HEAT TRANSFER IN NONISOTHERMAL LIQUID INJECTION EXPERIMENTS IN POROUS MEDIA

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This paper presents a study of heat transfer phenomena in bench-scale experiments of heat and mass flow in porous media (Atkinson, 1976). The intent of this work was to determine which heat transfer mechanisms are important in the bench-scale experiments being carried out in the Stanford Geothermal Program. The initial analysis considered the relatively simple case of nonisothermal single-phase liquid flow. However, the results can be applied to bench-scale experiments involving boiling water or brine flow (such experiments have been described by Chen, 1976).

Mathematical Modeling

A series of simplified mathematical models of heat and mass transport in fine-grained porous media were developed. The basis for the models was a physical system which consisted of cylindrical consolidated sandstone cores mounted in a Hassler-type coreholder. The coreholder system was placed inside a uniform temperature airbath. Hot or cold liquid water was injected into the core, and temperature distributions within it were measured as functions of time. These experimental results were reported by Arihara (1974).

The Arihara data were analyzed with new, simple models. Such models can be used to gain insight into the physical system because they display the interaction of the various assumed heat transfer mechanisms. Furthermore, since they contain fewer unknown or uncertain parameters, the comparison of the models with experimental results is easier than with more complicated models.

Four mathematical models have been developed. All of the models account for convective energy transfer, heat losses from the core, and thermal energy storage. However, each one includes different assumptions about heat conduction along the axis of the system, and about the nature of heat losses from the core. Easch of the models was studied and compared with both of the other models and with the experimental data of Arihara. The development of analytical solutions for the models simplified comparisons. None of the mathematical models could match observed experimental behavior accurately for the entire time of the experiments. However, each model did exhibit behavior which was important during some stage of the experiments, and as a group these models were able to isolate the important heat transfer mechanisms in the Arihara experiments. These theoretical results are discussed in the next section.

Results

It was determined that longtime, steady-state temperature behavior in the core was dominated by convection energy transfer in conjunction with steady heat losses from the sides of the core. This should cause the steady-state temperature profiles to be semi-log straight lines, as can be seen to be the case in Fig. 1. The slopes of the semi-log straight lines have negative values of $hP/(2.303\ wC_w)$ on $\log_{10}$ graph paper, where h is the overall heat loss coefficient from the core, P is the perimeter of the core, w is the mass flowrate through the core, and C_w is the specific heat of the flowing liquid. The one experiment which did not graph as a straight line in this figure had not reached steady-state.

During the early stages of hot or cold liquid injection, an effective axial thermal conduction mechanism was found to affect the temperature profiles strongly. This effect was not reduced at higher mass injection rates, because of the increased effect of mixing and dispersion mechanisms with increasing injection rate.

Early- and medium-time stages of hot or cold liquid injection were found to be affected strongly by transient heat losses through the core-holder system. These transients were caused primarily by the thermal capacity of the viton sleeve which surrounded the core. It was also found that the transients were controlled by a flowrate-dependent film coefficient between the core and coreholder sleeve.

The functional dependence between the core-coreholder film coefficient and the mass injection rate was estimated by comparing calculated temperatures with those reported by Arihara. The results of these comparisons are presented in Fig. 2. This figure also presents the results of Crichlow (1972), derived from experiments on an unconsolidated sandpack, and those of Colburn (1931), whose smallest particles were 1/8 in. granules. Figure 2 suggests an interesting trend in the data, particularly since Arihara's experiments were carried out on consolidated porous media with effective particle sizes of as much as ten times smaller than those of Crichlow. Experimental investigation of this functional dependence is continuing.

A Critique of Previous Modeling of Arihara's Liquid Injection Experiments

The single- and two-phase nonisothermal fluid flow experiments of Arihara have been used by various authors (Garg, *et al.*, 1975; Faust and Mercer, 1976; Thomas and Pierson, 1976) as a basis for checking sophisticated computer model results.

None of these computer models incorporated the phenomenon of transient heat losses through the coreholder.

For example, Garg, *et al.*, presented calculations for the CWI-S-4 experiment of Arihara, and compared computed and measured temperatures. Their model could handle only steady heat losses through the coreholder system. Their comparison appeared plausible for the limited range of time presented. However, analysis of the steady-state profile for this experiment

(See Fig. 1) indicates an overall heat loss coefficient from the core of 1.98 Btu/(hr ft^2 ^oF) while Garg, et al., used an effective value of 4.2 Btu/hr ft^2 ^oF). This higher heat loss coefficient caused the appearance of higher calculated heat losses from the core during the early stages of the experiment. This calculated behavior is consistent with the observed early-time behavior of the experiments. At longer times, however, the experiments showed a lower heat loss rate. If Garg, et al., had presented calculated temperatures for times greater than 45 minutes, these values would have been close to the values presented for 45 minutes. Thus, their model would have reached steady-state for the given physical parameters. Fig. 3 shows that the temperatures in the core actually continued to change for 105 minutes.

