

Experimental investigation of Rayleigh-Bénard convection patterns in low-concentration nanofluids

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This study investigates the influence of titanium dioxide (TiO₂) nanoparticles suspended in water on convection cells and heat transfer dynamics. To this end, a Rayleigh-Bénard experimental study was conducted for a water-TiO₂ nanofluid (<0.02% wt) in a cylindrical cavity with a diameter to height aspect ratio of 16. A shadowgraph was used to visualize the spatial and temporal evolution of convection cells in a Rayleigh regime (<10⁴), well suited for observing transitions and stability in flow patterns. The observations show that both colloidal stability and nanoparticle sedimentation strongly affect the evolution of convection patterns and heat transfer. These experiments qualitatively demonstrate that TiO₂ nanoparticles can enhance heat transfer under convective conditions, as inferred from the observed changes in convection cell pattern and flow organization. While nanofluids are typically designed to maximize colloidal stability, minimize agglomeration, and prevent sedimentation, our results challenge this paradigm by showing that sedimentation plays a key role in intensifying heat transport.

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I. INTRODUCTION

The development of heat-transfer fluids based on the “nanofluid concept” has received increased research interest [1]. These nanofluids consist of a liquid charged with heat-conducting nanoparticles. The nanoparticles are used to improve heat transfer and enhance the performance of heat exchangers, particularly in thermal power plants, nuclear reactors, and solar thermal collectors. Existing literature, includes extensive studies on the dynamics of thermally resistant microparticles in a convective fluid. For example, Martin *et al.* [2] studied the sedimentation of polystyrene microparticles (>0.21 mm and <0.50 mm). They showed that the number of particles suspended in a fluid decreases exponentially as a function of the Stokes velocity. They observed an equilibrium between particle re-entrainment and particle suspension when a large proportion of particles has already settled. Particle re-entrainment is a process that can affect flow over a long period. A few studies [3,4] have focused on this issue based on the study by Solomatov *et al.* [5]. They subsequently conducted an experimental study with polystyrene particles with diameter ranges off 15–35 μm and 60–100 μm at a concentration *c* of 1.5–2 wt %. They explained the re-entrainment by the formation of a dune at the base of the thermal plumes effected by horizontal tangential stress. When the thickness of the dune reaches a certain level, the vertical tangential stress can lift the particles. Therefore, a balance exists between the buoyancy stress and weight per unit area of

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the particles. Lavorel *et al.* [3] focused on the dynamics of particle sedimentation and the criteria for particle stability in the system. They carried out experiments with polymethyl methacrylate (PMMA) particles with a radius of $300 \pm 5 \mu\text{m}$ in a turbulent flow. Lavorel *et al.* confirmed the presence of a constant re-entrainment flow of particles from the boundary layer. They verified that particles settle at the Stokes velocity as a function of the relative density difference between the particles and fluid. They were also able to demonstrate the existence of an apparent viscosity at the particle surface due to turbulent flow. In 2017, Morize *et al.* [4] studied the resuspension of a bed of $250 \mu\text{m}$ polystyrene particles. They showed that the bed destabilization temperature is linearly dependent on the density difference. However, all of these studies were performed using microparticles. We then considered a decreased particle size and focused on nanoparticles, given that nanoparticles are considered mere tracers. An experiment conducted by Li *et al.* [6] showed a decrease in the heat transfer for different mass concentrations. They developed an experimental setup to observe the movement of polystyrene particles with diameters of 850 nm using a microscope. They were able to observe the Brownian motion and thermophoresis acting on the particles and showed that the particles slightly delayed the onset of convection. However, few experimental studies have focused on the effect of heat-conducting particles on convective heat transfer. Koyaguchi *et al.* [7] carried out a series of experiments using silicon carbide microparticles. They observed the formation of an interface between two layers: the first convective layer was governed by the sedimentation of particles and the fluid layer above. An increase in temperature led to the destabilization of the sedimented-particles layers, which caused the sudden homogenization of the particles in the fluid. They demonstrated the existence of an equilibrium between the increase in fluid density owing to the particles and decrease in density owing to an increase in temperature. Rao *et al.* [8] conducted an experiment with nanofluids and showed that with low volume concentrations of alumina ($<0.04\%$), the heat-transfer coefficient may be increased by 38% . They observed this increase through a reduction of the thermal boundary layer thickness and an increase in the number of convective rolls, for a Rayleigh number of approximately 10^5 . Khalili *et al.* [9] focused on the distribution of nanoparticles in a flow. They showed that the core of the flow and the surface beneath it contained more particles than the rest of the cavity. The nanoparticles remained trapped in the center of the vortex and, over time, the larger nanoparticles settled out. In 2009, Donzelli *et al.* [10] carried out an experimental study of convection with a highly concentrated Hyflon nanofluid ($c = 4\% \text{ wt}$). They observed two different behaviors depending on the initial distribution of the nanoparticles. For an initial homogeneous distribution, they observed either confined convection in one part of the cavity, which eventually disappeared [11], or stable oscillatory convection. When the nanoparticles initially settled, a conductive regime was observed. They concluded that nanoparticles degrade the heat transfer and modify the flow structure based on the nanoparticle distribution. While numerous theoretical studies have examined nanofluid instabilities [12–14], most rely on simplified models that neglect particle sedimentation in the energy equation, although its buoyancy effects are accounted for in the momentum equation. Nield *et al.* [13] studied a model with fixed nanoparticle distributions, which allowed for oscillatory instabilities. However, more realistic boundary conditions imposing zero nanoparticle flux at the walls were later shown to suppress such behavior [14]. Then Ruo *et al.* [12] showed that nanoparticles can strongly destabilize the flow, leading to unconditional instability when their volume fraction exceeds 0.1% . These models treat nanoparticles as a continuous fluid phase, allowing for spatial variations in concentration driven by Brownian motion and thermophoresis. However, they rely on idealized assumptions such as fixed or zero-flux boundary conditions and often neglect realistic sedimentation effects, limiting their applicability to experimental conditions. To the best of our knowledge, one theoretical study explicitly accounts for sedimentation in the energy equation when analyzing Rayleigh-Bénard instabilities in nanofluids. A study by Chang *et al.* [15], based on the Buongiorno model [16], added a term to consider the effect of sedimentation in the energy equation. The authors showed that the balance between sedimentation and thermophoresis is crucial for system stability and the convection threshold. Furthermore, an oscillatory state appeared when sedimentation and thermophoresis were of the same order of magnitude.

