Geothermal energy—

problems in heat and fluid flow

D. J. Ryley*

A brief general introduction is given to the subject of geothermal energy. Reviewing those papers from a recent conference† involving problems of heat and fluid flow provides a convenient framework for discussion under the broad headings: reservoir engineering, wellbore flow, prime movers, hot dry rock, waste heat disposal, geothermal convector, surface transmission of geofluid, space heating and district heating, agriculture and miscellaneous

Key words: *geothermal power, heat transfer, fluid mechanics*

Geothermal energy is an alternative energy source first exploited for power in 1904 at Larderello in Italy[1]. Worldwide installed capacity grew slowly until the so called energy crisis in 1973 which provoked a rapid increase in prospecting, in the development of specialized technology, and in the number of generating plants commissioned. By 1980, twenty-two countries had power plant in operation or planned and the total installed capacity exceeded 2000 MW; beyond 1982 it is estimated[1] as 6000 MW. As the subject may be largely unfamiliar to many readers a brief summary follows.

Geothermal areas are generally found at or near tectonic plate margins[1] but may be associated with geologically young intrusions or hot spots, thought to arise from mantle plumes, at locations on plates far from their margins[2]. Resources with a high base temperature may be employed for power, those at a lower temperature for a wide variety of uses including space heating, agriculture, aquaculture and processing[3]. Fig 1 shows the classification of resources.

All geothermal projects completed to date require a wellbore drilled to penetrate an underground aquifer which may lie at any depth. Experience and technology available in the petroleum industry are widely employed for this purpose. Following drilling, the wellbore is lined with steel piping and encased with cement on the outer surface; a wellhead stop valve and associated equipment is provided. All operations following drilling are referred to collectively as well 'completion'. The well may be self-flowing, either spontaneously or following 'stimulation'. If the height of the effective water table is insufficient to promote self-flow, a submerged ('downhole') pump must be provided.

The economic viability of a geothermal scheme is highly sensitive to the cost of drilling, which increases exponentially with the depth, the

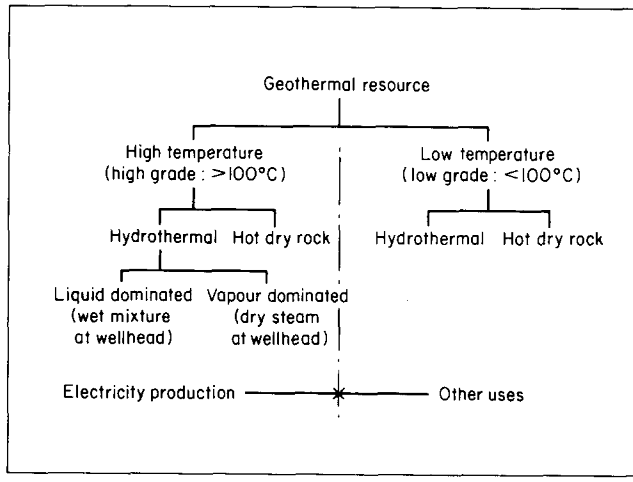

Fig 1 Classification of geothermal resources

exponent being in the range 1.4–2.6 (in 1979[4]). This is a consequence of the loss of penetration time during the withdrawal of the drill string for replacement of the drill bit, ie the ratio of cutting time to total time diminishes as the depth increases. Thus a deep but otherwise suitable aquifer may be too costly to exploit.

The liquid raised is seldom potable water and is referred to as 'brine' or 'geofluid'. Geofluids may have downhole temperatures as high as 350 °C, they may be extremely aggressive chemically and may have dissolved solids of up to 300 000 ppm. Such geofluids pose formidable problems for the design of downhole logging instruments, for steel casings and cement, for submerged pumps and possibly also for some of the surface plant.

A single typical wet borehole in which the total fluid is used with double flashing of the hot water yields between 3.5 and 7.5 MW gross power depending upon the exhaust conditions, whether atmospheric or about 0.13 bar. A number of wells are normally required to supply a power station and these must be spaced to prevent mutual interference. Some knowledge of the structure, extent, physical properties and probable life of the reservoir must be available. This need promotes the study of reservoir engineering.

* Department of Mechanical Engineering, The University of Liverpool, England, L69 3BX
† International Conference on Geothermal Energy, Florence, Italy, 11–14 May 1982. Organized by BHRA Fluid Engineering, Cranfield, Bedford, England, MK43 OAJ in association with Ente Nazionale per L'Energia Elettrica (ENEL), Italy

In free-flowing wells for which the downhole temperature exceeds approximately 100 °C, flashing occurs within the wellbore and the discharge is a two-phase saturated liquid/vapour mixture of dryness fraction typically 15–20%. This mixture may require surface transport for some distance. The phases may be separated and transported in tandem or the mixture may be transported in a single pipe. Alternatively a downhole pump may be employed to suppress flashing and thus only the high pressure liquid is transported.

A number of power cycles have been proposed, some using fossil fuel together with geothermal energy to enhance the thermal efficiency[5]. Cycles in common use employ

(1) Separation of liquid and vapour in the well ('single flash').
(2) Separated-steam/hot-water-flash ('double flash').
(3) A pumped well followed by surface flashing, single or double.

In (1), (2) and (3) the vapour is expanded in a turbine and the liquid is finally rejected.

(4) A closed working cycle with a secondary working fluid (eg Isobutane, Freon 12). Used liquid leaving the heat addition heat exchanger is rejected.

To avoid pollution by surface disposal of waste geofluids it is now becoming usual to re-inject waste liquid through a re-injection bore. This has the additional advantages that some of its enthalpy may be conserved and recycled and that subsidence of the surface, which can be as rapid[6] as 0.5 m/y, may be reduced.

Many extensive areas are known to have very hot rock at depth. The rock may be igneous and too impermeable to support an aquifer. In principle a heating loop can be made by drilling two wells in proximity into the hot basement and contriving a connecting passage by hydrofracturing.

Against this background, some individual papers presented at the Florence conference will be considered. Those chosen for review and comment describe problems in heat and/or fluid flow.

Reservoir engineering

The geothermal reservoir is inaccessible and information can only be obtained by boring wells or by employing one or more of the geophysical methods available for investigating underground anomalies[7]. Quantities of importance include the dimensions of the reservoir, its geological structure (faults, joints, etc), the porosity and permeability of the water-holding strata and of the adjacent strata. Clearly, every reservoir is unique in its physical dimensions and structure. Pressure drawdown, defined as the ratio of wellbottom pressure drop to mass discharge from the well, can be measured. Similarly for partially depleted reservoir recharge ('build-up') characteristics can also be measured. Some well data can be obtained from analysis of pressure transients and from the movement of injected trace elements. The statements just made in respect of pressure are also valid for temperature.

