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## GEOHERMAL RESERVOIR ENGINEERING RESEARCH

Henry J. Ramey, Jr., Paul Kruger,  
William E. Brigham, and  
A. Louis London  
Stanford University  
Stanford, California

The Stanford University research program on the study of stimulation and reservoir engineering of geothermal resources commenced as an interdisciplinary program in September, 1972. The broad objectives of this program have been: 1) The development of experimental and computational data to evaluate the optimum performance of fracture-stimulated geothermal reservoirs; 2) the development of a geothermal reservoir model to evaluate important thermophysical, hydrodynamic, and chemical parameters based on fluid-energy-volume balances as part of standard reservoir engineering practice; and 3) the construction of a laboratory model of an explosion-produced chimney to obtain experimental data on the processes of in-place boiling, moving flash fronts, and two-phase flow in porous and fractured hydrothermal reservoirs.

During the current annual period, both the geothermal chimney model and the two-phase boiling model were essentially completed and placed into operation. Also completed was a feasibility study of the potential of naturally occurring radon as a tracer for reservoir characteristics. Experiments are being initiated in several related aspects of mass and heat transfer in fractured rock and in-place boiling in porous media. Continued effort is underway in the development of the mathematical simulation model of geothermal reservoirs.

## I. INTRODUCTION

The Stanford University research program on the study of well stimulation and reservoir engineering of geothermal resources commenced as an interdisciplinary program in September, 1972. The broad objectives of this program have been:

- (1) The development of experimental and computational data to evaluate the optimum performance of fracture-stimulated wells in geothermal reservoirs.
- (2) The development of geothermal reservoir models to evaluate important thermophysical, hydrodynamic, and physical and chemical parameters based on fluid-energy-volume balances as part of standard reservoir engineering practice.

- (3) The construction of a laboratory model of an explosion-produced chimney in a well to obtain experimental data on the processes of in-place boiling, moving flash fronts, and two-phase flow in porous and fractured hydrothermal reservoirs.

The project was initiated as a joint program between the Civil Engineering Department of the School of Engineering and the Petroleum Engineering Department of the School of Earth Sciences. During the present year, assistance was provided by the Mechanical Engineering Department of the School of Engineering.

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Detailed results were presented at a project review to representatives from industry, university, and government agencies during May, 1974. Detailed results were presented in June, 1974 (Ref. 1), in project report SGP-TR-1.

## II. THE GEOTHERMAL CHIMNEY MODEL

A description of the geothermal chimney model and an analysis of the design requirements for the major components were discussed in Progress Report No. 1 (Ref. 2). The major test objectives of the model were also described in Progress Report No. 1. In summary, the model was designed to investigate the effectiveness of fracture stimulation of geothermal wells in increasing the extraction efficiency of geothermal energy. Experimental data are being obtained on the processes of in-place boiling, moving flash fronts, and two-phase flow in porous and fractured hydrothermal media. The general problems being examined included: (1) conditions for optimum energy extraction, (2) methods of cyclic and continuous recharge, (3) determination of heat transfer characteristics, (4) water quality aspects of produced geofluids, and (5) experimental data for mathematical models of stimulated reservoirs.

Analysis of the design requirements for the chimney model indicated that a maximum design temperature of 500°F and pressure of 800 psig would be an acceptable compromise between the desire to operate at the highest pressure and temperature conditions occurring in natural geothermal reservoirs and the need to minimize the thermal capacitance of the metal in the model.

### A. Description of the Chimney Model

A photograph of the chimney model on construction completion is shown in Fig. 1. Figure 2 is a schematic diagram of the chimney model system. The system operates in two primary modes: the "heating mode," which establishes the initial reservoir temperature and pressure conditions in a relatively short time, and the "fluid production mode," during which production from a fractured geothermal system is simulated.

## B. Initial Experiments

Initial experiments have been conducted to measure the heatup and cool-down transients of the geothermal chimney model. Analysis was made of the heating time required to bring the water/rock/vessel system to the desired initial reservoir conditions. A simplified "lumped parameter" analysis of the problem has been made in which the various masses of rock, water, and metal are considered to be at uniform temperature.

The lumped parameter approach assumes that all of the water is at uniform temperature and that the energy received from the electric heater is distributed uniformly to each water element.

