

## ONSET OF CONVECTION FOR A MISCIBLE FLUID IN A POROUS MEDIUM

Robert Behringer, Michael Carey, Mark Steen, and Laurens Howle, Duke University

We present experimental results for the onset of convection in a horizontal layer of porous medium saturated with a miscible binary mixture of ethanol and water. Previous theory[1] indicates a bifurcation to oscillatory convection for negative separation ratio, but we find steady convection at onset. We explore the possibility that enhanced mixing is at the root of these observations.

The experiments were carried out using a variety of different media and two different techniques. The first technique[2] is Magnetic Resonance Imaging (MRI), which allows us to non-invasively probe a variety of porous media. We directly measure the density of fluid in the pore space and the vertical velocity field. With MRI, we explored media constructed from foams and from sphere packings. The second technique[3] is a novel form of a shadowgraph. We construct special media which allow us to transmit light vertically through a porous layer. The media were made by constructing a grid of holes in plastic sheets which were then stacked vertically.

The basic form of the experiment consists of a layer of fluid-saturated porous medium that is heated from below. The control parameters are then the porous Rayleigh number,  $R$ , the separation ratio,  $\psi$ , the Lewis number,  $L$ , and the aspect ratio.  $R$  is a dimensionless measure of the vertical temperature difference across the layer.  $\psi$  characterizes the stabilizing influence of the concentration gradient.  $L$  is the ratio of diffusion times for mass and heat, and the aspect ratio is the ratio of a typical horizontal dimension and the height of the layer. We used  $\psi$ 's in the range  $-0.2 < \psi < 0$ , the Lewis numbers were  $\sim 0.01$ , and the aspect ratios were in the range 5 to 10. The horizontal planform of the convection layers corresponded to disks, rectangles, and annuli.

Measurements consisted of MRI velocity maps and temperature differences for MRI imaging. For the shadowgraph, we obtained images of the convective planform, and we also obtained high precision heat transfer data, i.e. data for the Nusselt number, all as functions of  $R$ .

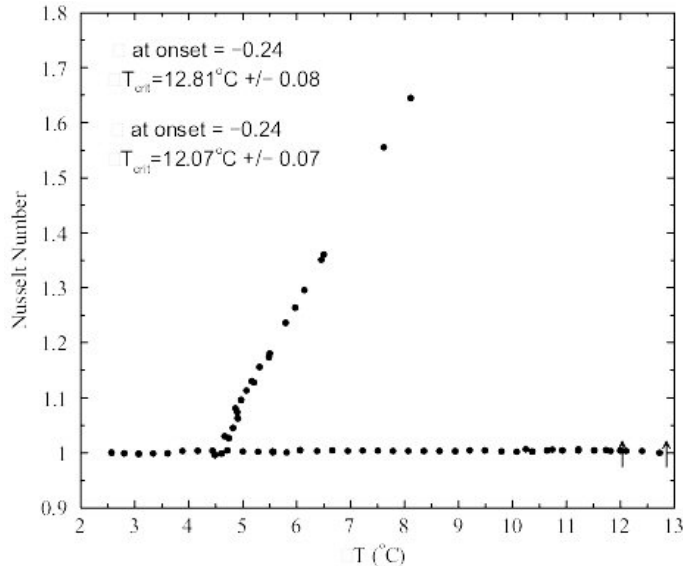


Figure 1. Nusselt Number vs. temperature difference across the layer showing the hysteretic transition to convection. On increasing  $R$ , we found that convection was initiated at the arrows, leading to large-amplitude steady convection.

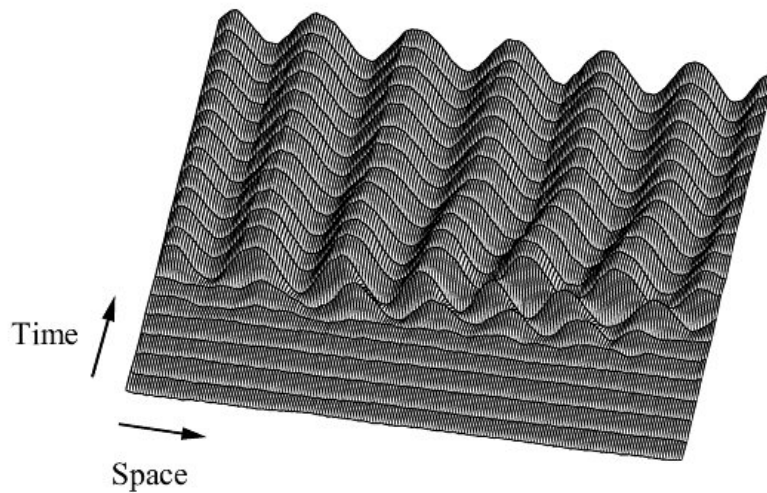


Figure 2. Space-time velocity map showing the vertical fluid velocity after a step change in  $R$ . After an initial transient that may be representative of damped oscillatory motion, steady convective rolls persist. In this case, the planform of the layer was a long thin rectangle, and this figure shows data along the long spatial dimension.

Regardless of method, we found that the onset of convection was characterized by a hysteretic transition to steady overturning convection rolls. By contrast, existing theory indicates that the transition to convection should be oscillatory. We note that for the bulk Rayleigh-Benard case, oscillatory phenomena have been routinely observed. Hence, this experimental finding is quite surprising. We show an example in Fig. 1, which gives high-precision Nusselt number data for a typical case using the shadowgraph technique. In Fig. 2, we show an example of a transient flow leading to steady convection for a long thin rectangular layer observed with MRI. The transient behavior suggests that oscillatory convection is strongly damped, if it is present at all.

We have pursued the possibility that the difference between previous theory and our observations is due to enhanced mixing. That is, as convection begins, the fluid is mixed as it passes through the solid matrix, thus leading to pure-fluid-like behavior. We have used a Lorentz-model truncation of the full set of equations describing convection in porous media. The momentum equation that we use is Darcy's law plus an additional term for enhanced mixing, as for instance in Bear[4]. Here, however, we assume that the strength of the mixing term grows as the square of the velocity, and assumption that is experimentally justified by direct measurement on our porous media, and that allows for theoretical simplicity. We find that an enhanced mixing term of strength  $M$  does change the bifurcation to match the experiments.

We then carried out additional NMR measurements to directly determine the strength of the mixing term for some of our porous media. The experimentally determined values of  $M$  were too small by roughly two orders of magnitude to account for our observations. Thus enhanced mixing does not appear to be the explanation for the observed phenomena, which remain unexplained.

## References

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