland. In the early 1800s, geothermal energy was used on what was then a large scale by the conte Franceso de Laderel to recover boric acid. The first mechanical conversion was in 1897 when the steam of the field at Larderallo, Italy, was used to heat a boiler producing steam which drove a small steam engine. The first attempt to produce electricity also took place at Larderello in 1904 with an electric generator that powered four light bulbs. This was followed in 1912 by a condensing turbine ; and by 1914, 8.5 MW of electricity was being produced. By 1944 Larderello was producing 127 MW. The plant was destroyed near the end of World War II, but was fortunately rebuilt and expanded and eventually reached 360 MW in 1981.

In the United States, the first attempt at developing the Geysers field was made in 1922. Steam was successfully, taped, but the pipes and turbines of the time were unable to cope with the corrosive and abrasive steam. The effort was not revived until 1956, till that time stainless steel alloys were developed that could withstand the corrosive steam, and the first electric generating unit of 11-MW capacity began operation in 1960. Since then 13 generally progressively larger units have been added to the system. After-ward number of units were planned which brought the total capacity to about 1500 MW by the late 1980. Other electric-generating fields of note are in New Zealand, Japan, Mexico, the Phillipines, the Soviet Union and Ice land (a large space-heating programme).

In 1979, the global electricity production from geothermal resources was 1872 MW and units under construction were of 1650 MW capacity. For space and process heat, total power utilization was 1281 MW. So that total power production was about 4850 MW. This power consumption is likely to grow up upto 100,000 MW by the turn of the next century.

It has been analysed that about 40 to 50% of total heat required by the society is a heat below 200°C. 30% heat is required at about 150°C. 20% heat is required at about 100°C.

Thus there is a vast scope to use geothermal energy for low temperature applications. There is a ample scope to develop geothermal power in India, but still development in geothermal field is in initial stage. There are about 340 known thermal areas in India, each represented by hot/warm spring. About 113 spring area, discovered so far where geothermal power is available. 46 of these systems are of high temperature type (above 150°C), which could generate 1838 MW for a period of 30 years. 59 of these are of intermediate temperature type (90° to 150°C), which could be considered for power generation using binary vapour cycle and other are of low temperature type below 90°C.

Till now only one pilot plant is in operation in puga valley, in Jammu and Kashmir, having 20 MW capacity. Another plant is at Parvati Valley, Himachal Pradesh is under construction. A 7.5 tonne capacity cold storage pilot plant based on geothermal energy was installed at Manikaran, Himachal Pradesh. A 5 kw pilot power plant is under fabrication at the National Aeronautical Laboratory, Bangalore. This plant will run on geothermal energy which will be recovered from the hot springs at Manikaran in Himachal Pradesh. Plans are being made to undertake further research and development studies in the area of geothermal energy. Exploitation of this energy source for non power sectors like poultry farming, mushroom cultivation, space heating is possible in this Country on fairly large scale.

It can be seen that while geothermal energy is not the sought after sole and long range solution to our energy problems, it nevertheless represents a not insignificant factor if its resources are developed in a careful and efficient manner.

Geothermal energy is also the one of the renewable energy sources, which are defined as those resources that draw on the natural energy flows of the earth (another term "the *alternative energy sources*" is also common in use). Renewable energy sources are so named because they recur, are seemingly inexhaustible, and are free for the taking. Geothermal energy has practically no intermittency, has the highest energy density, and is economically not far removed from conventional technologies. Geothermal energy is classified as renewable because the earth's interior is and will continue in the process of cooling for the indefinite future. Hence, geothermal energy from the earth's interior is almost as inexhaustible as solar or wind energy, so long as its sources are actively sought and economically tapped.

8.2. Estimates of Geothermal Power

The estimates vary very widely. However the following give a rough estimate. For a depth of 3 kms, the total stored energy of known fields is approximately 8×10^{21} Joules and for a depth of 10 km the total stored energy is estimated to be about 4×10^{22} Joules. The energy stored in hot springs is about 10% of the above quantities. If the above energy is extracted from a 3 km belt with 1% thermal energy recovery factor at a uniform rate of over a 50 year period, thermal power of 50 GW

is obtained. With a thermal electric conversion efficiency of 20% will yield only 10 GW of electric power. For the estimate based on a 10 km depth on electric power of 50 GW is predicted U.S.A. has 5—10% geothermal fields and India much less.

8.3. Nature of Geothermal Fields

It is convenient to classify earth's surface into three broad groups.

(1) *Non-thermal areas* having a temperature gradient of 10—40°C per km depth.

(2) Semi-thermal areas having a temperature gradient of 70°C per km depth.

(3) *Hyper-thermal areas* where the temperature gradients are many times greater than in non-thermal areas.

Geothermal fields may further be classified into three types :

(A) Hyper-thermal Fields

(1) *Wet fields.* Where the water is pressurized and temperatures are above 100°C. When they are led to the surface a fraction will be splashed into steam and a major part remains as the boiling water.

(2) *Dry fields.* They produce dry saturated steam or superheated steam at pressure above atmospheric.

(B) Semi-thermal Fields

These are capable of producing hot water at temperatures above 100°C.

8.4. Geothermal Sources

Five general categories (or kinds) of geothermal resources have been identified :

(1) Hydrothermal convective systems.

These are again subclassified as :

(*a*) Vapour-dominated or dry steam fields.

(*b*) Liquid-dominated system or wet steam fields, and

(*c*) Hot-water fields.

(2) Geopressure resources.

(3) Petro-thermal or Hot dry rocks (HDR).

(4) Magma resources.

(5) Valcanoes.

The hydrothermal convective systems are best resources for geothermal energy exploitation at present. Hot dry rock is also being considered.

Hydrothermal Systems. Hydrothermal systems are those in which water is heated by contact with the hot-rock, as explained earlier.

Vapor-dominated Systems. In these systems the water is vaporized into steam that reaches the surface in a relatively dry condition at about 200°C and rarely above 7 kg/cm^3 (8 bar). This steam is the most suitable for use in turbo electric power plants, with the least cost. It does, however, suffer problems similar to those encountered by all geothermal systems, namely, the presence of corrosive gases and erosive material and environmental problems. These type of systems are very less in numbers ; they are only five known sites in the world. The Geysers plant in the United States, the largest in the world today, and Larderello in Italy, are both vapor-dominated systems.

Liquid-dominated Systems. In these systems the hot water circulating and trapped underground is at a temperature range of 175 to 315°C. When tapped by wells drilled in the right places and to the right depths, the water flows naturally to the surface or is pumped upto it. The drop in pressure, usually to 7 kg/cm^2 (8 bar) or less, causes it to partially flash to a two—phase mixture of low quality *i.e.* liquid-dominated. It contains relatively large concentration of dissolved solids ranging between 3000 to 25,000 ppm and sometimes higher. Power production is adversely effected by these solids because they precipitate and cause scaling in pipes and heat exchanger surfaces, thus reducing flow and heat transfer. Liquid dominated systems, however, are much more plentiful than vapour-dominated systems, and, next to them, require the least extension of technology.

(2) **Geopressured Systems.** These resources occur in large, deep sedimentary basins. The reservoirs contain moderately high temperature water (or brine) under very high pressure. They are of special interest because substantial amounts of methane CH_4 (natural gas) are dissolved in the pressurized water (or brine) and are released when the pressure is reduced. Geopressured water is tapped in much deeper underground acquifers (it is a water-bearing stratum of permeable rock, gravel or sand), at depths between about 2400 to 9000 m. This water is thought to be at the relatively low temperature of about 160°C and is under very high pressure, from the overlying formation above, of about 1050 kg/cm^2 (more than 1000 bar). It has a relatively high salinity of 4 to 10 per cent and is often referred to as brine. The geopressured resources are quite large : they could be used for the generation of electric power and the recovery of natural gas if suitable technology could be developed and if individual reservoir productivity and longevity prove to be adequate.

(3) **Hot Dry Rocks.** (or Petrothermal Systems). These are very hot solid rocks occurring at moderate depths but to which water does not have access, either because of the absence of ground-water or the low permeability of the rock (or both). In order to utilize this resource, means must be found for breaking up impermeable rock at depth, introducing cold water, and recovering the resulting hot water (or steam) for use at the surface. The known temperatures of HDR vary between ~ 150 to 290°C. This energy, called petrothermal energy, represents by far the largest resource of geothermal energy of any type, as it accounts for large per cent of the geothermal resource. Much of the HDR occurs at moderate depths, but it is largely impermeable as stated above in order to extract thermal energy out of it, water will have to be pumped into it and back out to the surface. It is necessary for the heat transport mechanism that a way be found to render the impermeable rock into a permeable structure with a large heat-transfer surface. A large surface is particularly necessary because of the low thermal conductivity of the rock. Rendering the rock permeable is to be done by fracturing it. Fracturing methods that have been considered involve drilling wells into the rock and then fracturing by (1) high-pressure water or (2) nuclear explosives. Efforts in this direction are in progress.

(4) **Magma Resources.** These consist of partially or completely molten rock, with temperatures in excess of 650°C, which may be encountered at moderate depths, especially in recently active volcanic regions. These resources have a large geothermal energy content, but they are restricted to a relatively few locations. Furthermore, the very high temperatures will make extraction of the energy a difficult technological problem.

The geothermal resources outlined above and means used or proposed for their development are described more fully in the following sections.

8.5. Hydrothermal (Convective) Resources

These are wet reservoirs at moderate depths containing steam and/or hot water under pressure at temperatures upto about 350°C. These systems are further subdivided, depending upon whether steam or hot water is the dominant product. Hydrothermal resources represent only a small fraction of the potential geothermal resources, but they are the only ones that have been utilized commercially so far. If the temperature is high enough, the water or steam can be used to generate electricity, otherwise the geothermal energy is best supplied to process and space heating.

Hydrothermal resources arise when water has access to high temperature rocks, this accounts for the description as "hydrothermal". The heat is transported from the hot rocks by circulating movement (*i.e.* by convection of the water in a porous medium). The general geological structure of a hydrothermal convective region is shown in simplified form in Fig. (8.5.1). The molten rock (magma), raised by internal earth forces is overpaid by an impervious rock formation, through which heat is conducted upward. Above this is a permeable layer into which water has penetrated, often from a considerable distance. The permeability could result from fractures or intergranular pores. The heat taken up by the water from the rocks below, is transferred by a convection to a layer of impervious rocks above, (In convection, the heated water rises, because of its lower density, and then descends when it is cooled by transferring heat to the colder rocks above).

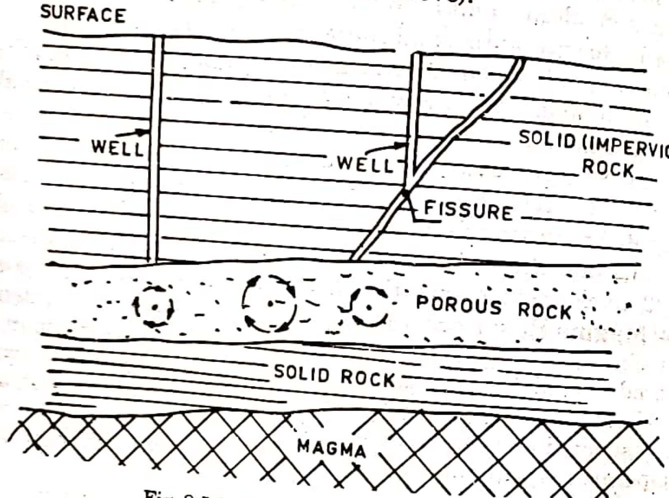


Fig. 8.5.1. Hydrothermal convenctive region.

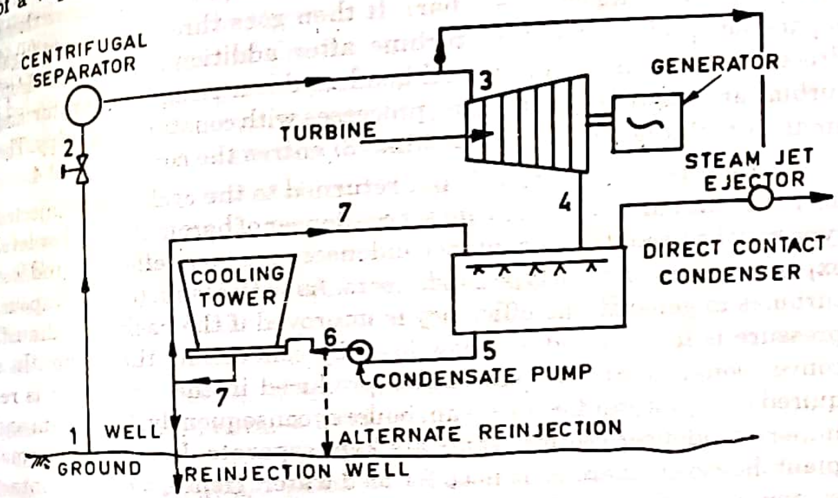
Hot water or steam often escapes through fissures in the rock, thus forming hot springs, geysers fumarols, etc. In order to utilize the hydrothermal energy, wells are drilled either to intercept a fissure or, more commonly, into the formation containing the water (*i.e.* the hydrothermal reservoir). Most hydrothermal wells range in depth from about 600 to 2100 m, although there are some shallower and deeper production wells. As already mentioned for practical purposes hydrothermal resources are further subdivided into vapor-dominated (Dry steam) and liquid-dominated (wet steam) types. In vapour dominated systems, the wells deliver steam, with little or no liquid water, usually at temperatures of about 150°C to 250°C but occasionally higher. Liquid dominated systems, on the other hand produce a mixture of steam and hot water.

