MRI of the Interplay between Fluid Dynamics and Heat Transfer

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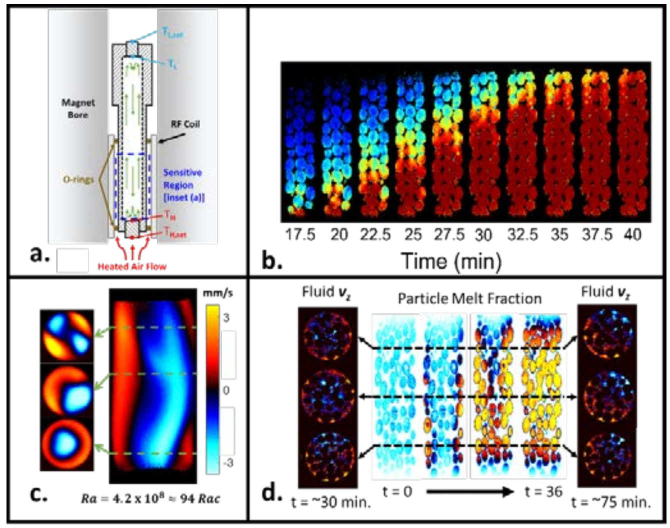

Fig. 1: (a.) A cross-sectional diagram of the flow cell with the sensitive region of the imaging coil outlined in blue. (b.) Forced convection melting of encapsulated wax. (c.) $\mathbf{v_z}$ velocity images of RBC convection show three different flow patterns in the transverse images over a 40 mm axial span. (d.) Change in preferential flow pattern after melting of wax at left and right. Central sequence shows melting starts at circumference edge.

Introduction:

MRI is a proven method for investigating convection in complex fluid systems [1, 2]. Its noninvasive nature allows time and space dependent changes to flow and structure to be captured without disruption to sensitive systems. This research investigates the interplay of fluid dynamics and heat transfer through Rayleigh-Bénard convection (RBC) with and without porous media packing. Figure 1a is a diagram of the flow cell, with a dashed blue box outlining the imaging region. In RBC, an adverse density-gradient is induced across the sample by heating the contained fluid from below. The stability of RBC is controlled by the Rayleigh number (*Ra*) of the flow and container aspect ratio (Γ= radius/depth). *Ra* is the ratio of the buoyancy forces to dissipation from thermal diffusion and viscosity in the fluid [3]. Therefore at low *Ra*, dissipation prevents fluid motion and heat flow is purely diffusive. The critical Rayleigh number (Ra_c) is the point at which buoyancy initiates convection. Above Ra_c, the fluid organizes itself into convective cells. As *Ra* is increased further, the flow spontaneously bifurcates, reorganizing itself into different flow patterns. Research here is focused on cylindrical containers of low-aspect ratios (Γ = 3/50) where fluid properties can change with height, wall effects are substantial [4] and industrial applications are often found (such as beer pasteurization or processing of canned foods). The study of bulk fluid RBC provides template velocity data for comparison to RBC in porous media which is difficult to study using other methods.

Methods: To study heat transfer in packed beds, the solid packing and pore filling fluid were chosen to be chemically distinct, preventing signal interference between the two domains. The pore-space was filled with a fluorinated heat-transfer fluid. At various stages of heating, PGSE experiments were performed at the ^{19}F frequency to measure spatially resolved velocity maps and non-spatially resolved distributions of average and fluctuating velocity for the pore fluid. For the solid packing, particles composed of wax micro-encapsulated into plastic spheres and agglomerated into larger particles (*d* = 3.5 mm) were chosen. The solid and liquid states of wax can easily be distinguished with MRI. At the ^{1}H frequency, the MSME sequence provided complementary MRI of particle-wax melt-fraction which could be interpreted as a temperature front [5].

Results and Discussion: Data on a forced convection system, the results of which are shown in figure 1b [5] established the methodology. Intra-particle melting, melt-front and coupling of fluid motions to particle heating were visualized in the experiments. RBC is more complicated due to complex flow cells where hysteresis has a strong effect, as previously determined [6]. It was found that circulation patterns were strongly dependent on height in the fluid column (figure 1c). During experiments on RBC in porous media, the effects of heat transfer on flow pattern formation were observed. The preferential flow pattern depended on the wax particles absorption and emission of energy (figure 1d).

Conclusions: The selection of packed bed components, which are chemically distinct, allows MRI visualization of the coupling of heat transfer to fluid flow. The use of phase change materials as temperature indicators in fluid systems provides a robust temperature front mapping method for a range of investigations.

References: [1] Blümich, "NMR imaging of materials." (2004). [2] Callaghan, "Principles of nuclear magnetic resonance microscopy." (1993). [3] Koschmieder, "Bénard cells and Taylor vortices" (1993). [4] Charlson, Int. J. Heat Mass Trans. (1971). [5] Skuntz, Chem. Eng. Sci. (2018). [6] Hof, Phys. Fluids. (1999).