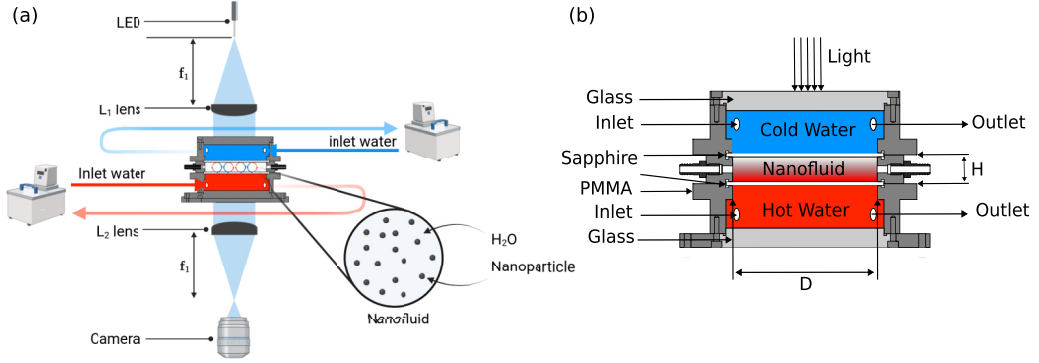


FIG. 1. Schematic of: (a) the experimental setup, (b) the cross section of the test cavity.

Numerous studies have already been published on the characterization of thermophysical properties such as thermal conductivity [17], viscosity [18], and stability as well as the preparation methods for nanofluids [19]. However, most of these works focus on effective properties or global heat transfer measurements [20], often assuming ideal colloidal stability and spatial homogeneity. Foundational studies such as those by Buongiorno [16] and Chang *et al.* [15] have contributed significantly to modeling nanofluid behavior, but they do not explicitly address how nanoparticles influence the evolution of flow patterns and local heat flux.

Yet, in nanofluid convection, flow pattern directly governs heat transfer. Understanding how nanoparticles alter convection cells through mechanisms such as colloidal stability and sedimentation, is essential to explain the observed enhancements in heat fluxes.

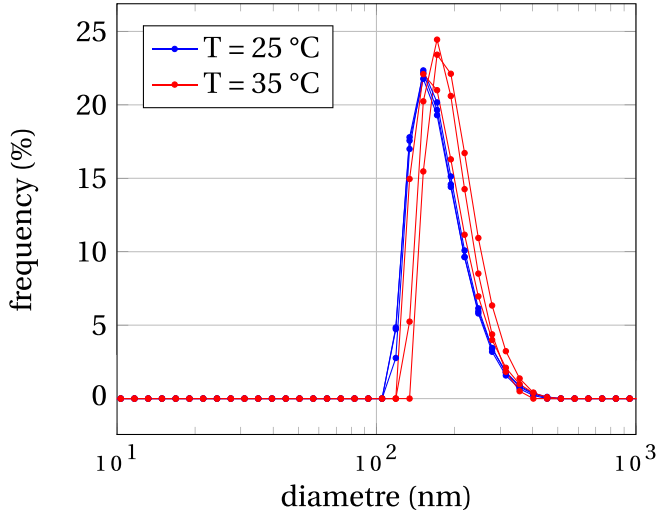
In this study, we address this gap by conducting Rayleigh-Bénard experiments using a diluted TiO_2 -water nanofluid. The device is coupled with an optical bench to visualize flow pattern evolution at low Rayleigh numbers, where comparison with pure fluid behavior helps identify how nanoparticles modify convection cells.