8.5.1. Vapour Dominated Systems

As indicated previously these are the most attractive geothermal resources because they are the most easily developed. They have the lowest cost and least number of serious problems. However they

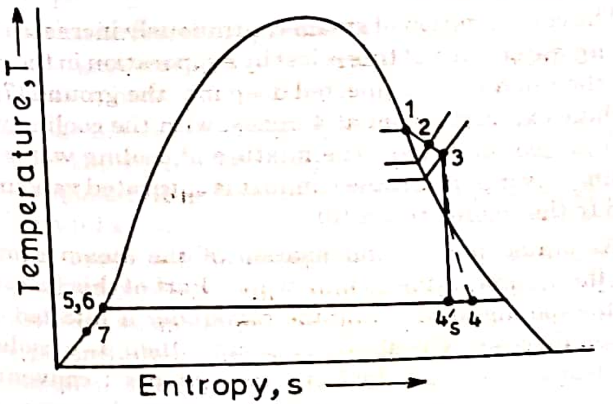
constitute only a few per cent of hydrothermal resources and a much smaller proportion of the accessible geothermal energy resources.

Figs. 8.5.2 (*a*) and 8.5.2 (*b*) show a schematic and T.S. diagram of a vapour-dominated power system. Dry steam from the wells is



(*a*)

Scheme of a vapour-dominated power plant.



(*b*)

Fig. 8.5.2. Vapour dominated system on T.S. diagram.

collected, filtered to remove abrasive particles and passed through turbines, which drive electric generators in the usual manner. The essential difference between this system and a conventional steam turbine-generator system, using fossil or unclear fuel, is that geothermal steam is supplied at a much lower temperature and pressure. The dry steam from the well (1) at perhaps 200°C is used. It is nearly saturated at the bottom of the well and may have a shut-off pressure upto about 35 kg/cm^2 is (= 35 bar). Pressure drops through the well causes it to slightly super heat at the well head (2). The pressure there rarely exceeds 7 kg/cm^2 (~ 7 bar). It then goes through a centrifugal separation and then enters turbine after additional pressure drop. Processes between well and well head, and centrifugal separator and turbine are essentially throttling processes with constant enthalpy. The steam after expansion in the turbine (3) entres the condenser at 4.

Because turbine flow is not returned to the cycle but reinjected back into the earth, a direct-contact condenser of barometric or low level type may be used. Direct contact condensers are more effective and less expensive than surface type condensers. As with steam (or any vapour) turbines in general, the efficiency is improved if the back (or exhaust) pressure is maintained at a low level by condensing the steam. In a conventional plant, the pure water produced in the condenser is required as feed water for the steam boilers ; consequently, the steam and impure condenser cooling water are kept separate. In a hydrothermal plant, however, there is no need for feed water. Hence, a direct-contact system is used at the Geysers in which the turbine exhaust steam is condensed by direct contact with cooling water. The resulting warm water is circulated through a mechanical-draft *cooling tower* and returned to the condenser.

The condensation of steam continuously increases the volume of the cooling water. Part of this is lost by evaporation in the cooling towers (6), and the remainder is injected deep into the ground (7) for disposal. The turbine exhaust steam at 4 mixes, with the cooling water (7) that comes from cooling tower. The mixture of cooling water coming from the cooling tower and turbine exhaust is saturated vapour at (5) that is pumped to the cooling tower (6).

As stated above condensation of the steam continuously increases the volume of the cooling water. Part of this is lost by evaporation in the cooling towers, and the remainder is injected deep into the ground for disposal. The ability to produce their own cooling water is a unique feature of many hydrothermal plants ; conventional steam turbine generating plants require an external source of condenser (make up) cooling water.

The surface condensers are also, however, used in some units with H_2S removal system.

Geothermal plants use much lower temperature and pressure steam and higher condenser pressures than conventional plants, and hence they are much lower in efficiency. At the Geysers installation, the more recent deep (roughly 2500 m) wells supply steam to the turbines at a temperature of about 180°C and a gauge pressure of 7.8 atm. (0.78 M Pa). (The temperatures and pressures in the reservoir are higher). For comparison, the steam temperature in a modern fossil-fuel plant may be about 550°C and the pressure 240 atm (24 M Pa). Hence, the geothermal electric plants require special low pressure turbines. Furthermore, because of the low steam temperature, the *thermal efficiency* (*i.e.* the proportion of heat supplied to the turbine that is converted into electric energy) is only about 15 per cent, compared with 40 per cent (or so) in a modern fossil-fuel plant.

The Geysers installation in California (U.S.A.), Larderello in Italy and Motsukawa, Japan are : good examples of dry steam fields. In U.S.A., the Geysers installation started commercially operation in 1960, its electric capacity has been steadily increased and reached about 1000 MW in 1980. This capacity is increasing further, as reservoir conditions are not affected.

Characteristics of Geothermal steam electric plants. A number of environmental effects are characteristics of geothermal-steam electric facilities. The steam may contain 0.5 to 5 per cent by weight of non-condensable gases which appear in the turbine exhaust. These gases consist mainly of carbon di-oxide with small amounts of methane and ammonia, which are largely harmless in the quantities present. In addition, the gases may contain upto 4 or 5 per cent of hydrogen sulfide ; not only does this gas have an unpleasant (rotten-eggs) odor, it can also be harmful to plant and animal life if it should accumulate. At the geysers, hydrogen sulfide is considered to be a nuisance rather than a hazard.

In the past the non-condensable gases have been released to the atmosphere where the hydrogen sulfide is gradually destroyed by oxidation. The products, however, are oxides of sulphur which can themselves be harmful at appreciable concentrations. Plans are therefore under way to remove most of the hydrogen sulfide from the gases before they are discharged.

The geothermal steam may also contain boron, arsenic ; mercury, and other potentially poisonous elements which, together with some of the ammonia, are found in the turbine condensate. These substances must be disposed of in a safe manner. This is achieved at the Geysers by the reinjection of excess condensate into the ground at a considerable depth.

The withdrawal of large amounts of steam (or water) from a hydrothermal reservoir may result in surface subsidence. Such subsidences have sometimes occurred in oil fields and are dealt with by injecting water into the ground. The reinjection of excess water from a geothermal steam electric plant may serve the same purpose. Care must be taken, however, that the water is reinjected at some distance from ground fault. Steam-electric plants of all types discharge to the atmosphere much of the heat present in the turbine exhaust steam. In the Geysers facilities this discharge occurs in the cooling towers. Because of the low thermal efficiency, a larger proportion of the heat supplied is discharged than from fossil-fuel or nuclear plants. Vaporization water in the cooling towers also result in the addition of large amounts of moisture in the atmosphere. Hitherto, geothermal steam has been used on a relatively moderate scale and the environmental effects of the heat and moisture have not been significant.

Example 8.5.1. A 250 MW vapour-dominated hydrothermal power plant uses saturated steam at 31 kg/cm^2 at shut-off. The steam is throttled to a turbine at inlet pressure of 9.55 kg/cm^2. A direct contact condenser operates at a pressure of 0.35 kg/cm^2 with the cooling-tower exist is at 25°C. The turbine polytropic efficiency is 0.80 and the turbine-generator combined mechanical and electrical efficiency is 0.9.

Calculate :

(*i*) Steam flow rate in kg/hr and m^3/kg ;
(*ii*) The cooling water flow kg/hr ;
(*iii*) Plant efficiency and
(*iv*) Heat rate.

Reinjection occurs prior to the cooling tower.

Solution. Refer Fig. 8.5.2 (*a*) and (*b*).

From steam tables.

Enthalpy at point 1 at (31 kg/cm^2) = 669.7 kcal/kg

$H_1 = H_2 = H_3$, enthalpy remains constant during throttling.

$\therefore \quad H_3 = 669.7$ kcal/kg.

At point 3, $\quad P_3 = 9.55$ kg/cm^2

Specific volume $v_{s3} = 0.22$ m^3/kg

Entropy $\quad S_3 = 1.580$

$T_3 = 190$°C (degree of superheat = 13°C)

Point 2 and 3 are in superheated region.

At point 1 steam is saturated, but at points 2 and 3, it becomes superheated. Here Mollier diagram can also be used to find the above parameters.

S_{4-s} at 0.34 kg/cm^2 = S_3

$x_{4-s} = 0.838$

and
$$H_{4-s} = h_s + xL$$
$$= 72 + 0.838 \times 556 = 538 \text{ kcal/kg}$$

(H_{4-s} can be read directly from Mollier's diagram)

Isentropic turbine work
$$= H_3 - H_{4-s} = 669.7 - 538 = 131.7 \text{ kcal/kg.}$$

Actual turbine work = $0.80 \times 131.7 = 105.36$ kcal/kg
$$H_4 = 669.7 - 105.36 = 564.34 \text{ kcal/kg}$$

h_{5-6} (ignoring pump work)
$$= 72 \text{ kcal/kg}$$
$$h_7 = h_5 = \text{sensible heat} = 25 \text{ kcal/kg}$$

$$\text{Turbine steam flow} = \frac{250 \times 0.860 \times 10^6}{105.36 \times 0.9}$$
$$= 1.838 \times 10^6 \text{ kg/hr } \textbf{Ans.}$$
$$= \dot{m}_4 \text{ say}$$

Turbine volume flow
$$= \frac{1.836 \times 10^6}{60} \times v_{s3}$$
$$= \frac{1.836 \times 16^6}{60} \times 0.22$$
$$= 6.732 \times 10^3 \text{ m}^3\text{/min.}$$

Cooling water flow $\dot{m}_7$:
$$\dot{m}_7 (h_5 - h_7) = \dot{m}_4 (H_4 - h_5)$$
$$\dot{m}_7 = \frac{H_4 - h_5}{h_5 - h_7} \dot{m}_4$$
$$= \frac{564.34 - 72}{72 - 25} \times 1.836 \times 10^6$$
$$= 19.21 \times 10^6 \text{ kg/hr. } \textbf{Ans.}$$

Heat added
$$= H_1 - h_6$$
$$= 669.7 - 72 = 597.7 \text{ kcal/kg.}$$

$$\text{Plant efficiency } \eta_p = \frac{\text{Actual turbine work} \times \eta_{mg}}{\text{Heat added}}$$

(η_{mg} = combined mechanical and electrical efficiency of turbine-generator)

$$= \frac{105.36}{597.7} \times 0.90 = 0.1586$$

$$\therefore \quad \eta_{plant} = 15.86\% \ \textbf{Ans.}$$

$$\text{Plant heat rate} = \frac{860 \times \text{heat added}}{\text{net work}}$$

$$= 860 \times \frac{597.7}{105.36 \times 0.90} = \frac{860}{\eta_{plant}}$$

$$= \frac{860}{.1586} = 5422 \text{ kcal/ kWH} \quad \textbf{Ans.}$$

8.5.2. Liquid-Dominated Systems (Wet steam fields)

In the liquid dominated reservoir, the water temperature is above the normal boiling point (100°C). However because the water in the reservoir is under pressure, it does not boil but remains in the liquid state. When the water comes to the surface the pressure is reduced; rapid boiling then occurs and the liquid water "flashes" into a mixture of hot water and steam. The steam can be separated and used to generate electric power in the usual manner. The remaining hot water can be utilized to generate electric power or to provide space and process heat, or it may be distilled to yield purified water.

The water comes with various degrees of salinity, ranging from 3000 to 280,000 ppm of dissolved solids, and at various temperatures. There are, therefore, various systems for converting liquid-dominated system into useful work that depend upon these variables. For liquid-dominated (*high temperature*) systems two methods which will be covered are :

(*a*) the *flashed-steam system*, suitable for water in the higher temperature range, and

(*b*) the *binary-cycle system*, suitable for water at moderate temperatures.

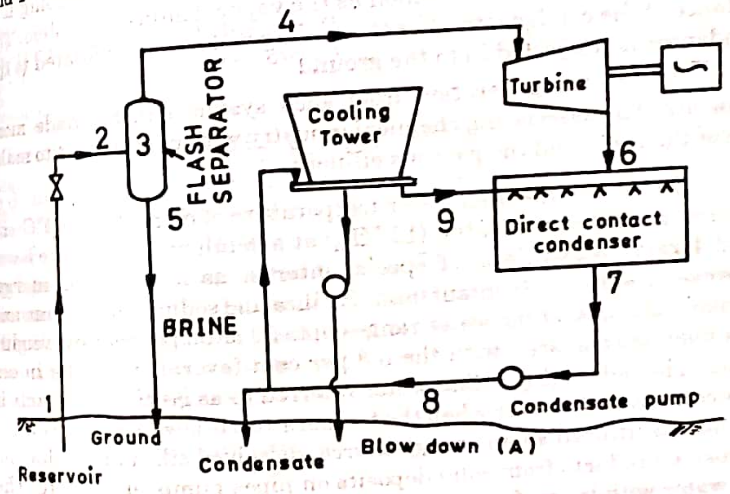
(*c*) A third method, called the *total flow system*, concepts of it is also covered, but this approach awaits further development.

Liquid-dominated (*low temperature*) system is also described in this section.

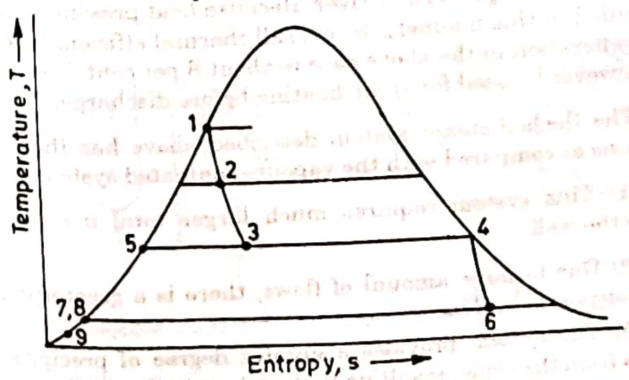
Liquid-dominated (high temperature) *system* : steam from liquid-dominated, high temperature reservoirs is being used in several countries to generate electric power. The most extensive development has been in the volcanic Wairakei field in Newzealand. The water in the hydrothermal reservoir is at the temperature of about 230°C and pressure of 40 atm (4 MP_a). The liquid originates mainly from depths of 600 to 1400 m and is flashed into a mixture of steam and water at the surface.

After passage through a *cyclone separator*, to remove the water, the steam is supplied to the turbine connected to electric generators. The maximum initial steam temperature is about 175°C and the gauge pressure is 3.5 atm (0.35 MP_a). The exhaust steam is condensed by direct contact with cold water from the nearby Waikaro river; the warm condenser cooling water is then discharged to the river. This simple procedure, which does not require, cooling towers, is possible only because of the ample flow of river water.