The lumped parameter approach is generally considered to be adequate when the Biot number is small, i. e.,

$$Bi = \frac{hL}{k} < 0.1 \quad (1)$$

For rocks with an equivalent diameter of 1 inch, the Biot number for typical chimney conditions is 0.8. Although the Biot number for the rock appears to be larger than 0.1, experience has shown that during the slow heating transient, the temperature difference between the water and the rock is only about 1°F.

The lumped parameter approximation for the metal sections is valid because the Biot numbers for the metal portions of the vessel in contact with water are small. The biot number for the vessel wall is 0.025.

An initial model was developed consisting of four lumped masses. Since the computer costs for the four-mass model transient runs were relatively high and it became apparent that the rock temperature was essentially the same as the water temperature for these operating conditions, a simpler two-mass model was devised for the system. The model consists of one mass for the water and rock at uniform temperature  $T_1$  and a second mass at temperature  $T_2$  for all of the metal in contact with hot water during the heatup process. The two simultaneous differential equations in  $\theta_i = T_i - T_\infty$  are:

$$M_1 C_1 \frac{d\theta_1}{dt} + h_1 A_1 (\theta_1 - \theta_2) = S \quad (2)$$

$$M_2 C_2 \frac{d\theta_2}{dt} + h_1 A_1 (\theta_2 - \theta_1) + h_2 A_2 \theta_2 = 0 \quad (3)$$

Let

$$a_1 = \frac{h_1 A_1}{M_1 C_1}, \quad a_2 = \frac{h_1 A_1}{M_2 C_2}, \quad a_3 = \frac{h_2 A_2}{M_2 C_2}, \quad \text{and} \quad \bar{S} = S/M_1 C_1 \quad (4)$$

With initial conditions  $\theta(0) = \theta(0) = 0$ , and assuming constant coefficients and heat source, the solution to this problem is:

$$\theta_1 = \frac{\bar{S}(m_1 + a_2 + a_3)}{(m_1 - m_2)m_1} (e^{m_1 t} - 1) + \frac{\bar{S}(m_2 + a_2 + a_3)}{(m_2 - m_1)m_2} (e^{m_2 t} - 1) \quad (5)$$

$$\theta_2 = \frac{\bar{S} a_2}{m_1(m_1 - m_2)} (e^{m_1 t} - 1) + \frac{\bar{S} a_2}{m_2(m_2 - m_1)} (e^{m_2 t} - 1) \quad (6)$$

where the inverse time constants  $m_1$  and  $m_2$  are given by:

$$m_{1,2} = 1/2(a_1 + a_2 + a_3) \pm 1/2[(a_1 + a_2 + a_3)^2 - 4a_1 a_3]^{1/2} \quad (7)$$

The system parameters for this problem are  $h_1 A_1 = 4500$ ,  $h_2 A_2 = 110$ ,  $M_1 C_1 = 630$ , and  $M_2 C_2 = 825$ .

The heat losses from the system to its surroundings are of major importance in determining the heat transfer from the rock media. The heat transfer problem is complex due to the irregular vessel shape, various insulation thicknesses, and fin effects from valves and other noninsulated objects. Since the heat loss cannot be predicted with sufficient accuracy, an experimental approach has been used in which the system is heated to an initial high temperature. During cooling, the temperature-time history is measured at various places in the system. The effective heat transfer conductance to the surroundings can then be evaluated from the slope of the water and metal mean temperature-time data. This results from an analytic solution of the cooldown transient (Ref. 1).

Data from the first completed cooldown run (Run No. 032774) are shown in Fig. 3.

Many additional heating and cooling runs have been made, and operation of the chimney model will continue. Extension to operation with boiling brines with recharge is programmed for 1975-1976. Study of movement of flash fronts will continue, and development of a mathematical model is in progress. A study of heat transfer coefficients for fluid flow past large rock particles is also in progress.

### III. BENCH-SCALE MODELS

The test objectives and apparatus involved in the bench-scale models were presented in Progress Report No. 1 (Ref. 2). In brief, these experiments were designed to test fundamental concepts for nonisothermal boiling two-phase

flow through porous media. This work is aimed at the entire reservoir, while the chimney model deals most directly with the well-bore and near-well reservoir conditions. The combination should be broadly useful in the new field of geothermal reservoir engineering.

