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► **To cite this version:**

Nicolò R Sgreva, Christel Métivier, Anthony Teixeira, Tien Dung Le, Sébastien Leclerc. Experimental velocity and temperature measurements for natural convection in a highly porous medium. 2023. hal-04286807

**HAL Id: hal-04286807**

**<https://hal.science/hal-04286807>**

Preprint submitted on 15 Nov 2023

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# Experimental velocity and temperature measurements for natural convection in a highly porous medium

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## Abstract

We present natural convection experiments at low-to-moderate porous media Rayleigh number  $Ra$  in a fluid-saturated structured plastic foam with porosity of 0.83 heated from below. This is motivated by the lack of detailed experiments on thermal convection in these systems, although they are of great interest for many engineering applications. Our experiments were carried out using Magnetic Resonance Imaging (MRI), which allowed us to obtain quantitative measurements of velocity vectors together with temperature fields in the bulk of the fluid-saturated sample. The results obtained are compared with those for classical porous media (e.g. packed beds of spheres) and with theoretical predictions.

For our system, we found the onset of convection at  $Ra_c = 41.9$ , with a critical wavenumber  $\alpha_c \approx \pi$ . For  $Ra < Ra_c$ , velocities always remain below the accuracy of the measurement and temperature fields remain homogeneous and linear in the vertical direction. For  $Ra_c \leq Ra < 308$ , the flow has a stable convective patterns in forms of axisymmetric, straight or deformed rolls. At about  $Ra = 308$ , the flow enters in a transitional regime in which the convective rolls begin to deform. At the highest  $Ra$  tested, the convective pattern takes the form of cross-rolls. The intensity of convection is estimated through the large-scale mean squared velocity  $U^2$ . For  $Ra > 70$ , we obtain  $U \sim Ra^{\frac{1}{2}}$ .

The heat transfer is investigated by evaluating the Nusselt number from temperature fields. We found that the local  $Nu$  reflects the flow structure: higher values of local  $Nu$  correspond to cold down-welling regions,

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and smaller  $Nu$  to warm up-welling regions. Finally, we found that the averaged Nusselt number for the whole system increases linearly with  $Ra$  with a slope equal to 2.

*Keywords:* Solid foam, Natural convection, Magnetic Resonance Imaging (MRI), Porous media

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## 1 Introduction

Thermal convection in porous media is a key aspect in many natural phenomena and engineering applications. The former include convective flow of magma in partially crystallized reservoir (Tait and Jaupart, 1992) and groundwater circulation (Diersch and Kolditz, 2002). While in industry, examples include insulation systems (Rees and Lage, 1996) and thermal energy storage systems (Agyenim et al., 2010). In the case of thermal energy storage systems, porous media can be combined with phase change materials to form composite systems in which heat is stored and released more efficiently. In this case, the most commonly used macroscopic supports are highly porous open-cell solid foams (Zhang et al., 2021). In fact, these composite systems can store a large amount of phase change material, have a large surface area to volume ratio, and improve the melting rate (Yao et al., 2018). These are made of different materials and typically have a randomly organized solid structure or are characterized by unit cells with a specific geometry (Qureshi et al., 2021). When these composite systems are subjected to a temperature gradient, heat is transferred by conduction and, depending on the system and boundary conditions, by convection. The competition between the two heat transfer mechanisms depends on the thermal properties of the materials employed, the ability of the fluid to flow between the pores, and the heating position (Gasow et al., 2022; Krishna et al., 2009).

In these cases, a configuration of thermal convection of interest is the porous medium analogue of the Rayleigh-Bénard convection, where a fluid-saturated porous medium is uniformly heated from below and cooled from above. In this case, the fluid flow regime is characterized by the porous medium Rayleigh number ( $Ra$ ), defined as

$$Ra = Ra_f \times Da = \frac{\rho g \beta \Delta T H K}{\eta \kappa_{\text{eff}}}, \quad (1)$$

where  $Ra_f$  is the Rayleigh number for a non-porous fluid layer and  $Da =$

28  $K/H^2$  is the Darcy number. In eq. (1),  $\rho$  indicates the density of the fluid,  $\beta$   
 29 its thermal expansion coefficient,  $\eta$  its viscosity;  $g$  is the acceleration due to  
 30 gravity,  $H$  the thickness of the layer,  $\Delta T$  the temperature difference across  
 31 this thickness,  $K$  the permeability and  $\kappa_{\text{eff}}$  the effective thermal diffusivity  
 32 of the system. From linear stability analysis, when  $Ra$  remains smaller than  
 33 a critical value, i.e.  $Ra < Ra_c$ , the conductive regime remains stable, the  
 34 temperature field is uniform and there is no flow (Lapwood, 1948; Horton  
 35 and Rogers Jr, 1945). The critical value  $Ra_c = 4\pi^2$  has been verified several  
 36 time for different types of porous media and fluids (Nield and Bejan, 2017).  
 37 Large-scale convection in form of cellular motion develops for  $Ra > Ra_c$ . For  
 38 sufficiently small  $Ra$  ( $Ra_c < Ra < 300$ ), numerical computations based on  
 39 spectral method show that convection is stable and the convective pattern  
 40 is characterized by various types of rolls: counter-rotating rolls, superposi-  
 41 tion of counter-rotating rolls, and polyhedral cells (Caltagirone and Fabrie,  
 42 1989). For larger  $Ra$ , the flow is perturbed and becomes less stable due to  
 43 boundary-layer instabilities. The background cellular structure is preserved  
 44 until the transition to high- $Ra$  convection from which rolls are completely  
 45 destabilized (Hewitt, 2020). Most experimental work at low-moderate  $Ra$ ,  
 46 however, reports irregular polygons from the onset (Howle, 2002), and only  
 47 a few experiments have succeeded in reproducing the predicted pattern evo-  
 48 lution (e.g. Howle et al., 1997; Shattuck et al., 1997). The latter were per-  
 49 formed with classical porous media (packed beds of beads or ordered grids)  
 50 with relatively low porosity ( $\sim 0.4$ - $0.5$ ).

51 The case of natural convection in highly porous systems was studied by  
 52 Kathare et al. (2008) and Davidson et al. (2009) who used water-saturated  
 53 metal and carbon foams. They performed heat transfer measurements and  
 54 found that the Nusselt number increases with increasing  $Ra$  less than re-  
 55 ported for beads. Moreover, for relatively small  $Ra$ , the heat transfer en-  
 56 hancement provided by the metal foam occurs mainly by conduction. Shiina  
 57 and Hishida (2010) studied the effects that an anisotropic effective thermal  
 58 diffusivity has on the onset of convection in a highly porous system formed  
 59 by thin wires deployed between the two horizontal plates. In this case, the  
 60 critical Rayleigh number was found to depend on both  $Da$  and the degree of  
 61 thermal diffusion anisotropy.

62 Despite the importance of natural convection, in-depth experiments in  
 63 porous media, and especially in highly porous systems, remain rare because  
 64 they are particularly difficult to carry out. In most of them, an idealized  
 65 granular medium (e.g., packed beds of spheres) or a Hele-Shaw cell is used to

66 model the porous medium (Hewitt, 2020). Although the latter allows optical  
67 access, it cannot be used to analyze three-dimensional flows and materials  
68 with more complex geometries (e.g., with different pore sizes, different pore  
69 paths, etc.). On the other hand, the use of a standard porous matrix limits  
70 the use of classical optical devices for flow visualization and generally forces  
71 the use of invasive measurement techniques. For this reason, most exper-  
72 imental work focuses on measurements of heat transfer within the system,  
73 without examining the velocity and temperature fields of the convective fluid.

74 In recent years, a few experimental techniques have been proposed and  
75 tested to resolve fluid flow in the bulk of a fluid-saturated porous material.

76 Combining heat transfer measurements and optical measurement tech-  
77 niques, Ataei-Dadavi et al. (2019) studied natural convection in a porous  
78 medium consisting of a bed of packed coarse spheres. Using fluids and porous  
79 media with the same refracting index, they have been able to visualize both  
80 velocity and temperature fields. They found two regimes of heat transfer: a  
81 reduced regime at low  $Ra$ , due to the poor penetration of fluid flow through  
82 the pores, and a second regime for higher  $Ra$ , in which heat transfer is en-  
83 hanced through the porous medium due to the increased rate of flow penetra-  
84 tion across the pores. However, this experimental approach limits the choice  
85 of system, which must consist of transparent materials with a refracting index  
86 similar to that of the liquid within it.

87 A different way to visualize flow through an opaque media is by using  
88 Magnetic Resonance Imaging (MRI). In this respect, the first attempt was  
89 done by Shattuck et al. (1995) and Shattuck et al. (1997), who used MRI to  
90 measure velocity field and investigate convective patterns at various  $Ra$  in  
91 a packed beds of spheres heated from below and cooled from above. They  
92 found that in disordered media, localized convection begins at  $Ra < Ra_c$   
93 due to packing defects that lead to locally larger porosity. In ordered media  
94 convection is characterized by convective rolls up to  $5Ra_c$ , but with smaller  
95 wavelength than those predicted by theory. Also, for slightly larger  $Ra$  (up  
96 to  $8Ra_c$ ), they obtained a time-dependent state where upward flow regions  
97 move randomly in a larger area of downward flow.

98 Although MRI can provide quantitative information on velocity and tem-  
99 perature, after this first attempt only a few other authors have used this  
100 technique to investigate convection in porous media. Weber and Kimmich  
101 (2002) studied thermal convection in a random-site percolation network using  
102 MRI for velocity and temperature mapping. Skuntz et al. (2018) and Skuntz  
103 et al. (2021) analyzed the fluid flow and the melting front of a non-isothermal

104 packed bed of beads containing a phase change material. And Wang et al.  
105 (2021) carried out experiments of buoyancy-driven convection in an hetero-  
106 geneous pack of beads. In all these cases, the porous medium was designed  
107 by stacking beads together, strongly limiting the maximum possible porosity  
108 of the system (the typical porosity for beds of packed spheres is  $\phi \sim 0.40$ ).

109 In this work we aim to study natural convection at low-to-moderate  $Ra$   
110 an open-cell solid foam with high porosity ( $\phi > 0.80$ ). This is motivated by  
111 the lack of detailed experiments on convection in structured solid foam, al-  
112 though it is an extremely important topic for many engineering applications.  
113 For this purpose, we carried out experiments using a Kelvin-cell foam as a  
114 solid matrix filled with Newtonian liquids. The fluid-saturated foam is then  
115 placed in a cylindrical cavity heated from below and cooled from above. We  
116 use MRI to measure velocity vectors and temperature fields of the convective  
117 fluid within the solid matrix. The materials used during the experiments and  
118 their properties are discussed in sect. 2. In sect. 3 we detail the experimental  
119 setup and we describe the protocols used for MRI measurements. Results for  
120 the onset of convection, evolution of convection patterns, intensity of con-  
121 vection and heat transport are reported in sect. 4. Here we also compare  
122 the results obtained for the convection in solid foam with those reported in  
123 literature for more classical and idealized porous media. The paper ends with  
124 a summary and some concluding remarks in sect. 5.

