# TRANSIENT STEAM FLOW IN POROUS MEDIA - THEORY AND EXPERIMENT

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## INTRODUCTION

A previous workshop summary (Herkelrath and Moench, 1978) described laboratory studies of transient steam flow in a porous medium. The results indicated that the time required for steam-pressure transients to propagate through the medium was as much as 30 times greater than predicted by standard noncondensable gas-flow theory. It was hypothesized that the delay in the steam pressure breakthrough was caused by adsorption of steam in the porous sample. This "adsorption lag effect" has been incorporated into the following revised model of steam flow in a porous medium.

## THEORY

The steam-flow model used was basically that developed by Moench and Atkinson (1978), modified to take steam adsorption into account (Moench and Herkelrath, 1978). The equation used to describe one-dimensional, linear steam flow in a porous medium is

$$\frac{\partial}{\partial Z}\left(\frac{\rho_v K}{\mu_v}\frac{\partial P}{\partial Z}\right) = \phi\frac{\partial}{\partial t}\left(\rho_v(1-S)\right) + q' \qquad (1)$$

in which the variables are as defined in table 1. This equation differs from the standard transient gas flow equation in that a sink or source term for steam, q', has been added to account for adsorption or vaporization of adsorbed water. In the analysis, the Klinkenberg effect (Klinkenberg, 1941) was taken into account by assuming that the permeability was a function of pressure:

$$K = K_o(1 + b/P) \qquad (2)$$

A simplified form of the energy equation was used in the model:

$$L_v q' = H_c\left(\frac{dT}{dt}\right) \qquad (3)$$

To obtain equation 3, it was assumed that temperature changes in the porous medium occur only as a result of phase changes.

In the model it was assumed that water adsorption occurs in the porous medium at steam pressures below the saturated vapor pressure. The vapor pressure of adsorbed water was assumed to be a function of the temperature and the amount of water adsorbed:

$$P = P(T,S) = P_0(T)\ R(S) \qquad (4)$$

$P_0(T)$ represents the saturated vapor-pressure function, and $R(S)$ is the function relating the relative vapor pressure in the porous material to the fraction of the pore space which is filled by adsorbed water.

The equations were solved using the finite-difference methods developed by Moench and Atkinson (1978).

## EXPERIMENTS

The steam-flow experiments were modeled after the classic transient gas-flow experiments reported by Wallick and Aronofsky (1954). The test medium used was a uniform cylindrical pack of a natural unconsolidated, fine sand. In the experiments reported here, the sample was initially evacuated at the running temperature, and then exposed to a low pressure steam source until temperature, pressure, and amount of water adsorption were constant throughout. High pressure steam was then abruptly introduced at one end ($Z=0$), and the resulting pressure transient was measured with a pressure transducer at the other end of the cylinder ($Z=L$), which was closed to provide a zero-flow boundary. Values of the parameters are shown in table 2.

Results of the experiments are summarized in figures 1 and 2. Figure 1 consists of plots of the steam pressure at $Z=L$ as a function of time since the step increase in pressure occurred at $Z=0$. When the same pressure boundary conditions were imposed using nitrogen gas as the fluid, the pressure breakthrough was 10 to 25 times faster than that shown in figure 1.

Figure 2 is a plot of the equilibrium vapor pressure in the sample as a function of the amount of water adsorption, expressed as liquid saturation. These data were obtained by exposing the sample to a known relative humidity until equilibrium was obtained, and then weighing it to determine the amount of adsorption. These results are very similar to those reported by Hsieh (1980).

To simplify the numerical calculations, the $R(S)$ function was obtained by least-squares fitting the adsorption isotherm to the empirical function

$$R(S) = 10^{-\left(10^{(A-S)/B}\right)} \qquad (5)$$

## DISCUSSION

The empirical vapor-pressure-lowering curve obtained at 100°C was used in the model to simulate the experiments run at 100°C, 125°C and 146°C. The 100°C data were used because a complete set of data at higher temperatures was not available. However, the results of the pressure-transient simulations were affected only by changes in slope of the vapor-pressure curve, and preliminary data indicated only a small change in the slope at increased temperature.

As shown in figure 1, agreement between theory and experiment is excellent for all the runs, thus verifying the model for the conditions of study. It should be emphasized that no fitting has been done to obtain the theoretical curves; all the parameters were measured independently.

A U.S. Geological Survey open-file report is being prepared to document these results more completely.