The term "geothermal reservoir engineering" is an adaptation of "petroleum reservoir engineering," the branch of engineering which deals with assessment, and planning, of optimum development of petroleum reservoirs. Fortunately, there is much that is useful for geothermal engineering in the literature of oil recovery. Oil recovery by steam injection (Ref. 3) and underground combustion (Ref. 4) present some of the important features of nonisothermal two-phase flow which appear pertinent to geothermal reservoirs. But there has been only one specific study of the flow of single-component (water) two-phase (thus nonisothermal) flow in porous media (Ref. 5). In particular, there is no information on the important phenomena involved when normally immobile liquid saturations (practical irreducible water saturation) vaporize with pressure reduction.

The first bench-scale model planned is a steady-state flow experiment involving linear flow (in the axial direction) through a cylindrical core.

#### A. The Linear Flow Model

The linear flow model was described in Progress Report No. 1 (Ref. 2). All necessary components have been acquired, and fabrication of the preliminary test model has been completed. A schematic diagram of the completed apparatus is shown in Fig. 4. Two types of porous media have been used to date: a Berea sandstone core, and several synthetic consolidated sandstone cores. Fondu calcium aluminate cement, silica sand of about 100 Tyler mesh size, and water were used as the materials to make the synthetic cores. The mixture was poured into a mold formed with a plastic tubing in which a glass tubing for a liquid content probe and a thermocouple tubing were held in place. The liquid saturation probe was originally developed by Baker (Ref. 6) in connection with a study of oil recovery by injection of steam. The instrument uses the difference in dielectric constant between the liquid water and steam present in the pore space.

It was decided to run a series of basic single-phase experiments prior to performing the boiling two-phase, nonisothermal flow experiments. These included: (1) measurement of absolute permeability to gas and liquid water at a range of temperatures, (2) injection of hot water into a system containing water at a lower temperature, (3) cold water injection into a system containing hot water initially, and (4) injection of steam into a system containing liquid water at a lower temperature. Selected results are presented in Ref. 1.

Figure 5 presents temperature versus distance along the core for injection of hot water into a core initially at room temperature, as an example. Much useful information can be extracted from data such as are shown in Fig. 5. Basic information on single-phase nonisothermal flow, effective thermal conductivities in the direction of flow, and heat loss radially from the core may be found. In regard to radial heat loss, two determinations can be

of interest: (1) the thermal efficiency of the injection, and (2) the overall heat transfer coefficient for the core within the sleeve to the surroundings. Both types of evaluation have already been made successfully.

#### IV. LABORATORY EXPERIMENTS

During the last year, it has become apparent that several laboratory experiments should be run in parallel rather than in series if the application of research results to practical problems can be made to meet national energy objectives. For this reason, several experiments were moved up in the program time schedule. These included experiments on heat and mass transfer in porous fractured rocks and fractured nonporous rocks, and operation of geothermal reservoir models.

##### A. Heat and Mass Transfer in Porous and Fractured Media

Fractured porous rocks contain two types of void space: macropores, which are void volumes between rock fragments, and micropores, the pore space inside individual rock fragments. Micropores may be either natural porosity or fractures. Fluid flow through certain geothermal reservoirs is expected to occur primarily through the macropores. However, if mass transfer does take place between the water inside the micropores and potentially cooler water in the macropores, heat extraction by circulating fluids may be significant.

The study of mass transfer phenomena inside a highly fractured geothermal reservoir can be simplified by measurement of mass transfer within individual rocks. An effective means of making such studies is by addition of a tracer to the micropore water. A tracer which has proven of immense value in studies requiring chemical and physical properties essentially similar to water is the radioactive isotope of hydrogen,  $^3\text{H}$ , (tritium, T), available in the form of tritiated water, HTO. The preliminary laboratory experiments involve spherical rocks initially saturated with tritiated water. These rocks are suddenly immersed in a completely mixed tank of unlabeled water, and measurements of the concentration of the tritiated water in the external water are made as a function of time. A mathematical model has been designed to represent this physical system (see Ref. 1).

An important property of fractured rock in a geothermal reservoir is its thermal conductivity. The importance of artificial fracturing methods to stimulate the productivity of geothermal reservoirs will depend partly on the change in the thermal conductivity of the rock caused by fracturing. To our knowledge, there is no information on the effect of crack porosity on the thermal conductivity of rock samples. Thermal conductivity measurements will be made before and after stressing of rock samples. The pressure effects (vaporization of pore fluid and crack closure) will be examined by measuring the thermal conductivity of samples saturated at elevated temperature with varying confining pressures. The heat pipe effects will be examined by producing a temperature gradient along the core axis. The use of fluids to saturate the rock with different latent heats of vaporization should show the extent of an increase in heat conduction due to the heat pipe effect in cracked rock specimens (see Ref. 1).