## 125 **2. Materials and their properties**

### 126 *2.1. Fluids*

127 Two different Newtonian fluids were used during our experiments: glyce-  
128 rol (85 wt% solution in water) and a paraffin (hexadecane).

129 The glycerol aqueous solution was prepared by adding demineralized wa-  
130 ter to pure glycerol, with the latter used as received from the supplier (Fisher  
131 Chemical, with a stated purity of 99 %). Its thermophysical properties at a  
132 temperature of 25 °C are summarized in Table 1. The density  $\rho$  was measured  
133 at ambient atmospheric pressure with a DMA 5000M Anton-Paar densime-  
134 ter. The coefficient of thermal expansion  $\beta$  was evaluated from the density  
135 measurements from  $\beta(T_0) = -\rho^{-1}(T_0)(\partial\rho/\partial T)_{T_0}$ , with  $T$  being the tempera-  
136 ture and  $T_0$  the reference temperature. The viscosity  $\eta$  was measured with a  
137 stress-controlled AR-G2 rheometer (TA instrument) in rotational mode. The  
138 measured values (Table 1) are in good agreement with those expected for the  
139 same glycerol aqueous solution, see for instance Takamura et al. (2012).

Table 1: Material properties at  $T = 25$  °C.  $\rho$  is the density,  $\eta$  the dynamic viscosity,  $\lambda$  the thermal conductivity and  $\beta$  the coefficient of thermal expansion. The standard uncertainties  $u_a$  for the measured properties are  $u_a(\rho) = 0.01$  kg m<sup>-3</sup>,  $u_a(\eta) = 5 \times 10^{-4}$  Pa.s, and  $u_a(\beta) = 2.7 \times 10^{-6}$  °C<sup>-1</sup> with  $u_a(T) = 0.01$  °C. The other material properties are from: <sup>[a]</sup>: Sgreva et al. (2023) and <sup>[b]</sup>: Sgreva et al. (2022).

Material	$\rho$ (kg m <sup>-3</sup> )	$\eta$ (Pa.s)	$\lambda$ (W m <sup>-1</sup> K <sup>-1</sup> )	$\beta$ (°C <sup>-1</sup> )
85 wt% glycerol	1215.92	0.0818	0.310 <sup>[a]</sup>	$5.066 \times 10^{-4}$
Hexadecane	770 <sup>[b]</sup>	0.003 <sup>[b]</sup>	0.150 <sup>[b]</sup>	$8.861 \times 10^{-4}$ <sup>[b]</sup>
Plastic foam	1192 <sup>[a]</sup>	-	0.192 <sup>[a]</sup>	-

140 Hexadecane was supplied by Sigma-Aldrich and labeled as 99% pure.  
 141 Samples of hexadecane were used as received, i.e. without any further pu-  
 142 rification or removing impurities. A complete characterization in terms of  
 143 thermophysical properties of this paraffin is given in Sgreva et al. (2022)  
 144 and Klochko et al. (2022). The values we report in Table 1 are those given  
 145 in these last references. The crystallization temperature of hexadecane is  
 146  $T_s = 17.3$  °C (Sgreva et al., 2022). In all experiments with this fluid, the  
 147 applied temperatures were always larger than  $T_s$  and the material was always  
 148 in liquid phase.

## 149 2.2. The porous medium

150 A structured solid foam with open cells was used as a porous medium.  
 151 The foam sample was 3D-printed using a light-sensitive photopolymer resin  
 152 (Monocure 3D Rapid, Monocure Pty Ltd., Australia). The 3D model (Fig.  
 153 1) is made by assembling individual Kelvin-type cells to form a cylindrical  
 154 disk of diameter  $D = 114$  mm and height  $H = 26$  mm. The Kelvin-type unit  
 155 cell has a diameter (i.e. the distance between two opposing square faces)  
 156 of 6.5 mm, and cylindrical struts with an approximate diameter of 1.2 mm.  
 157 The printed foam sample consists then of four vertically stacked cells.

158 A sample's porosity of  $\phi = 0.83 \pm 0.02$  was estimated from both magnetic  
 159 resonance images and via water (volume) absorption. Density and other  
 160 relevant thermal properties of the solid plastic are reported in Sgreva et al.  
 161 (2023). According to it, at a temperature of 25 °C, the density of the solid  
 162 plastic is 1192 kg m<sup>-3</sup>, the thermal conductivity is 0.192 W m<sup>-1</sup>K<sup>-1</sup> (Table  
 163 1), and the heat capacity is 1.56 kJ kg<sup>-1</sup>K<sup>-1</sup>.

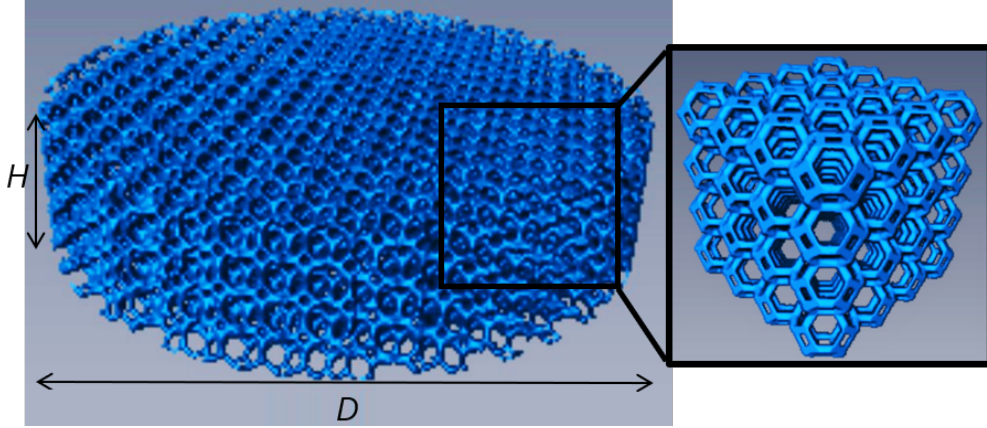


Figure 1: 3D model used to print the foam sample. The foam disk has a diameter  $D = 114$  mm and a height of  $H = 26$  mm.

164 *2.3. Effective properties of the system*

165 In order to evaluate  $Ra$  from eq.(1), two properties of the volume sample  
 166 are required: the effective thermal diffusivity  $\kappa_{\text{eff}}$  of the whole system (i.e.  
 167 solid matrix and fluid together) and the permeability  $K$  of the porous matrix.

168 Although  $\kappa_{\text{eff}}$  depends on the thermal diffusivity of the solid matrix and  
 169 the saturating fluid, expressing it as a weighted arithmetic average of the  
 170 two contributions is usually not recommended, especially when the thermal  
 171 conductivity of the different phases is very different from each other (Smith  
 172 et al., 2013).

173 In our case, the effective thermal diffusivity of the system consisting of the  
 174 85% aqueous glycerol solution and the solid foam was previously measured  
 175 experimentally in Sgreva et al. (2023) and the resulting effective thermal  
 176 diffusivity is  $\kappa_{\text{eff}} = 9.83 \times 10^{-8} \text{ m}^2\text{s}^{-1}$  (Table 2). For the case where the satu-  
 177 rating fluid is hexadecane a direct measurement is not available. However, as  
 178 shown by Smith et al. (2013) and Sgreva et al. (2023), an estimation of  $\kappa_{\text{eff}}$   
 179 can be obtained through the Hashin-Shtrikman model (Hashin and Shtrik-  
 180 man, 1962). The latter is based on the volume fraction of the different system  
 181 components and their thermal conductivities. By using this equivalent model  
 182 and the weighted average of the volumetric heat capacity of solid and liquid  
 183 phase, the effective thermal diffusivity for the hexadecane-saturated foam is  
 184  $\kappa_{\text{eff}} = 8.97 \times 10^{-8} \text{ m}^2\text{s}^{-1}$  (Table 2).

185 Because of the different viscosities of the saturating fluids and the different



Table 2: Effective thermal properties and permeability of the two systems used for the experiments.

Property	Foam + 85wt% glycerol	Foam + hexadecane
Thermal diffusivity ( $\kappa_{\text{eff}}$ )	$9.83 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$	$8.97 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$
Volumetric heat capacity ( $\rho c_P$ )	$2.95 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$	$1.75 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$
Permeability ( $K$ )	$2.83 \times 10^{-7} \text{ m}^2$	$2.83 \times 10^{-7} \text{ m}^2$

186 effective thermal diffusivities, the two systems used for the experiments result  
 187 in two different Prandtl numbers,  $Pr = \eta/(\rho\kappa_{\text{eff}})$ . At around  $T = 25 \text{ }^\circ\text{C}$ ,  
 188 we obtain a moderate Prandtl number for the hexadecane-saturated foam  
 189 ( $Pr = 43.5$ ) and a larger Prandtl number for the glycerol-saturated foam  
 190 ( $Pr = 688.1$ ).

191 For an ideal porous medium made by packed beds of spheres, the perme-  
 192 ability  $K$  is defined by the Kozeny–Carman equation. In the case of highly  
 193 porous systems, such as solid foams, the latter model cannot be used and  
 194 the permeability must be evaluated by experiments or numerical simulations  
 195 of pressure drop (Yang et al., 2021). These experiments have some com-  
 196 plexities, such as the difficulty in establishing the flow regime (Dukhan and  
 197 Minjeur, 2011) and the proper definition of the morphological parameters  
 198 used as characteristic length scale (Kumar and Topin, 2017), that can lead  
 199 to incorrect estimates of flow characteristics. In our case, the permeability  
 200 was numerically estimated by solving the Stokes flow on the digital 3D geom-  
 201 etry used to print the foam sample. A cubic portion of dimension  $26 \times 26 \times 26$   
 202 mm with a voxel size of  $0.1 \text{ mm}^3$  was cropped from the initial 3D image  
 203 of  $114 \times 114 \times 26$  mm (Fig. 1), and was then segmented and meshed by us-  
 204 ing AVIZO software. COMSOL Multiphysics software based on the finite  
 205 element method was used to solve the Stokes equations with the Dirichlet  
 206 boundary condition for the pressure at two opposite faces of the domain in  
 207 order to obtain the velocity field. The permeability in the flow direction (the  
 208 direction perpendicular to the faces where the pressure is imposed) can be  
 209 calculated from the Darcy’s law by averaging the velocity field in this direc-  
 210 tion. Since the sample is isotropic, simulation in only one direction is needed  
 211 to estimate the permeability value. The value of permeability obtained in  
 212 this way is  $K = 2.83 \times 10^{-7} \text{ m}^2$  (Table 2), leading to  $Da = 4.2 \times 10^{-4}$ . In the  
 213 same way, we evaluated the tortuosity of the digital porous medium from  
 214 the effective diffusion coefficient. This led to a value for the tortuosity of the

215 foam of 1.3.