II. EXPERIMENTS

A. Materials and protocol

The experiments were performed in a cylindrical cavity (inspired by [21]) with a diameter of $D = 110$ mm and a thickness of $H = 6.875$ mm. Figure 1(b) shows the experimental cavity. The aspect ratio $\Gamma = D/H$ is equal to 16. The vertical walls of the cavity comprise 2-cm-thick PMMA to ensure good thermal insulation of these side walls. The horizontal walls comprise glass and transparent sapphire to visualize the convective cells using a shadowgraph. The nanofluid is confined between the sapphire plates, which are 2 mm thick and have a thermal conductivity of $35 \text{ Wm}^{-1}\text{K}^{-1}$. The upper plate is cooled by a flow of water at temperature T_c whereas the lower plate is heated by a flow of water at T_h . The temperature difference $T_h - T_c$ (ΔT) is controlled by two thermostatic baths with an accuracy of ± 0.1 °C. Figure 1(a) shows the complete set-up of the optical bench.

A parallel beam of light is passed through the fluid to visualize the movement of the hot and cold fluid streams. Variations in the refractive index as a function of temperature modulate the light intensity. The hot currents diverge the light (dark area) and cold downward currents converge the light (bright line); this is called a shadowgraph [22]. To achieve this, a 660-nm-red light-emitting diode coupled with an optical fiber with a core of $400 \mu\text{m}$ and numerical aperture of 0.5 are deployed. Two achromatic lenses with focal lengths of $f_1 = 333$ mm and diameters of 135 mm are used. The convection patterns are recorded using a camera (D850, Nikon, Japan). The resolution is 5504×5504 pixels with 8-bit sampling. Throughout the experiment, images were acquired at 2 min intervals, corresponding to $0.35 \tau_D$, where τ_D represents the characteristic heat-diffusion time


 FIG. 2. Size distribution of TiO_2 .

in the vertical direction of the nanofluid. The experiments are conducted with a water-based TiO_2 nanofluid (99.9%, Nanoshel, India) at two different mass concentrations (0.01% wt and 0.02% wt) as the working fluid. The thermal conductivity of TiO_2 is equal to $8 \text{ W m}^{-1} \text{ K}^{-1}$ [23]. The size of the nanoparticles is measured by dynamic light scattering using a nanoparticle analyzer (sz-100, Horiba, Japan) and we obtain an average hydrodynamic diameter of 170 nm (Fig. 2).

Because of the low concentration, we consider the kinematic viscosity ν and thermal conductivity κ of the nanofluid to be approximately equal to those of water. During the experiments, the Prandtl number, defined as $\text{Pr} = \nu/\kappa$, is set to 6.1. Before each experiment, the solution is passed through an ultrasonic bath for 1 h to break down agglomerates. The nanofluid is then mixed using a magnetic stirrer and inserted into the cavity. The water tank is temporarily heated to the top to obtain a resting stratified fluid with stable density. During this time, we record a time series of 150 photographs to determine the reference image I_0 with no convection movement. No thermodiffusion phenomena are observed during this period. We use thermostatic baths to set the T_h and T_c temperatures, thereby providing the temperature difference ΔT required to achieve the desired Rayleigh number, defined as $\text{Ra} = g\alpha\Delta T H^3/\nu\kappa$, where g is the gravitational acceleration and α the thermal expansion coefficient. This protocol is repeated to avoid hysteresis phenomena [10,24], which depend on the initial particle distribution.

B. Image processing

The intensity of image $I(x, y)$ during the experiment is proportional to the Laplacian of the refractive index [22]:

$$\frac{I((x, y) - I_b(x, y))}{I_0(x, y) - I_b(x, y)} \propto \int_0^H \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \ln(n) dz, \quad (1)$$

where I_0 is the intensity of the light with no thermal gradient, and I_b is the intensity characterizing the thermal noise of the camera. To determine I_0 , we apply a Fourier transform to each pixel and filter the time signal using a low-pass filter. After the filter is applied, the filtered sample is averaged for each pixel.