## B. Geothermal Reservoir Physical Models

Whiting and Ramey (Ref. 7) presented the application of energy and material balances to geothermal reservoirs. Although applied to a field case with success, later applications indicated a need for modification (see Refs. 8, 9, and 10). The need for actual data to test conceptual models has been apparent for some time (Ref. 11). Previous works concerned unconsolidated sand models, although a study by Strobel did include a consolidated sand. Strobel's study concerned cyclic production and reheating of a single consolidated sandstone geothermal reservoir model. This work will be repeated with both natural and synthetic sandstone cores with more complete instrumentation.

## V. RADON IN GEOTHERMAL RESERVOIRS

The study of radon occurrence and transport in geothermal resources has been undertaken as an initial evaluation of the use of radon as a diagnostic tool for studying the performance of geothermal reservoirs. Another objective was the evaluation of environmental implications of radon release. This study includes three major tasks: (1) selection and implementation of a method for measuring radon, (2) evaluation of possible field sampling techniques, and (3) survey of actual radon occurrence in geothermal resource areas, both vapor- and liquid-dominated.

Radon emanation has been studied with respect to groundwater flow, natural gas production, and uranium prospecting (e.g., Refs. 12, 13, and 14). The extent of radon release to convective geofluids is dependent on several factors including the distribution of radium through the rock matrix and the surface area available for escape of recoiling radon atoms into the fluid. For homogeneous rock, the release of radon is related to particle size. In heterogeneous material other factors may obscure particle size dependence (see Ref. 1).

The question of radon as a possible environmental contaminant has been raised by Scott (Ref. 15), largely on the basis of data obtained in New Zealand resource areas. Large radon concentrations were observed in fumaroles and pools in the Rotorua-Taupo region. Therefore, our sampling program was conducted with a view to estimating the magnitude of any potential environmental problem. Some of the tasks already accomplished include: (1) development of a Radon Measuring System and construction and testing of the apparatus, (2) development of a field sampling technique, and (3) start of a field survey program with collection of samples from The Geysers steam field and from the Imperial Valley. Results are presented in Ref. 1. Field surveys are continuing.

## VI. MATHEMATICAL MODEL

Advances have been made in the modeling of geothermal fluids production in three main directions. The first direction is a general view of the many complex thermal, fluid dynamic, and other physical processes. The second direction is the formulation of a mathematical description of a simplified system

to obtain a solution describing the behavior of this system. The third direction is matching the bench-scale experimental results to simulate the boiling flow of steam and water at elevated temperatures. Figure 6 presents the results of one simulation of a bench-scale geothermal reservoir model experiment. Figure 6a presents the computed pressure history, while Fig. 6b presents the computed liquid content of the system. Although not shown, the temperature history of the system was also computed (see Ref. 1, Fig. 48). Development of a more sophisticated model continues.

## VII. CONCLUDING REMARKS

During 1974, the main components of most projects in the Standard Geothermal Program were completed and initial runs performed successfully. Augmentation of system instrumentation, completion of improvements in design, and collection of experimental data are in progress. All projects are developing satisfactorily.

## NOMENCLATURE

- $h$  = heat transfer coefficient (Btu/hr-ft<sup>2</sup>-°F)  
 $L$  = characteristic length of body (ft)  
 $k$  = thermal conductivity (Btu/hr-ft-°F)  
 $H_1A_1$  = heat transfer conductance from water/rock to metal (Btu/hr-°F)  
 $H_2A_2$  = heat transfer conductance from metal to surroundings (Btu/hr-°F)  
 $M_1C_1$  = heat capacitance of metal in chimney (Btu/°F)  
 $M_2C_2$  = heat capacitance of metal in chimney (Btu/°F)  
 $S$  = energy source (electric heater) (Btu/hr)