(*a*) **The Flashed-Steam System.** This is illustrated by the flow and T-S diagram of Figs. (8.5.3 *a* and *b*). Water from the under-ground



(*a*) Schematic of a liquid dominated single-flash steam system.



(*b*) T-S diagram of a liquid dominated single flash steam system.

Fig. 8.5.3.

reservoir at 1 reaches the well head at 2 at a lower pressure. Process 1-2 is essentially a constant enthalpy throttling process that results in a two-phase mixture of low quality at 2. This is throttled further in a flash separator resulting in a still low but slightly higher quality at 3. This mixture is now separated into dry saturated steam at 4 and saturated brine at 5. The latter is reinjected into the ground.

The dry steam, a small friction of the total well discharge (because of low quality at 3), and usually at pressures below 7 kg/cm^2 gauge (0.7 MP_a), is expanded in a turbine to 6 and mixed with cooling water in a direct-contact condenser with the mixture at 7 going to a cooling tower in the same fashion as the vapor-dominated system. The balance of the condensate after the cooling water is recirculated to the condenser is reinjected in to the ground.

The power generation from such system can be made more economical by associating chemical industry with power plant to make use of the brine and the gaseous effluent.

Because of the high water temperature of more than 300°C and a pressure of about 120 atm. (12 MP_a) at a depth at 1200 m, the lower (and larger) reservoir is of special interest as a source of energy. However, the mineral content (mainly silica and sodium, potassium and calcium chlorides) of the water ranges upto 20 or 30 per cent by weight; this may be compared with the 3.3 per cent (average) of salts in sea water. The hot, highly saline water referred to as *geothermal brine*, is very corrosive. Moreover when the temperature is lowered, as it is when the heat is utilized as an energy source, dissolved silica and salts and corrosion products from solid deposits on pipes pump surface etc. The hot-water withdrawn from the steam-water separator after flashing is also discharged to the well or river. Because heat present in the water is discarded in this manner, the overall thermal efficiency for electric power generation in the above case is about 8 per cent. The hot water could however be used for space heating before discharge.

The flashed-steam system described above has the following *limitations* as compared with the vapour-dominated system.

(1) This system requires much larger total massflow rates through the well.

(2) Due to large amount of flows, there is a greater degree of ground surface subsidence.

(3) The system provides a greater degree of precipitation of minerals from the brine, resulting in the necessity for design of valves, pumps, separator internals, and after equipment for operation under scaling conditions.

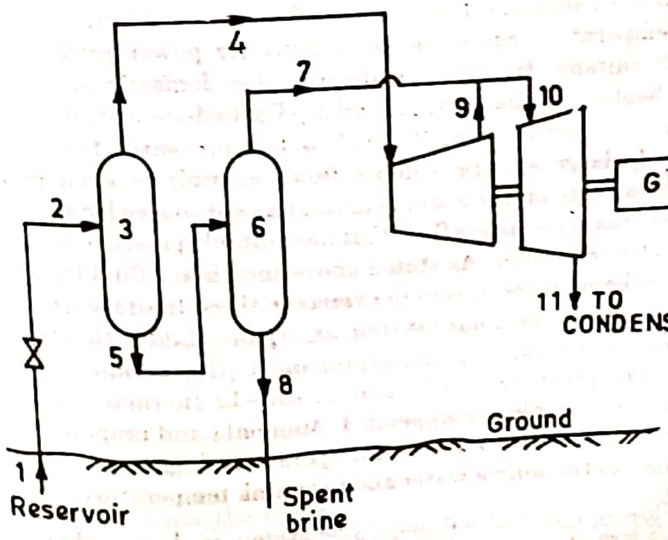
(4) Greater corrosion of piping, well casing, and other conduits.

(5) Many times temperature and pressure of the water may not be sufficient to produce the flash steam.

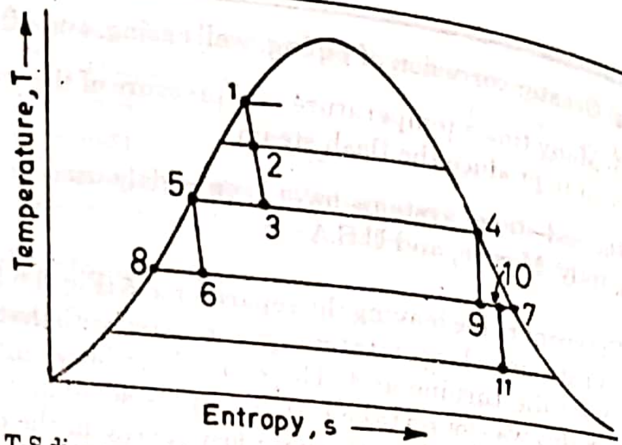
Flashed-steam systems have been widely used in Japan, New-zealand, Italy, Mexico, and U.S.A.

The spent brine leaving the separator at 5 (Fig. 8.5.3) has a large mass-flow rate and a large total energy compared with that in the steam used to drive the turbine at 4. The ratio of the brine enthalpy to the steam enthalpy was found to be 1.31 : 1. Improvement in the cycle would therefore use some of this otherwise lost energy in the cycle. *Double flash cycle* can give more power than the single flash cycle under the same condition.

Figs. (8.5.4 *a* and *b*) show a schematic flow and T-S diagram of a double flash steam system. Depending upon the original water conditions, the brine at 5 is admitted to a second, lower-pressure separator, where it flashes to a lower-pressure steam (6) that would be admitted to a low-pressure stage in the turbine. The remaining spent brine at 8 is reinjected in to the ground. An example of the double-flash system is the 50 MW Hatchobaru plant build on the island of Kyushu in Japan. It uses an innovative steam condenser and gas extraction system and a dual-admission double-flow steam turbine.



(*a*) Schematic of liquid-dominated double flash steam system.



(b) T-S diagram of the liquid dominated double flash system

Fig. 8.5.4.

(b) **Liquid-Dominated Systems : Binary Cycle.** In order to isolate the turbine from corrosive or erosive materials and/or to accommodate higher concentration of noncondensable gases, the binary cycle concept is now receiving considerable attention as an alternate power cycle concept. This is basically a Rankine cycle with an organic working fluid. A heat exchanger system is used to transfer a fraction of the brine enthalpy to vaporize the secondary working fluid. Expansion through a turbine to a lower pressure, fixed by the heat rejection temperature, provides the means for power generation.

About 50 per cent of hydrothermal water is in the moderate temperature range of ~ 153 to 205°C. This water which is available in lower temperature ranges is unsuitable for power production. It is however suitable for direct utilization for domestic and industrial process heating. If this water is used in a flashed-steam system, it would have to be throttled down to such a low pressures that results in excessively large specific volume flows as well as even poor cycle efficiencies. Instead this water is used as a heat source for a closed cycle that uses another working fluid that has suitable pressure temperature volume characteristics. As stated above the binary fluid (or two fluid) system, is being investigated to overcome these limitations of flashed steam system. In the binary system an organic fluid with a low boiling point, such as *isobutane* (2 methal propane) C_4H_{10} (normal boiling point at one atm. pressure = 10°C) and Freon—12 (normal boiling point – 29.8°C) are usually recommended. Ammonia and propane may also be used. The working fluid would operate at higher pressures, corresponding to the source water and heat-sink temperatures.

Flow diagram of a binary-cycle system is shown schematically in Fig. (8.5.5). Hot water or brine from the under-ground reservoir,

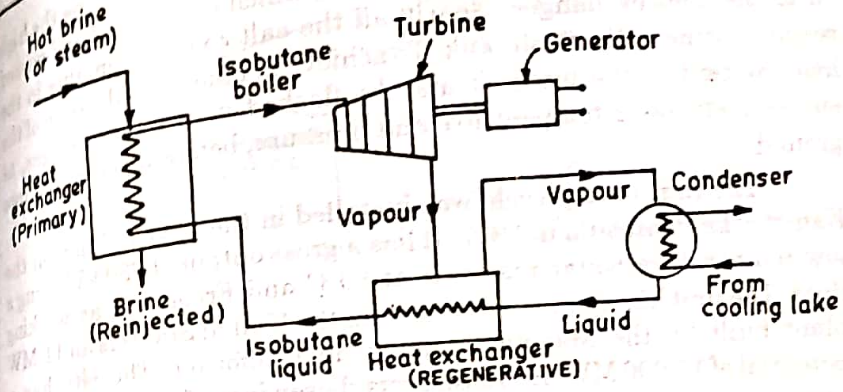


Fig. 8.5.5. Binary-fluid geothermal power system.

either as unflashed liquid or as steam producing by flashing is circulated through a primary heat exchanger. In the heat exchanger the hot brine transfer its heat to the organic fluid thus converting it to a superheated vapour that is used in a standard closed Rankine cycle. The vapour drives the turbine-generator. The exhaust vapour from the turbine is cooled in the regenerative heat exchanger and then condensed, using either and air-cooled condenser or a water-cooled condenser and cooling tower. The condensed liquid organic fluid is returned to the primary heat exchanger by way of the regenerative heat exchanger. The hot geothermal fluid and the organic fluid, constitute the two fluids of the binary-fluid system.

The condenser is cooled by water from a natural source, if available, or a cooling tower circulation system. The blow down from the tower may be reinjected to the ground with the cooled brine. Make-up of the cooling-tower must be provided however.

In the binary cycle there are no problems of corrosion or scaling in the working cycle components, such as the turbine and condenser. Such problems are confined only to the well casing and the heat exchanger. The heat exchanger is a shell-and-tube type so that no contact between brine and working fluid takes place.

If the temperature and salinity of the geothermal brine are not high, the tendency for solids (scale) to deposit on surfaces in the heat exchanger is not too great. The liquid brine under pressure may then be pumped directly through the heat exchanger and reinjected into the geothermal reservoir.

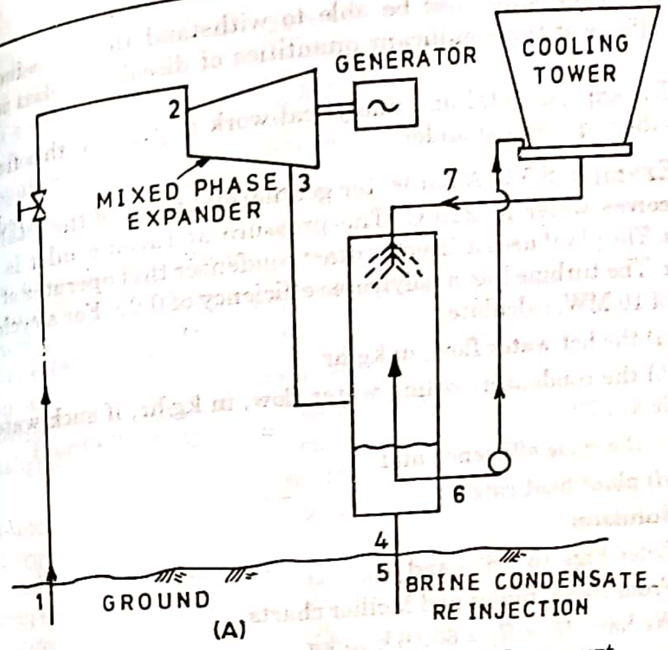
However, where the temperature and salinity of the brine are high, this procedure may not be practical because the heat exchangers may soon be rendered ineffective by scale deposition. Methods for scale control and removal are being developed, but in the meantime the high temperature brine is flashed into steam, which is scrubbed and passed on to the heat exchanger. Nearly all the salt content remains in the residual brine in the flash tank. To achieve maximum utilisation of the heat content of the brine, it may be flashed in two more stages, at successively lower temperature and pressure, before it reinjected into ground.

The first binary cycle was installed in the Soviet Union on the Kamchatka Peninsula in 1967. It has a gross output of 680 kW using a low temperature water reservoir at 80°C and Freon—12 as working fluid. The first binary cycle to be built in the United States is an 11-MW plant built by the Magma Company in California. The site has a potential of 10,000 MW. Isobutane was chosen in preference to Freon-12 primarily because of its lower cost. A second U.S. binary cycle plant is being built at Raft River Idaho. It is a 10 MW plant.

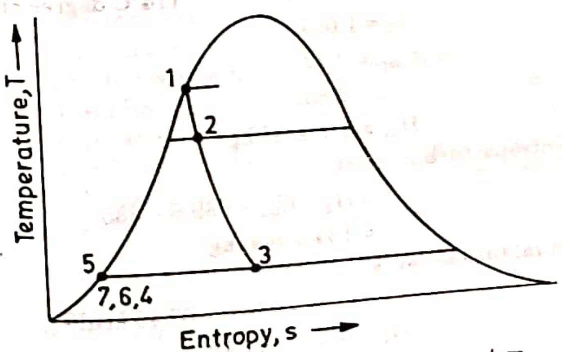
(c) **Total Flow Concept.** A third approach called the *total-flow concept* would utilize both the kinetic energy and the heat energy of the steam-liquid mixture produced by flashing the geothermal brine. The overall efficiency for conversion into electrical energy should be greater than in the methods described above in which only the heat content of the brine is utilized. One proposed total flow system utilizes the principle of the Lysholm machine known in this connection as the helical rotary (or screw) expander (or mixed phase expander). The expander is simply a compressor in reverse.

The principle of the total flow concept is simple. The flow and T-S diagrams are shown in Fig. (8.5.6 *a* and *b*). The hot brine from geothermal well at 1 is throttled to 2, where it becomes a two-phase mixture of low quality. The two phases at this point are not separated, the full flow is expanded to 3, condensed to 4. Then the brine is reinjected into the ground at 5. Comparing the T-S diagrams of Figs. (8.5.3 *b*) and (8.5.6 *b*) show that the throttling process 2-3 that occurs in the flash separator in the former is no longer necessary and that, considering equal pressures at 2, the full available energy at 2 is used in the latter, while part of it is destroyed in the former as a result of throttling. In addition the flow in the flashed-steam turbine and hence the work per unit flow from the well head is only a small fraction, equal to the quality in the flash separator, x_3, of the total flow and work that would occur in the latter.