More practically, the resulting image of thermal convection is a function of variations in the refractive index, which is dependent on variations in temperature. Equation (1) can be rewritten for

a pure fluid in the following manner:

$$\frac{I((x, y) - I_b(x, y))}{I_0(x, y) - I_b(x, y)} \propto \int_0^H \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) dz. \quad (2)$$

In the presence of nanoparticles, Eq. (2) can be expressed as a function of the nanoparticles. The transmitted image for a low concentration [25] becomes

$$\frac{I((x, y) - I_b(x, y))}{I_0(x, y) - I_b(x, y)} = \exp(-C_N C_e H), \quad (3)$$

where C_N [part./m³] is the volume concentration of the particles, and C_e refers to the extinction cross sections of all particles in the volume.

Experimentally, the amplitude of the intensity variations in the transmitted image increases owing to the presence of particles. Consequently, the intensity variations owing convection cells are masked by these increased fluctuations, making the convection cells difficult to discern. To overcome this, we applied the Neperian logarithm to Eq. (3). The logarithmic function of an image compresses the upper pixel values while stretching the lower values. Dark pixels are stretched to upper values, whereas light pixels are compressed to lower values. Because the dynamic range is too wide due to the nanoparticles, the logarithm can be used to accentuate details in the darker parts of the image without saturating the lighter parts.

III. RESULTS AND DISCUSSION

For Rayleigh number values close to the threshold Rayleigh value ($Ra_c = 1708$), we conducted experiments with a nanofluid (water-TiO₂) with two different particle concentrations. The images obtained from the shadowgraphs are presented and interpreted. Furthermore, the physical data from our experimental setup enables heat diffusion time estimates, $\tau_D = H^2/\kappa$. Figure 3 shows the flow patterns for various instances for a concentration of 0.01% wt and Rayleigh number equal to 1.82×10^3 . A few seconds after the application of the thermal gradient, this scenario corresponds to a steady state of pure fluid flow in a cylindrical cavity [26,27]. In contrast, the black circles are more intense than the other areas, as some nanoparticle sedimentation has begun ($\approx 5.57 \tau_D$) under the effect of the downward flow. However, this state becomes destabilized [Fig. 3(c)], and the formed umbilicus moves closer to the edge of the cavity and ruptures [Fig. 3(d)] due to a secondary flow [28].

Figure 4 shows the convection with nanoparticles and light transmission. Light is scattered by the Rayleigh effect [25] and deflected by refractive-index gradients. The opacity of the agglomerates and thermal gradients are the two mechanisms responsible for the shades of grey in the images. The black bands in the images are indeed sedimented particles, as they are visible to the naked eye at the bottom of the tank. The nanoparticles agglomerate, and the size of the piles increases from nanometric to micrometric. A thin micrometric layer is created in the lower thermal boundary layer, as shown in Fig. 4.

Figure 5 shows the flow after the rupture of the umbilicus and represents the evolution of the flow from a characteristic time $t_0 = 318 \tau_D$. Transient and unsteady flows are shown in the video in the Supplemental Material [29]. These four images reflect a nonperiodic radial flow propagating from the top to the bottom. We obtain a nonstationary flow regime close to the convection threshold $Ra/Ra_c \approx 1.066$. The wavelength of the flow is determined from shadowgraph images and averaged over five characteristic images. The resulting wavelength is between 17 and 29 mm with an average wavelength of 23.6 mm and a roll propagation speed of approximately 1–3 $\mu\text{m/s}$. This order of magnitude of speed is similar to that reported by Croquette *et al.* [28]. Therefore, this phenomenon has already been studied with different fluids for low (gas) or moderate ($Pr < 7$) Prandtl numbers [30–32]. This “turbulence” resembles the slow movement of the rolls, with irregular wandering. This phenomenon is often called weak turbulence, low-frequency (spatial) turbulence or phase

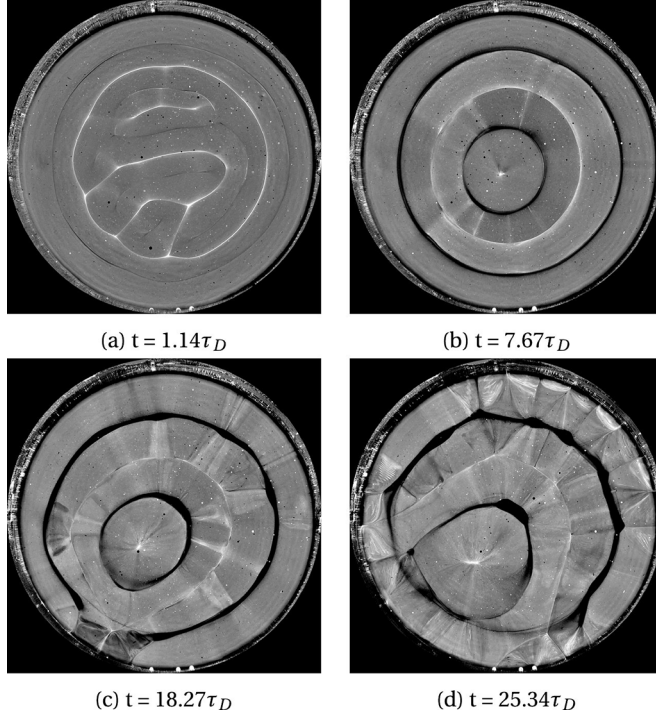


FIG. 3. Evolution of the TiO_2 transient $\Gamma = 16$, $\Delta T = 0.4$ K, $Ra = 1.82 \times 10^3$, $c = 0.01\%$ wt.