The reservoir will usually contain hot water or superheated water often in association with non-condensable gases (eg CO_2), but in a few cases such as The Geysers in California, 'vapour-dominated' wells may deliver superheated steam. Recently it has been found that vapour-dominated reservoirs store much more steam than is predicted and studies[8,9] show that considerable quantities of water may be held in micropores in the form of absorbed molecular layers. The same effect has been reported by Barelli *et al* [10], who employ with profit a computer simulation program for studying reservoir behaviour.

For the study of interference and hence of well spacing[11], an appeal may be made to experiment if the wells already exist and to test the results against a computer model[10] provided the structure and geometry of the reservoir formation are reasonably well established. A study of well spacing for a vapour-dominated reservoir with vertical recharge was presented by Mountfort[12]. The flow interface between the reservoir and the wellbore presents many problems which arise both from the physical characteristics (faults, joints, etc) of the reservoir and from reservoir leaks and re-charging flows. Aspects of these problems have been studied by Moench[13] and Ehlig-Economides and Economides[14].

Wellbore flow

Single phase geofluid flow in vertical pipes is well understood and the bottomhole mass flow rate may be calculated from a knowledge of the pipe diameter, liquid density and liquid velocity. If the bottomhole temperature T exceeds 100 °C and the flow is adiabatic, flashing will commence at the level for which the pressure equals the saturation pressure for T. Upward flow thereafter will be two-phase and the pattern of association between the phases will follow the sequence: bubble flow, slug flow, churn flow and annular flow, although the well exit may be reached before the sequence is completed. Irrespective of the pattern, the flow may be modelled as 'separated flow' in which the liquid and vapour streams are independent. For analytical convenience, the remaining well height may be subdivided into a number of intervals each with a defined pressure drop. For every interval an appeal is made to conservation of mass, energy and momentum. The respective thermodynamic properties of vapour and liquid are known for the given pressures at inlet to and exit from each interval. For complete solution of each succeeding interval the system of equations is closed by specifying the local values of the two-phase friction f_{TP} and the slip factor K(= velocity of vapour/velocity of liquid). A vast amount of experimental information exists concerning both f_{TP} and K.

The step-by-step solution of the two-phase flow properties from the onset of flashing to the wellbore exit may conveniently be found for any specified flowrate using the computer. A number of programs already exist[16].

Biliki *et al*[15], employing these methods, have written a comprehensive program for the analysis of a two-phase wellbore flow designed to cover a range of conditions. Their program caters for five sequential flow patterns and two increases in well diameter.

It is also adaptable to the chemistry of the brine and provides corrected values for saturation pressure, liquid viscosity, liquid enthalpy and enthalpy of evaporation in accordance with the equivalent dissolved NaCl content. The program also tests for the possible onset of choking in the pipe exit. Using the concept of availability they apply their model to several site-specific cases, using geothermal resources in the USA, to examine design alternatives: uniform diameter versus stepped well; self-flowing versus pumped well; and pumped well versus both uniform and self-flowing wells.

Also employing the methods described above, Ryley and Parker[16] compared computer analyses with experimental data for each of two wells, one in Cerro Prieto, Mexico, and the other at Krafla, Iceland. For both wells agreement between theory and practice was very close for the two-phase pressure distribution but disparities were found in both cases for the temperature distribution. In each case a reference to the saturation temperature for a proven pressure indicated inaccuracies in the temperature-measuring equipment and/or in the experimental techniques. The difficulty of accurate downhole temperature measurement generally arises from the hot environment. This is an area which is attracting active study.

After surveying most of the world's drilled wells, Karlsson[17] observed that the majority of high temperature wells have the same sequence of pipe diameters†: $13\frac{3}{8}$ in anchor casing, $9\frac{5}{8}$ in production casing and $8\frac{1}{2}$ in open hole or 7 in slotted liner if needed. Using conditions similar to those prevailing in the Krafla field in Iceland (wellbottom enthalpy 1620 kJ/kg, wellhead pressure 8.0 bar, 1000 m production string and 2000 m total well depth) he made estimates of the relative total cost for a completed well for five different diameters of productive casing. The 'standard' $9\frac{5}{8}$ in production pipe diameter was used as a reference and, with all other factors common, the well outputs were estimated using a computer routine similar to that described above. His results show that the relative cost of producing steam in the Krafla area is minimized for a production casing of $11\frac{3}{4}$ in diameter. This suggests that money might be saved by an analysis of bore size prior to drilling rather than accepting unthinkingly the 'standard' design.

Prime movers

The normal prime mover is the steam turbine. It may accept, direct from the well, superheated steam as at The Geysers in California, or saturated steam as at Larderello in Italy. The wells currently in common use produce a two-phase mixture in which saturated liquid preponderates; if an orthodox turbine is to be used the liquid and vapour are separated, the vapour being expanded in the turbine and the liquid rejected. By flashing the liquid at a reduced pressure (the 'flash' cycle) additional vapour at a lower pressure may be recovered for the production of work. In theory any number of flash stages may be employed but diminishing returns in increasing thermal efficiency usually limit the number to two. Any cycle which employs only the enthalpy drop available from the vapour is necessarily inefficient as the wellhead dryness fraction is always low. (Pure water at 350 °C if flashed to 100 °C yields a mass dryness fraction of approximately 50% only.) Much ingenuity has been expended upon devices that purport to extract energy from the saturated liquid also. Thus an attempt was made to devise a 'total flow' impulse turbine[18] which would expand with a high efficiency, a two-phase geofluid of entry dryness fraction 12% and upwards. This project failed, basically because of the excessive friction in the flow passages. A more successful machine is the rotary separator turbine[19].

The most promising alternative type of prime mover appears to be the Lysholm rotary helical screw expander[20]. This is a positive displacement machine (Fig 2), which operates by direct expansion of the two-phase mixture within a pair of rotors rotating at the same speed and maintained in phase by gear wheels of equal diameter. Fluid enters through the nozzle control valve into the high pressure chamber at A (Fig 2). As the rotors revolve the chambers elongate continuously providing a successively increasing volume from A to D.