The other characteristic of total flow concept system is that it requires the use of a *mixed phase expander* powered by a two phase mixture of low quality (as indicated by point 2 in figure). Whereas flashed steam systems and vapour-dominated systems rely on axial-flow multistage steam turbines similar to those used in conventional



(*a*) Schematic of a liquid-dominated total flow concept.



(*b*) T-S diagram for liquid-dominated total flow system.

Fig. 8.5.6.

power plants, only difference is that they are designed for much power pressures. These turbines use relatively clean high quality or even superheated steam.

The *requirements* of mixed phase expanders are that they should be able to overcome the losses associated with the impingement of liquid droplets on blades (turbine operates less efficiently as the quality decreases). They must also be able to withstand the corrosive and erosive effects of the significant quantities of dissolved solids in the brine.

The experimental and analytical work is going in this field to develop the required expander.

Example 8.5.2. A hot water geothermal plant of the total flow type receives water at 225°C. The pressure at turbine inlet is 10.5 kg/cm^2a. The plant uses a direct contact condenser that operates at 0.35 kg/cm^2a. The turbine has a polytropic efficiency of 0.65. For a cycle net output of 10 MW, calculate :

(*a*) the hot water flow, in kg/hr :

(*b*) the condenser cooling water flow, in kg/hr, if such water is available at 27°C,

(*c*) the cycle efficiency and

(*d*) plant heat rate.

Solution.

Refer Figs. (8.5.6) *a* and *b*.

From steam tables and Mollier charts,

We have $H_1 = H_2 = 669.6$ kcal/kg

Pressure at point 2, is 10.5 kg/cm^2

Thus, $T_2 = 195°C$ (14°C degree of superheat)

$s_2 = 1.567$

$v_{sup} = 0.27$

$x_{3s} = 0.832$

$H_{3s} = 535$ kcal/kg

Isentropic turbine work

$= H_2 - H_{3s} = 669.6 - 535$

$= 134.6$ kcal/kg

Actual turbine work

$= 0.65 \times 134.6 = 87.49$ kcal/kg

$H_3 = 669.6 - 87.49$

$= 582.11$ kcal/kg

h_{4-5} (ignore pump work)

$h_4 = 72.4$ kcal/kg

h_6 at 27°C $= 27.0$ kcal/kg

Turbine steam flow or Hot water flow :

$$= \frac{\text{Power output}}{\text{Actual turbine work}}$$

$$= \frac{10 \times 10^6 \times 0.86}{87.49}$$

$= 0.983 \times 10^5$ kg/hr. **Ans.**

Condenser cooling water flow $\dot{m}_4$:

$$\dot{m}_3 \times (H_3 - h_4) = \dot{m}_4(h_4 - h_6)$$

or $$\dot{m}_3 = \frac{582.11 - 72.4}{72.4 - 27} \times 0.983 \times 10^5$$

$= 14.03 \times 10^5$ kg/hr. **Ans.**

Heat added $= H_1 - h_4$

$= 669.6 - 72.4 = 597.2$ kcal/kg

Plant efficiency $= \dfrac{\text{Turbine work}}{\text{Heat added}}$

$= \dfrac{87.49}{597.2} = 0.1465 = 14.65\%$ **Ans.**

Plant heat rate $= \dfrac{860}{\text{Plant efficiency}}$

$= \dfrac{860}{0.1465} = 5870$ kcal/kWh. **Ans.**

Liquid Dominated (Low temperature) **Systems** (Hot water resources). The low temperature below 150°C, liquid dominated reservoirs are the most numerous hydrothermal source in the world. The main use would be to provide heat for homes, commercial, industrial, and agricultural buildings, including greenhouses and animal shelters, and for food and industrial processes. Hot water can also be utilised for air conditioning and refrigeration. The general principles of possible applications are the same as those considered in connection with solar energy thermal applications.

Because the water temperature is not very high, little mineral matter is extracted from the rock medium ; hence, the mineral salt content of the water is usually small. The geothermal water is then not very corrosive, and it can often be circulated directly through a heat distribution system and reinjected into the ground. If there is danger of corrosion, however, a heat exchanger would be used to transfer heat from the natural hot water to ordinary service water which is then distributed. The relatively small geothermal water circuit could then be made of more expensive corrosion-resistant materials. Economic use of the hot water referred to above depends on the proximity of utilization centres. It does not appear to be feasible at present to transport hot water for distances greater than about 24 km. This is so partly because of the cost of the pumps, piping etc., and partly because heat losses increase with distance. The cost of installing a distribution system in an existing city would be prohibitive, but in a new housing development the hot-water piping could be laid at the same time as that for service water. If the hot water can not be used directly in the vicinity of its source, the heat may be converted into electrical energy which can be transmitted to more distant points. A binary cycle could be used in which the hot water serves to vaporize and heat a liquid of low boiling point, as described earlier. Whether or not such a system for generating electricity will prove to economic depends on circumstances (*e.g.* cost of drilling wells, temperature of the hot water, availability of condenser cooling water, etc.).

8.6. Geopressured Resources

Drilling for oil and gas has revealed the existence of reservoirs containing salt water at moderately high temperatures and very high pressures in a belt some 1200 km in length. Because of the abnormally high pressure of the water, up-to 1350 atm. (137 MPa) in the deepest layers, the reservoirs are referred to as geopressured. This was observed along the Texas and Louisiana coasts of the Gulf of Mexico (U.S.). The geopressured hot water (or brine) reservoirs were apparently formed by accumulation of geothermal heat stored over several million years, in water trapped in a porous sedimentary medium by the overlying impervious layers. The upward loss of heat is relatively small and there are no obvious surface indications of the deep, high temperature reservoirs. In typical geopressured systems in Texas, the pressures are from 680 to 950 atm. (68 to 95 MPa) and temperatures from 160 to 200°C at depths from 4 to 5 km. Higher pressures and temperatures have been measured at greater depths. The amount of dissolved salt in the water varies with the location and depth of the reservoir, ranging from very small to about three times that in sea water.

A special feature of geopressured waters (or brines) is their content of methane (natural gas). The energy value of the brines thus depends on their temperature. The solubility of Methane in water at normal pressure is quite low, but it is increased at the high pressures of the geothermal reservoirs. When the water is brought to the surface and its pressure reduced, the methane gas is released from solution. The gas content of geopressured brine is usually about 1.9 to 3.8 cu m. gas per cu m. water but higher values have been reported in brief tests. However, the amount of natural gas recoverable economically from geopressured reservoirs is presently unknown.

8.7. Hot Dry Rock Resources or Petrothermal Systems

Petrothermal systems are those that are composed of hot dry rock (HDR) but no underground water. They represent by far the largest geothermal resource available. The rock, occurring at moderate depths, has very low permeability and needs to be fractured to increase its heat transfer surface. The thermal energy of the HDR is extracted by pumping water (or other fluid) through a well that has been drilled to the lower part of the fractured rock. The water moves through the fractures, picking up heat. It is then travels up a second well that has been drilled to the upper part of the rock and finally back to the surface. There, it is used in a power plant to produce electricity.

These types are not associated with hydrothermal activity. Such resources, with rock temperatures exceeding about 200°C at depths upto 5 km, are estimated to be significant and worthy of development as a source of energy. Hot dry rocks exist because they are impermeable to water or because water does not have access to them. Quite often both conditions occur ; that is to say, the rocks are impermeable and there is little or no surface water in the vicinity. In principle, the recovery of heat from such hot dry rocks involves breaking up or cracking the rock to make it permeable and then introducing water from the surface. The water is heated up by the rock and is returned to the surface where the heat is utilized as stated above.

There are two methods to tap this geothermal energy one possible method is to detonate a high explosive at the bottom of a well drilled into the rock. This may be a nuclear explosive. Water would be injected into this well, circulated through the cavities so formed to extract heat from the rock. The water or water-steam mixture is withdrawn through another well (Fig. 8.7.1).

Another method is to use hydraulic fracturing to produce the heat transfer surface and permeability required to extract energy at a high rate from hot dry rock. Hydraulic fracturing, which is performed by pumping water at high pressure into the rock formation, is commonly used in oil and gas fields to improve the flow. The crack produced in this manner is roughly in the from of a large, thin vertical disk, resembling a pancake, possibly a few hundred meters in diameter but less than a centimeter thick. Heat can then be extracted from the hot rock by circulating water through the crack.

The hot water or water steam mixture is utilized for generation of electricity with a binary liquid system using Freon (R—114) as the turbine working fluid.

A feature of this scheme is that, as the reservoir heat is depleted with time, temperature differences within the rock result in stresses that cause the original fractures to propagate, thereby unlocking more HDR surface to the water and resulting in a pancake-shaped fracture zone.

It is believed that HDR systems offer more flexibility in operation and design than other geothermal systems. For example, the designer can have a choice of water flow rates and temperatures by drilling to various depths, and the operator can change pumping pressure and hence flow rates to suit load conditions.

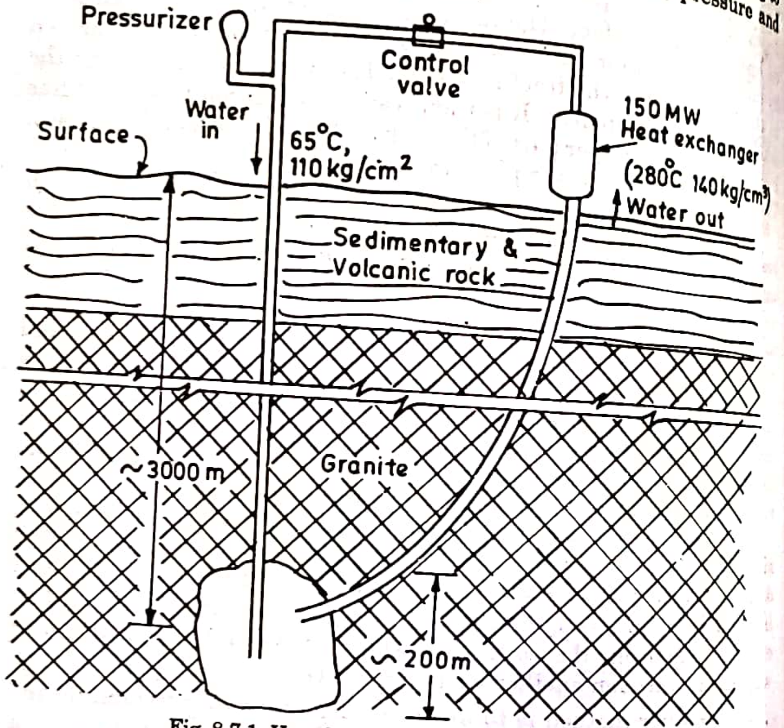


Fig. 8.7.1. Heat Extraction from Hot dry Rocks.

One of the uncertainties associated with the hydraulic fracturing and heat extraction procedure is the useful life time of the cracked region. This can be determined only be continued testing. However computer modeling suggests that, as heat is extracted, the cracking should be increase with time and make more hot rock accessible to water. The effective life time of the fractured system should thus be extended.

There are problems which are faced by developers include leakage of water (or other fluid) underground and the necessity of make up for it from resources above ground, the effect of the water or fluid on rock composition ; material carryover with the fluid, and cost. It should be noted that two wells are to be drilled instead of the one for the hydrothermal energy and that these wells are drilled deeper and in much harder rock. This is expected to make petrothermal exploitation very costly, unless the underground rock being developed is very hot.

Many more studies on the mechanical, thermo-dynamic ; and economic aspects of petrothermal systems are necessary before commercial exploitation becomes feasible.

8.8. Magma Resources (Molten rock-chamber systems)

In some cases, especially in the vicinity of relatively recent volcanic activity molten or partically molten rock (*i.e.* magma) occurs at moderate depths (*e.g.* less than 5 km). The very high temperature above 650°C and the large volume make magma a substantial geothermal resource. However, extraction of the heat from the molten rock will be difficult and may not be feasible for some time.

A concept being studied for the U.S. Department of energy by the Sandia National Laboratories is to place a heat exchanger within the magma. Heat would be transferred to a suitable liquid and brought to the surface. The hot liquid could be used to produce a working fluid, possibly steam, to operate a turbine and electric generator. The liquid would then be recirculated through the heat exchanger in the magma. One problem would be to construct a heat exchanger that will withstand the high temperatures of the magma. Another is to maintain flow of the viscous magma around the heat exchanger to provide a steady supply of heat and to prevent deposition of solid.

The capital cost of discovery, development and installation of geothermal heating systems have tended to discourage their use for power generation or process heating. Of course exceptions are the areas where geothermal resource was found by chance or was known to exist at shallow depths. For the production of electric power from geothermal sources however, the costs are comparable to or lower than those of all other methods except hydro-electric. Although the geothermal energy sources that are now used for electric power generation are of the shallow-steam reservoir type but in near future with technological developments, deeper reservoirs, fractured rocks and other schemes like molten magma will probably be used and may become economical in future.

8.9. Comparison of Flashed Steam and Total Flow Concept

A cycle diagram comparing the various liquid, dominated (the flashed steam) and total flow methods on the T-S diagram is shown in

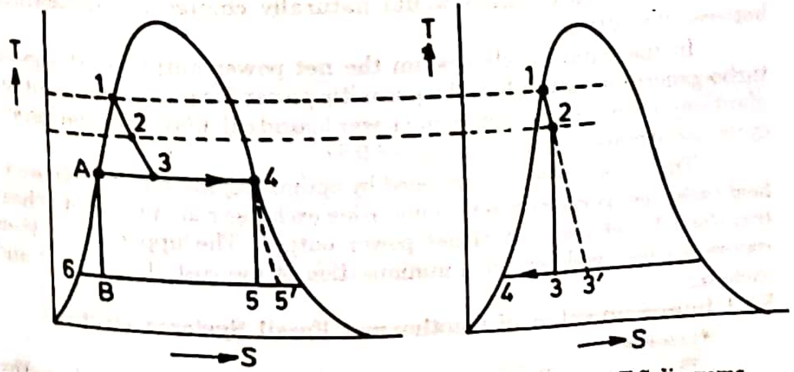


Fig. 8.9.1. Flashed steam process and total flow process on T-S diagrams.