### 216 3. Setup and methods

#### 217 3.1. Experimental setup and protocols

218 To investigate natural convection in the fluid-saturated solid foam, we  
219 used an experimental setup similar to that used in Noel et al. (2022) and  
220 Leclerc and Métivier (2018). The setup consists of a cylindrical PMMA  
221 cavity containing the saturated foam (Fig. 2a). The cavity has the same  
222 dimension as the foam disk, that is, an inner diameter of  $D = 114$  mm and  
223 a height of  $H = 26$  mm (aspect ratio  $\Gamma = D/H = 4.4$ ). The solid foam was  
224 inserted into the cavity by ensuring good contacts with the internal wall of  
225 the PMMA cavity (i.e. no significant gap between foam and cavity wall), and  
226 afterward it was carefully filled with the fluid. Air bubbles were removed by  
227 manually shaking the device with the help of two small tubes inserted later-  
228 ally into the cavity through the PMMA ring. The absence of air bubbles was  
229 also verified during the experiments directly from magnetic resonance im-  
230 ages. Temperatures above ( $T_{up}$ ) and below ( $T_{dw}$ ) the cavity were imposed by  
231 water flows from temperature-controlled water baths. Each temperature was  
232 measured with two K-type thermocouples (uncertainty of 1%), one placed at  
233 the inlet of the water flow and one at the outlet. In this way,  $T_{up}$  and  $T_{dw}$   
234 indicate the average of the measured inlet and outlet temperatures above and  
235 below the cavity, respectively. Good thermal contacts between water flows  
236 and the sample were provided by two 3.1-mm-thick sapphire plates with a  
237 thermal conductivity of around  $35 - 40 \text{ W m}^{-1}\text{K}^{-1}$ . The small thickness and  
238 the large thermal conductivity of these plates lead to negligible temperature  
239 variations within them. The device was also insulated with a thick layer of  
240 insulating foam added to the outside of the side wall.

241 We applied the following protocol for the experiments. The fluid-saturated  
242 foam was initially kept under isothermal conditions ( $T_{up} = T_{dw} = T_0$ , with  
243  $T_0$  being an initial temperature) for a minimum of 5 hours. When thermal  
244 equilibrium was reached, to obtain convection a temperature difference of  
245  $\Delta T = T_{dw} - T_{up} > 0$  was imposed between top and bottom surfaces.  $\Delta T$   
246 was afterwards varied by imposing further increments or decrements. The  
247 waiting time between each change of  $\Delta T$  varied from a minimum of 5 hours  
248 to more than 12 hours. Temperature and velocity fields within the sample  
249 were measured at the steady-state. During the entire procedure, the mean  
250 temperature  $T_m = (T_{dw} + T_{up})/2$  was always kept constant at around  $24 \text{ }^\circ\text{C}$ .

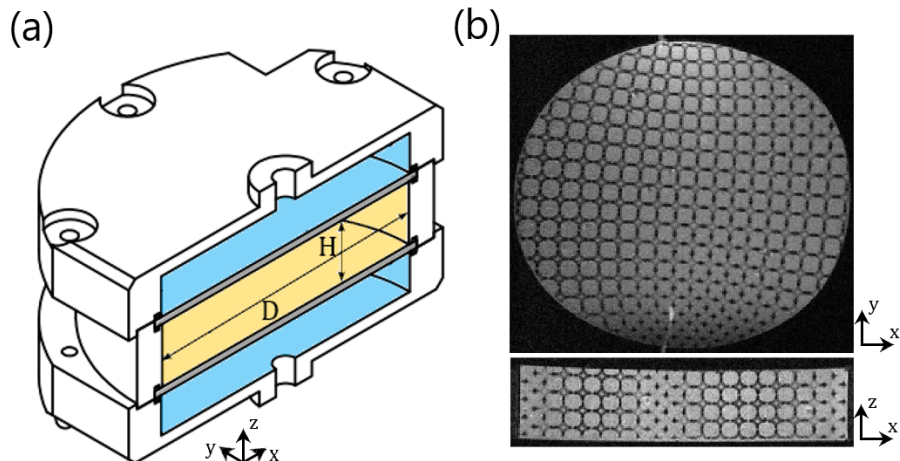


Figure 2: (a) Scheme of half of the experimental setup. We indicate in yellow the cavity containing the sample. (b) Proton density image of a 2 mm horizontal slice (along the  $xy$ -plane) and vertical slice (along the  $xz$ -plane) of the fluid-saturated solid foam. The horizontal image is taken at half the height of the cavity (i.e.  $H/2$ , with  $H = 0$  on the lower plate of the cavity), while the vertical image crosses the cavity along its central axis.

251 *3.2. Magnetic Resonance Imaging (MRI)*

252 MRI experiments were performed with a Bruker Avance Biospec 24/40  
 253 spectrometer in a temperature-controlled room at  $T_{\text{room}} = 24$  °C. The spec-  
 254 trometer was equipped with a 200-mm wide gradient coil delivering a 200  
 255 mT/m maximum gradient strength and a 160-mm wide quadrature resonator.  
 256 The horizontal magnetic field and the proton resonance frequency were 2.34  
 257 T and 100.3 MHz, respectively.

258 MRI images were acquired with a slice thickness of 2 mm in a field of  
 259 view of  $120 \times 120$  mm. Horizontal images were acquired in the  $xy$ -plane at  
 260 mid-height of the cavity (i.e., at  $H/2$ ), while vertical images were acquired in  
 261 the  $xz$  and  $yz$  planes along the center axis of the cavity (Fig. 2b). Because  
 262 of the relatively large extent of the setup relative to the resonator and the  
 263 gradient coil, the accuracy of MRI measurements is highest in the central  
 264 part of the images, while the boundaries of the images are characterized by  
 265 slight distortions of the acquired signal (Leclerc and Métivier, 2018).

266 MRI was used for three types of measurements: to identify (i) different  
 267 phases (i.e., the solid foam and the fluid in it), and to obtain (ii) temperature  
 268 fields and (iii) velocity vectors in the fluid. To do so, the following MRI  
 269 protocols were used.

270 (i) Identification and reconstruction of the solid foam geometry were car-  
271 ried out by acquisition of fast proton density maps using Rapid Acquisition  
272 with Relaxation Enhancement (RARE) experiments (Hennig et al., 1986).  
273 The identification of the solid structure is possible because of its very fast  
274 transverse relaxation time, which leads to absence of signal. Images were  
275 acquired with resolutions of  $128 \times 128$  and  $256 \times 256$  pixels (for a minimum  
276 pixel length of 0.47 mm). We used an echo time ( $t_E$ ) of 14 ms, a repetition  
277 time ( $t_R$ ) of 1000 ms, and a RARE factor of 8.

278 (ii) Magnetic Resonance Thermometry (MRT) was used to obtain temper-  
279 ature fields of the saturating fluid (Leclerc and Métivier, 2018). Temperature  
280 can be achieved when the transverse component of the magnetic relaxation  
281 time ( $T_2^{\text{NMR}}$ ), i.e. the time required for the magnetization vector to return to  
282 its equilibrium state after being subjected to a perturbation, shows a mono-  
283 tonic dependence with temperature. In our case, this occurred only for the  
284 aqueous solution of glycerol, but not for hexadecane. For hexadecane, the  
285 relaxation time did not show a strong dependence on temperature, thus not  
286 allowing MRT to be used. For 85 wt% glycerol,  $T_2^{\text{NMR}}$  images were obtained  
287 by Multi-Slice Multi-Echo (MSME) sequences (Leclerc and Métivier, 2018).  
288 We used 12 consecutive echoes,  $t_E = 20$  ms and  $t_R = 1000$  ms. Images had  
289 a resolution of  $128 \times 128$  pixels and were averaged 16 times. The final tem-  
290 perature fields were obtained after a calibration performed under isothermal  
291 conditions, in which the correlation between temperature and  $T_2^{\text{NMR}}$  was es-  
292 tablished (Fig. 3). The global uncertainty for MRT measurement evaluated  
293 during the calibration process is  $u(T) = 0.96$  °C, with a standard uncertainty  
294  $u_a(T) = 0.95$  °C and an uncertainty on  $T_{up}$  and  $T_{dw}$  due to thermocouple  
295 measurements of 0.10 °C (Leclerc and Métivier, 2018).

296 (iii) Magnetic Resonance Velocimetry (MRV) was used to obtain velocity  
297 fields of the fluid within the porous medium. Velocity images were obtained  
298 using similar protocols and the same pulse sequence of that of Noel et al.  
299 (2022). We used spin-echo imaging sequences together with flow encoding  
300 gradient pulses to acquire images with a  $128 \times 128$  pixel resolution. The gra-  
301 dient pulse duration was  $\delta = 4$  ms, the gradient separation time  $\Delta_G = 12$   
302 ms,  $t_E = 28$  ms, and  $t_R = 800$  ms or  $t_R = 1000$  ms for experiments with glyc-  
303 erol or hexadecane, respectively. We used a minimum flow encoding gradient  
304 pulse intensity of  $G_{\min} = 0$  mT/m. Because of the different velocities reached  
305 during convection in the two fluids, we used a maximum gradient intensity of  
306  $G_{\max} = 180$  mT m<sup>-1</sup> for the 85 wt% glycerol solution and  $G_{\max} = 175$  mT m<sup>-1</sup>  
307 for hexadecane. The velocity field in the direction of the application of the

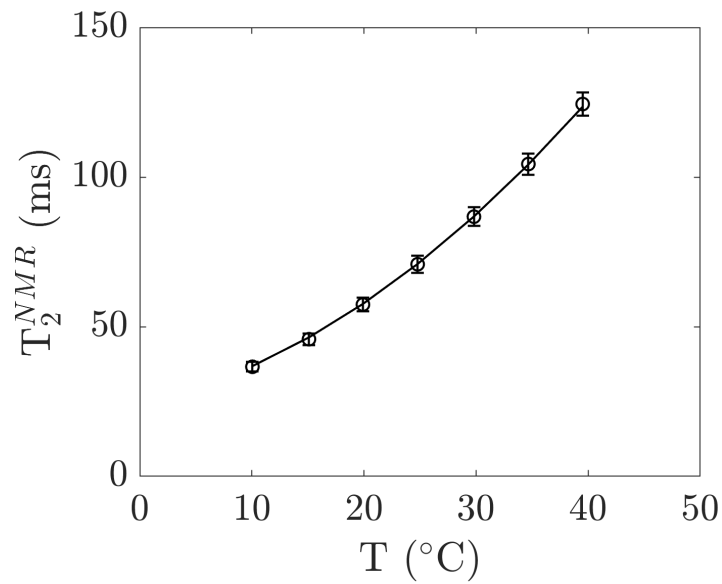


Figure 3: MRT calibration for the foam saturated with the 85 wt% glycerol solution at isothermal conditions ( $T = T_{up} = T_{dw}$ ). The figure displays the transverse components of relaxation time  $T_2^{NMR}$  as a function of imposed temperature  $T$ . Data points are fitted by the second order polynomial fit  $T_2^{NMR} = 24.161 + 0.835T + 0.043T^2$ .