A prototype 1 MW screw expander has recently undergone trials at Cerro Prieto (Mexico), Roosevelt (Utah), and is to be tested in Italy and later in New Zealand[21]. Gonzalez[22] reports briefly on the tests conducted at Cerro Prieto. The machine showed a maximum isentropic efficiency of 68% and a heat rate of 67×10^3 kJ/kWh. It was run at a rotor screw speed of 3000 r/min, the pressure ratio was 6.6 and

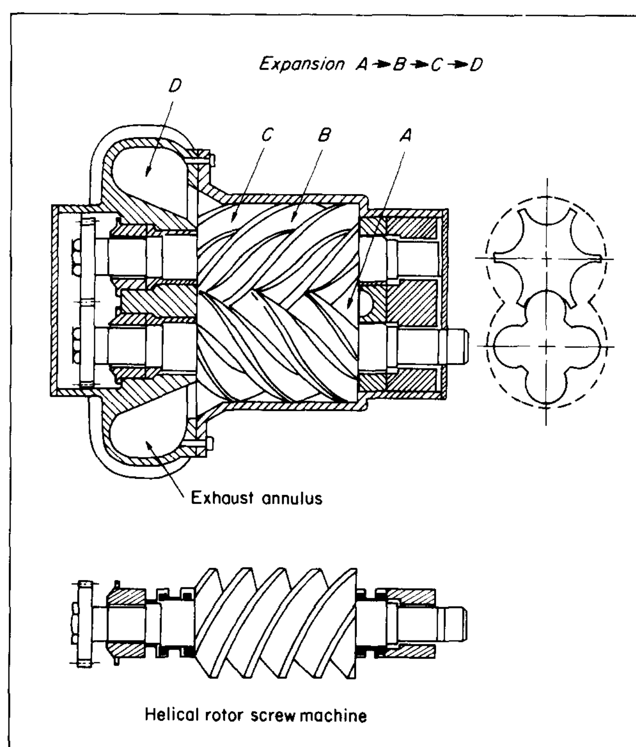

Fig 2 Helical rotor screw machine (after ref 22)

† Throughout the literature and the industry, pipe specifications remain in Imperial units. The equivalent diameters are 340 mm, 245 mm, 216 mm, and 178 mm, respectively

volume expansion ratio was 9.1. Performance was compared with a 60 kW screw expander which showed a lower isentropic efficiency. This type of machine is believed to be largely free from clogging and scaling and accepts a wide range of steam conditions but is limited in power output by the physical size that can be manufactured and the volume ratio of expansion (≃10) permitted by the geometry of the rotors.

The bubble lift cycle (blc) was originally devised and analysed in 1977 at Heriot-Watt University. Work has been continued at the University of Iceland by Jonsson *et al*[23]. Fig 3(a) shows the arrangement of a demonstration rig and Fig. 3(b) is schematic. The working fluid in the riser is a bubbly two-phase mixture of Refrigerant 113 (R 113). The mass flowrate $\dot{m}_g$ of the vapour from the boiler induces a mass flow rate $\dot{m}_f$ up the riser pipe. The R113 vapour is condensed in the reflux condenser and the return flow $\dot{m}_f$ in the downcomer pipe operates the free-running propeller ('turbine'). The circulation is maintained by the density difference in the two columns. A simple analysis shows that the actual work done W_a is related to R113 properties, ρ_g and h_{fg}, the riser area A and the velocity therein U, the Carnot efficiency and the work W_m available in the absence of losses is given by:

$$W_a = \left(\frac{\rho_g h_{fg}}{2}\right)(AU)\left(\frac{\Delta T}{T_1}\right)\left(\frac{W_a}{W_m}\right) \qquad (1)$$

Two conceptual designs have been worked out to size a plant of 1 MW capacity.

The spread of interest in the binary cycle was reflected in several papers presented at the conference. Salucci *et al*[24] described in some detail a 500 kWe Rankine cycle plant currently under manufacture. The working fluid is R114. The evaporator/liquid heater accepts geofluid at 140 °C and rejects it at 90.5 °C. The cycle operates between 15.3 bar, saturated vapour and 3.4 bar and has an estimated efficiency of 5.5%. The single-stage turbine has an overhung rotor to facilitate sealing and runs at 7500 r/min.

The Raft River (Idaho) geothermal project is now nearing completion. It has involved nearly eight years of research activity in both electric and non-electric geothermal applications and a general overview was presented by Mink *et al*[25]. The 5 MWe power plant which utilizes a dual-boiling isobutane binary cycle is in the testing stage. Geofluid at 130–145 °C is produced from four 1500–2000 m wells and the waste liquid is re-injected through two 1200 m wells. This project also provides facilities for research into the use of geothemal energy for agriculture, aquaculture, biomass production, wetland studies and space conditioning.

Looking ahead to when it may be possible to recover geofluid at 170 °C from wells in England, Hirons *et al*[26] presented a conceptual design for a 4 MWe plant based on R12 which was chosen from thirteen candidate working fluids. They made an estimate of the overall cost of the plant and suggest the cost of power as 3.2–4.2 p/kWh.

In the People's Republic of China only 432 (19.4%) of 2225 known geothermal sites have base temperatures exceeding 60 °C. Since 1971, therefore, China has concentrated on the development of small binary cycle power plants. Cai Yihan[27] described research on the working medium, on heat exchangers, on turbines and on economics and explained how small installations are used to complement other sources of energy.

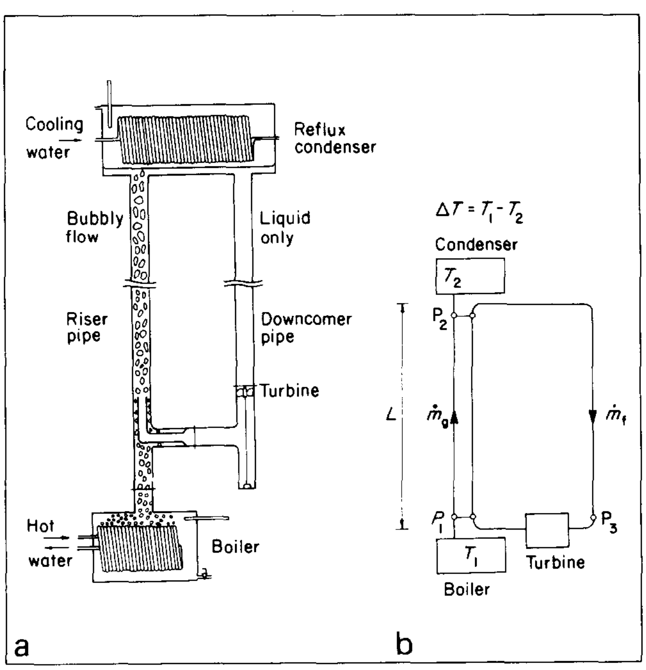

Fig 3 Apparatus for bubble lift cycle (after ref 23)

Energy from hot dry rock (hdr)

All geothermal energy to date, for whatever purpose it has been used, has been based on the exploitation of aquifers. Energy is known to exist in hot dry rock (hdr) but its extent is hard to estimate because most of the geochemical and geophysical techniques developed for geothermal exploration depend either directly on the presence of fluids in the rocks or cannot discriminate between thermal anomalies due to conduction or to hydrothermal convection[28]. Nevertheless, in the USA, where an inventory of hdr energy has been attempted[28], there is strong evidence that such stored energy greatly exceeds that in hydrothermal convection systems. Thus at depths between 3 and 7 km there is believed to be over 1400 times the energy in hydrothermal systems at temperatures ⩾90 °C to depth 3 km.