Fig. (8.9.1). From the comparison it is very much obvious that direct expansion of the total well head product is thermodynamically the simplest and provides an upper bound on cycle efficiency regardless of the number of stages of separation used in the flashed steam system.

In both the systems condensing is accomplished with a barometric direct-contact condenser. For high salinity water, however, the condenser for the total flow system will require modification to separate brine fraction from the vapour-fraction in order to prevent fouling of the cooling system.

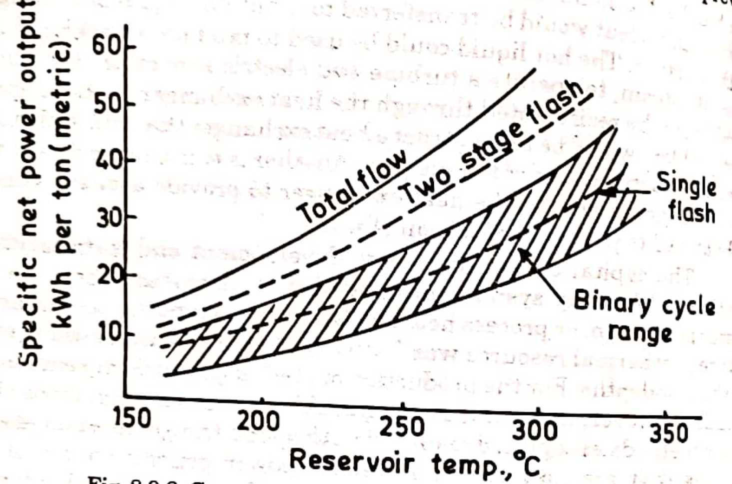


Fig. 8.9.2. Comparison of various liquid dominated systems.

Fig. (8.9.2) shows the results of an analytical comparison of various liquid dominated systems. The curves indicating that the total flow concept produces the highest specific power per unit mass-flow rate at the well head. The calculations were based on the same condeser temperatures of 50°C (120°F), the same turbine efficiencies of 85 per cent, and the same in-plant-power requirements of 30 per cent of the gross. Differences in these would naturally change the differences between the curves.

In the binary cycle system the net power output is the gross turbo-generator output less the parasitic power for pumping and other plant requirements. An upper and lower bound calculated for the binary cycle performance is given in Fig. (8.9.2).

The above curve was obtained by optimizing the system relative to heat exchanger performance by minimizing exchanger area per unit of heat transferred and per unit of net power output. The upper curve then represents the condition for a minimization of the cost of both well and exchanger.

8.10. Interconnection of Geothermal Fossil Systems (Hybrid Systems)

The concept of hybrid geothermal-fossil fuel systems utilizes the relatively low-temperature heat of geothermal sources in the low-temperature end of a conventional cycle and the high temperature heat from fossil-fuel combustion in the high temperature end of that cycle. The concept thus combines the high-efficiency of a high-temperature cycle with a natural source of heat for part of the heat addition, thus reducing the consumption of the expensive and non-renewable fossil fuel.

Arrangement for hybrid plants : There are two arrangements :

(*i*) geothermal preheat, and (*ii*) fossil superheat.

Geothermal preheat arrangement is suitable for low-temperature liquid-dominated systems whereas fossil superheat system is suitable for vapour-dominated and high temperature liquid-dominated systems.

1. Geothermal-Preheat Hybrid Systems. In these systems, the feed water of a conventional fossil-fueled steam plant is heated by low temperature geothermal energy. Geothermal heat replaces some or all, of the feedwater heaters, depending upon its temperature. A cycle operating on this principle is illustrated schematically in Fig (8.10.1), In it, geothermal heat heats the feed-water throughout the low-temperature end prior to an open-type deaerating heater. It is followed by a boiler feed pump and three closed-type feedwater heaters with drains cascaded backward. These receive heat from steam bled from higher-pressure stages of the turbine. No steam is bled from the lower pressure stages because geothermal brine fulfills this function.

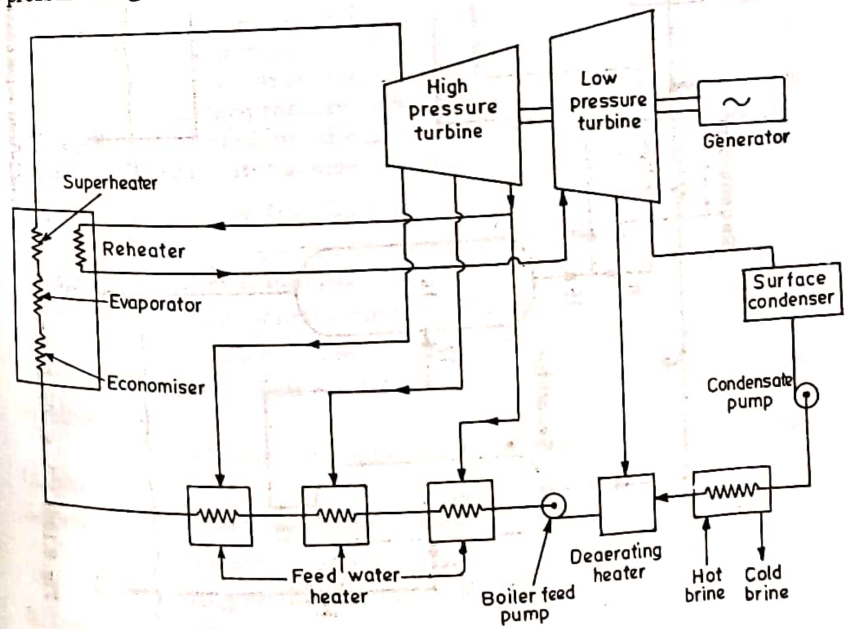


Fig. 8.10.1. Schematic of a geothermal preheat hybrid system.

2. Fossil-Superheat Hybrid Systems. In these systems, the vapour-dominated steam or the vapour obtained from a flash separator in a high-temperature liquid-dominated system is super-heated in a fossil-fired superheater. Based on this principle, a cycle is illustrated in Fig (8.10.2) and T-S diagram of the system is shown in Fig. (8.10.3). The

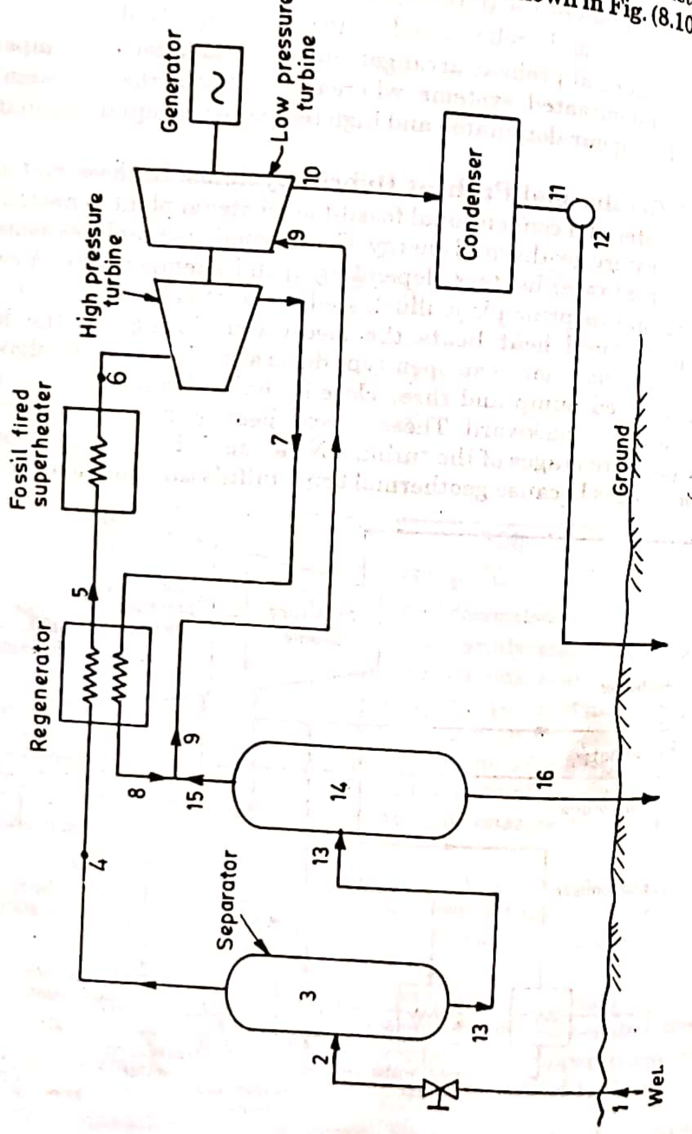


Fig. 8.10.2. Schematic of a fossil-superheat hybrid system with two-stage flash separator, regenerative and fossil-fired superheater.

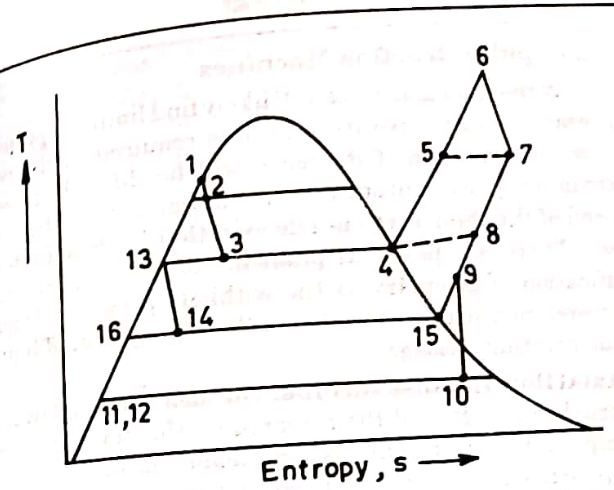


Fig. 8.10.3. T-S diagram for Fossil-superheat systems in Fig. (8.10.2).

system consists of a double-flash geothermal steam system. Steam produced at 4 in the first-stage flash separator is preheated from 4 to 5 in a regenerator by exhaust steam from the high-pressure turbine at 7. It is then superheated by a fossil fuel-fired superheater to 6, and expands in the high-pressure turbine to 7 at a pressure near that of the second-stage steam separator. It then enters the regenerator, leaves it at 8, where it mixes with the lower-pressure steam produced in the second-stage flash separator at 15, and produces steam at 9, which expands in the lower-pressure turbine to 10. The condensate at 11 is pumped and reinjected into the ground at 12. The spent brine from the second-stage evaporator is also reinjected into the ground at 16.

8.11. Prime-Movers for Geothermal Energy Conversion

The prime-movers can be classified as below :

1. Impulse/Reaction machines

(a) Axial flow—curtis, Rateau steam turbine.

(b) Radial inflow—Francis turbine, multiple disc drag turbine.

(c) Radial outflow—rotating nozzle (pure reaction), Hero's turbine.

(d) Multiple disc turbine—bladeless impulse or reaction drag turbine.

2. Positive displacement machines

(a) Helical, screw expander.

(b) Rotating oscillating vane machine.

3. Impulse machines

(a) Tangential flow-pelton wheel, Re-entry type turbine.

(b) Axial flow, De-Laval turbine, Curtis turbine.

8.11.1. Impulse Reaction Machines

Generally reaction machines will likely find limited applications. Since the pressure and temperature drop is required in the rotating component, scale formation if it occurs will be difficult to remove. Further, maximum power output requires a high ratio of tip speed to absolute speed of the fluid at the nozzle exit, that leads to high speeds and stresses. There are practical problems of maintaining rotating seals, modification of geometry as the withheld pressure drops with time and lowered nozzle efficiency due to the segregation of liquid and vapour in the rotating passage.

(*a*) **Axial flow Impulse turbine.** The idea of axial flow impulse turbine is tried in USSR, and the research on the performance of an axial flow impulse turbine to which water/steam mixtures are admitted through expansion nozzle is conducted at the Lawrence Livermore laboratory, it was found that the power developed from the water/steam mixtures from a text bore was virtually the same as that produced from the steam phase alone from the same well, but that the optimal rotational speed was nearly twice as much with the steam as with the wet mixture.

(*b*) **Radial outflow turbines.** Two phase outflow nozzle driven reaction machine is shown in Fig. (8.11.1). The hot water at high pressure is expanded through a nozzle to a pressure below the saturation pressure of hot water, water vapours are produced. As the specific volume of water vapour is less than that of the liquid water only a small

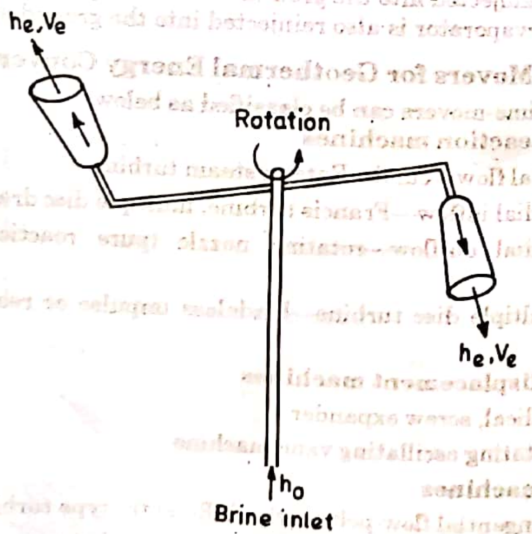


Fig. 8.11.1. Radial outflow turbine.

fraction of liquid needs to vapourise to give a mixture primarily rich in gas phase with water droplets entrained in it. If the liquid droplets are assumed to be at the same velocity as the gas then

$$\frac{U^2}{2gJ} = h_i - h_e = \text{heat drop.}$$

If the nozzle is stationary then workdone = 0, but if say two nozzles are attached to shaft then a rotating-couple will act and make it rotate.

Advantages

(*i*) The principle is simple.

(*ii*) Construction too is easy.