308 gradient is obtained from the difference between the image acquired with  
 309  $G_{\max}$  and that with  $G_{\min}$ . Following this protocol, the velocity resolution is  
 310  $5 \times 10^{-5} \text{ m s}^{-1}$ . The global uncertainty for MRV measurements is then esti-  
 311 mated from reference images under isothermal conditions in  $u(v) = 6.8 \times 10^{-5}$   
 312  $\text{m s}^{-1}$ , with  $v$  being the measured velocity.

313 Differently from MRT where the relaxation time does not depend on  
 314 the amount of fluid in each voxel, Partial Volume Effect (PVE) arises during  
 315 MRV if the solid matrix and the saturating fluid are both present in the same  
 316 voxel. In this case, the voxel signal depends also on the fluid volume fraction  
 317 in it. In our case, the latter is estimated from normalized RARE images. The  
 318 normalization is done between the RARE maximum signal, corresponding  
 319 to a voxel containing only fluid, and the minimum signal corresponding to  
 320 a voxel of only solid material. The final velocity image,  $I_{\text{velocity}}^{\text{final}}$ , is then  
 321 obtained as follows:

$$I_{\text{velocity}}^{\text{final}} = (I_{\text{velocity}}^{\text{raw}} - I_{\text{velocity}}^{\text{ref}}) \times I_{\text{RARE}}^*, \quad (2)$$

322 where  $I_{\text{velocity}}^{\text{raw}}$  is the velocity image originally acquired,  $I_{\text{velocity}}^{\text{ref}}$  is a reference  
 323 velocity image obtained without fluid motion ( $\Delta T \leq 0$ ), and  $I_{\text{RARE}}^*$  is the  
 324 normalized RARE image for the fluid volume fraction.

## 325 4. Experimental results

### 326 4.1. Velocity and temperature measurements and onset of convection

327 Figure 4 shows an example of vertical velocity (Fig. 4a) and temperature  
 328 field (Fig. 4b) within the sample for steady convection at  $Ra = 123$  obtained  
 329 with MRV and MRT, respectively. Here the fluid saturating the solid foam  
 330 is the glycerol solution and the imposed temperature difference is  $\Delta T =$   
 331  $22.3 \text{ }^\circ\text{C}$ . Images were acquired 5 hours after setting the temperatures. In  
 332 the vertical scan of Fig. 4b, we also report the contour of three isotherms  
 333 ( $20 \text{ }^\circ\text{C}$ ,  $25 \text{ }^\circ\text{C}$  and  $30 \text{ }^\circ\text{C}$ ) to better distinguish temperature distribution.  
 334 Figure 4 highlights the good agreement between velocity and temperature  
 335 fields in both planar and vertical scans. In fact, the upward flow (positive  
 336 vertical velocity) corresponds well to the warmer regions of the fluid, while  
 337 the downward part of the convective pattern matches the cooler areas.

338 The convective pattern obtained in Fig. 4 is characterized by convection  
 339 rolls. This is similar to results of Shattuck et al. (1997) and Howle et al.  
 340 (1997) for ordered porous media but with a lower porosity ( $\phi \leq 0.5$ ) than in

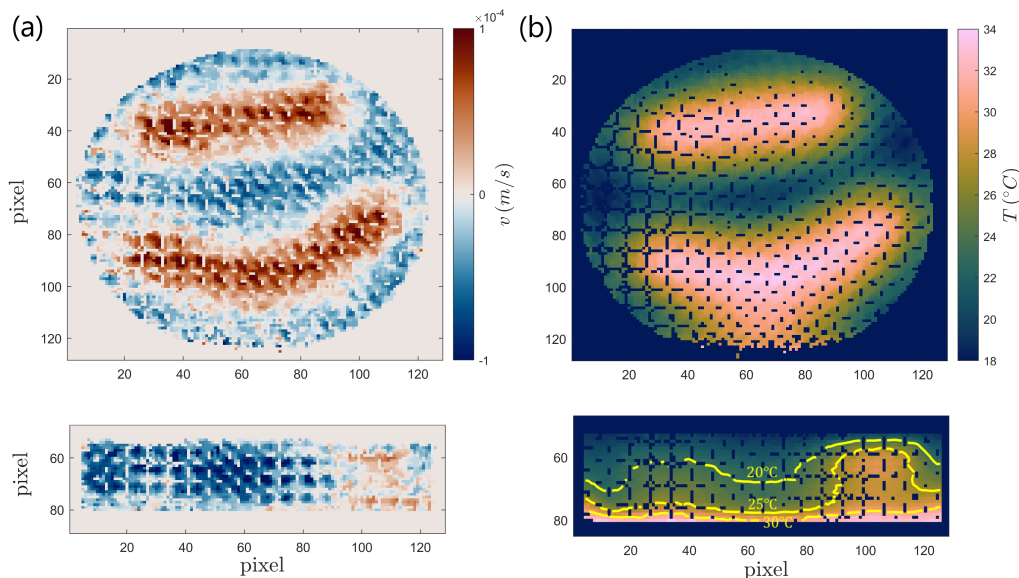


Figure 4:  $\Delta T = 22.3^\circ\text{C}$ ,  $Ra = 123.0$ ,  $Da = 4.2 \times 10^{-4}$  and  $Pr = 688.1$ . (a) Vertical velocity field. (b) Temperature field. In the vertical cross-section of the temperature field we highlight the isotherms at  $20^\circ\text{C}$ ,  $25^\circ\text{C}$  and  $30^\circ\text{C}$ .

341 our case. Moreover, from Fig. 4 it can be seen that the obtained macroscopic  
 342 flow structure has a larger length scale than the pore scale. This represents  
 343 one of the conditions needed for the flow to be described by the Darcy's  
 344 law. The other is a negligible inertia term relative to viscous drag (Nield  
 345 and Joseph, 1985). In our case, this can be estimated by evaluating the local  
 346 Reynolds number  $Re^*$  based on the permeability of the medium, that is

$$Re^* = \frac{|\mathbf{v}| K^{0.5} \rho}{\eta}, \quad (3)$$

347 where  $|\mathbf{v}|$  is the local velocity magnitude. For an inertia-free flow,  $Re^*$  must  
 348 be small ( $Re^* \ll 1$ ). This translates in terms of Rayleigh number as (Hewitt,  
 349 2020):

$$\frac{Ra Da^{0.5}}{Pr} \ll 1. \quad (4)$$

350 The uncertainties for these non-dimensional numbers are discussed in Ap-  
 351 pendix A.

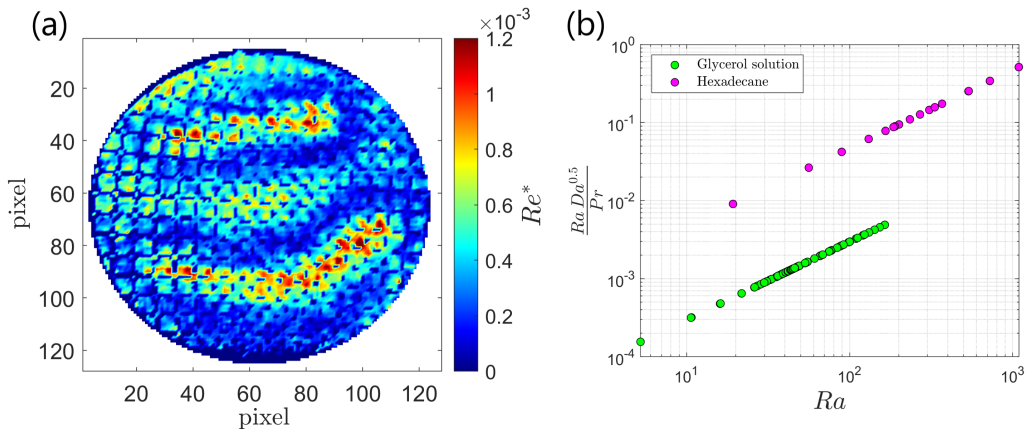


Figure 5: (a) Local Reynolds number  $Re^*$  for convection at  $Ra = 131.2$ ,  $Da = 4.2 \times 10^{-4}$  and  $Pr = 688.1$ . (b) Conditions needed for the flow to be described by the Darcy's law as a function of  $Ra$  for all our experiments.

352 Fig. 5a shows an example of  $Re^*$  calculated from the velocity field obtained  
 353 from MRV for  $Ra = 131.2$ . In this case,  $Re^*$  remains much smaller  
 354 than 1, which indicates that, under these conditions, the flow is inertia-free  
 355 and can be described by the Darcy's law. Even considering the relatively  
 356 large pores and the large porosity of our sample foam, this is valid for the  
 357 majority of the experiments presented here. Only few experiments conducted  
 358 with hexadecane are near the limit set by eq. (4), see Fig. 5b. In the follow-  
 359 ing, the latter are used for qualitative purposes only.

360 Given the good correspondence between temperature field and velocity  
 361 field at the same  $\Delta T$ , we estimate the critical difference of temperature ( $\Delta T_c$ )  
 362 above which convection occurs directly from the temperature maps in the  
 363 horizontal  $xy$ -plane. In fact, under our experimental conditions, temperature  
 364 variations near the onset are better resolved than velocities, since the latter  
 365 have very low values.