It can thus be seen that care must be taken if one wishes to avoid a situation where a mathematical model is calibrated against experimental results using incorrect values for some physical parameters. It is important that all of the relevant physics be discovered and incorporated into the mathematical model before doing such a calibration.

Summary

This paper has discussed an analysis of the heat transfer phenomena in the bench-scale experiments being carried out in the Stanford Geothermal Program. The basis of this analysis was a series of simplified mathematical models of heat and mass transport in fine-grained porous media. The analysis determined that the thermal capacity of the coreholder system caused heat losses from the core which were not steady at early and medium times. This phenomenon had not been recognized previously. This was in spite of the fact that various authors previously had attempted to match the experimental behavior under discussion with their sophisticated computer models. These computer models did not account for the transient nature of the heat losses from the core.

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FIGURE 1. GRAPH OF log ($T_{external}$ - T) VS DISTANCE ALONG THE CORE FOR THE COLD WATER INJECTION EXPERIMENTS OF ARIHARA

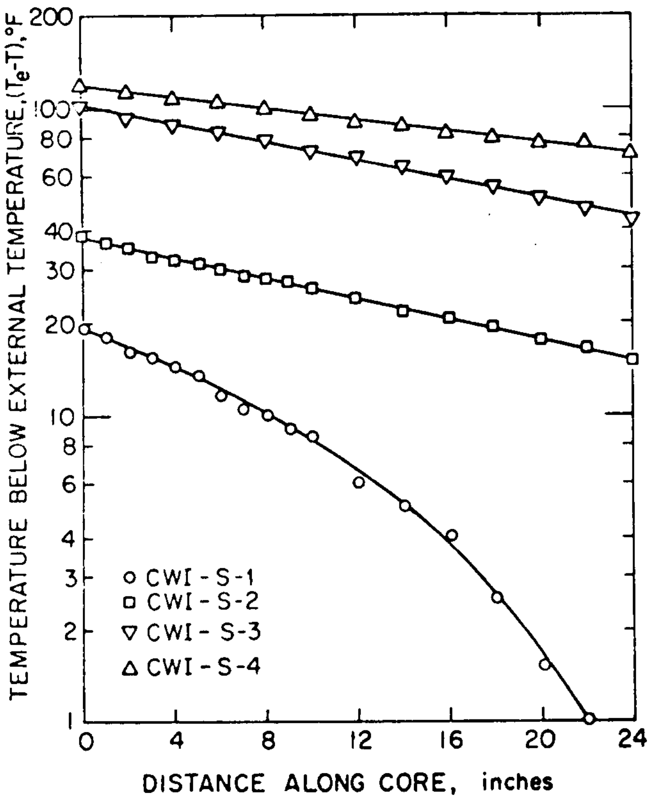
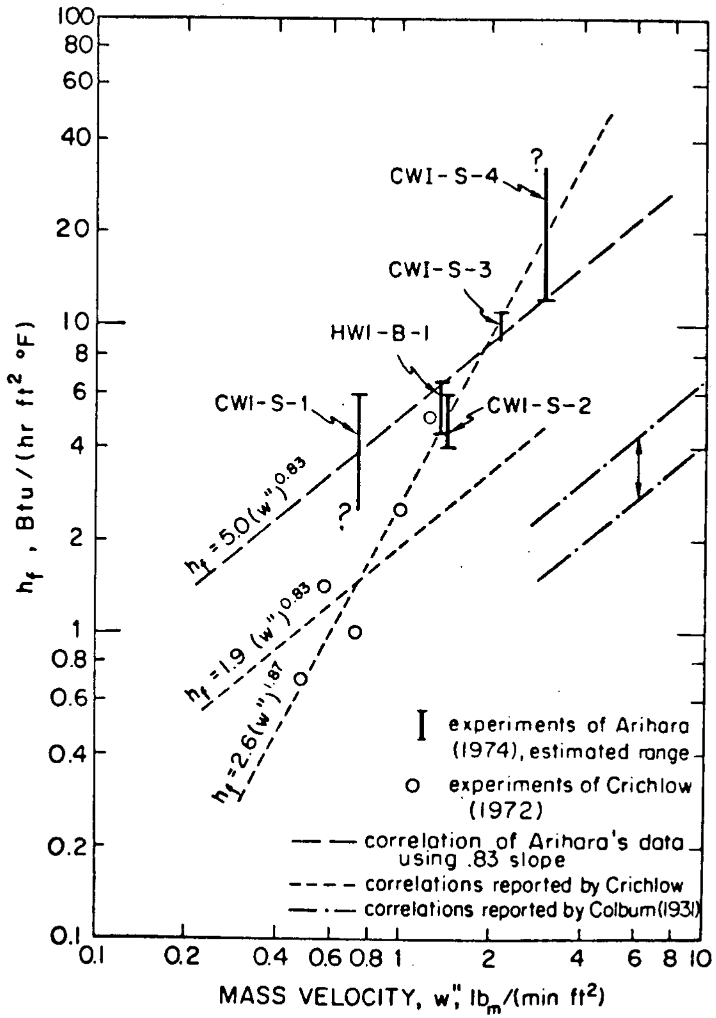