Disadvantages are :

(1) For reasonable outputs the exhaustages velocity relative to nozzle has to be 330 m/sec (1000 ft/sec).

(2) To accelerate the liquid droplets to the same velocity as that of the gas large nozzles are required.

(3) Fluid friction on the droplets made the process irreverssible.

(4) There is a gas drag on the nozzles as a result of rotational speed in the exhaust chamber.

(*c*) **Hero's Turbine** (Armstead-Hero turbine). The intended purpose of this concept is to provide a cheap turbine capable of handling wet or dry geothermal fluids at the well heads of newly sunk productive bores, so as to put to immediate use the fluid that would normally be blown to waste. It would thus serve as a pilot plant. As a pilot plant it could be moved from field to field as new fields are explored. It is a reaction turbine of the simplest type. For use with dry steam the arrangement shown in Fig. (8.11.2*a*) is used, steam being admitted

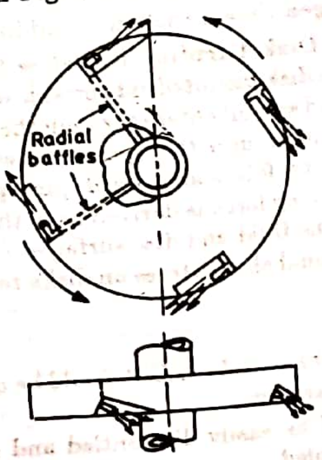


Fig. 8.11.2 (*a*)

through the hollow shaft and discharge through tangential peripheral nozzles provided with small axial rake to clear the exhaust away from the flat cylindrical rotor. For wet steam, the two phases would be separated within the rotor itself by centrifugal action and the use of scoop Fig. (8.11.2*b*) that enable the water to be discharged at a velocity

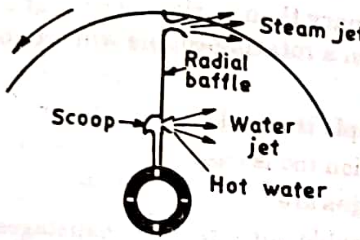


Fig. 8.11.2 (*b*)

appropriate to its intrinsic heat energy (which would be less than that of the steam discharged at the periphery). The water jet quantity would be self-adjusting owing to the behaviour of boiling water when passing through bell mouthed orifices. Advantage is taken of the moderate sacrifice of efficiency resulting from a large drop in rotational speed to limit the speed to a practicable maximum value.

Advantages :

(1) As already mentioned it is the cheap type of turbine that can handle all quality geothermal fluids (by changing fixed nozzles). Absence of blades make it simple.

(2) It can serve as a pilot plant.

(3) It could also be used as an emergency stand by unit for which high efficiency is unimportant.

Disadvantages. Steam friction would limit its high efficiency.

(*d*) **Multiple Disk Turbine** (Bladeless turbine). This consists of closely spaced thin disk mounted side by side on a shaft. Geothermal fluid (hot water or/and steam) enters through the nozzles acquires high velocity and is admitted into the spaces between the discs at the periphery and directed to follow an inward spiral path towards a central exhaust port. The driving force is derived from the frictional boundary layer drag between the fluid and disc surfaces (*i.e.* during its passage the fluid exerts frictional shear stress on disks resulting in net torque on the shaft).

Advantages :

(1) Such a machine as described would be quite easy and cheap to construct and to maintain.

(2) Discs could be easily dismantled and cleaned of chemical deposits and reassembled.

Disadvantages. No detailed analysis has been made so far. As the basic mechanism for momentum transfer is friction drag and the much of energy would be wasted in frictional turbulence and the possibility that the entrained liquid droplets will be thrown radially outward by centrifugal forces, the turbine efficiency is low.

8.11.2. Positive Displacement Machines

(A) Keller Rotor Oscillating Vane Machine. This is a positive displacement machine designed to handle all quality geothermal fluids. Its somewhat fanciful action is self evident from Fig. (8.11.3).

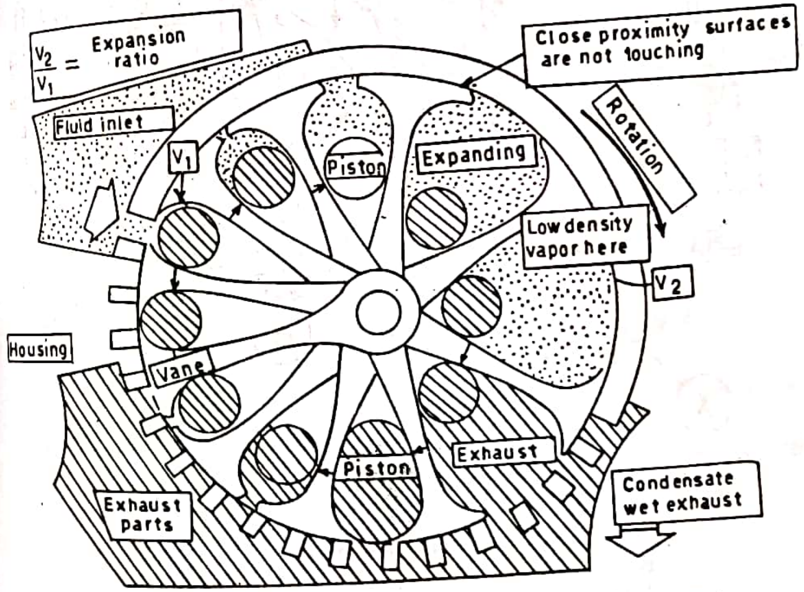


Fig. 8.11.3. Diagrammatic representation of the KROV (Keller Rotor Oscillating Vane) positive displacement machine.

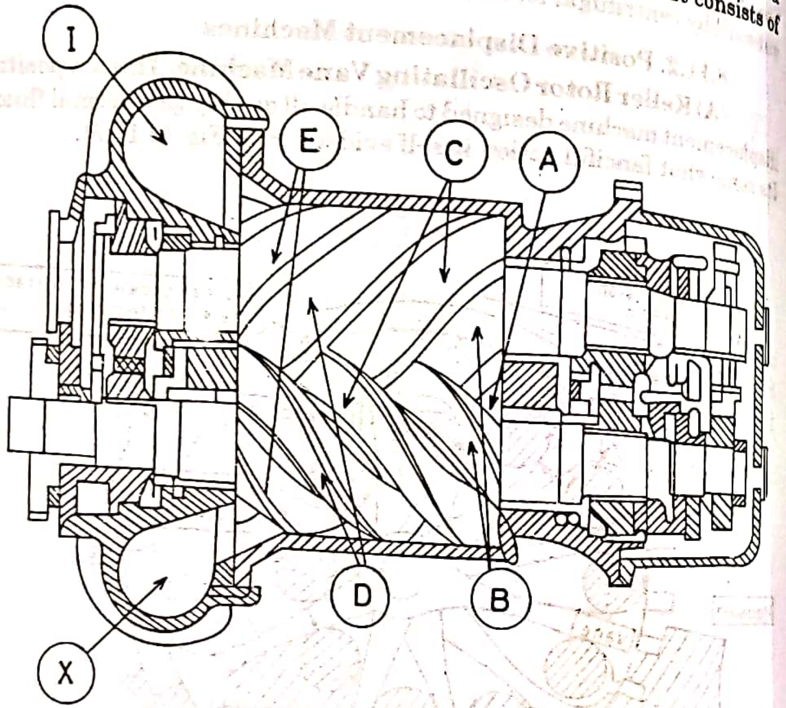
Advantages. The advantage is that it can handle variety of geothermal fluids, (dry steam and or/geothermal hot water, it can handle very wet steam too).

Disadvantages : (1) It is mechanically quite complex and dependent upon the contact between the rotor piston and vane for sealing during expansion. Even then it offers high expansion ratios.

(2) The efficiency of the device is thus low due to the above mentioned reason.

(B) The Helical Rotor Expander (Sprankle HPC prime movers Hydrothermal Power Co.) :

A prototype of this machine is actually working in the Salten Sea area, California. It is illustrated in Fig. (8.11.4 *a* and *b*). It consists of

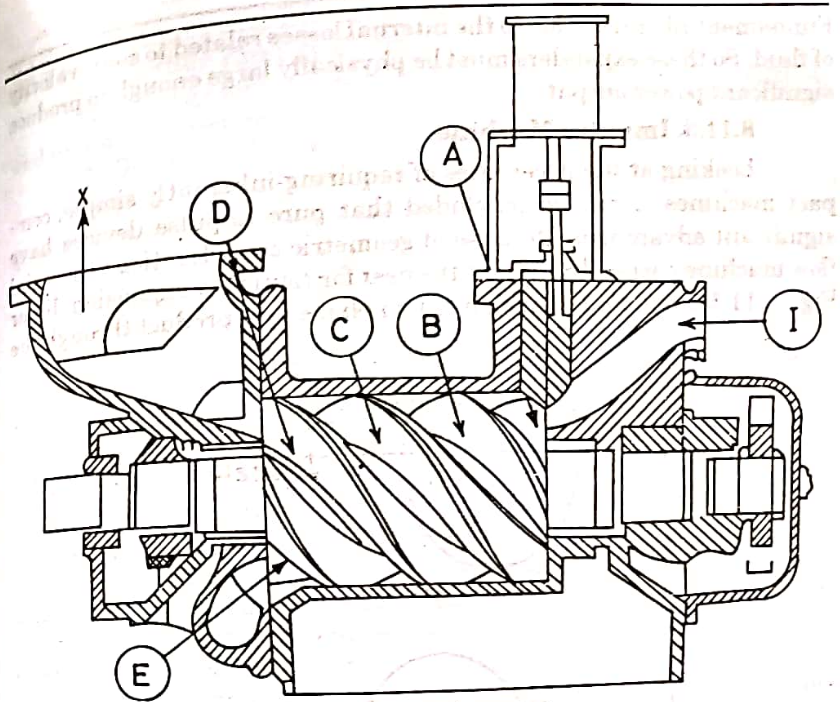


PLAN SECTION VIEW

(*a*)

A High pressure entry pocket
B, C, D } Successive regions occupied by expanding fluid as the passage elongates, and the point of meshing of the screws appears to retreat axially from the expanding prime.
E
I Inlet port
X Exhaust port

two intermeshed helical gears. Such a machine when driven by external power can work as a compressor, when used in reverse it can act as a positive displacement prime mover. It is principally meant for hot brines. The hot brine is admitted to the rotors at point. A, and passes through the helical passages B, C and D falling in pressure and flashing off vapour as it proceeds, being finally exhausted from E. The pressure exerted by the fluid upon the helical vanes produces a rotary driving force. It is thus a two phase flow machines.



SIDE SECTION VIEW

(*b*)

Fig. 8.11.4. The Sprankle (Hydrothermal Power Co.) double helical hot brine expander.

Advantages : (1) It is mechanically simple and self clearing as a result of rotor-to-rotor case relative motion.

(2) The makers are offering units upto 5 MW capacity and claim that the process approximates to an isentropic expansion from a saturated liquid. Thus the efficiency of the unit is high.

(3) No scale deposition problem arises with 1000 hrs of continuous operation with brines.

Disadvantages : (1) If the brine concentration is at the saturated salts are likely to be deposited on the helical and stator surfaces and the rubbing action is alleged to form a hard salt surface, sealing the machine against leakage and short circuiting of fluids past their intended path through the machine.

(2) The machine weight per kW of output is quite high.

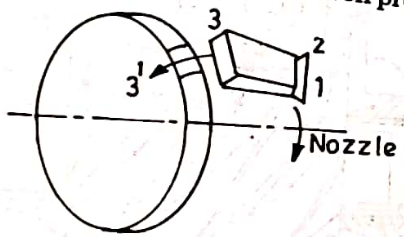
(3) It will also be necessary to establish whether the long term effects of flashing will be damaging to the machine surfaces in a way that cavitation damages the marine propellers.

(4) Positive displacement machines are limited in volume flow rate capacities relative to impulse reaction or pure impulse ones.

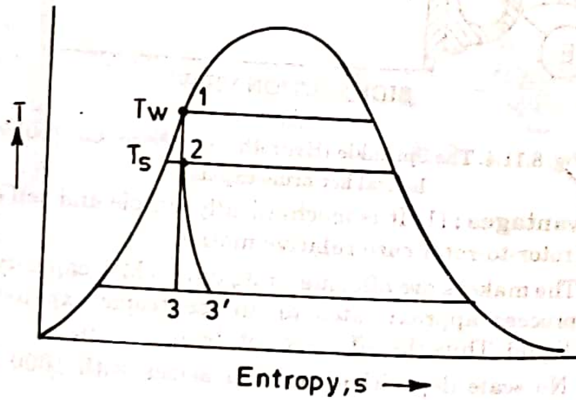
Fundamentally this is due to the internal losses related to sonic velocity of fluid. So these expanders must be physically large enough to produce significant power output.

8.11.3. Impulse Machine

Looking at the necessities of requiring-inherently simple, compact machines it can be concluded that pure impulse devices have significant advantages. Because of geometric considerations the axial flow machine currently appears the best for total flow expansion. Refer Fig. (8.11.5 *a* and *b*). Expansion of two phase well product through the



(*a*)



(*b*)

Fig. 8.11.5. Principle of Impulse Machine for Geothermal Power Plant.

convergent-divergent nozzle converts the brine thermal energy at high well-head pressure at 2 to kinetic energy in the form of high velocity fluid stream at back pressure 3. The wheel efficiency is a measure of the wheel's ability to convert fluid kinetic energy in to shaft work. It is a function of blade geometry, turbulence, fluid friction, exist losses fanning losses etc. Advantages are already given above (like simplicity, compactness, high mass flow handling capacity, high efficiency.)

The disadvantage is that the intersection of liquid droplets with the turbine blade during passage of the two phase supersonic flow lessens the efficiency.

8.12. Advantages and Disadvantages of Geothermal Energy over other Energy Forms

This energy form possess distinct *advantages* over conventional and new energy sources :

(1) Geothermal energy is versatile in its use.