366 For the case where the fluid is the aqueous solution of glycerol,  $\Delta T_c$   
 367 is found by evaluating the variance  $\sigma^2$  of the images acquired at different  $Ra$ .  
 368 This procedure is similar to that used by Hébert et al. (2010) to detect the  
 369 onset of convection in the classical Rayleigh-Bénard configuration using the  
 370 shadowgraph method. In our case, to achieve higher accuracy, the variance  
 371 is computed within a squared region of length  $50 \pm 6$  mm at the center of the



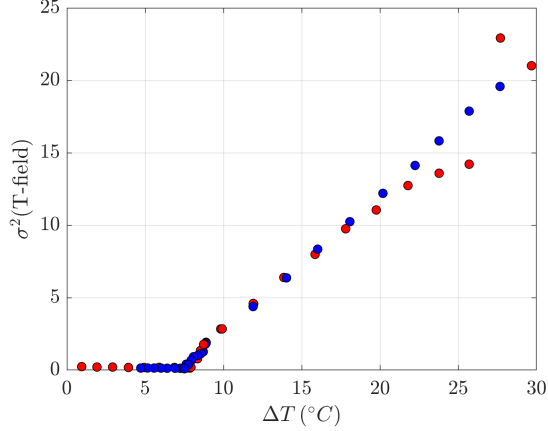


Figure 6: Variance  $\sigma^2$  of the temperature field acquired on the  $xy$ -plane as a function of the imposed  $\Delta T$ . The fluid is the glycerol aqueous solution. Blue symbols refer to decreasing  $\Delta T$ , while red symbols refer to increasing  $\Delta T$ .

372 temperature image obtained on the  $xy$ -plane.

373 The variance of the horizontal temperature field is plotted versus the  
 374 imposed  $\Delta T$  in Fig. 6. Red symbols refer to experiments conducted by  
 375 increasing  $\Delta T$ , and blue symbols to those conducted by decreasing  $\Delta T$ . In  
 376 both cases, the variance of the temperature field shows an abrupt increase  
 377 at a specific critical value of  $\Delta T$ . In the case of Fig. 6, this occurs at  $\Delta T_c =$   
 378  $7.6 \pm 0.1$  °C. Below this temperature,  $\sigma^2$  is stable around zero, indicating  
 379 a very homogeneous and constant temperature field within the estimation  
 380 area. This condition refers to the case where convection has not developed  
 381 yet. For  $\Delta T \geq \Delta T_c$ , the variance of the temperature field increases with the  
 382 imposed temperature difference. The jump of  $\sigma^2$  between  $\Delta T = 25.7$  °C and  
 383  $\Delta T = 27.7$  °C (red symbols in Fig. 6) is caused by a change in the convection  
 384 pattern. We will discuss this aspect in the next section. The value of  $\Delta T_c$   
 385 and the fluid properties listed in Table 1 lead to a critical Rayleigh number of  
 386  $Ra_c = 41.9$ , with an uncertainty of  $u(Ra_c) = 2.1$ . The latter is in very good  
 387 agreement with the theoretical value of  $Ra_c = 4\pi^2$  expected for standard  
 388 porous media.

#### 389 4.2. Convection patterns

390 The convective pattern in terms of vertical velocity field for different  
 391  $Ra$  is shown in Fig. 7. Here the Rayleigh number is expressed as reduced

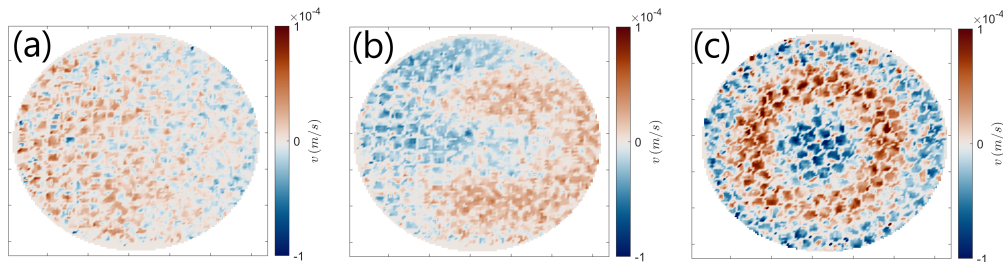


Figure 7: Convective pattern for different  $\epsilon$  and  $Pr = 688.1$ . Here we show the vertical velocity fields for the  $xy$ -plane at  $H/2$  obtained from MRV. (a)  $\epsilon = -0.48$ , (b)  $\epsilon = 0.13$ , (c)  $\epsilon = 0.83$ .

392 Rayleigh-Darcy number  $\epsilon$ , that is

$$\epsilon = \frac{Ra - Ra_c}{Ra_c}. \quad (5)$$

393 In this case,  $\epsilon$  was varied from -0.48 to 1.00 ( $Pr = 688.1$ ). For  $\epsilon = -0.48$   
 394 (Fig. 7a), no motion is recognizable, the velocity always remains below the  
 395 accuracy of the measurement, and the image shows only the magnitude of  
 396 noise. Under similar conditions, Shattuck et al. (1997) show that convection  
 397 can appear along side-walls if porosity increases locally due to structural  
 398 defects in the porous medium or due to poor thermal insulation. This is  
 399 not our case, where for  $\epsilon < 0$  the onset of convection was never observed  
 400 either in the bulk of the cavity or along its walls. This is also confirmed by  
 401 MRT measures. As pointed out previously, at small  $Ra$ , MRT provides better  
 402 visualizations than MRV because less noisy. The temperature fields obtained  
 403 at  $\epsilon < 0$  show an homogeneous and quasi-constant temperature in the regions  
 404 of the image not affected by signal distortion during scan acquisition. This  
 405 is shown in Fig. 8a by the normalized temperature profile  $T/\bar{T}$  along a  
 406 cavity's diameter  $d$  (Fig. 8b), with  $\bar{T}$  being the mean temperature along  $d$ .  
 407 For  $\epsilon = -0.48$ ,  $T/\bar{T}$  remains relatively flat compared to cases with larger  $\epsilon$   
 408 (Fig. 8a), especially toward the center of the cavity where the effect of signal  
 409 distortion is minimal, indicating an homogeneous temperature field.

410 When  $\epsilon$  is raised slightly above 0, convection is well established in the bulk  
 411 of the fluid layer. For  $\epsilon = 0.13$ , two thick parallel rolls can be recognizable  
 412 from both velocity (Fig. 7b) and temperature fields (Fig. 8b). Compared  
 413 with the previous case, now the temperature profile across the convective pat-  
 414 tern becomes more wavy, showing a clear increase in temperature variation

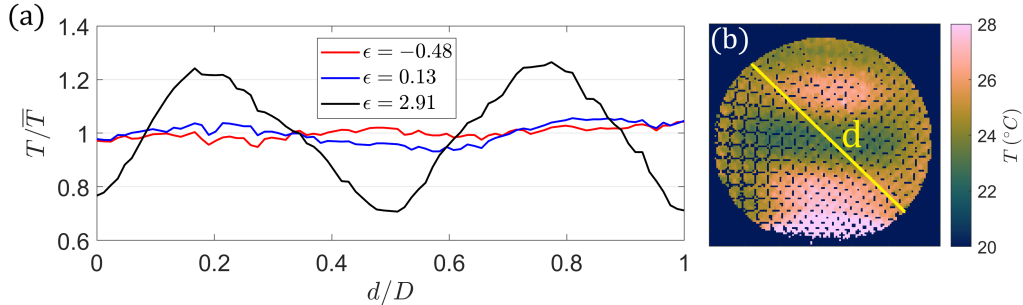


Figure 8: (a) Temperature profile along the cavity’s diagonal  $d$  (indicated in (b)) for  $\epsilon = -0.48$ ,  $\epsilon = 0.13$ , and  $\epsilon = 2.91$ . The temperature is normalized by the mean temperature  $\bar{T}$  along  $d$ .  $d$  is normalized by the cavity diameter  $D$ . (b) Temperature fields at  $\epsilon = 0.13$ .

415 along  $d$  (Fig. 8b). The wavelength  $\lambda$  associated with the critical condition of  
 416 motion can be estimated as the distance between the two rolls (e.g. distance  
 417 between the local maxima of the temperature field). For  $\epsilon = 0.13$  (Fig. 8b),  
 418 we obtain a normalized wavelength  $\lambda/H$  of  $2.04 \pm 0.15$ , leading to a critical  
 419 wavenumber  $\alpha_c = (2\pi H)/\lambda = (0.98 \pm 0.08)\pi$ , very close to the value  $\alpha_c = \pi$   
 420 predicted by linear stability theory (Nield and Bejan, 2017).

421 In all the experiments we carried out, we found stable rolls up to  $\epsilon = 5.43$ ,  
 422 corresponding to  $Ra = 270.2$ . In this range of  $\epsilon$  (i.e.  $0 < \epsilon < 5.43$ ) the  
 423 convective rolls organize themselves mainly as axisymmetric rolls (Fig. 7c),  
 424 parallel rolls (Fig. 11a), or somewhere in between where one roll is slightly  
 425 deformed and follows the shape of the container (Fig. 4). These different  
 426 patterns developed in the same interval of  $\epsilon$  are very likely due to variations  
 427 of thermal boundary conditions at the sidewalls (Croquette et al., 1983).

428 In the case of axisymmetric rolls, the velocity field of Fig. 7c suggests  
 429 the presence of small secondary convective structures perpendicular to the  
 430 sidewall. To better display them, in Fig. 9a we plot only the positive verti-  
 431 cal velocity obtained for  $\epsilon = 0.64$ . Here, between the main axisymmetric roll  
 432 and the cavity’s sidewall, several narrow, elongated, upward-moving struc-  
 433 tures surrounded by regions of down-welling are visible. Although images  
 434 resolution does not allow us to evaluate their exact size and geometry, veloci-  
 435 ties corresponding to these voxels are large enough to be quantified by MRV.  
 436 This is done in Fig. 9b where the normalized positive vertical velocity is aver-  
 437 aged along concentric circles with different radial coordinate  $r$  centered in  
 438 the center of the image. It can be seen that the maximum positive average  
 439 velocity is obtained at the axis of the main roll, while toward the central