The principle of hdr energy exploitation is to fracture artificially a volume of rock at depth such that cold water pumped in through a downpipe may be heated in transit through the rock before recovery through a rising pipe. The heat transfer problems are to ensure that:

- A sufficient area of rock is swept to ensure adequate heating of the water.
- The energy drawdown with time, as shown by a progressive temperature decrease in the recovered water, should be as small as possible.

The qualities required for a successful artificial reservoir are:

1. The hydraulic resistance ('impedance') of the system should be low since power for circulating pumps must be supplied from the gross output of the plant.
2. The loss of circulating water should be as small as possible.

Fracture of underground rock is promoted by firing explosives at depth, hydrofracturing, or both. Hydrofracturing consists of filling the borehole and associated cracks, etc with water and applying elevated pressure at the surface. The manner in which rocks break subject to the constraints imposed by their original physical structure, anisotropy, incipient cracks and tectonic stresses is the province of rock fracture mechanics, a rapidly developing study.

Pioneer hdr work in the USA is at Fenton Hill, New Mexico, and a progress report was presented by Smith[29] who gave a synopsis of some 12 years of work divided into two phases. In the phase I research loop (Fig 4(a)) the heat recovered is normally dissipated by heat exchangers to the atmosphere, but a 60 kVA (net) electrical-generating unit was operated at convenient times on a by-pass loop. The Phase II loop is currently under construction. Two holes (Fig 4(b)) have already been drilled with their lower sections directionally drilled to be parallel in a vertical plane with a displacement of 380 m. Connecting fractures as shown have still to be created. The Phase II system is designed to approach the requirements of a commercial geothermal energy system with regard to temperature, rate of heat extraction and useful lifetime.

Pioneer work on rock fracturing is also in progress in Cornwall, England. Batchelor[30] describes in some detail the creation of a hdr system by combined explosive and hydraulic fracturing. The fracture system differs from that described by Smith[29] and consists of the interlinking of directionally drilled wells by the hydraulic stimulation of existing natural joints after the manner of the conceptual diagram shown in Fig 5; the heat transfer problems to be solved remain the same.

Terrestrial heat is transported by conduction (solid rock) and convection (magma, geofluid). hdr technology requires, in particular, detailed information on the dependence of the thermal properties of crustal crystalline rocks on temperature, pressure, moisture and mineralogy up to 5 km depth. In a given hdr region the crustal thermal conductivity controls the geothermal gradient. The drilling depth required to reach rock at a specified temperature will vary with the depth variation of thermal conductivity, ie with the temperature dependence of the conductivity. To predict accurately a temperature, T, at depth, z, it is necessary to know accurately the function $T = T(z)$. Fig 6 shows a plot of an extrapolated temperature profile based on an observed surface value of temperature and conductivity with two different values of $T = T(z)$. The disparity in depth is serious for temperatures 450–500 K and could lead to substantial errors in the estimate of drilling costs given the exponential rise of drilling cost with depth.

