LABORATORY INVESTIGATIONS
OF STEAM PRESSURE-TRANSIENT
BEHAVIOR IN POROUS MATERIALS

by

W. N. Herkelrath and A. F. Moench
U. S. Geological Survey .
Menlo Park, Calif. 94025

Introduction

Transient flow of noncondensable gas in porous materials has been thoroughly investigated, and good agreement between the gas-flow equation and experiments has been reported in the petroleum-engineering literature (Wallick and Aronofsky, 1954). This theory has been widely used in computer simulations of pressure-transient behavior in vapor-dominated geothermal steam reservoirs (e.g., Moench and Herkelrath, 1978).

However, few laboratory experiments involving steam flow in porous materials have been reported. In order to test the applicability of the gas-flow theory to steam flow, we developed a laboratory system to investigate the transient flow of steam through unconsolidated porous materials. Pressure-transient experiments were carried out by imposing a step change in gas pressure at one end of a cylinder of porous material, and measuring the pressure as a function of time at the other end.

Apparatus

A schematic diagram of the experimental apparatus is shown in figure 1. The steam-flow system was enclosed in an oven which had a temperature uniformity of $\pm 0.5^{\circ}C$. All components, including valves and pressure transducers, operated at high temperatures inside the oven to avoid temperature gradients and steam condensation in the system.

The sample holder consisted of stainless steel pipe in which unconsolidated porous materials were densely packed. The results reported here were obtained with a pack of the 0.053 mm to 0.125 mm sieved fraction of a natural desert sand. The bulk density and porosity of the sample were 1.7 g/cm3 and 0.32, respectively.

Steam was obtained by boiling pure water or $CaCl_2$ brine stored in a large reservoir inside the oven. At any given temperature the steam pressure above the liquid in the reservoir was approximately equal to the vapor pressure of the solution.

Pressure-transient tests were also run with air or nitrogen gas which was supplied from a pressure regulating system outside the oven.

In the experiments reported here, the sample was brought to a low initial pressure, and then a constant higher gas or steam pressure was applied at the top of the sample by opening the appropriate pneumatic valve. The pressure at both ends of the sample was measured continuously with pressure transducers during the resulting pressure buildup.

Results

Typical pressure buildup curves obtained in the experiment are shown in figure **2.** Results of tests with air agreed well with the .one-dimensional gas-flow equation (Aronofsky, 1954) :

$$\frac{K}{2\mu} \frac{\partial^2 P^2}{\partial Z^2} = \phi \frac{\partial P}{\partial t} \tag{1}$$

In equation 1, P is the gas pressure, Z is the distance from the top of the sample, μ is the fluid viscosity, ϕ is the sample porosity, **K** is the intrinsic permeability, and **t** is the time. **A** good **fit** to the air pressure buildup data was obtained by assuming a permeability of 3.0 Darcys in the theoretical calculations.

However, when the same pressure boundary conditions were imposed using steam as the fluid, large time delays in the pressure response were observed. The time required for pressure buildup was increased by as much as a factor of **thirty.** This is illustrated by comparing the curves for air buildup and steam buildup at $100^{\circ}C$ in figure 2. A **fit** to the standard theory could only be obtained by assuming an unreasonably low permeability of 0.1 Darcy.

Discussion

The delayed pressure response was probably caused by condensation. Despite the fact that the steam pressure was less than the saturation vapor pressure throughout the experiment, condensation occurred in the sample. **A** liquid saturation as high as three percent by volume was measured by weighing the sample at the end of pressure-transient runs.

Condensation of the steam probably occurred because the vapor pressure of liquid water in a porous medium is reduced. This "vapor-pressure-lowering" effect, commonly observed in soil systems, is caused by adsorption and gas-liquid interface curvature in the small pores of the medium. The dependence of the liquid saturation in the sample upon vapor pressure was determined at high temperature by allowing the sample to equilibrate with salt solutions of known vapor pressure in the reservoir. The results of these tests are shown in figure 3. Also shown for comparison are room temperature data published by Westcot and Wierenga (1974).