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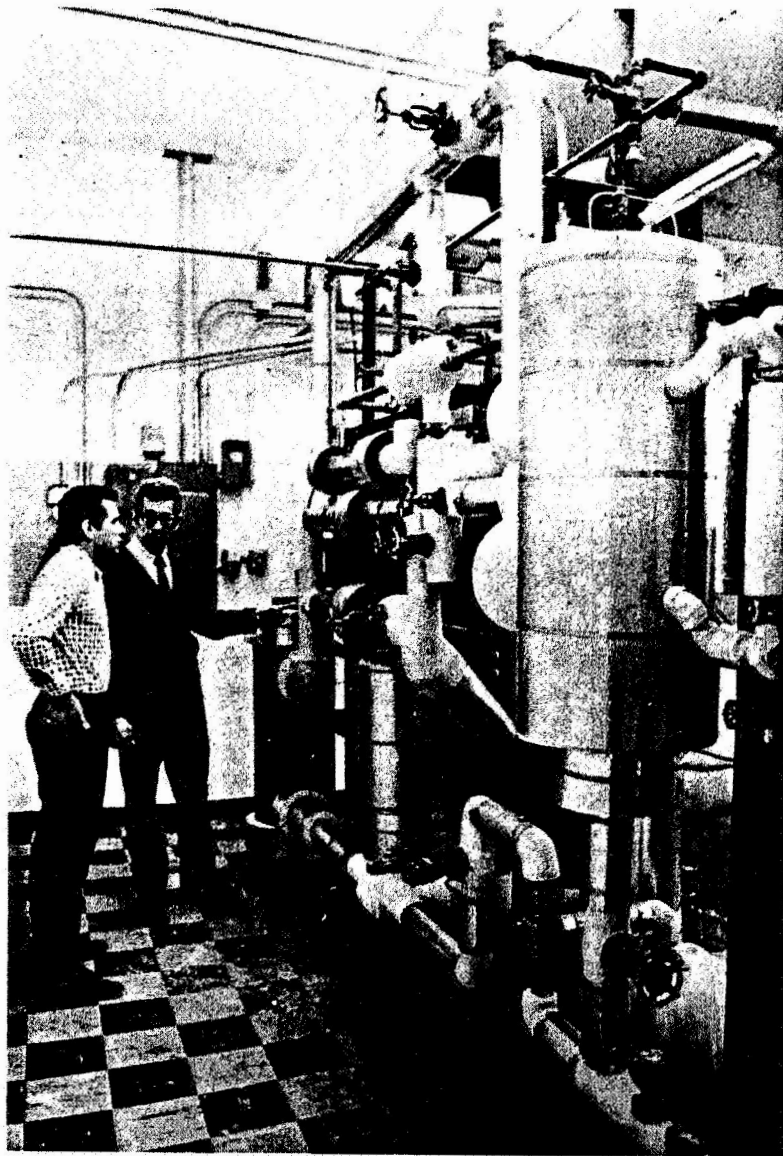