Table 1

Notation

A and B = Fitting factors in relative vapor-pressure function
$b$ = Klinkenberg slip factor
$H_c$ = Heat capacity of porous medium
$K$ = Permeability
$K_o$ = Intrinsic permeability
$L$ = Sample length
$L_v$ = Latent heat of vaporization
$P$ = Steam pressure
$P_o(T)$ = Saturated vapor-pressure function
$q'$ = Rate of steam adsorption
$R(S)$ = Relative vapor-pressure function
$S$ = Liquid saturation, fractional
$T$ = Temperature
$t$ = Time
$Z$ = Position in sample
$\mu_v$ = Viscosity of steam
$\phi$ = Porosity
$\rho_v$ = Vapor density

Table 2

Values of Parameters*

$A = 8.65 \times 10^{-3}$

$B = 2.30 \times 10^{-2}$

$b = 1.4 \times 10^{5}$ dynes/cm$^{2}$

$H_c = 3.2 \times 10^{-1}$ cal/cm$^{3}$°C

$K_o = 3.6 \times 10^{-8}$ cm$^{2}$

$L = 61.0$ cm

$\phi = 0.42$ cm$^{3}$/cm$^{3}$

*Remaining parameters are known properties of water at prevailing temperature and pressure

## REFERENCES

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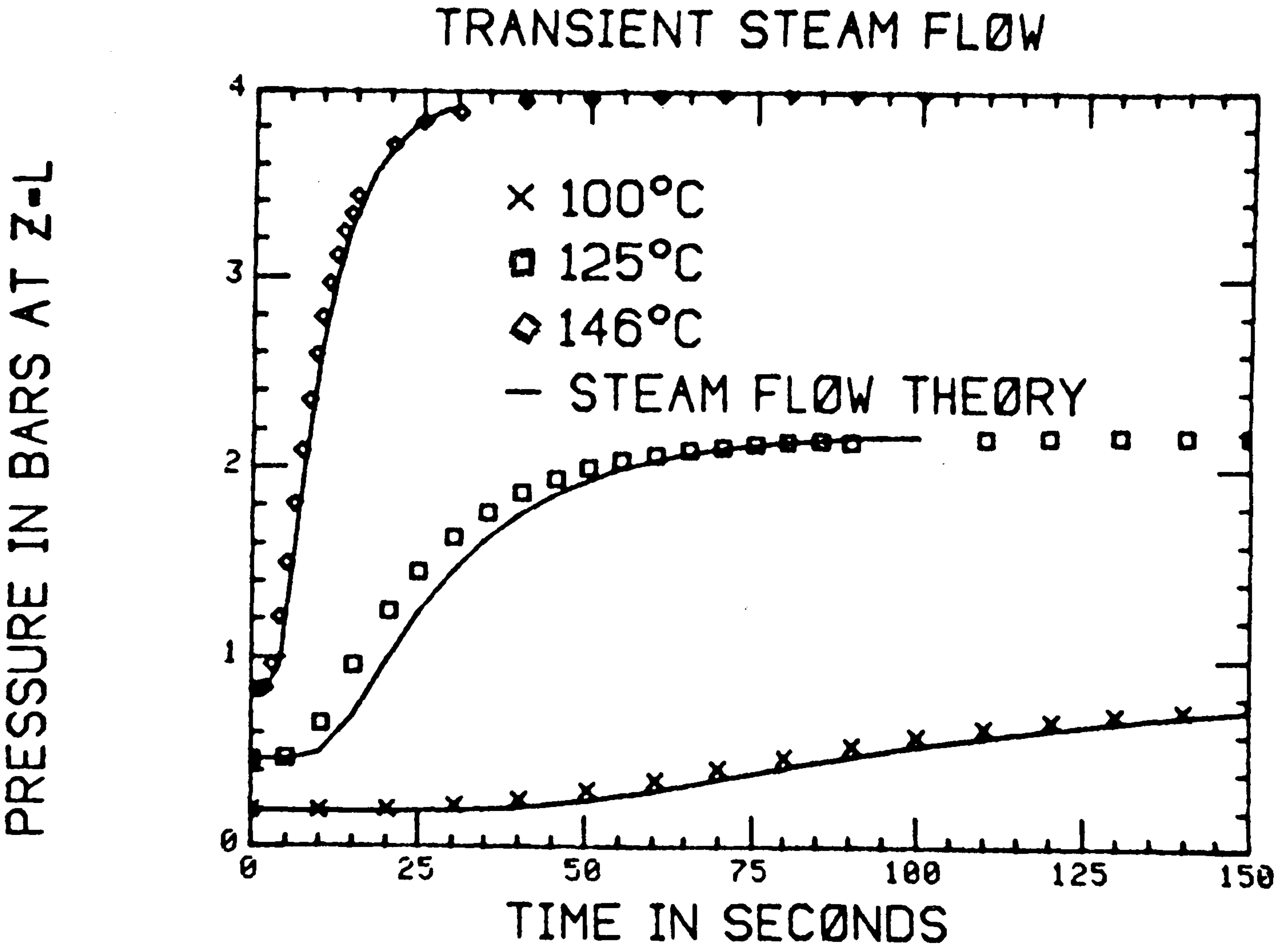

Figure 1. Steam pressure at the closed end of the porous cylinder (Z=L) as a function of the time since a step increase in pressure was imposed at Z=0. The solid lines represent computer simulations of the experiments.