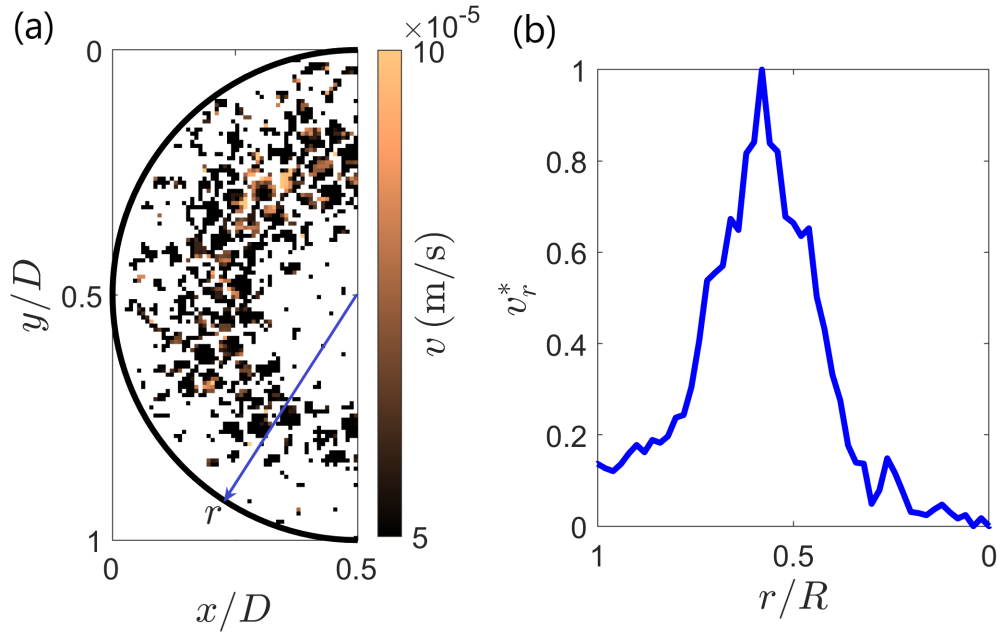


Figure 9: Axisymmetric convective pattern. (a) Positive vertical velocity image for half of the  $xy$ -plane.  $\epsilon = 0.64$ ,  $Pr = 688.1$ . The thick black line delimits the wall of the cavity (with  $R = D/2$  the cavity's radius). (b) Averaged positive vertical velocity normalized over its maximal value ( $v_r^*$ ) along the radial direction.

440 region of the image, almost zero positive velocities are measured. On the  
 441 other hand, in the region near the side wall, the presence of these upward-  
 442 moving narrow rolls results in an average positive velocity larger than zero  
 443 and equal to about 15 percent of the maximum average positive velocity.  
 444 The same phenomena has been observed for classic Rayleigh-Bénard convec-  
 445 tion. For instance, Croquette et al. (1983) observed unstable axisymmetric  
 446 patterns characterized by the break down of the roll near to the sidewall  
 447 to form a set of smaller rolls perpendicular to the cylindrical sidewall. In their  
 448 case, the entire axisymmetric pattern later vanishes into a structure made of  
 449 fairly regular rolls that always end perpendicular to the sidewalls. However,  
 450 in our case the axisymmetric pattern remained stable throughout the entire  
 451 duration of the experiment (up to a maximum of about 60 hours after the  
 452 imposition of  $\Delta T$ ), during which the acquired images showed no changes in  
 453 the convective pattern.

454 In Fig. 10 we show the main convective patterns obtained for another

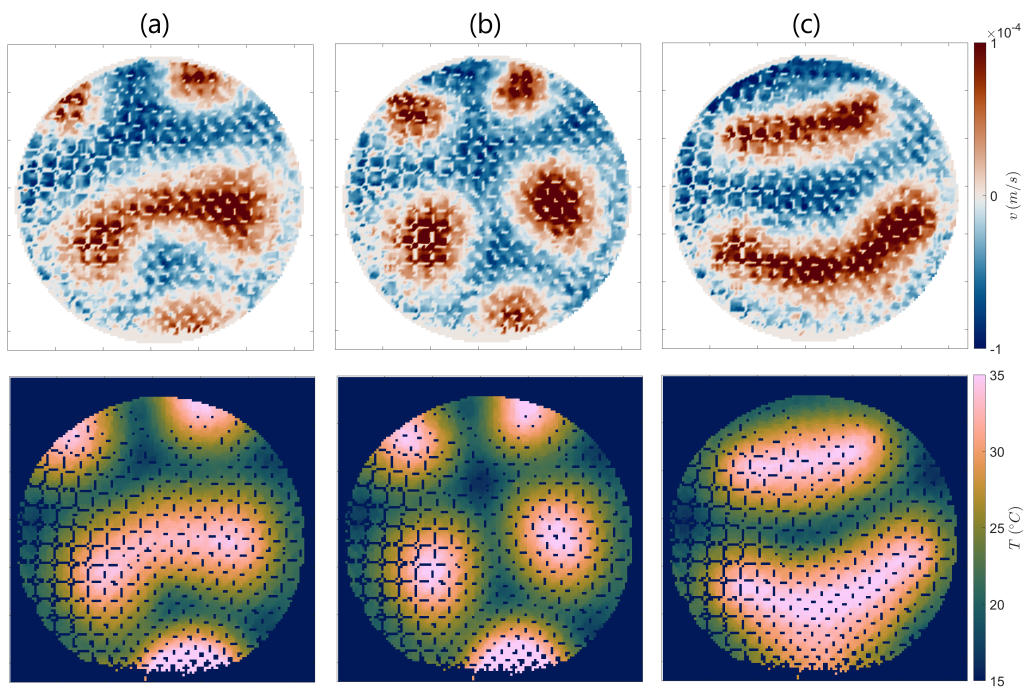


Figure 10: Different patterns for relatively small  $\epsilon$ . The first row shows the vertical velocity images, while the second row shows the corresponding temperature field ( $Pr = 688.1$ ). (a)  $\epsilon = 2.38$ , (b)  $\epsilon = 2.64$ , (c)  $\epsilon = 2.91$ .

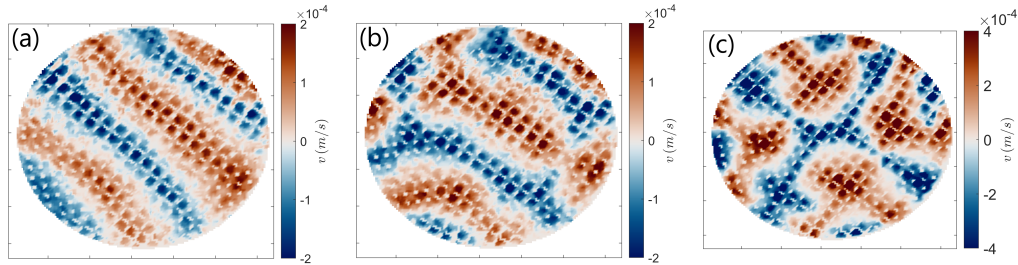


Figure 11: Convective pattern for hexadecane and different  $\epsilon$  ( $Pr = 43.5$ ). Here we show the vertical velocity fields for the  $xy$ -plane at  $H/2$  obtained from MRV. (a)  $\epsilon = 4.57$ , (b)  $\epsilon = 6.32$ , (c)  $\epsilon = 25.0$ .

455 experiment where  $\epsilon$  was varied from 0.82 to 2.91 ( $Pr = 688.1$ ). In this case,  
 456 images were obtained by increasing the previous temperature step by 2 °C.  
 457 From  $\epsilon = 0.82$  to  $\epsilon = 2.38$  we obtained the same pattern. In this case,  
 458 both the velocity field and the temperature field show a warm up-rising roll  
 459 at the center of the cavity and several warm plumes near the sidewall (Fig.  
 460 10a). At the next temperature rise ( $\epsilon = 2.64$ ), the central roll splits into two  
 461 ends, resulting in polygonal cell pattern (Fig. 10b). Finally, at  $\epsilon = 2.91$   
 462 the different warm patches re-connect together to form two main rolls almost  
 463 parallel each others (Fig. 10c). Interestingly, in this case the two rolls do  
 464 not reach the sidewall, but no smaller structures are visible between them  
 465 and the sidewall. The pattern change from Fig. 10b to Fig. 10c results in a  
 466 sudden change in the variance of the temperature field in the  $xy$ -plane. This  
 467 corresponds to the jump of  $\sigma^2$  shown in Fig. 6 (red symbols).

468 The pattern evolution described above was not obtained when  $\epsilon$  was de-  
 469 creased from  $\epsilon = 2.91$  to  $\epsilon = 0.05$ . When  $\epsilon$  was decreased, the pattern  
 470 obtained at the highest  $\epsilon$  (i.e. the rolls in Fig. 10c) remained stable until  $\Delta T$   
 471 was reduced to  $\Delta T_c$ . This hysteresis in pattern evolution may be related to  
 472 non-Boussinesq effects. These specific experiments were indeed carried out  
 473 with glycerol solution as the saturating fluid, and the applied temperature  
 474 difference corresponding to the polygonal cell pattern observed while increas-  
 475 ing  $\Delta T$  (Fig. 10b) was  $\Delta T = 27.7$  °C. A similar hysteresis, in which both  
 476 rolls and hexagonal convection pattern can be stable at the same  $Ra$ , takes  
 477 place in Rayleigh-Bénard convection when the temperature dependence of  
 478 fluid properties, such as thermal expansion coefficient and viscosity, is suf-  
 479 ficiently large to result in up-down asymmetric conditions in the fluid layer  
 480 (Busse, 1967; Darbouli et al., 2016).

481 Beside axisymmetric and deformed rolls, from  $\epsilon = 2.95$  we observed also  
482 stable parallel straight rolls. An example of them is shown in the velocity  
483 field of Fig. 11a for hexadecane ( $Pr = 43.5$ ,  $\epsilon = 4.57$ ). In this case, the  
484 wavenumber is  $\alpha = (1.14 \pm 0.10)\pi$ , slightly larger than  $\alpha_c$ . This is in agree-  
485 ment with the conditions for stable two-dimensional parallel rolls predicted  
486 by theory (Joseph, 1976). In this case, rolls remained stable until  $\epsilon \approx 6.32$ ,  
487 corresponding to  $Ra \approx 308.0$  and  $\Delta T = 1.68$  °C. After that, rolls begin to  
488 deform leading to a transitional regime (Fig. 11b). The  $Ra$  we obtained for  
489 the beginning of this transition matches that predicted by numerical simu-  
490 lations for the transition from a stationary convection regime to a periodic  
491 regime characterized by the superposition of counter-rotating rolls. This  
492 latter transition, that takes place for  $Ra$  in between 300 and 390 (Kimura  
493 et al., 1987; Caltagirone and Fabrie, 1989), marks the beginning of thermal  
494 boundary-layer instabilities that perturb (without completely destabilize) the  
495 underlying convective structure (Hewitt, 2020). When  $\epsilon$  is increased further,  
496 we finally achieved a clearer cross-roll pattern (Fig. 11c).