Fig. 1. Photograph of chimney model system showing operating controls

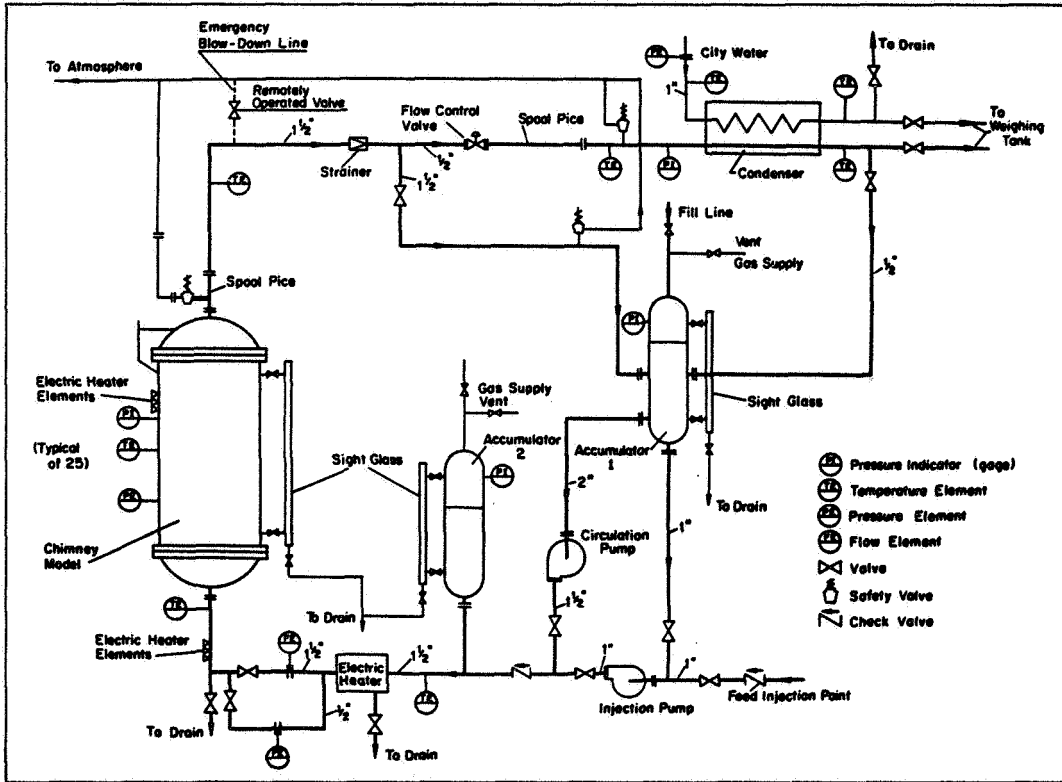


Fig. 2. Piping and instrumentation diagram of the chimney model system

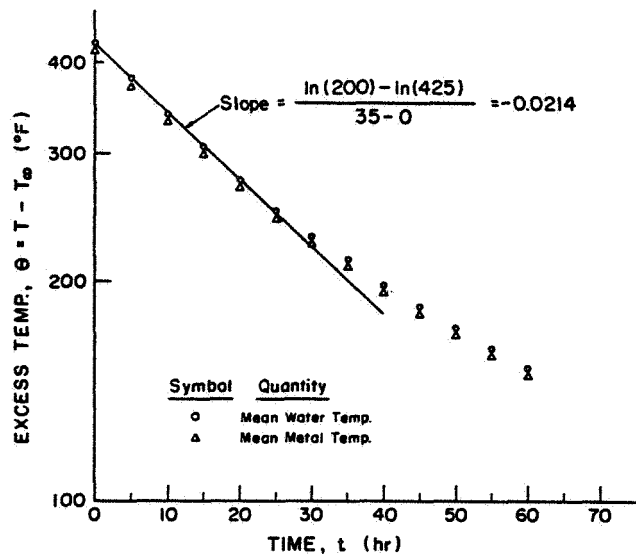