turbulence, because spatiotemporal variations in the phase are observed for Rayleigh numbers very close to the threshold.

Ahlers *et al.* [31] studied phase turbulence ($Ra = 1.141 Ra_c$) in a cylindrical cavity with an aspect ratio $\Gamma = 30$ with pure water ($Pr = 5.7$). In this case, the vertical thermal diffusion time scale was approximately 53 s. They showed that the first errant rolls appeared after $40 \tau_D$, whereas in our experiment, this occur after $35 \tau_D$. Thus, with fewer diffusion cycles, a longer diffusion time, and a

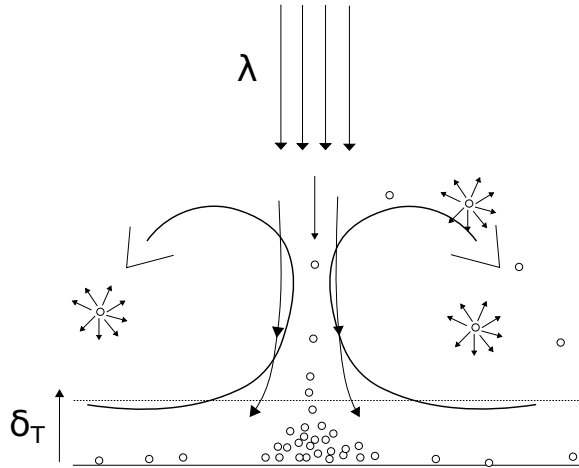


FIG. 4. Schematic of shadowgraph with nanoparticles.

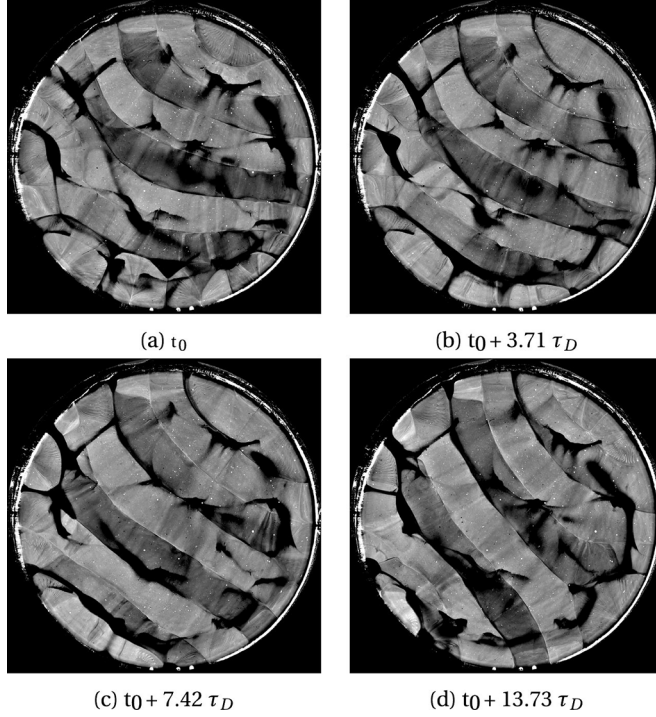


FIG. 5. Nonperiodic time-dependent solutions TiO_2 $\Gamma = 16$, $\Delta T = 0.4$ K, $Ra = 1.82 \times 10^3$, $c = 0.01\%$ wt.

higher Prandtl number, we obtain wandering rolls more quickly than Ahlers *et al.* This indicates that the thermal diffusion is more efficient in our experiment because of the nanoparticles. Furthermore, Steinberg *et al.* [26] studied convection in a cylindrical cavity ($\Gamma = 15$) with water ($Pr = 6.1$) and thermal diffusion time of 180 s. They performed an experiment similar to ours with the same Prandtl number, but a slightly smaller aspect ratio. They also examined the flow near the threshold with Rayleigh number $Ra = 1.13 Ra_c$. After $15 \tau_D$ they observed the flow symmetry breaking, whereas for our experiment, this took approximately $12 \tau_D$. The instationarity developed slightly, but not significantly, faster in our case. After $500 \tau_D$, Steinberg *et al.* did not observe any phase turbulence. In an equivalent experiment, we observed phase turbulence, unlike in the study by Steinberg *et al.* [26]. A comparison with their experiments [26,31] shows that the TiO_2 nanoparticles modify the convection and patterns. Subsequently, in another experiment with a lower Prandtl number [31], we obtain an unsteady flow, and the appearance of rolls occur more quickly with a higher Prandtl number. We believe that the fraction of nanoparticles that settled and agglomerated locally at the bottom of the tank increases the conductive heat flux in the thermal boundary layer. This change in heat flux increased the temperature of the fluid, resulting in a lower effective Prandtl number.