#### 497 4.3. Intensity of convection

498 The intensity of convection for  $Ra > Ra_c$  can be evaluated from the  
499 velocity image by calculating the squared mean large-scale flow velocity ( $U^2$ )  
500 since  $U^2 \sim E_K$ , with  $E_K$  being the kinetic energy. The large-scale velocity is  
501 defined as the surface integral of the magnitude of the velocity field  $\mathbf{v}$ , that  
502 is

$$U^2 = \int_s \|\mathbf{v}\|^2 ds, \quad (6)$$

503 where  $s$  is the area of the velocity image on the  $xz$ -plane. In our case,  $U^2$  is  
504 calculated as the sum of the square of the velocity components for each pixel  
505 of the velocity image.

506 Fig. 12 shows the large-scale velocity as a function of  $Ra$ . Here  $U$  is  
507 normalized by the characteristic thermal diffusion velocity,  $\kappa_{\text{eff}}/H$  (with  $H$   
508 being the height of the cavity and  $\kappa_{\text{eff}}$  the effective thermal diffusivity). For  
509  $Ra_c < Ra < 70$ , a correlation between  $U$  and  $Ra$  is hard to identify because  
510 data are very scattered. This is due to both the difficulty of distinguishing  
511 low velocities from background noise and the underestimation of velocity  
512 due to the accuracy limit of the MRV. For  $Ra > 70$ , Fig. 12 shows that  
513 the normalized bulk velocity scales with  $Ra$  as  $U \sim Ra^{1/2}$ . This is the same  
514 scaling obtained by weakly-nonlinear theory for classical Rayleigh-Bénard

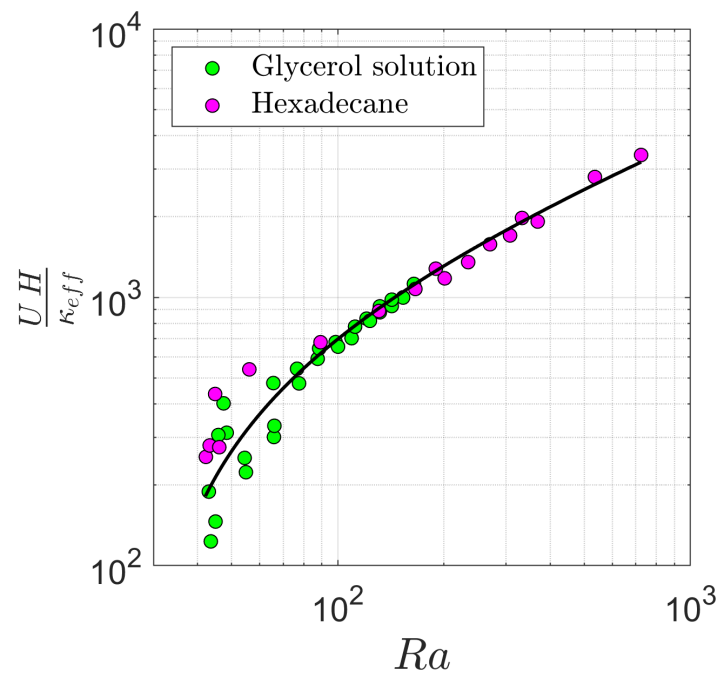


Figure 12: Normalized mean large-scale velocity  $U$  as a function of  $Ra$ . The solid line is the equation  $y(x) = ax^{1/2} + b$ , with  $a = 147.3$  and  $b = -774.4$ .



515 convection at relatively small  $Ra$  (Schlüter et al., 1965), and for convection  
 516 at low  $Re$  in porous media made by packed beds of spheres (Palm et al.,  
 517 1972).

#### 518 4.4. Heat transport

519 An aspect of interest in fluid-saturated porous media heated from below  
 520 is to define the degree to which heat transfer is increased by convection.  
 521 This can be captured by plotting the Nusselt number ( $Nu$ ), namely the ratio  
 522 between the total heat transferred in the system and the heat transferred by  
 523 conduction alone at the same temperature difference, as a function of  $\epsilon$ . For  
 524  $\epsilon < 0$ , heat is only transferred by conduction and  $Nu = 1$ . On the other  
 525 hand, when convection starts ( $\epsilon \geq 0$ ), the total heat transferred consists of  
 526 a part due to conduction and a part due to convection leading to  $Nu > 1$ .

527 In our experiments with glycerol,  $Nu$  can be evaluated from the tempera-  
 528 ture field obtained by MRT. To do so we used either the vertical cross-section  
 529 in the  $xz$ -plane or the one along  $yz$ -plane, depending on the orientation of  
 530 the convection pattern of each single experiment. In fact, some experiments  
 531 are characterized by rolls parallel to one of the acquisition planes, limiting  
 532 their use for evaluating heat transfer. To evaluate  $Nu$  we used only those  
 533 images where at least one convective cell was well-resolved.

534 Fig. 13 shows an example of the local Nusselt number obtained for  $\epsilon =$   
 535 0.62. The local  $Nu$  is calculated as

$$Nu = \frac{-\lambda_{\text{eff}} \frac{\partial T}{\partial z}}{-\lambda_{\text{eff}} \frac{\Delta T}{H}}, \quad (7)$$

536 where the term  $-\lambda_{\text{eff}}(\partial T/\partial z)$  is the total thermal flux, the term  $-\lambda_{\text{eff}}(\Delta T/H)$   
 537 is the conductive flux through the sample cavity, and  $\lambda_{\text{eff}}$  is the effective ther-  
 538 mal conductivity of the system. The total thermal flux is obtained from our  
 539 experiments by evaluating  $\partial T/\partial z$  on the first three pixels from the bottom  
 540 surface of the acquired images. Fig. 13a shows an example of the temperature  
 541 field on the  $xz$ -plane used to calculate  $Nu$ . Here the convective rolls form two  
 542 well-defined ascending warm regions surrounded by descending cold regions.  
 543 The local  $Nu$  (Fig. 13b) calculated for each pixel-column of the temperature  
 544 image follows this latter trend.  $Nu$  takes on relatively higher local values in  
 545 colder regions, while decreasing as it approaches the warmer regions, with  
 546 a minimum around the central axes of the latter. The slightly noisy trend  
 547 for  $Nu$  is mainly due to the noise on the temperature field, especially in the

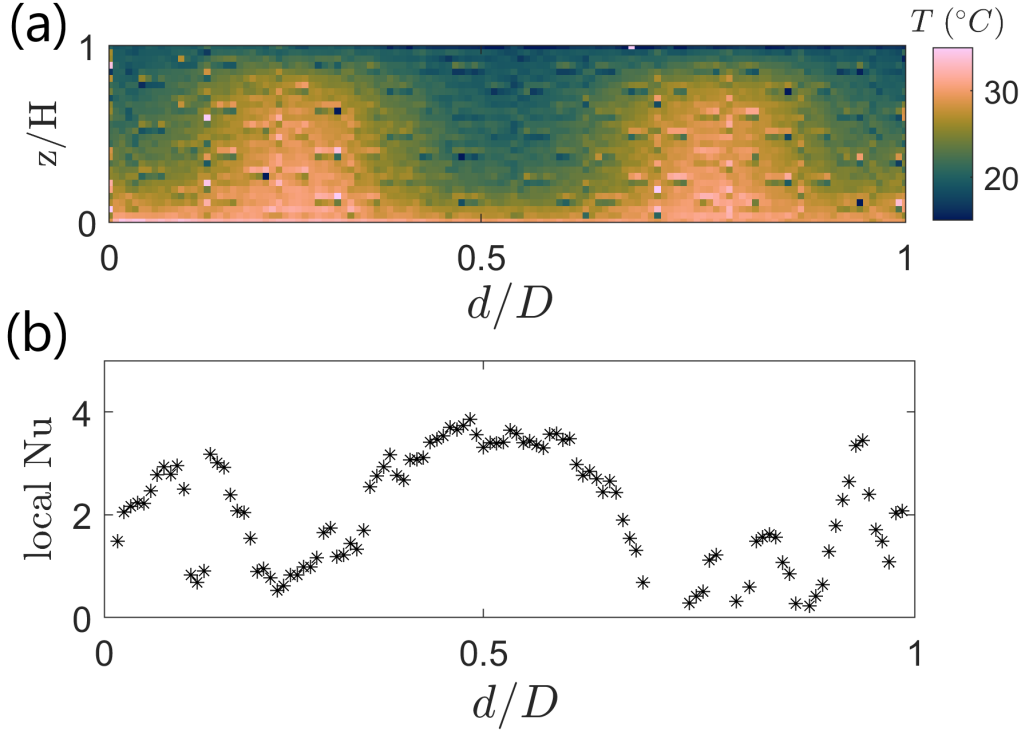


Figure 13:  $Pr=688.1$ ,  $\epsilon = 0.62$  and  $\Delta T = 13.3$  °C. (a) Measured temperature field on the  $xz$ -plane during convection. (b) Variation of the local Nusselt number along the normalized cavity's diameter  $d/D$ .

548 first pixels near the bottom boundary. Given the resolution used to acquire  
 549 these images, the interface between the cavity's bottom surface and the fluid  
 550 above it is not always well resolved and may lead to some variation in the  
 551 calculated local  $Nu$ .

552 From Fig. 13b one can evaluate the average Nusselt ( $\overline{Nu}$ ) for a given  $\epsilon$   
 553 as

$$\overline{Nu} = \frac{1}{\Sigma} \int_{\Sigma} Nu d\Sigma, \quad (8)$$

554 with  $\Sigma$  being the cavity's surface. The standard uncertainty is evaluated in  
 555  $u_a(\overline{Nu}) = 0.1$ . For the case in Fig. 13 we obtained  $\overline{Nu} = 2.1$ . Fig. 14  
 556 reports the average Nusselt as a function of  $\epsilon$  for all the experiments carried  
 557 out using glycerol as saturating fluid. As expected, we recovered  $\overline{Nu} = 1$  for

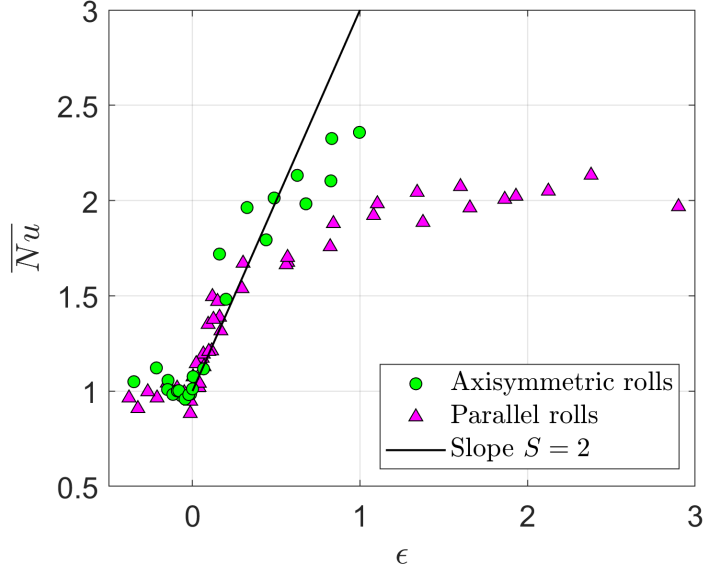


Figure 14: Average  $\overline{Nu}$  as a function of  $\epsilon$  ( $Pr = 688.1$ ). The different symbols represent the planes on which temperature images were acquired. The solid line shows a slope  $S = 2$ .