Fig. 3. Experimental cooldown transient for chimney model loaded with water only

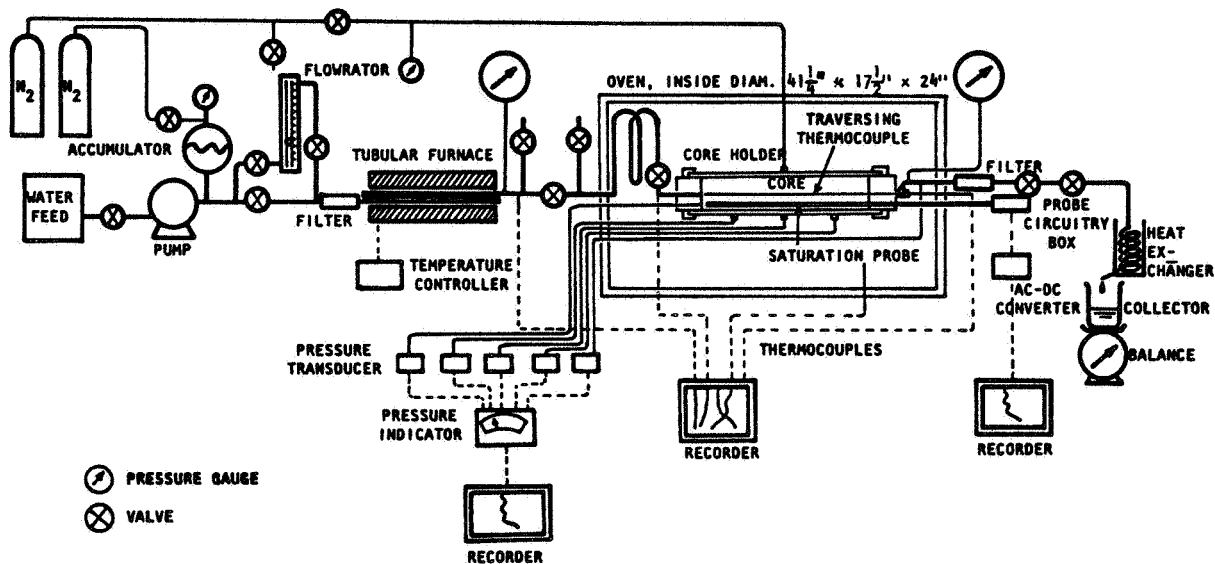


Fig. 4. Schematic diagram of the linear flow model apparatus

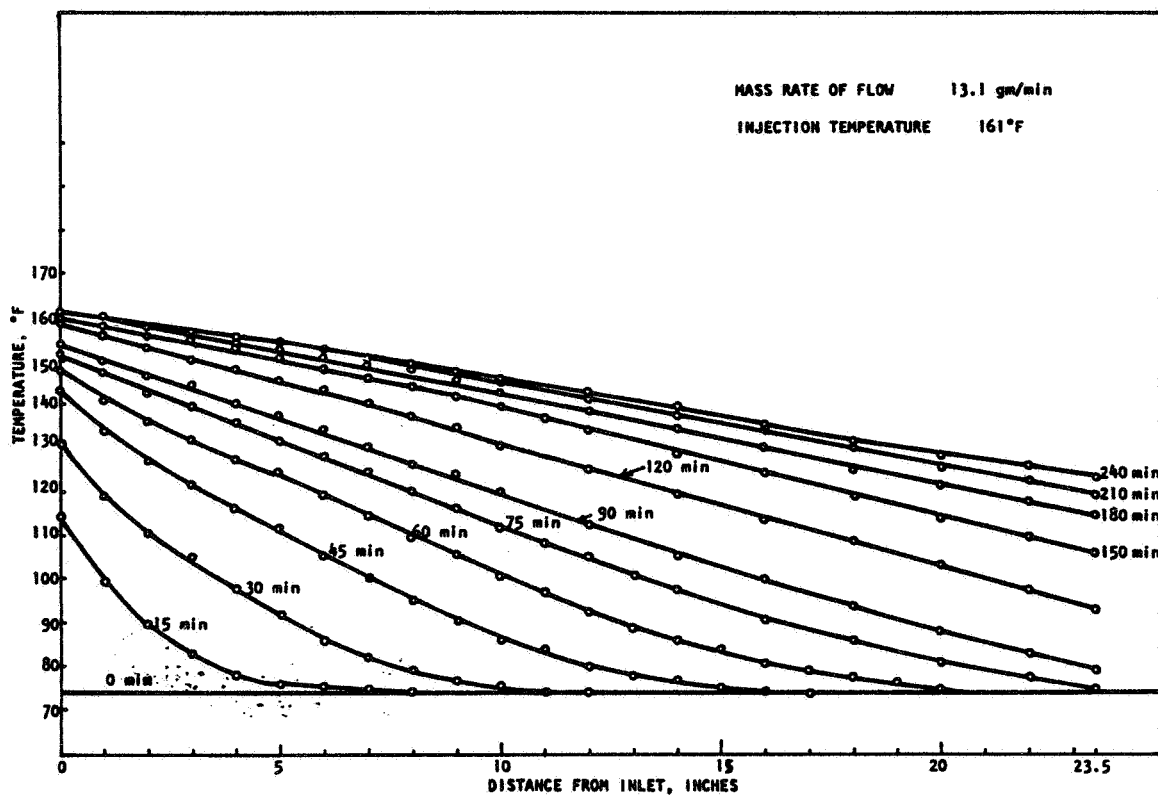