When condensation occurs, **a** sink term for steam should be added to equation 1 to preserve the mass balance. Moench and Atkinson (1979) showed that the rate of steam condensation, q_s, can be expressed as

$$q_s = \frac{H_c}{L} \frac{\partial T}{\partial t} \tag{2}$$

in which H_c is the heat capacity of the porous medium, L is the latent heat of vaporization, and T is the temperature.

Vapor-pressure lowering can be incorporated into this theory by assuming that T is a function of both steam pressure and liquid saturation, S. The steam-flow equation fur small changes in temperature and liquid saturation can be expressed as

$$\frac{\partial}{\partial Z} \left(\frac{\rho K}{\mu} \frac{\partial P}{\partial Z} \right) = \phi \, [1-S] \, \rho C_t \, \frac{\partial P}{\partial t} + \frac{H_c}{L} \left(\frac{\partial T}{\partial P} \frac{\partial P}{\partial t} + \frac{\partial T}{\partial S} \frac{\partial S}{\partial t} \right) \tag{3}$$

in which ρ and C_t are the density and compressibility of steam, respectively. Estimates of the sink term indicate that it is one to two orders of magnitude larger than the compressibility term. Accounting for condensation in this way results in an increase in the predicted response time which is of the same order of magnitude as found in the experiments. However, possibly because of errors in the determination of system parameters, good quantitative agreement between the modified theory and the experimental results has not yet been achieved.