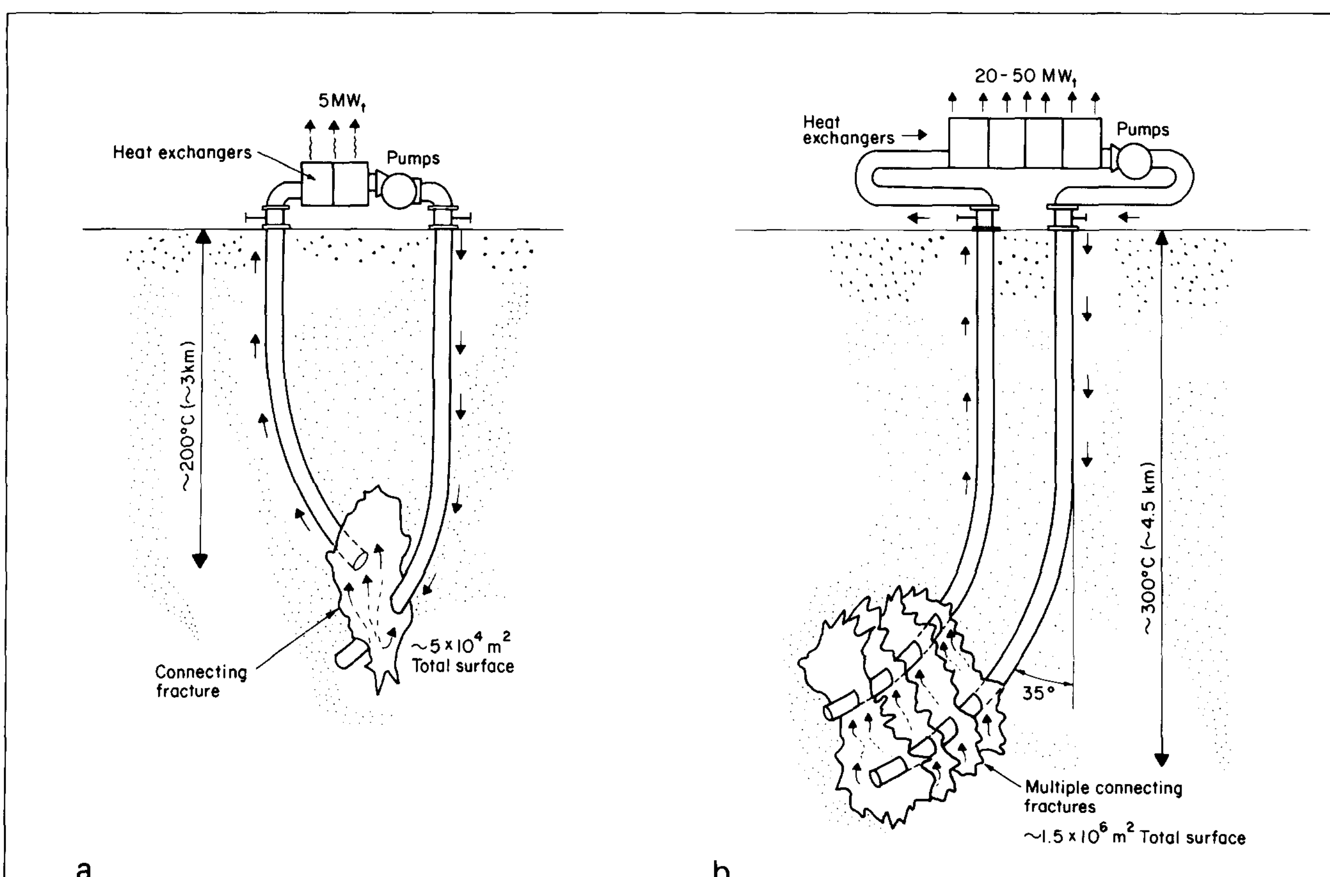

Fig 4 (a) Research (Phase I) system and (b) engineering (Phase II) system (after ref 29)

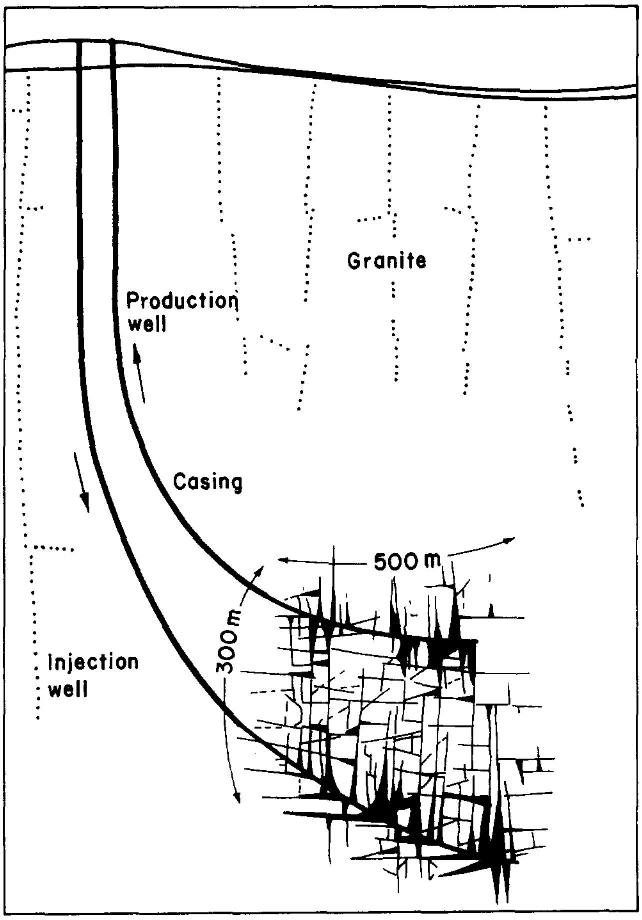

Fig 5 A conceptual diagram of a hot dry rock system in south west England (after ref 30)

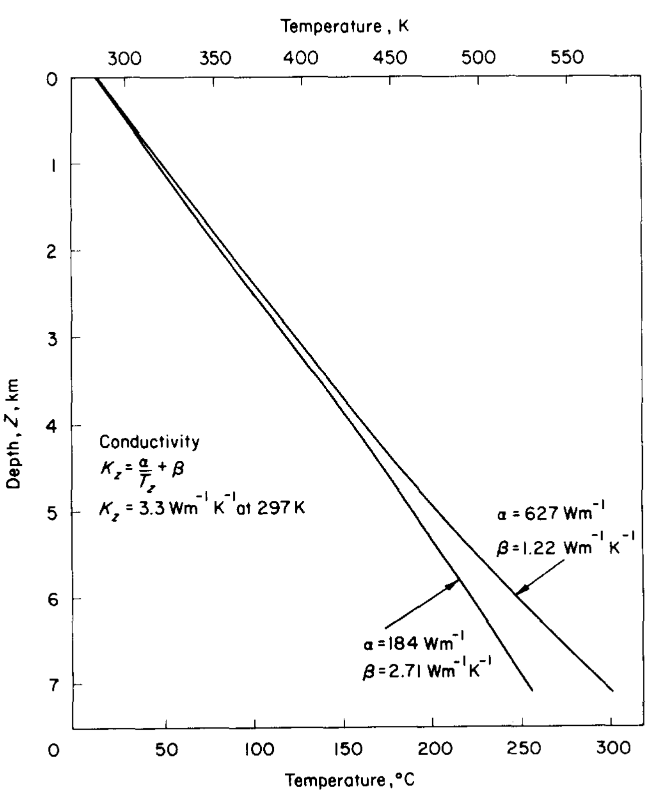

Fig 6 Crustal temperature profiles (after ref 31)

Sartori and Francis[31] describe a new method for fast laboratory determination of the temperature dependence of thermal conductivity for rock and other poor conductors. The method has a number of advantages over the divided-bar and needle-probe methods[32].

Waste heat disposal

Low thermal efficiency consequent upon the relatively low-temperature heat sources results in the disposal of heat per kW of generating capacity being 3–4 times greater for geothermal power plant than for the fossil- or nuclear-fuelled plant. The most economical methods of heat dissipation require the evaporation of water and this raises severe problems in arid areas. The major hydrothermal resources in the USA are located in the West where water is in short supply. Robertson[33], with emphasis on this area, lists some of the methods currently being studied for reducing the cost of waste heat dissipation and for conserving water. Some of the more interesting and significant methods are:

- Allowing the plant output to vary with the ambient conditions. This method is applicable to turbines using a working fluid other than steam for which the turbine efficiency is less sensitive to back pressure variation. This variable-capacity concept is thus well suited to binary geothermal stations.
- Using ammonia to transport waste heat from the turbine condenser to air-cooled coils. By using a phase-change circulating fluid, heat transfer rates can be enhanced and the capital cost of heat exchangers and piping reduced.