(2) It is cheaper, compared to the energies obtained from other sources both zero fuels and fossil fuels.

(3) Geothermal energy delivers greater amount of net energy from its system then other alternative or conventional systems.

(4) Geothermal power plants have the highest annual load factors of 85 per cent to 90 per cent compared to 45 per cent to 50 per cent for fossil fuel plants.

(5) Geothermal energy is the least polluting compared to the other conventional energy sources.

(6) The greatest attraction of geothermal energy is its amenability for multiple uses from a single resource.

(7) Geothermal energy is the renewable resource that has practically no intermittency, has the highest energy density, and is economically not far removed from conventional technologies, Geothermal energy is classified as renewable because the earth's interior is and will continue in the process of cooling for the indefinite future. Hence, geothermal energy from the earth's interior is almost as inexhaustible as solar or wind energy, so long as its sources are actively sought and economically tapped.

This energy has also got the following *disadvantages* :

(1) Overall efficiency for power production is low, about 15 per cent, compared to 35-40 per cent for fossil fuel plants.

(2) The withdrawal of large amounts of steam or water from a hydrothermal reservoir may result in surface subsidence (or settlement).

(3) The steam and hot water gushing out of the earth may contain H_2S, CO_2, NH_3 and radon gas etc. If these gases are vented into the air, air pollution will be a real hazard. These gases are to be removed by chemical action, before they are discharged.

(4) Drilling operation is noisy.

(5) Large areas are needed for exploitation of geo-thermal energy as much of it is diffused.

8.13. Applications of Geothermal Energy

There are three main applications of the steam and hot water from the wet geothermal reservoirs :

(1) Generation of electric power,

(2) Industrial process heat and

(3) Space heating for various kinds of buildings.

One of the greatest benefits of geothermal energy is its varied application and versatility. Though electric power generation has been demonstrated and has taken a place of pride, still there are many other important applications. The following list is the indicative of the industries that would benefit from low grade heat between 200-250°C. *The list does not include power generation, space heating, farming and balneology.*

Desalination

Many chemical industries including extraction of valuable minerals from geothermal fluids :

Salt production from sea water
Heavy water production
Protein and vitamin production
Sulphur and sulphuric acid production
Textile industry
The dye industry
Paper manufacture
Mining, including : recovery acid upgrading of minerals
Mining in areas of intense frost (*e.g.* Siberia)
Peak dying
Plastic manufacture
Alumina from bauxite
Rayon production
Total gasification of coal (Lurgi process)
Timber seasoning
Refrigeration and Air conditioning
Mushroom culture
Powdered coffee production
Dried milk production
Fruit and juice canning and bottling
Cattle feed from Bermuda grass
Sugar processing (with the use of bagasse as an industrial material, and not as a fuel)
Sugar beet industry
The bottling of mineral water
Fish drying and fish meal production
Other food processing and corning
Crop drying (Seawood, grass etc.)
Molasses fermentation
Road heating in frosty climates
Anti-freeze for fire-fighting
Sewerage heat treatment.

Table 8.13.1. Applications of Geothermal Energy at different Temperatures

Sat. Steam	210	
	200	
	190	
	180	Evaporation of highly concentrated solutions Refrigeration by Ammonia absorption → Conventional Power Production Digestion of paper pulp (kraft)
	170	Heavy water *viz.* Hydrogen sulphide process Drying of diotomacious earth
	160	Drying of fishmeal, Drying of timber
	150	Alumina *via* Bayer's process
	140	Drying farm products at high rates : Canning of food → Conventional Power Production
	130	Evaporation in sugar refining : extraction of salts by evaporation and crystallisation. Fresh water by distillation.
Hot Water	120	Most multi-effect evaporation concentration of saline solution.
	110	Drying and curing of light aggregate cement slabs.
	100	Drying of organic materials, seaweeds, grass, vegetables, etc. washing and drying of wood.
	90	Drying of stock fish : Intense de-icing operation.
	80	Space heating (building and green houses)
	70	Refrigeration (lower temperature limit)
	60	Animal husbandry. Green houses by combined space and hot bed heating.
	50	Mushroom growing Balneology
	40	Soil warming
	30	Swimming pools, biodegradation, fermentations, warm water for year round, mining in cold areas, De-icing.
	20	Hatching of fish : Fish farming.

High grade heat is generally more versatile in applications including power generation. Whenever low grade heat is more suited to heating purposes and certain process industries.

The non-electrical application of geothermal energy is an important part of the total geothermal energy consumption. The total installed capacity of the geothermal power is only few MW compared to non-electrical consumption. The non-electrical uses of geothermal energy is about 50% of that exploited for the better known electrical use. As already mentioned that the electrical conversion efficiency is of the order of 10-12 per cent.

Low enthalpy geothermal fluids are used in the following sectors :

(1) Balneology

(2) Agriculture

(3) Aquaculture

(4) Climate control

(5) Industrial applications.

Current industrial applications of geothermal energy are given in the table (8.13.1).

Space Heating. Geothermal energy for space heating is of great importance in some countries in Iceland, for instance where about 50% of the population enjoys such heating for its homes. The geothermal fluids for such applications usually come from geothermal reservoirs at temperatures ranging from 60 to as high as 150°C. Thermal fluids within the temperature range occur at economically acceptable depths in many parts of the world, and extensive areas are known. Thus wide-spread use of this form of energy is possible.

Although geothermal space heating may serve a single house in the rural area, the most usual approach is distinct heating surfaces which serve whole areas, towns, or a city. As a rule, space heating by geothermal energy causes minimal pollution problems, in as much as there is no smoke and warm effluents are distributed widely to the sewage system in many areas where such systems have been installed the cost of energy provided is very low when compared with fossil fuels. A depreciation time for equipment of 20 to 30 years is generally used for economic evaluations.

Most distribution systems where hot water is the heating medium are single pipe system which involves the discharge of the water to the sewage system after use. The distribution temperature of the water is preferably in the range 80 to 90°C, and will cooldown to around 40°C upon use. The supply mains to the distribution system will ordinarily discharge into the storage tanks which help in taking care of daily fluctuations in hot water load. Booster pumping is usually necessary in order to maintain sufficient pressure in the distribution system.

In *house heating* application, generally central heating systems are used for houses. The hot water usually is admitted directly to these systems and discharged to sewage after use.

Agricultural and Related Applications. Geothermal energy for heating green houses is important in a number of countries. Since the temperature of the heat source will vary greatly from one location to the next, as well as variations in heating requirements, the surface area of the radiator system (often consisting of bare pipes) must be carefully tailored to local conditions. Heating fluid temperatures well above 100°C are rarely practical. Small green houses may take advantage of heat in the effluent from ordinary space heating systems. The most important crops of heated green houses of this type include

cut flowers, tomatoes, cucumbers, and seedlings of many varieties. Animal husbandry, fish farming, and hatching stations also frequently take advantage of available geothermal hot water.

Climatic Variations. Generally geothermal energy to date has been exploited for those most obvious of applications : (1) for the generation of electric power, particularly more recently with distribution and shortage problems associated with fossil fuels ; and (2) dating back many more years, for space heating and some secondary heating applications in colder climates, as has been representative of the situation in Iceland. Only modest attention has been given thus far by engineers and planners to the exploitation of geothermal energy sources which may be located in warmer climates as for cooling and for processing and manufacturing applications. In certain climatic situations, since refrigeration may be achieved through heating, it is suggested that the load factor may be improved by supplying heat for refrigeration as needed, as well as for heating when needed.

Process Heating. Since geothermal energy resources exit in many countries, it is of interest to point out some common factors which affect the viability of exploitation. Since the application for heating in cold climates and the generation of electric power are obvious uses and are receiving considerable attention, it may be well to concentrate on the possibilities for process heating uses in any climate.

Examples of application of geothermal energy for process use are given in Table 8.13.2.

Table 8.13.2. Geothermal Energy for Process Use

Product	*Application*	*Form of geothermal energy*
Pulp and Paper	Evaporating, digesting drying	Steam
Timber drying and seasoning	Drying, seasoning	Steam, hot water
Diatomic processing	Drying, heating de-icing	Steam
Sea wood drying	Drying	Hot water
Washing of wool	Heating and drying	Steam, hot water
Curing and drying of building material	Heating and drying	Steam, Hot water
Salt recovery from Sea water	Evaporation	Steam
Brewing distillation	Heating and evaporation	Steam

8.14. Material Selection for Geothermal Power Plants

Most geothermal waters contain dissolved solids. The total amount of dissolved solids is typically in the range of 300—1500 ppm (parts per million), of which silica amounts to some 25—50%. The dominant ions are sodium, chloride, and sulphate. In some areas saline geothermal waters occur resulting from sea water perculating, into the bedrock and mixing with fresh water of meteoric origin in various portions. Where seawater does not enter geothermal systems, variations in the thermal-fluids composition can be related to reservoir temperature and be correlated with mineral solubilities and ion-exchange equilibria with hydrothermal minerals. Geothermal water also contains some dissolved gases such as carbon dioxide, hydrogen sulfide, and to a lesser extent, hydrogen and ammonia. The transfer of carbon dioxide and hydrogen sulfide into the steam phase upon flashing may cause some harmful effects to some materials. When the steam condenses, substantial amounts of the carbon dioxide and hydrogen sulfide are dissolved in the condensate and render it quite acidic (pH 3—5) ; the acid condensate is highly corrosive.

Initially, when geothermal power plants were built, the same materials were used as for conventional steam power plants and experience was obtained-through failures. The general principle is that the better the alloy in regard to high-strength properties, the worse it behaves. A good deal could be deducted from careful inspection of parts, such as casing and valves after exposure for some time to geothermal fluids. Experience showed severe cutting of valve seats and faces where leakage of wet steam took place. Many valves adequate in other industries were found to be incapable of making a tight seal or closing against the flow under pressure. Stellating of the faces was the remedy and use of stainless-steel trim seemed to remedy the problem.

By the time large geothermal turbines started to be built, evolution of blade material had already settled on 12—13% chrome steel as the best all-around material. It was found to standup to hydrogen sulfide as long as it was not in the hardened state. Stellating of the blades has also been found necessary because of the wetness of the steam (approximately 12—14%). So far only limited number of manufacturers produce geothermal turbines.

To summarize, materials which have been found, through experience and testing, to perform well in various geothermal environments throughout the world and which are least corrosive in nature are :

1. *Carbon steel*, to be used for dry- and wet-steam transmission pipes and separators.

2. *Stainless steel* for nozzles and diaphragms, 12—13% chrome stainless steel for rotors.

3. Austenitic stainless steel for most metal components in the condensate cooling system.

4. Aluminium or stainless steel for most structures in atmospheric exposures.

5. Platinum or gold-rhodium platings for surfaces of electrical contacts and tin plating of all insulated copper.

6. Redwood and Douglas fir for cooling tower fill, polyvinyl chloride also preferred because of its strength and fire-retardant qualities.

8.15. Geothermal Exploration

The existence of a geothermal field is often apparent from steam or hot water at the surface. Because of high costs of geothermal drilling, however, something needs to be known about the energy potential of a reservoir before drilling is undertaken. In some geothermal fields, the surface indications provide meager (or misleading) information as to the reservoir capacity.

At present, relatively little is known about methods for predicting geothermal reservoir characteristics procedures under study include the following :

(i) *rate of upward heat flow in the ground* ;

(ii) *chemical compositions of surface and ground waters* ;

(iii) *electrical resistivity of the ground at depth* ; *and*

(iv) *passive and active seismic measurements.*

These procedures are discussed briefly below. In addition, gravity and magnetic surveys can sometimes provide useful information.

Heat Flow Rate. The heat flow (or flux) in the ground is measured in bore holes to a depth of about 100 m or more. It is commonly expressed in *heat flow units* (HFU), where 1 HFU is equal to 10^{-6} calorie per sq cm per sec (0.0418 watt per sq m). The observation of substantially higher value would indicate a possible geothermal reservoir.

Water Chemistry. Analysis of hot well or spring water can often indicate the probable origin of the water and the reservoir temperature. Concentration of mineral salts in the water may be used to distinguish between geothermal reservoirs of different types.

Electrical Resistivity. Measurements are made of the electrical resistivity of the ground at a surface depth at many points and also at several depths at a fixed location over a potential geothermal reservoir. The electrical resistivity depends largely on the salinity and temperature of the ground water and the porosity of the rocks. A low resistivity may indicate the presence of hot and/or saline water. Hot water containing substantial amounts of dissolved mineral salts is often present in wet geothermal reservoirs.

Seismic Monitoring. Geothermal reservoirs may be associated with persistent microseismic (minor earthquake) activity which can be readily directed by a *seismometer*. This is referred to as a passive seismic technique. There are some indications that the microseismic signals may be related to reservoir depth and temperature gradient.

Active seismic surveys are similar to those used in exploring for oil. A shock wave is generated in the ground by means of an explosion or impact with a heavy mass. The signals defected at a distance can provide information about the subsurface structure. More needs to be known, however, concerning the response of geothermal reservoirs in order to interpret the results.

8.16. Geothermal Well Drilling

Drilling into geothermal reservoirs is usually conducted with rotary bits in a manner similar to that used in drilling for oil or gas. Geothermal drilling is, however, more difficult and expensive. The temperatures, upto 350°C, encountered in geothermal drilling are higher than in oil (or gas) well drilling ; moreover, it may be necessary to penetrate hard, abrasive volcanic rocks. Even the best tungsten carbide bits suffer excessive wear and must be renewed frequently. The drilling muds used to lubricate and cool the drill bit deteriorate rapidly at temperatures above about 175°C. The deterioration results in an increase in viscosity, thus making circulation of the mud more difficult. The mud may form a hard, caked lining in the bell bore and ruin the production.

In dry formations or where water-bearing strata have been ceased off, a stream of air can be used instead of drilling mud. The high air velocity required to remove rock cuttings can, however, weaken the drill-pipe string by abrasion ; the drill pipe must therefore be replaced more often than in oil-well drilling. Where water is encountered, there is no choice at present other than to use ordinary drilling mud.