558 subcritical conditions and a sharp transition at the onset of bulk convection.  
559 For  $\epsilon > 0$ ,  $\overline{Nu}$  increases linearly until about  $\epsilon = 0.5$  where the slope begins  
560 to decrease until it saturates. The difference between the symbols in Fig.  
561 14 reflects the different acquisition planes used to estimate  $Nu$ . We used  
562 images along the  $xz$ -plane for experiments developing axisymmetric rolls,  
563 and images along the  $yz$ -plane for parallel rolls that are perpendicular to the  
564 image plane. Results for the axisymmetric case are the most reliable. This  
565 is due to the small signal distortion near the sidewall on the  $xz$ -plane and  
566 the fact that the local  $Nu$  can be easily integrated on the cavity's surface  $\Sigma$   
567 given the axisymmetric conditions. On the other hand, to avoid the higher  
568 lateral distortion, for images of parallel rolls only a portion corresponding to  
569 one wavelength of the temperature field on the  $yz$ -plane was used. Together  
570 with the fact that the convective pattern is not axisymmetric, in this case  
571 the local  $Nu$  cannot be integrated over the entire surface of the cavity but  
572 only along the direction of the profile ( $\overline{Nu}_y$ ). This leads to values of  $\overline{Nu}_y$   
573 for parallel rolls that can only reflect an approximation of the real  $\overline{Nu}$ .

574 For both parallel and axisymmetric rolls, the results we obtained for the

575  $\overline{Nu}-\epsilon$  correlation in the interval  $0 < \epsilon < 0.5$  show a linear trend with a  
 576 slope  $S = d\overline{Nu}/d\epsilon = 2$  (Fig. 14). The same slope is maintained for  $\epsilon >$   
 577  $0.5$  in the case of axisymmetric rolls. This is in agreement with the slope  
 578  $S = 2$  predicted theoretically by Joseph (1976) for an unbounded porous  
 579 layer (aspect ratio  $\Gamma \rightarrow \infty$ ) with  $Pr Da^{-1} \rightarrow \infty$ . We recall that the aspect  
 580 ratio in our case is  $\Gamma = 4.4$  and  $Pr Da^{-1} = 1.6 \times 10^6$  for glycerol and  
 581  $Pr Da^{-1} = 1.0 \times 10^5$  for hexadecane.

582 Because of the accessibility of heat transfer measurements in experiments,  
 583 this slope has been investigated experimentally in the past for several differ-  
 584 ent systems. For a creeping flow through packed beds of spheres, Elder (1967)  
 585 found a slope of  $S = 1$ , and Shattuck et al. (1997) found  $S = 0.73 \pm 0.05$  for  
 586 aspect ratios  $\Gamma = 8 - 9$ . Similar slopes were found by Howle et al. (1997),  
 587 who obtained  $0.53 < S < 1.35$  depending on the type of porous medium  
 588 employed. Again with beads, Close et al. (1985) found that  $S$  is affected by  
 589 the aspect ratio of the system, with a decrease in  $\Gamma$  leading to an increase  
 590 in  $S$ . Beside porous media made by packed spheres, the  $\overline{Nu}-\epsilon$  curve for a  
 591 fluid-saturated highly porous metal foam was investigated by Kathare et al.  
 592 (2008) and Davidson et al. (2009). For  $\epsilon > 0$ , the value of  $S$  they obtained  
 593 is smaller than what we obtained in our system. This difference may be  
 594 related to the different geometry and/or different thermal properties of the  
 595 solid foam. That is, to the different viscous drag between a foam with regular  
 596 structure and large pores (such as the one used in our experiments) and one  
 597 with random structure and smaller pores. Or to the departure from the local  
 598 thermal equilibrium between solid matrix and saturating fluid in the case of  
 599 a highly conductive metal foam.

## 600 5. Conclusion

601 In this work, we carried out experiments of thermal convection at low-to-  
 602 moderate  $Ra$  in a fluid-saturated solid foam heated from below and cooled  
 603 from above. The solid foam consists of a 3D-printed open-cell structured  
 604 plastic matrix with a porosity of  $\phi = 0.83$  and four unit cells stacked on top  
 605 of each other. Experimental investigations involving thermal convection in  
 606 these types of porous media are essential because of their wide use in many  
 607 heat and mass transfer applications, such as in latent heat thermal energy  
 608 storage systems.

609 Natural convection in our system was studied using Magnetic Resonance  
 610 Imaging (MRI). This technique allowed us to provide for the first time quan-

611 titative measurements of velocity vectors and temperature fields in the con-  
612 vecting fluid. The results obtained were compared with those for classical  
613 porous media (e.g. packed beds of spheres with  $\phi < 0.5$ ) and with theoretical  
614 predictions.

615 For our system, we first evaluated the relative importance of the inertia  
616 term to the viscous resistance during convection. Even considering the large  
617 porous size and high porosity of the foam, for the range of  $Ra$  over which the  
618 experiments were performed, we obtained  $Re^* < 1$  and thus an inertia-free  
619 flow that can be effectively described by Darcy's law.

620 Next, we investigated the critical conditions of motion and the different  
621 convection patterns. We found the onset of convection at  $Ra_c = 41.9$ , with  
622 a critical wavenumber of  $\alpha_c \approx \pi$ , very close to the value predicted by linear  
623 stability theory for Rayleigh-Darcy configuration. For  $Ra < Ra_c$ , we never  
624 observed convection. In this case, the velocities always remain below the  
625 accuracy of the measurement and temperature fields remain homogeneous  
626 and constant. For  $Ra_c \leq Ra < 308$ , the flow organizes in stable rolls,  
627 the latter in forms of axisymmetric, straight or deformed rolls. At about  
628  $Ra = 308$ , the flow enters in a transitional regime in which the convective  
629 rolls begin to deform. At the highest  $Ra$  tested, the convective pattern  
630 takes the form of well-developed cross-rolls. The intensity of convection  
631 was estimated through the large-scale mean squared velocity  $U^2$ , since  $U^2 \sim E_K$ ,  
632 with  $E_K$  as the kinetic energy of the system. For  $Ra > 70$ , we obtained  
633  $U \sim Ra^{\frac{1}{2}}$ , as it is for classic Rayleigh-Bénard convection without the porous  
634 layer.

635 Finally, we estimated the Nusselt number from temperature fields. The  
636 local  $Nu$  reflects the temperature distribution: higher values of local  $Nu$  cor-  
637 respond to cold down-welling regions, and smaller  $Nu$  to warm up-welling  
638 regions. The averaged Nusselt number for the whole system ( $\overline{Nu}$ ) was esti-  
639 mated from the local  $Nu$  of images with axisymmetric convective rolls and  
640 parallel rolls. We obtained  $\overline{Nu} = 1$  for subcritical conditions and a sharp  
641 transition at the onset of convection. For experiments with axisymmetrical  
642 rolls, when convection begins,  $\overline{Nu}$  increases as  $\epsilon$  increases with a linear trend  
643 with a slope  $S = 2$ . This is in agreement with the slope predicted by theory,  
644 but is different from the slopes obtained in other experiments using different  
645 systems. The differences with other experiments reported in the literature  
646 may be associated with the different viscous drag that different porous ma-  
647 trices can generate, the departure from local thermal equilibrium if the solid  
648 and liquid components have very different thermal properties, and/or the

649 non-homogeneity of the porous medium.

## 650 **Appendix A.**

651 Uncertainties related to material properties measured in this work and  
 652 those related to MRI techniques are reported in Sections 2.1 and 3.2, re-  
 653 spectively. The uncertainty in the non-dimensional numbers is estimated by  
 654 the error propagation method (Moffat, 1988). For a generic non-dimensional  
 655 number  $R$ , this writes

$$u(R) = \sqrt{\sum_{i=1}^N \left( \frac{\partial R}{\partial X_i} u(X_i) \right)^2}, \quad (\text{A.1})$$

656 with  $R$  as a function of  $N$  independent variables ( $X_i$ ), each with its own  
 657 uncertainty  $u(X_i)$ . This leads, for instance, the uncertainty for the Prandtl  
 658 number (defined as  $Pr = \eta/(\rho\kappa_{\text{eff}})$ ) being

$$u(Pr) = \sqrt{\left( \frac{\partial Pr}{\partial \eta} u_a(\eta) \right)^2 + \left( \frac{\partial Pr}{\partial \rho} u_a(\rho) \right)^2 + \left( \frac{\partial Pr}{\partial \kappa_{\text{eff}}} u_a(\kappa_{\text{eff}}) \right)^2}, \quad (\text{A.2})$$

659 with  $u_a(\eta) = 5 \times 10^{-4}$  Pa s,  $u_a(\rho) = 0.01$  kg m<sup>-3</sup>, and  $u_a(\kappa_{\text{eff}}) = 3.5 \times 10^{-9}$   
 660 m<sup>2</sup>s<sup>-1</sup> (Sgreva et al., 2023). This results in  $u(Pr) = 24.9$  for the glycerol-  
 661 saturated foam and  $u(Pr) = 7.4$  for hexadecane-saturated foam.

662 Uncertainties for the other non-dimensional numbers are obtained in the  
 663 same way, i.e. according to eq. (A.1) and their definitions. For the Rayleigh  
 664 number, we estimate  $u(Ra_c) = 2.1$  at the onset of convective motion for the  
 665 glycerol-saturated foam. For that we consider, in addition to the uncertain-  
 666 ties given above, also  $u_a(H) = 0.01$  mm,  $u_a(\beta) = 2.6$  °C<sup>-1</sup> and  $u_a(T) = 0.10$   
 667 °C for the temperature at the upper and lower cavity's surfaces.

## 668 **Acknowledgments**

669 This work was funded by the operation STOCK'NRJ, co-financed by  
 670 the European Regional Development Fund within the framework of the Pro-  
 671 gram FEDER-FSE Lorraine and Massif des Vosges 2019–2023. This work is  
 672 also part of the project CONVINCES, financially supported by the French  
 673 National Research Agency (Grant No. ANR-21-CE50-0029).

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