Fig. 5. Temperature vs distance for hot water injection

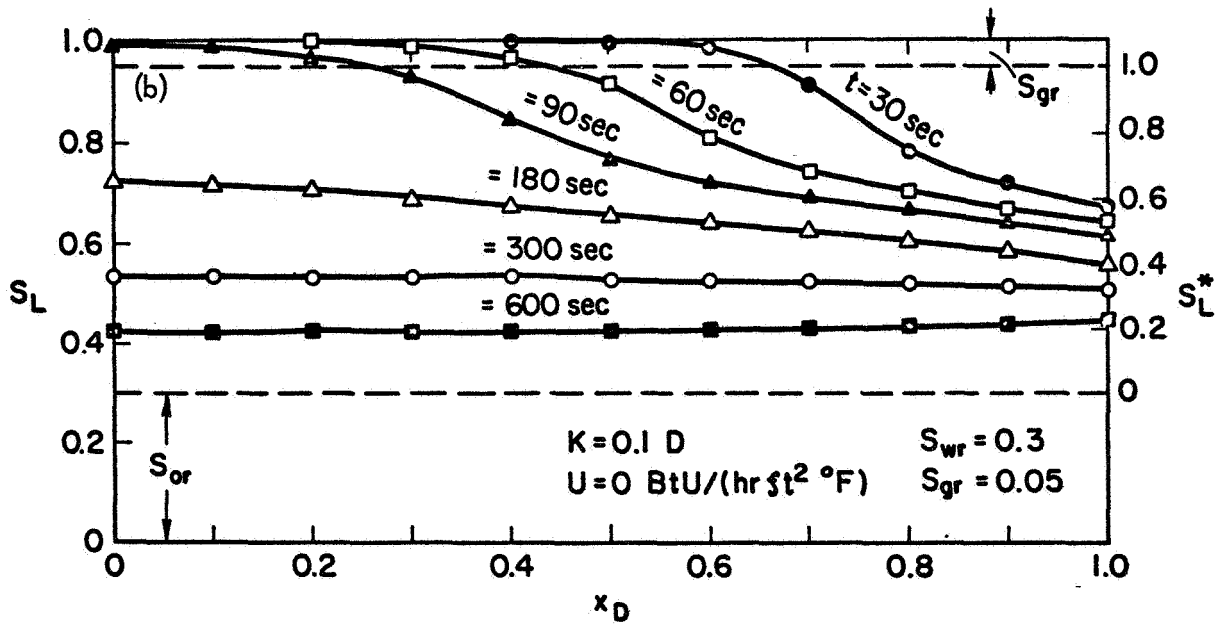
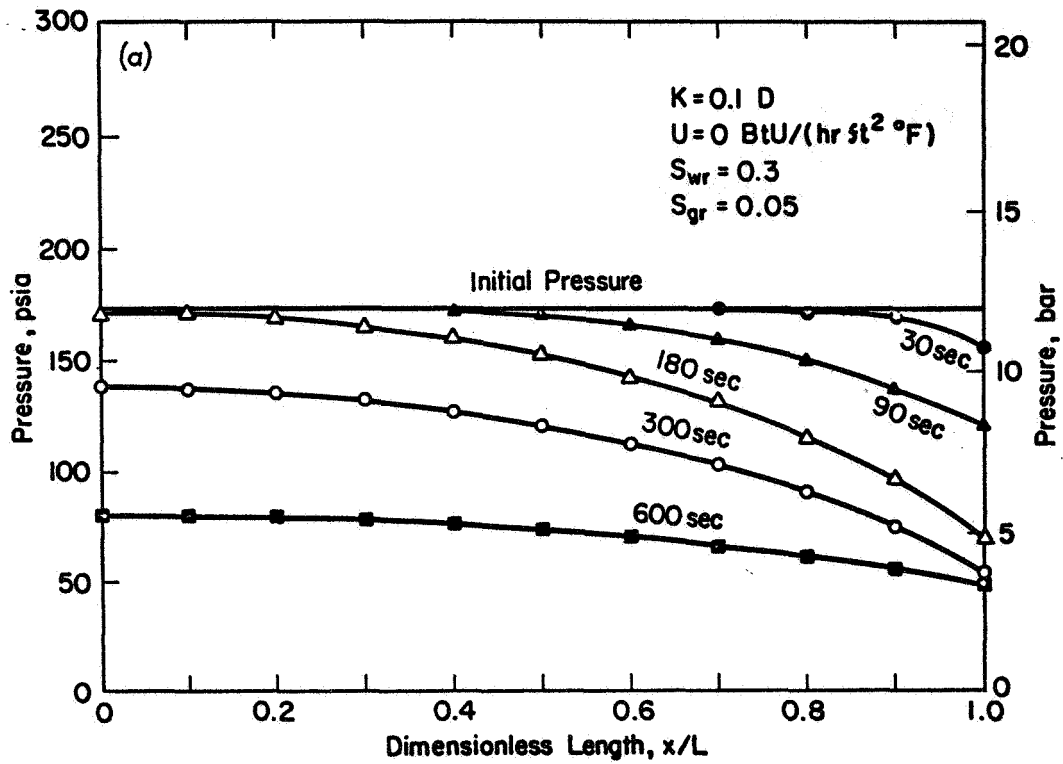


Fig. 6. (a) Simulation No. 1 of pressure history, (b) simulation No. 1 of saturation history