The effects of vertical heterogeneity on gravity current flows in porous media

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1. INTRODUCTION & OBJECTIVE

Gravity currents are the type of flows driven primarily horizontally, due to the density differences between two fluids. In porous media, gravity currents occur during various applications that include carbon sequestration, seawater intrusion into groundwater, or geothermal processes. Problems relevant to gravity currents, therefore, have been active topics of research for the past several decades in the porous media community (Hesse et al. 2007, Ciriello et al 2016).

Gravity currents have been studied both experimentally and theoretically, and most of investigations have focused on sharp-interface flows, which implies that the injected fluid does not mix with the ambient fluid. However, some recent laboratory experiments, for example by Huppert et al. (2013) and Sahu & Flynn (2017), show otherwise that mixing during a gravity current flow can be significant and in fact can alter the flow behaviour from what is found in a homogeneous medium.

To understand the mixing dynamics of gravity currents, Szulczewski & Juanes (2013) studied this problem in a confined porous medium, where they found that mixing between the two fluids occur either due to diffusion or Taylor dispersion depending on the time scale of the flow. Extending this work, Sahu & Neufeld (2020) investigated a similar problem but in an unconfined porous medium. They showed that mechanical dispersion occurs vertically due to the horizontal velocity of the gravity current. Motivated from the laboratory experiments, Sahu & Neufeld (2020) also derived a theoretical model that predicts the amount of mixing in the gravity currents in porous media.

Both these studies focused on homogeneous porous media, whereas the subsurface aquifers are usually heterogeneous in nature. In fact, the vertical heterogeneity in form of permeable strata is very common. In this work, therefore, we aim to investigate the behaviour of gravity currents in layered porous media, particularly focusing on the amount of mixing.

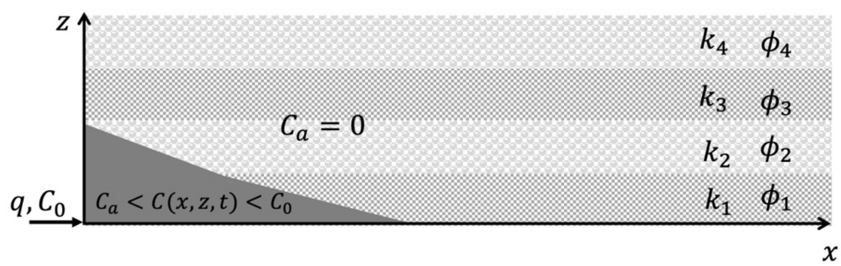

Figure 1. Schematic of the experimental setup showing different layers of permeabilities (k) and porosities (ϕ). The porous medium is saturated with a fluid of zero solute concentration and a dense fluid of solute concentration C_0 is injected at the bottom left boundary with the flow rate q.

2. RESULTS & HIGHLIGHTS OF IMPOINTANT POINTS

An schematic of the experimental setup is shown in figure 1. We performed laboratory experiments by changing the flow rate and concentration of the injected fluid and the permeability and thicknesses of the permeable layers. In total, around 40 experiments were performed that gave comprehensive idea on the behaviour of gravity currents in layered media. Experimental images during the flow were captured through a DSLR camera and the images were postprocessed in Matlab to find the parameters of interest, which included the gravity current profile and concentration. An example of the propagation of gravity current in time and associated profiles and mixing are shown in figure 2.

We find that due to sudden jump in the permeability vertically, there occurs an override of the injected fluid which eventually results into Rayleigh-Taylor instabilities. These instabilities enhance the rate of mixing between the gravity current and the ambient fluid. Our lab experiments, on comparison with the results from Sahu & Neufeld (2020) for a homogeneous case, suggest that the scale of mixing in a heterogeneous medium could be as high as $O(2)$ than that in a homogeneous medium for similar flow conditions and medium properties. The increased rate of mixing does not only decrease the concentration rapidly, but also dictates the gravity current shape. Reduced concentration makes the gravity current lighter, thus decreasing the horizontal buoyancy. This allows the gravity current flow vertically more easily than horizontally. As a result, the gravity current becomes thicker rapidly.

A gravity current is usually modelled as a long and thin flow, such that boundary layer assumptions are applicable. Our results, however, conclude otherwise that due to the enhanced mixing in a heterogeneous medium, the gravity current tends to break the long and thin assumption much more quickly, requiring the gravity current to be modelled as a two-dimensional flow.

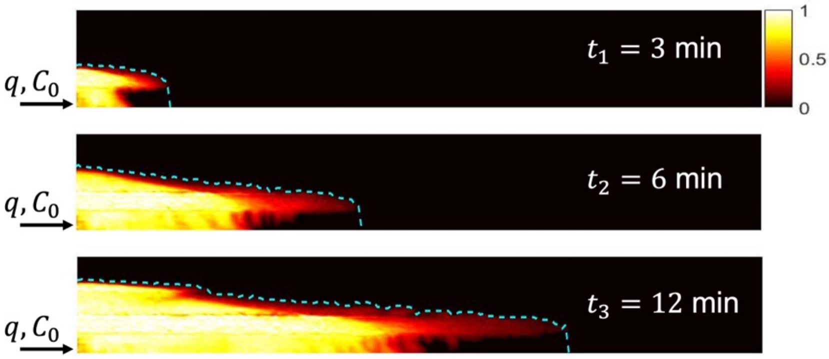

Figure 2. Post-processed gravity current images at different times from the beginning of injection of the dense fluid. The colour bar represents the fluid concentration, which has the value of $C/C_0 = 1$ at the inlet and $C/C_0 = 0$ in the ambient.

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