References

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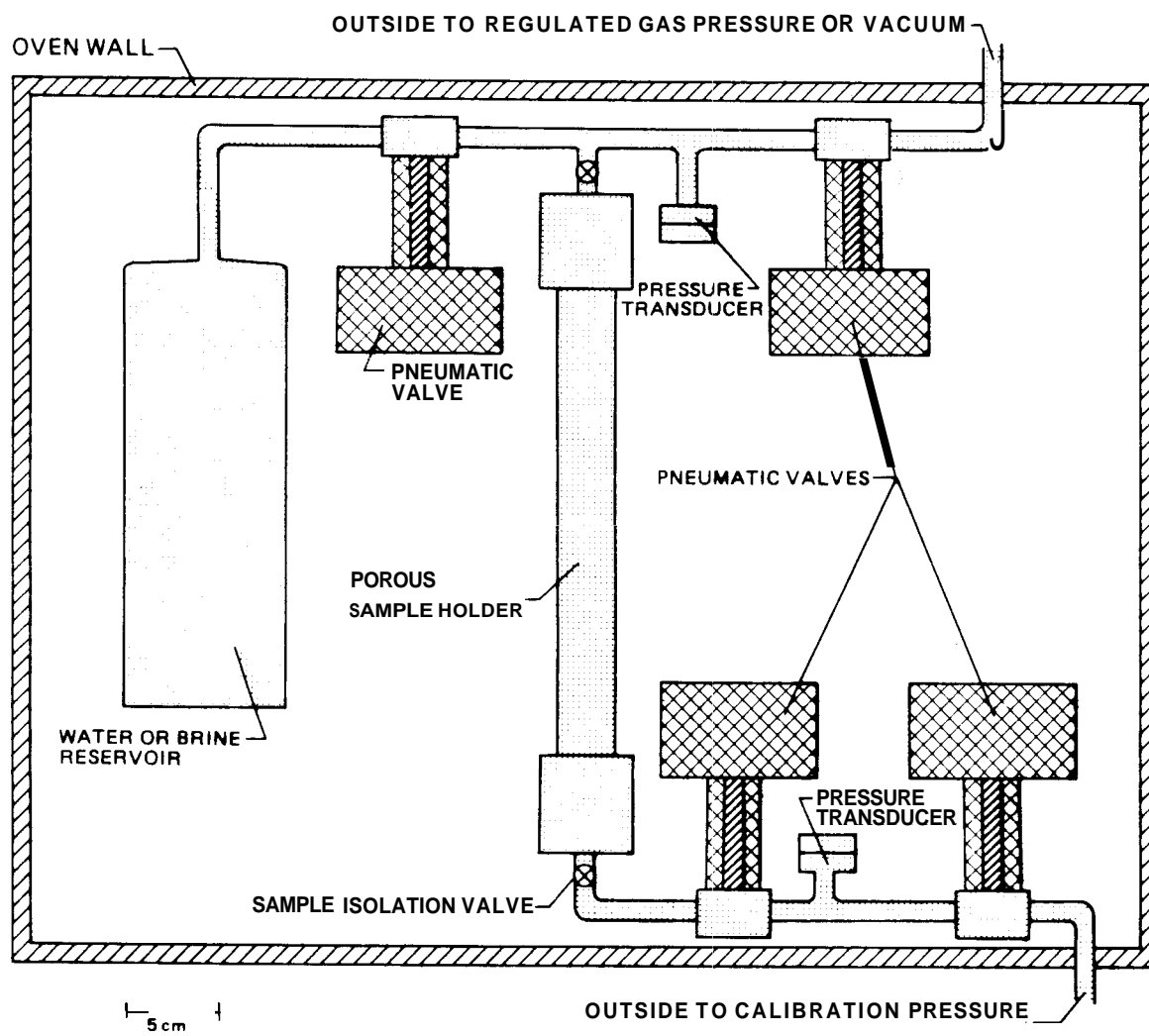
FIGURE 1 – **Schematic diagram** of **stream-pressure-transient apparatus**
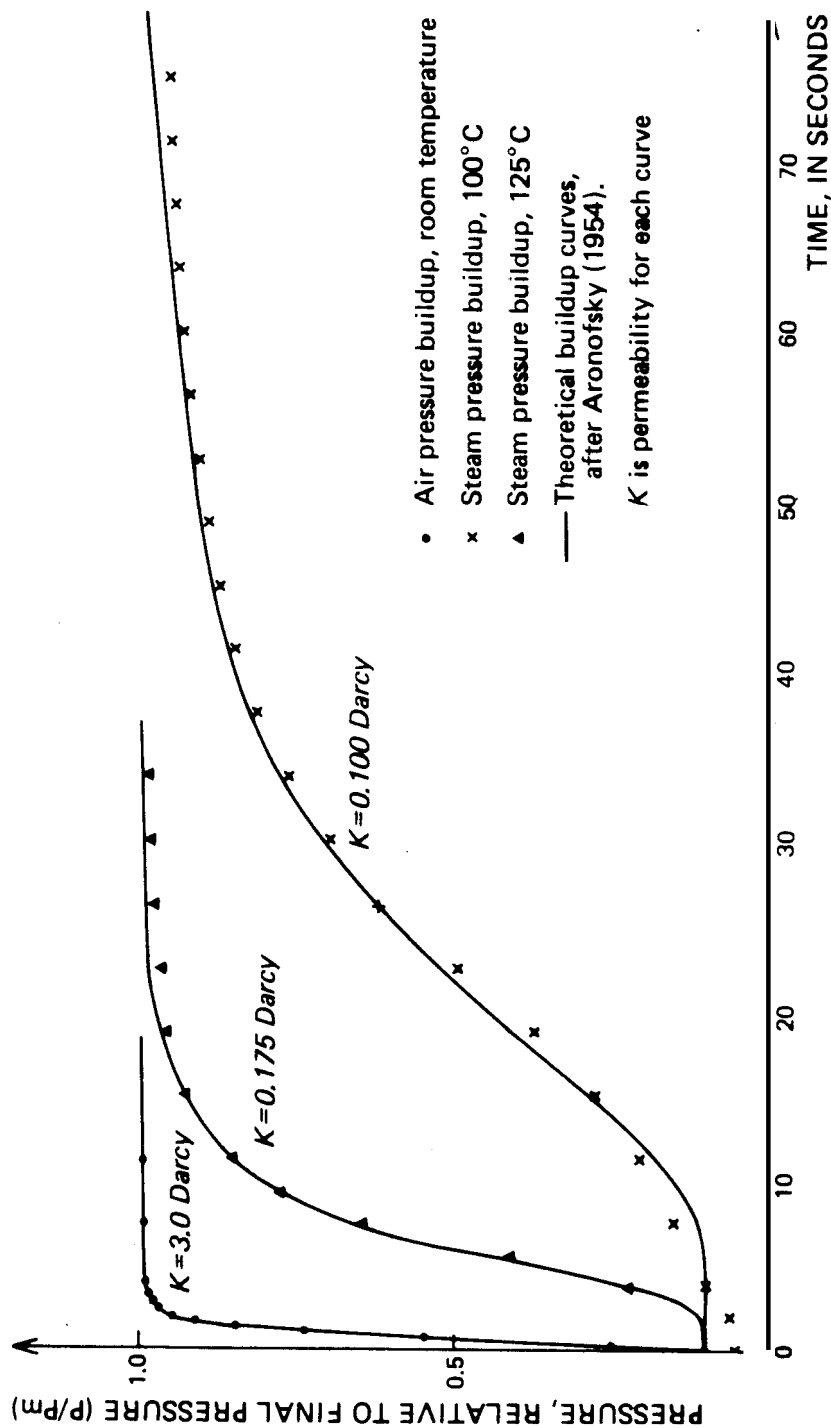
FIGURE 2 – **Pressure** transient behavior in unconsolidated fine sand; comparison of air and steam pressure buildup