The Rayleigh number is then increased, while maintaining a constant concentration. Figure 6 shows the onset of convection for $Ra = 4.55 \times 10^3$. We obtain a pattern similar to that shown in Fig. 3(b); however, the umbilicus does not break at the edges. The flow then becomes quasistationary and identical to that of pure water [26]. Figure 6(b) shows the appearance of the sedimentation superimposed on the upward flow. Gradually, the particle sediment increases and form a cluster of particles in the center of the cavity [Fig. 6(d)]. The nonagglomerated particles remain in suspension, causing light rays to appear between the rings owing to the particle concentration gradient. For this experiment, we use an average wavelength of 38 mm within the range of 36–41 mm.

The volume of the central cluster increases over the course of the experiment (Fig. 7) due to sedimentation. When the cluster reaches a certain size, it is transported away by convection. During

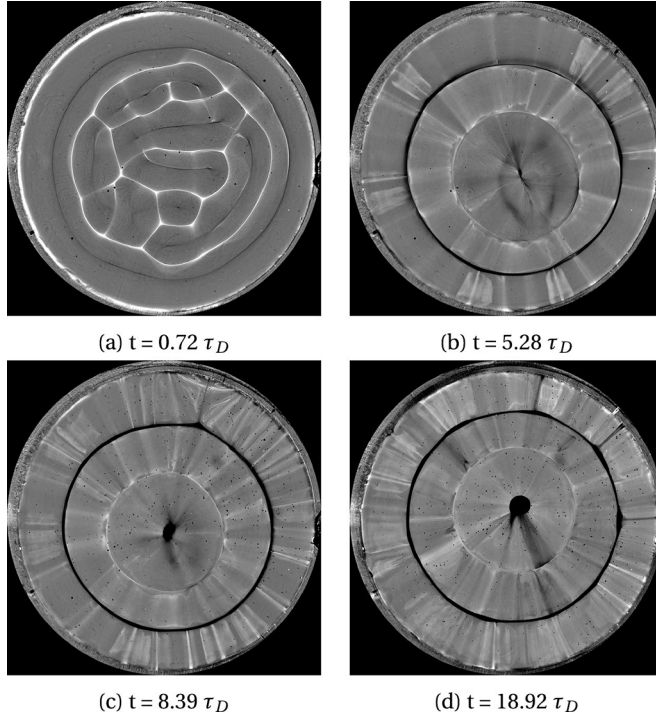


FIG. 6. TiO_2 instationary evolution $\Gamma = 16$, $\Delta T = 11$ K, $\text{Ra} = 4.55 \times 10^3$, $c = 0.01\%$ wt.

the experiment, the cluster is broken several times by convection without having a preferred direction. Figure 7 illustrates this phenomenon. The transient regime and various successive explosions of the nanoparticle clusters are shown in the video in the Supplemental Material [33]. The following images have a different contrast than the other Figures to better distinguish the particle concentration gradients. At $t_e = 200.3 \tau_D$, the particle cluster begins to be carried along by the convective flow, because its apparent surface area has increased. The rapid fragmentation of this cluster occurs in all directions [Fig. 7(b)]. During this explosion phase, the torus of the descending flow stretches upward [Fig. 7(d)], loses symmetry, and oscillates around its equilibrium position. Subsequently, the particles are advected and progressively gathered at the center of the cell using convection rolls. After analysis, we observe that every $60 \tau_D$, the particle cluster reaches a certain volume and is again fragmented by convection. These periodic burst explosions are caused by the nonuniformity of the surface state of the lower sapphire wall. Moreover, the deposition of particle sediments on the wall affects the thermal boundary layer and locally modifies the conductive heat flux by creating hot spots. This contributes to a local increase in the fluid temperature, which leads to asymmetry in the thermal boundary layer, making the convective rolls unstable [34,35].