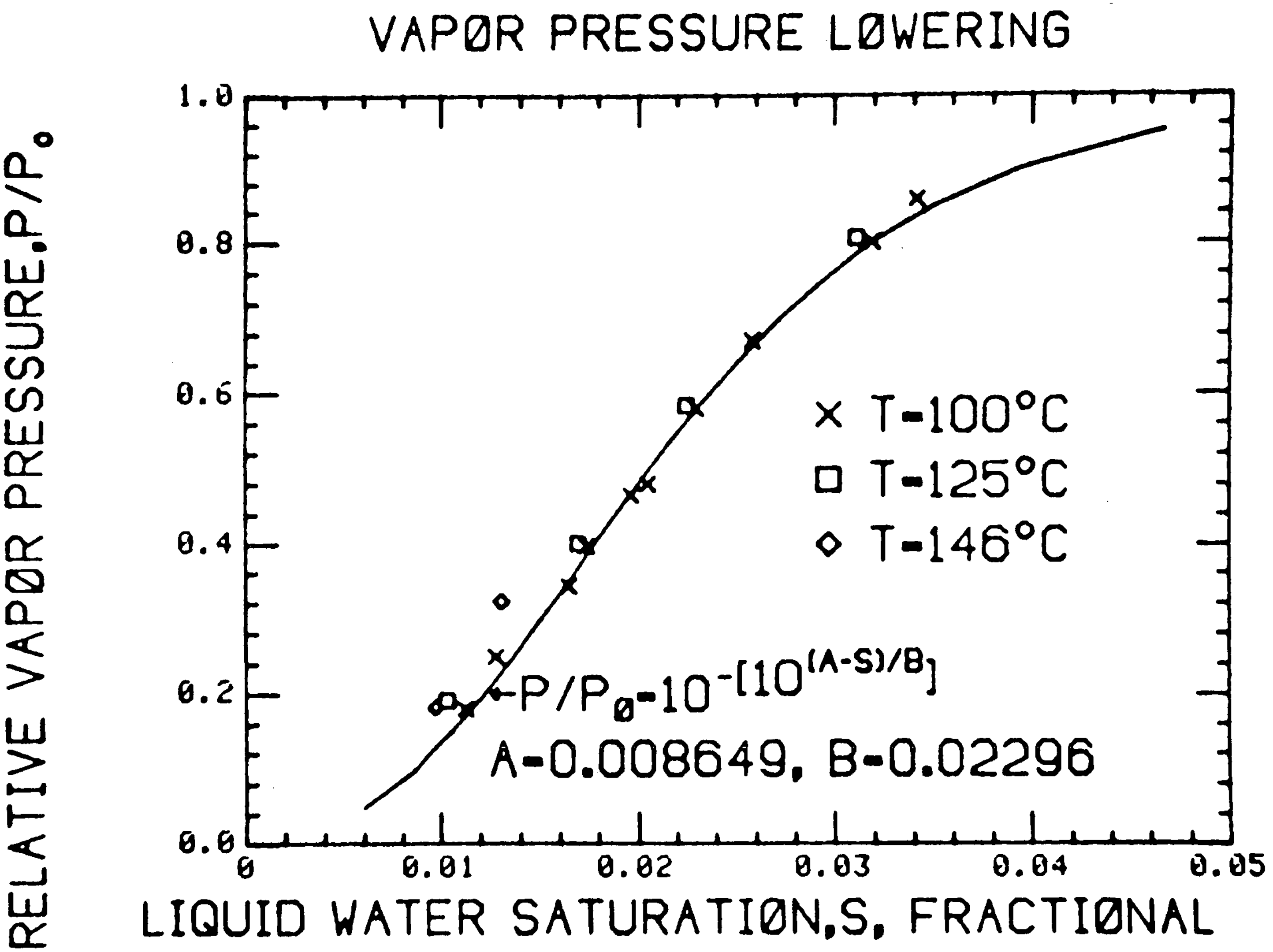

Figure 2. Equilibrium relative vapor pressure in the porous sample as a function of the amount of water adsorption, expressed as a liquid saturation. The solid line represents the empirical equation which was used in the steam-flow simulations.