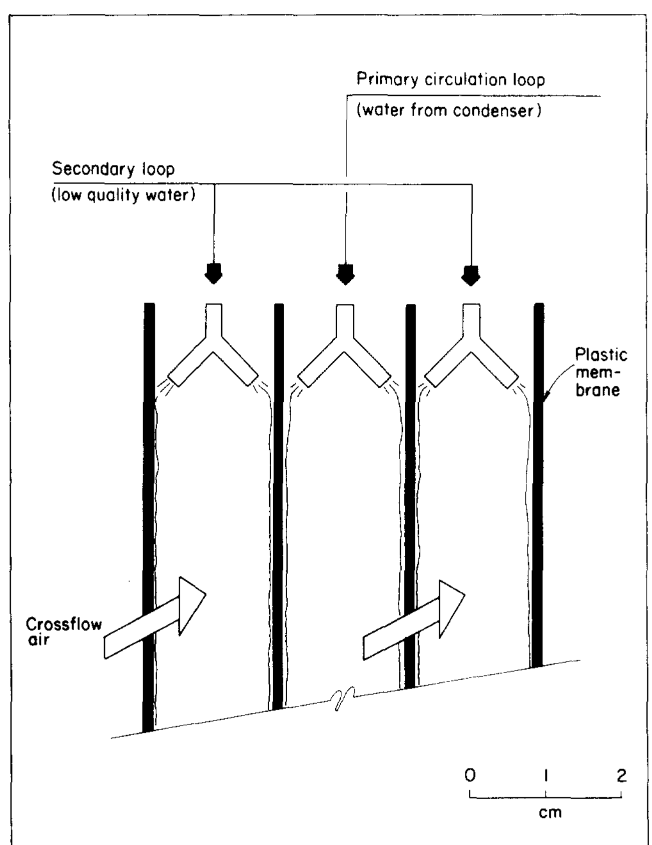

Fig 7 Schematic representation of plastic membrane, or binary cooling tower (after ref 33)

- Developing a plastic membrane type wet/dry cooling tower (Fig 7). The primary loop can be used as an open or closed system. The secondary loop may be used with air alone or air/water. A tower using this construction is well adapted to geothermal work as it is less susceptible than conventional equipment to sealing, fouling and corrosion.
- Using circulating water storage. Cost may be reduced and water savings promoted if heated condenser circulating water is stored until night-time when ambient conditions are most favourable for heat rejection to the atmosphere.
- Developing tubes with enhanced heat transfer surfaces. One method of securing this is to improve the overall heat transfer coefficient by the use of vertical tubes having fluted surfaces. Using various fluting configurations on the outside for the condensation of fluorocarbons, ammonia and isobutane, Combs[34] found that the outside composite film coefficients improved by factors of 6–7 compared with those for smooth tubes. Extension of the tests[35] to include the effects of internal as well as external fluting indicated an improvement of 17% in the overall coefficient over that which arose from external fluting only.

The importance of this work is set in perspective when it is realized that water shortage is so severe in some areas of western USA that all major consumers are in competition for the available supplies.

Geothermal convector

It has long been recognized that the energy in a hydrothermal flow might be more readily exploited were it not necessary to raise the geofluid to the surface, ie if a satisfactory downhole heat exchange, or equivalent, could be devised. This would also avoid problems of surface disposal, pollution or re-injection. A system for transferring heat up the well ('geothermal convector') without raising the liquid was described by Cannaviello[36]. It is in principle a gravity-operated heat pipe employing a heat exchanger as an evaporator immersed in the geofluid at the wellbottom. The internal vapour generated ascends to the wellhead and the transported heat is withdrawn by a second heat exchanger promoting condensation. Extensive studies have been conducted on a 20 kW prototype using R11 as the transport fluid. The geothermal source is at depth of 5 m and a temperature of 61 °C. Design studies have been made for a 100 kW unit.

Surface transmission of geofluid

The Krafla geothermal plant, described by Eliasson *et al*[37], is on a constructive plate margin, the Mid-Atlantic Ridge, where the Ridge transverses the eastern part of Iceland. This site is probably more subject to seismic and volcanic activity than that of any other geothermal power station yet constructed. The problems arising from so thermally active an area comprise the possibility of damage to the plant and modification of the geofluid properties including increased concentrations of non-condensible gases. Provision is made in the design to withstand earthquakes up to 6.5 Richter at 1 km radius. The pipelines each transport two-phase fluid from the wellhead to the separators and the separated vapour traverses a further 500 m to the power station. Pressure drops in the pipelines were calculated using the Lockhart–Martinelli[38] method and agreed well with the measured values.

Space heating and district heating

For domestic heating it is possible to utilize directly geofluids with a temperature as low as 50 °C[39], although 80 °C is a recommended convenient temperature. Geothermal domestic heating has a long history, early plant being small in capacity. The first scheme of significant size was in Reykjavik, Iceland, commissioned in 1930[39]. The heating system supplied some 70 houses, 2 public swimming pools, a school and a hospital. The installation was progressively extended until in 1975 approximately 99% of all the buildings in the city were thus heated, the demand[6] being 557 MWt. Domestic heating schemes are now in operation in Hungary, New Zealand, USSR, USA, France and other countries. One is under consideration for a site in Southampton, England, based on a single well in the city centre.

France has been very active in this area and foresees in the late 1980's an installed geothermal heating capacity equal to a yearly saving of 10^6 Tonnes of Oil Equivalent (TOE). France has 12 geothermal heating schemes scheduled for use in the 1982–1983 winter. A saving of 2×10^6 TOE seems a realistic objective for the European Economic Community in the early 1990's[40].

The use of geothermal energy for district heating is well established in the western USA. The city of Klamath Falls, Oregon, has been employing hot water from wells for some 80 years[41]. Some 400 wells from 30–600 m depth provide access to hot water in the range 20–110 °C which has been used for heating homes. Downhole heat exchangers have been used since 1930. A district heating scheme has been commenced to heat 14 government buildings which will have a peak heating load of 6.2 MWt supplied from two wells producing 48 kg/s of primary loop water at 104 °C. It is hoped to extend the system later to include the whole commercial district, an additional peak load of 42 MWt. Of particular interest is the use, for the secondary loop, of a buried pipeline made of insulated reinforced fibreglass plastic.

The city of Reno, Nevada, is ideally suited for district heating and some heating schemes already exist. Hot geofluid at a temperature of approximately 180 °C is available from Steamboat Hot Springs some 14 km south of Reno. Two papers were presented[42,43]; both agree that geothermal heating could provide considerable saving relative to the cost using natural gas. Atkinson estimates that the total peak load for a heating system[42] is approximately 140 MWt and the annual heat consumption is 3.1×10^8 kWh.

Geothermal energy is not necessarily cheaper than natural gas in the Western part of the north American continent. Thus Vigrass[44], in a design study for district heating in the neighbourhood of Regina, Saskatchewan, investigated a possible 2 km well delivering water at 59 °C. He found that the local consumer density was too low to allow geothermal heating to compete economically with low-priced natural gas which had penetrated all the sizeable local markets.