Efforts are being made to improve the techniques and reduce the costs of drilling wells into geothermal reservoirs. These efforts include the development of : (1) improved drill bits including special synthetic diamond bits, (2) drilling techniques that do not require rotary bits or which permit changing the cutting face while the bit is down-hole, (3) high-temperature drilling fluids and well cementing materials, and (4) well-logging instruments that can operate at high temperatures. (Well logging involves the lowering of various instruments down a well hole to provide indications of the characteristics of the formation being penetrated).

8.17. Operational and Environmental Problems

Geothermal process is not altogether a very clean process unless certain precautions are taken ; otherwise there may be pollution and

relative effects. Fortunately all these precautions can be taken easily and without spending large amounts of money. For all this it is necessary first to be aware of the possible sources of geothermal pollution and to avoid these. All such are given below briefly.

1. *Solid particles and noncondensable gases.* Steam and water from both hydrothermal systems contain, besides the dissolved solids in the water, entrained solid particles and noncondensable gases. The entrained solids are removed, usually be centrifugal separators at the well head. They are further removed by strainers, usually before turbine entry. The noncondensables gases are mostly CO_2 (about 80 percent), plus varying amount of CH_4, (methane), H_2, N_2, NH_3 and H_2S (Hydrogen sulphide). In new well, the percentage of these gases is higher ($\simeq$ 4 per cent). Besides finding their way with the fluid into the plant equipment, the noncondensables also partly escape the atmosphere *via* the particle centrifugal separators, the condensor ejectors, and in some cases the cooling towers.

The presence of the noncondensable gases has several effects. First, the large quantity of these gases, relative to noncondensables in conventional steam systems, necessitates the careful design of adequate gas ejectors to maintain vacuum in the condenser. Second, although the presence of acid forming gases cause no particular problems in dry steam lines that are made of ordinary carbon steels, their corrosive effect in wet conditions necessitates the use of stainless steel in all equipment exposed to wet steam or condensate. Such equipment includes turbine erosion shields and shaft seals, exhaust duct lining, condenser lining, condensate lines and pumps, and metal parts in cooling towers, (condensers in geothermal plants may be of the direct-contact type, and hence cooling towers are exposed to geothermal condensate). In the turbine, steam nozzles and blades subjected to dry or high quality steam are usually made of 11 to 13 per cent chrome steel. The nozzles are usually designed with large throat areas on a wide pitch to minimize scaling. Because nickel is particularly sensitive to H_2S corrosion, it is not recommended for use in the rotor. The cooling towers are usually designed with plastic fill and concrete shells, the later coated with coal-tar epoxy. Aluminium is recommended for condensate pipes and valves that are made large enough to allow low velocities and hence erosion. Aluminium is also recommended for switchyard structures that are in the open but in a generally corrosive atmosphere.

H_2S is almost always present in geothermal field. This if present in excess quantities may cause harmful effects on the bearings. This also attacks electrical equipments and it mav have adverse effects on crops and on river life.

At power plants it occurs in high concentration at the gas ejector discharge points. At some places, all regular escape path of H_2S are being trapped and the gas is being burned to form SO_2 which is then scrubbed with cooling tower water. Elemental sulphur is then precipitated and filtered out, while the contaminated water is reinjected into the ground. Where river cooling is adopted, some H_2S would escape in solution in the cooling water. With large river flow this is not of importance but in small streams, the only solution could be the conversion to cooling towers.

A further effect of the noncondensables is that they are environmentally undesirable because they partly escape into the atmosphere. Most are corrosive in the normally damp atmosphere of the plant site and are noxious and toxic and hence major air pollutants. The most objectionable are H_2S and, to a lesser extent, NH_3. The incondensable gases that accompany the bore fluids consists of CO_2. With high CO_2 content in water discharged into the rivers can aggrovate weed growth.

(2) *Re-injection.* Re-injection would avoid discharging large quantities of heat into rivers, with consequent hazards to fisheries, and would also avoid infecting rivers and stream with toxic substances emitted from the bores which would endanger down stream drinking water supplies, fisheries and farming activities. Since the removal of huge quantities of underground water is known to cause land subsidence reinjection could at least mitigate this. Reinjection minimizes surface pollution.

(3) *Land-Erosion.* Closer control, replanting of shrubs and trees, more careful site selection and improved construction methods are helping to solve this problem. The close spacing of several walls within a single levelled area, combined with directional drilling could help in this respect.

(4) *Noise.* Noise pollution is another problem. Exhausts, blow-downs and centrifugal separation are some of the sources of noise that necessitate the installation of silencers on some equipment. The noise cause a serious health hazard. Workers on new well sites have to wear ear-plugs or muffs lest their hearing be damaged. Reinjection could eliminate noise due to flashing steam where hot water is now being discharged to waste.

(5) *Water-borne poisons.* The water phase in wet fields sometimes contain toxic mercury, arsenic, ammonia etc., which if discharged could contaminate water downstream. Highly saline bore water too may be harmful. Possible solution to this include reinjection, disposal into sea through ducts and channels and the use of evaporator ponds.

(6) *Air-borne poisons.* From various points harmful substances may escape into the air at thermal sites. These may contain radioactive

materials also. Horizontal well discharge in a controlled direction could be a solution to this problem. Systematic monitoring is advisable in this case.

(7) *Heat pollution.* The necessary adoption of relatively low temperature for geothermal power production results in low efficiencies and emission of huge quantities of waste heat. In wet fields, enormous source of heat wastage can arise from the reinjection of very hot unwanted bore water into rivers and streams or into storage ponds and then into atmosphere. Heat pollution in river water can damage fisheries and encourage growth of unwanted water weeds. Possible remedies include re-injection of surplus cooling tower water and unwanted bore water, the generation of additional power by means of binary fluid cycles etc. The escape of heat from cooling towers may affect local elimate.

(8) *Silica.* Silica can be particularly troublesome with distinct heating systems. Re-injection of silica-loaded waters could flow up the permeability of the substrate thus necessitating the constant changing of bore re-injection sites. Settlement ponds could mitigate this trouble.

(9) *Subsidence.* The withdrawl of huge quantities of underground fluids from a wet field can cause substantial ground subsidence, which could cause fitting and stressing of pipelines and surface structures. Re-injection is really the best solution to this problem. As stated earlier reinjection also minimizes surface pollution. Large extractions and reinjection also pose the possibility of seismic disturbances.

(10) *Seismicity.* Some fears have been expressed that prolonged geothermal exploitation could trigger off earthquakes especially if reinjection is practised in zones of high shear stress where fairly large temperature differentiation occur.

(11) *Escaping steam.* Huge volumes of flash steam escaping into the air could cause dense fog to occur, which may drift across to nearly roads and cause traffic hazards. The proportion of escaping steam should be small.

(12) Geopressured water, in addition to the above problems, is thought to carry large quantities of sand, especially at the high flows required. The result is increased erosion and scaling problems.

8.18. Geothermal Energy in India : Prospects

Brief History of Investigation. Between 1963 and 1965 the National Geophysical Research institute, the Geological survey of India and the Jadavpur University Calcutta, spearheaded respectively, heat flow, geotectonic and geochemical studies encompassing the field of research and development relating to geothermal resource evaluation.

In 1968, 1972, and 1973, the hot springs committee of the ministry of irrigation and power and separate sub committees of the National Committee on Sciecnce and Technology classified all the 250 known hot springs of India on a Geotectonic basis, by grouping them into geothermal provinces and by indentifying the pattern and the required priorities of exploration and exploitation under short term and long term plans.

In 1971, encouraged by the finding of the hot springs committee's report the Government of India launched a Geothermal Resource Development project in Manikaran, Himachal Pradesh, with the assistance and collaboration of the United Nations Development Programme.

Also in 1973, the first large scale and systematic field investigations in the country for the exploration and utilization of geothermal resources was taken up under the lead agency of the Geological Survey of India, in one of the remote and relatively backward regions of the country *i.e.* Puga in Ladakh, Jammu and Kashmir state, where fossil fuels were non-existant and hydro power resources were difficult and costly to develop. Many national agencies such as Atomic Energy Commission, National Geophysical Research Institute and Geo-logical Survey of India cooperated to integrate and execute geological, geophysical, geochemical and drilling activities in Puga area.

This integrated activity was continued in the Puga and chumathang geothermal fields of Ladakh in 1974 and was also extended to cover two other geothermal fields at Manikaran and Kasol in the state of Himachal Pradesh and Sona in Haryana State.

Geothermal Occurrence in India. Important geothermal provinces and the places where hot springs occur in India are :

(*i*) N.W. Himalayan geothermal province
(*ii*) North India precambrian province
(*iii*) Cambay Graben province
(*iv*) East Indian Archaean province
(*v*) N.E. Himalayan Geothermal sub province
(*vi*) Naga-Lushai Geothermal province
(*vii*) Damodar valley Graben province
(*viii*) Mahanadi valley Graben province
(*ix*) Narbada Tapti Graben province
(*x*) Godavary valley Graben province
(*xi*) South Indian Archaean precambrian Geothermal province
(*xii*) West coast Geothermal province, and
(*xiii*) Andaman Nicobar Geothermal province.

Potential of Geothermal Resources in India. There are about 340 known thermal areas in India, each represented by hot or warm springs. Many more areas are being discovered and reported, in the 12 well defined geothermal provinces.

The total stored heat potential of the 93 systems considered is 36.87×10^{18} calories, which is equivalent to the combustion energy of 5160 million tonnes of coal or 25440 million barrels of oil. 38 of these systems are of high temperature type whose heat energy could be considered for electrical power generation. Their estimated cumulative potential for power generation is of the order of about 500 MW for 100 years or 1650 MW for a 30 years period of utilization.

Of the remaining thermal areas, 49 are of intermediate temperature and 6 are of low temperature geothermal resources type which could best be used for non-electrical applications. Their cumulative stored heat potential is 19.37×10^8 calories out of which only 1.135×10^8 calories could be beneficially put to practical utilization. Since most of the non-transportation energy needs could be met at temperature below 150-200°C and if the potentials of all 93 systems is considered for non-electrical applications the cumulative beneficial heat will be of the order of 2.185×10^{18} calories. If this heat is to be supplied from electrical power, 10,000 MW of electricity could be required for 30 years period.

Thus these springs have a potential to substitute about 10,000 MW of electricity could be required for 30 yrs period. Thus these springs have a potential to substitute about 10,000 MW of electricity if utilization potentials are available near each site. This is roughly 10% of the total anticipated power production in India by the turn of the century.

Utilization Studies. Several pilot projects were undertaken by Geological Survey of India in collaboration with other agencies such as N.A.L. Bangalore, IIT Delhi in the geothermal area of North-West Himalayan province, which have conclusively proved the vast potentialities for exploitation.

A pilot project for "space heating" at puga, in Ladakh in 1975 at an altitude of 4500 M, involved construction of a shed and using steam at 125°C, at 2.5 kg/cm^2 from a nearby geothermal well for heating the space, with the help of an aluminium finned, copper, tube radiator converter. A difference of 25°C was achieved with respect to the ambient temperature.

The another project named "*Green house pilot project*" at Chumathang, (Ladakh, 4400 m altitude) in 1974, was commissioned. It utilizes hot water from a nearby geothermal well to heat the soil and environment of a green house separately. Heating of soil was done by laying zig-zag pipes below the complete area of soil and allowing geothermal fluid to pass through them. This project proved that 41 varieties of plant including flowers, creepers, vegetables, and trees can be grown even at the peak of winter using geothermal energy and constructing green house, whereas normally no germination is possible for 10 months in a year in this area. This project was undertaken by Geological Survey of India in collaboration with "Field Research Laboratory" at Leh.

A third pilot project "cold storage plant" has been recently commissioned at Manikaran (Himachal Pradesh) by the joint collaboration of Geological Survey of India, IIT Delhi, and Himachal Pradesh Government. This plant avails the hot water at 90°C from a nearby geothermal well and cold water at 10°C from the Parbati river, flowing nearby, and is capable of removing 400,000 kcal/hr of heat to obtain a permanent cold storage temperature of 5°C. This can if successful help the local farmers to store nearly 15,000 tonnes of fruits and potatoes after the harvest and enable them to sell them throughout the year at a uniform price.

A 5 kW pilot power plant is under fabrication at National Aeronautical Laboratory, Bangalore. This plant will run on geothermal energy which will be recovered from the hot springs at Manikaran in Himachal Pradesh. This will utilize a binary cycle process using R-113 as the working fluid.

All these studies have confirmed the suitability of the resources for utilization for various purposes. Plans are being made to undertake further research and development studies in the area of geothermal energy.

Questions

8.1. (a) Define a Geothermal source.

(b) Classify Geothermal sources.

8.2. What are the sub classification of hydrothermal convective systems? Describe a vapour dominated or dry steam field.

8.3. A 100 MW vapour-dominated system as shown in Fig. (8.5.2) uses saturated steam from a well with a shut-off pressure of 28 kg/cm^2 a steam enters the turbine at 5.6 kg/cm^2 a and condenses at 0.14 kg/cm^2 a. The turbine polytropic efficiency is 0.82 and the turbine—generator combined mechanical and electrical efficiency is 0.90. The cooling-tower exist is at 21°C. Calculate the necessary steam, kg/hr, and m^3/min ; the cooling water flow, kg/hr, and the plant efficiency and heat rate, kcal/kwh, if reinjection occurs prior to the cooling tower.

[**Ans.** 0.844×10^6 kg/hr, 5.2×10^3 m^3/min, 13.72×10^6 kg/hr, 16.49%, 5213 kcal/kwh]

8.4. What are the limitations of a flashed steam system? What are the advantages of double flash system?

8.5. Describe a Binary cycle system for liquid dominated system.

8.6. Describe the principle of total flow concept. Compare it with other system.

8.7. Describe the main types of turbines in brief, which may be used for Geothermal energy conversion.

8.8. What are the advantages and disadvantages of Geothermal energy forms?

8.9. What are the main applications of Geothermal energy?

8.10. What are the possible sources of Geothermal pollution? How these are avoided?

8.11. Give a brief note on prospects of Geothermal energy in context to India.