The legend for the figure reads:

• Air pressure buildup, room temperature
× Steam pressure buildup, 100°C
▲ Steam pressure buildup, 125°C
— Theoretical buildup curves, after Aronofsky (1954).

K is permeability for each curve

Axis labels: TIME, IN SECONDS (horizontal); PRESSURE, RELATIVE TO FINAL PRESSURE (p/pm) (vertical)

Curve labels: K=3.0 Darcy, K=0.175 Darcy, K=0.100 Darcy
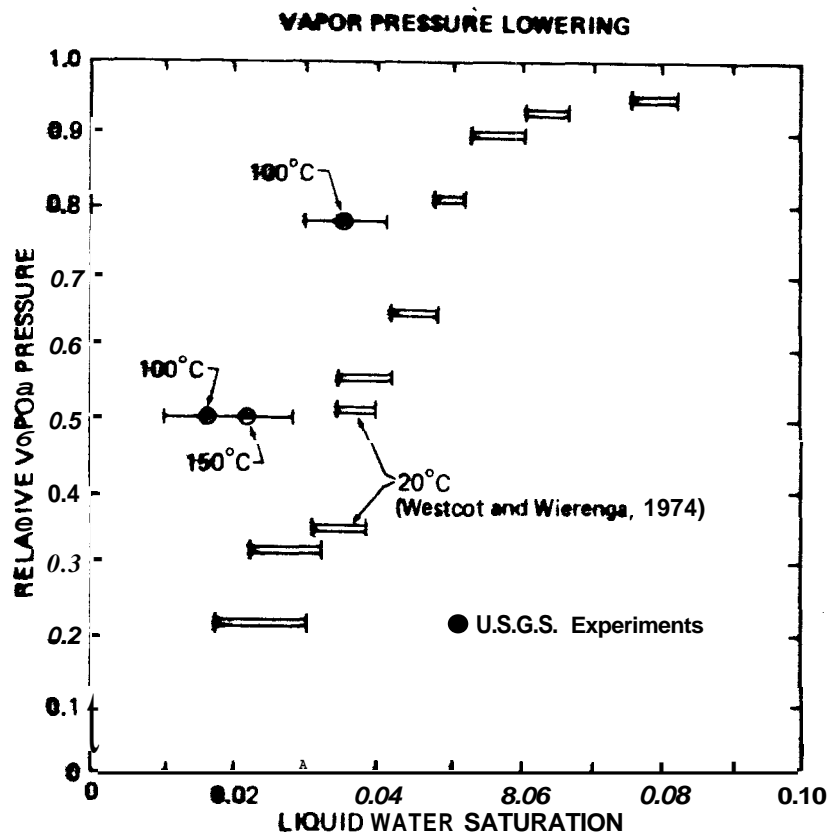
VAPOR PRESSURE LOWERING

FIGURE 3. –Dependence of relative 'vapor pressure upon liquid saturation in a fine sand. **All** of the measurements with doubled error bars were made at 20°C by Westcot and Wierenga (19 74).