In situations where the geofluid temperature is low, a condition applying widely in Europe and in particular in France in the Paris and Aquitane Basins, it may still be possible to exploit the geofluid economically for space heating by employing a heat pump. Ungemache[40] discussed the technology and economics of this combination in the context of installations within the European Economic Community. A study of such an installation suitable for a group of four identical apartment buildings to be constructed at Mons, Belgium, was presented by Pilatte and Bougard[45]. Each building of 80 apartments has a nominal load of 975 kWt and is supplied by the heating system shown in Fig 8. The data included on the diagram result from a computer optimization to minimize annual running costs. The estimated saving in primary energy is 10^6 kWh/y, or 47%, compared to a gas or fuel heating system.

Two recent developments have arisen from the need to exploit low grade energy for heating. One is the 'polytropic' heat pump which consists basically of an assembly of boiling and condensing units which permit the system to work as a 'heat transformer' capable of collecting and transferring heat at varying temperatures and thus adaptable to geothermal heating in which the source is a base load at a fixed flow rate and temperature. The thermodynamic cycle is a reversed Rankine cycle without superheat. With little entropy production it has a high coefficient of performance. The other recent development[46] is the 'Ecovector', a high efficiency convector heater for space heating. The thermal power, W, of a convector is given by:

$$W = hA\theta_m \tag{2}$$

where h is the heat transfer coefficient, A the exchange area and θ_m the logarithmic mean temperature difference between water and air. With low grade geothermal heat the value of θ_m is less than that of the usual 'radiator' and for acceptable heat output it is necessary to increase the hA product in Eq (2). It is not usually practicable to increase A significantly and efforts are made to increase h. This is done by extending the convector upwards to provide a funnel for increasing the air flowrate above the special finned heating tubes. The Ecovector can, of course, be used in conjunction with a heat pump.

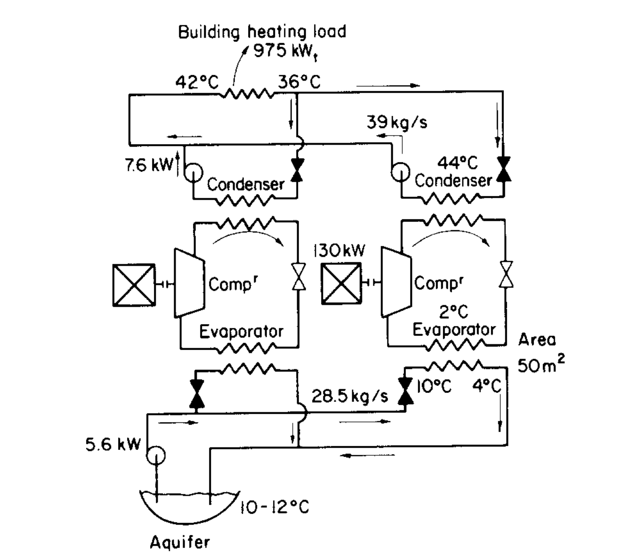

Fig 8 Optimized heating system using heat pumps (after ref 45)

Agriculture and miscellaneous

In Yugoslavia it is currently illegal to build new oil- or gas-fired boiler plant; Popovski and Dimitrov[47] describe the exploitation for agricultural purposes of geothermal springs at Kotchany where the temperature is 78 °C and the maximum flowrate 225 kg/s. The hot water is used sequentially in a series of greenhouses before being discharged at 20 °C or less. The total production area is 310 000 m^2 and the geothermal contribution to the total input is 57.8 MW. Existing liquid fuel boilers supply 21 MW.

Even in localities which appear thermally unpromising some energy may be available and Michaelides[48] reports positively on a feasibility study to utilize geothermal heat in Delaware, USA, for industrial and agricultural products, particularly for poultry processing.

Comments

It will be clear from the above that the exploitation of geothermal energy for power and other purposes is now widespread and that the subject has extensive and rapidly developing bases in both technology and the earth sciences. It is bringing into focus new problems in fluid mechanics and heat transfer not only within the specialist spheres of, say, reservoir engineering and terrestrial heat flow, but in many contexts within the domain of readers of this journal. Interdisciplinary in nature and with its own inherent fascination, geothermal energy offers scope for pioneering work to any members of the heat and fluid flow fraternity who may be seeking a new challenge.

References

Most of the papers referred to were presented at The International Conference on Geothermal Energy, Florence, Italy (May 11–14, 1982). They are published by BHRA Fluid Engineering, Cranfield, Bedford, UK, MK43 0AJ. To avoid repetition these papers will be designated Florence.

1. **DiPippo R.** Geothermal energy as a source of electricity. *U.S. Department of Energy, Division of Geothermal Energy, Washington D.C. 20585. Jan. 1980*
2. **Burke K. C. and Wilson J. T.** Hot spots on the earth's surface. Continents adrift and continents aground. *Scientific American, p. 58, 1976*
3. **Lindal B.** Industrial and other applications of geothermal energy. *UNESCO, 1973, 135*

4. **Ryley D. J. and DiPippo R.** Drilling for geothermal resources. *in* 'Sourcebook on the production of electricity from geothermal energy.' *Kestin J., DiPippo R., Khalifa H. E. and Ryley D. J. (eds) Section 2.4, p. 136. US Department of Energy, Division of Geothermal Energy, Washington DC 20585. March 1980*

5. **DiPippo R., DiPippo E. A., Kestin J. and Khalifa H. E.** Compound hybrid geothermal-fossil power plants: thermodynamic analyses and site-specific applications. *J. Eng. for Power, 103, 797–804, Oct. 1981*

6. **Armstead H. C. H.** Geothermal Energy. *E. and F. N. Spon, London, 1978*

7. **Dobrin M. B.** Introduction to Geophysical Prospecting. *McGraw-Hill, Edn. 3, 1976*

8. **Hsieh C.** Vapour pressure lowering in porous media. *Ph.D. Thesis, Stanford University, 1980*

9. **Economides M., Ostermann R. and Miller F.** Implications of adsorption and formation fluid composition on geothermal reservoir evaluation. *Florence, Paper C1, 149–162, Vol. 1*

10. **Barelli A., Ceron P., Carrador G. and Peano A.** On computer modelling on Travale geothermal field. *Florence, Paper C2, 163–174, Vol. 1*