FIGURE 2. GRAPH OF THE CORE-COREHOLDER FILM COEFFICIENT, h_f, VS. MASS VELOCITY, w"



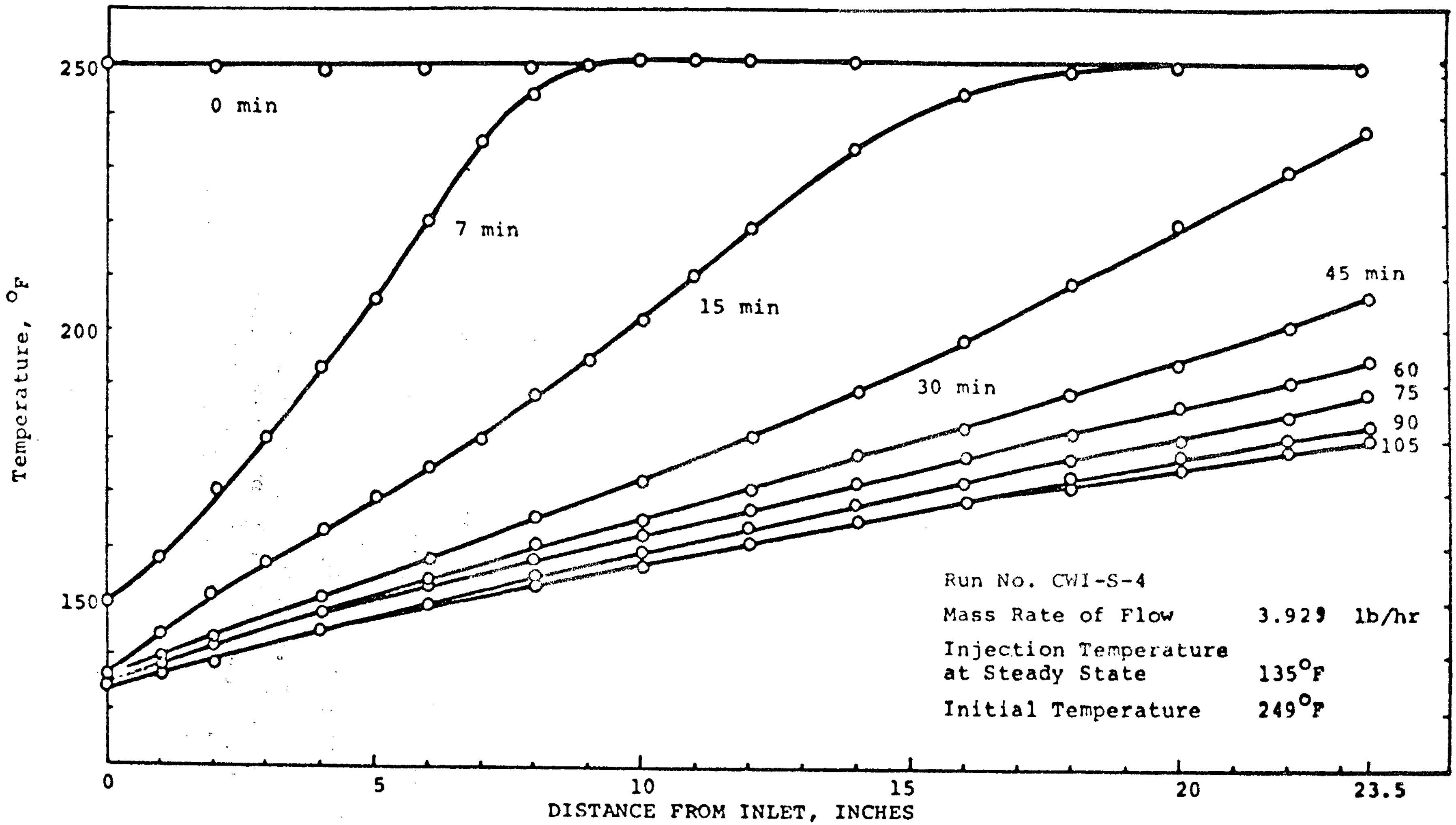


FIGURE 3. TEMPERATURE VS. DISTANCE FOR COLD WATER INJECTION SYNTHETIC SANDSTONE; RATE = 3.929 lb/hr, TEMP. = 135°F