Figure 8 shows the obtained results for a higher (twice: 0.02% wt) nanoparticles concentration (video in the Supplemental Material [36]). Figure 8(a) illustrates the onset of convection in the transient regime with strong light signals representing the flow of cold water. This state rapidly destabilizes and particle sedimentation occurs. In Fig. 8(b), a radial flow resembling progressive waves is observed. However, this is not phase turbulence, because the Rayleigh number is too high to be in this regime. Moreover, the order of magnitude of the speed of these waves is $16 \mu\text{m s}^{-1}$, which is five times higher than that in the phase turbulence domain. These unstable waves have an average wavelength of approximately 29 mm, ranging from 24 to 33 mm, which corresponds to a reduction of approximately 25% compared with the previous experiment ($c = 0.01\%$ wt). Subsequently, the flow oscillates between two nonstationary patterns. Figure 8(c) shows the progressive waves, and

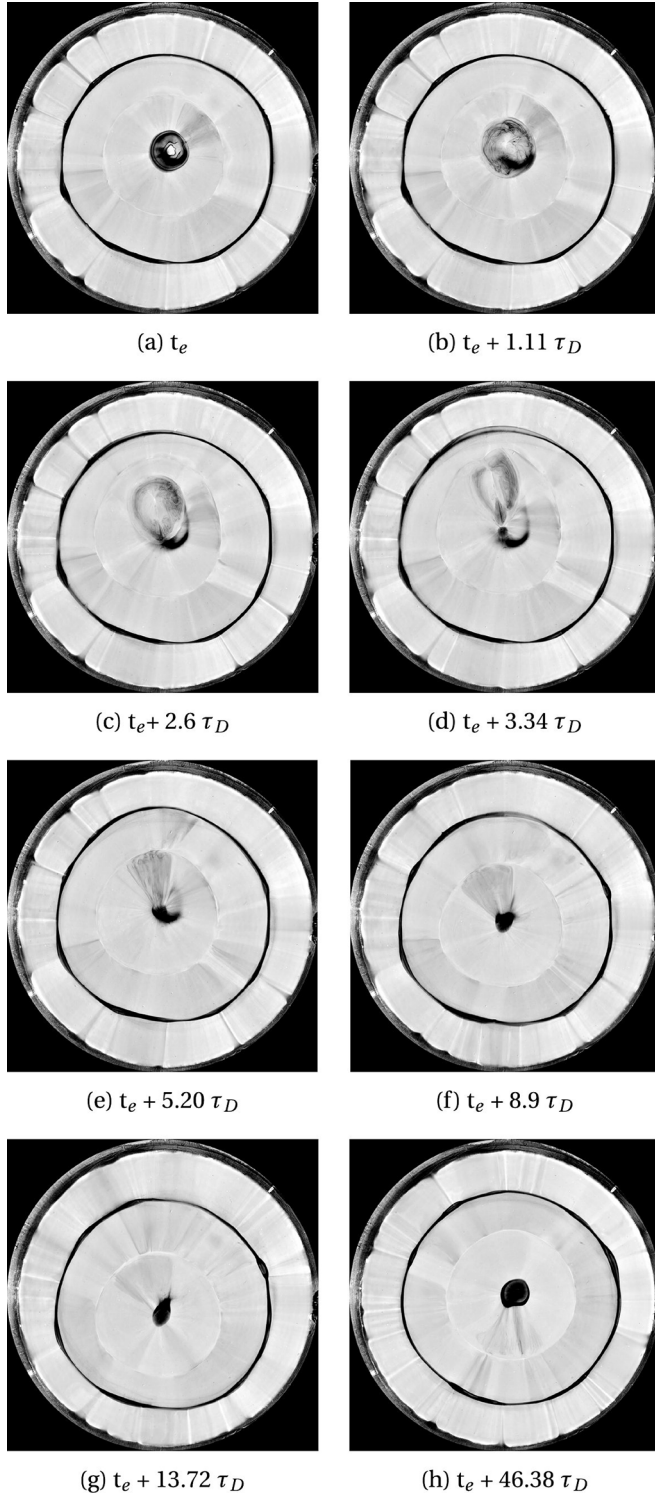


FIG. 7. Bursting sediment pile $\Gamma = 16$, $\Delta T = 1$ K, $Ra = 4.55 \times 10^3$, $c = 0.01\%$ wt.