11. **Todd D. K.** Groundwater Hydrology. *J. Wiley, Edn. 2, 1980*

12. **Mountfort M. V.** Well spacing for a vapour-dominated geothermal reservoir with vertical recharge. *Florence, Paper C5, 195–202, Vol. 1*

13. **Moench A.** Geothermal well test analysis in horizontally stratified formations including wellbore storage and skin effects. *Florence, Paper D4, 267–279, Vol. 1*

14. **Ehlig-Economides C. A. and Economides M. J.** Analysis of a geothermal well test in a predominantly linear flow system. *Florence, Paper D5, 281–292, Vol. 1*

15. **Bilicki Z., DiPippo R., Kestin J., Maeder P. F. and Michaelides E. E.** Available work analysis in the design of geothermal wells. *Florence, Paper H4, 227–248, Vol. 2*

16. **Ryley D. J. and Parker G. J.** Flowing geothermal wells: Cerro Prieto well M.91 and Krafla well KJ-9.1; computer analysis compared with experimental data. *Florence, Paper C4, 187–194, Vol. 1*

17. **Karlsson T.** Optimization of geothermal well diameter. *Florence, Paper D8, 317–328, Vol. 1*

18. **Austin A. L.** Status of the development of the total flow system for electric power production from geothermal energy. *Sourcebook*[4], *Section 4.4, p. 504*

19. **Cerini D. J.** Demonstration of a rotary separator for two-phase brine and steam flows. *Biphase Energy Systems, Research Cottrell, Santa Monica, Ca. USA. Report TID-28519, Jan. 1978*

20. **House P. A.** Helical rotor expander applications for geothermal energy conversion. *Lawrence Livermore Laboratory, University of California, Report UCRL-52043, April 1976*

21. News of Geothermal Energy Conversion Technology. *Lawrence Berkeley Laboratory, University of California* 3, *2, Dec. 1981*

22. **Gonzalez J. L.** Performance comparison of total flow machines of helical rotor-screw expander type. *Florence, Paper H1, 195–200, Vol. 2*

23. **Jonnson V. K., Einarsson J. G. and Cornwell K. J.** The bubble lift cycle for generation of power from low grade heat. *Florence, Paper H7, 275–281, Vol. 2*

24. **Salucci B., Centemari L., Caniato G. and Costantino F.** A 500 kWe orc plant for recovery of heat from geothermal water. *Florence, Paper H5, 249–263, Vol. 2*

25. **Mink L. L., Lease R. D. and Nichols C. R.** The Raft River, Idaho, 5 MWe binary project. *Florence, Paper H8, 283–294, Vol. 2*

26. **Hirons B. W., Smith I. K. and Turtle J.** The conceptual design of a 4 MWe organic fluid power plant for a geothermal resource. *Florence, Paper H6, 265–274, Vol. 2*

27. **Cai Yihan.** Research work on binary cycle geothermal power generation in China. *Florence, Paper A5, 49–56, Vol. 1*

28. **Muffler L. J. P.** Hot dry rock. Assessment of geothermal resources in the United States—1978. *US Department of Energy, Washington DC 20585. Geological Survey Circular 790, 1979*

29. **Smith M. C.** Progress of the US hot dry rock program. *Florence, Paper J1, 303–319, Vol. 2*

30. **Batchelor A. S.** The creation of hot dry rock systems by combined explosive and hydraulic fracturing. *Florence, Paper J3, 321–342, Vol. 2*

31. **Sartori A. and Francis M. F.** A live-source method for the measurement of temperature dependence of thermal conductivity of rocks. *Florence, Paper J6, 369–381, Vol. 2*

32. **Tye R. P. (ed.)** *Thermal Conductivity. Vols 1 and 2. Academic, New York, 1969*

33. **Robertson R. C.** Waste heat disposal from US geothermal power plants—an update. *Florence, Paper F4, 429–440, Vol. 1*

34. **Combs S. K.** An experimental study of heat transfer enhancement for ammonia condensing on vertical fluted tubes. *Oak Ridge National Laboratory, TN, USA, Report ORNL-5356, Jan. 1978*

35. **Domingo N.** Condensation of Refrigerant-11 on the outside of vertical enhanced tubes. *Oak Ridge National Laboratory, TN, USA, Report ORNL/TM-7797, Aug. 1981*

36. **Cannaviello A. C., Carotenuto A. C., Reale F., Casarosa C., Latrofa E. and Martorano L.** An advanced system for heat transfer from geothermal low and medium enthalpy sources. *Florence, Paper G4, 63–80, Vol. 2*

37. **Eliasson E. T., Bjornsson G., Matthiasson M., Maack R., Sigfusson S. and Jonsson V. K.** Collection and transmission of two-phase geofluid at the Krafla geothermal plant, Iceland. *Florence, Paper H2, 201–215, Vol. 2*

38. **Lockhart R. W. and Martinelli R. C.** Proposed correlation of data for isothermal two-phase two-component flow in pipes. *Chem. Eng. Prog. 1949* ***45****, 39–48*

39. **Einarsson S. S.** Geothermal space heating and cooling. *Proceedings of the Second UN Symposium on the Development and Use of Geothermal Resources, San Francisco, USA, May 1975, Vol. 3, 2117–2126*

40. **Ungemache P.** Development of low grade geothermal resources in the European Community—present status—problem areas—future prospects. *Florence, Paper G1, 1–41, Vol. 2*

41. **Lund J. W.** Current status of geothermal utilisation in Klamath Falls, Oregon. *Florence, Paper G9, 121–130, Vol. 2*

42. **Atkinson D. J. and Huxstable D. D.** Geothermal district heating for Reno, Nevada, USA. *Florence, Paper G5, 81–96, Vol. 2*

43. **Reisman A. and Peterson E.** The economic feasibility of geothermal district heating: a case study. *Florence, Paper G15, 181–194, Vol. 2*

44. **Vigrass L. W.** Geothermal energy from the Williston sedimentary basic at Regina, Canada. *Florence, Paper B4, 113–122, Vol. 1*

45. **Pilatte A. and Bougard J.** Optimization of heat pump components for space heating using low grade geothermal resources. Example of a case study. *Florence, Paper G11, 143–156, Vol. 2*

46. **Grossin R., Roth B. and Soupalt O.** A new type of convector used for space heating with low temperature geothermal water. *Florence, Paper G12, 157–164, Vol. 2*

47. **Popovski K. and Dimitrov K.** Kotchany geothermal agricultural project. *Florence, Paper G7, 97–109, Vol. 2*

48. **Michaelides E. E.** The use of low temperature geothermal heat in Delaware. *Florence, Paper G8, 111–120, Vol. 2*