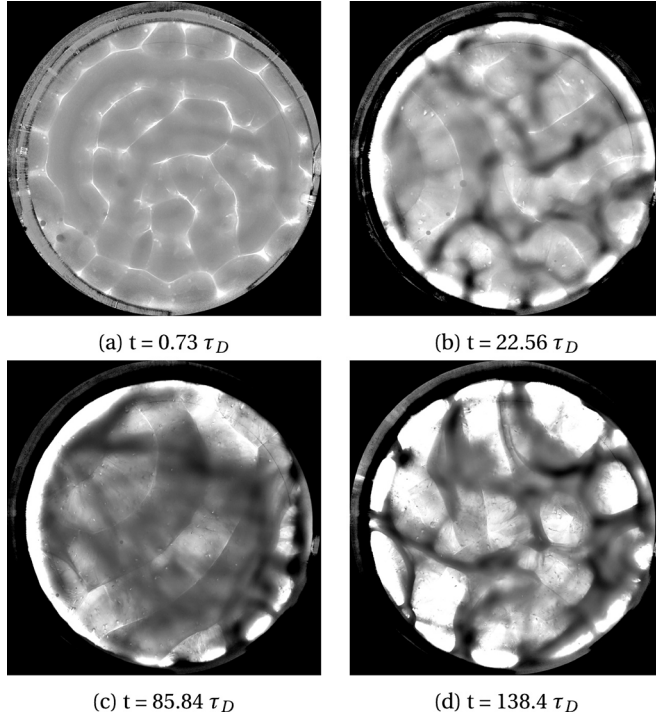


FIG. 8. Unsteady flow TiO_2 $\Gamma = 16$, $\text{Ra} = 4.55 \times 10^3$, $c = 0.02\%$ wt.

Fig. 8(d) shows the appearance of sediment in the form of alveoli. In contrast, the ring pattern presented in Fig. 6(d) completely disappears, giving way to these two unstable states. Over the course of the experiment, a change in the gray shade is noted in the four images, because some of the particles have sedimented. The areas of low concentration correspond to better light transmission and, therefore, to the white color of the photos; resulting in higher observed contrast. We also notice a permanent haze in the images due to the Rayleigh scattering of light caused by the higher concentration of suspended nanoparticles. Higher sedimentation intensifies the heat flux in the thermal boundary layer and contributes to a higher effective conductivity in this layer. This new heat flux breaks the symmetry of the temperature profile and renders the convective rolling even more unstable. This instability is visually reflected by a lower effective Prandtl number, which increases the nonlinear terms and hydrodynamic instability.

Figure 9 shows the same experiment as previously shown; however, this experiment starts from an initial state in which the particles have settled. This new initial condition changes the transient regime, as shown in the video in the Supplemental Material [37]. Figure 9(a) shows the unstable coexistence of the hexagonal cells and convective rolls. This coexistence eventually disappears for the hexagonal cells with a downward flow towards the center [Fig. 9(b)]. A magnified view of Fig. 9(b) shows the hexagonal cells with yellow corners and the circular deposition of the particles. The appearance of this coexistence and the hexagonal cells is only possible when the temperature of the lower plate varies sinusoidally over time [38]. Furthermore, Krishnamurti [34] showed that when the temperature difference increases over time, hexagonal cells with a downward flow at their center appear. This experiment confirms that the sedimentation of particles increases the heat flux of the lower thermal boundary layer and, therefore, the average temperature of the fluid. This nonuniform increase in heat flux makes the rolls unstable, as shown in Figs. 8 and 7.

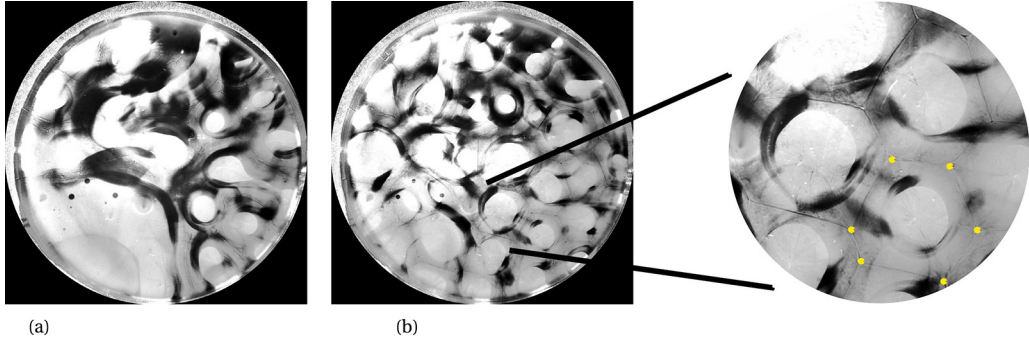


FIG. 9. Unsteady competition in convective patterns $\Gamma = 16$, $Ra = 4.55 \times 10^3$, $c = 0.02\%$ wt. (a) Hexagonal and roll patterns and (b) hexagonal g -cells.

IV. CONCLUSION

This study investigates the Rayleigh-Bénard convection in a cylindrical cavity with a low concentration ($<0.02\%$ wt) TiO_2 nanofluid for a Rayleigh range $<10^4$. To achieve this, an experimental setup was developed along with an optical bench that allowed the patterns to be viewed using a shadowgraph. The aim was to observe the influence of nanoparticles on the convection patterns and heat transfer. Based on the experimental results, we can conclude that the distribution of nanoparticles is unstable, because some of them agglomerate after a few thermal diffusion times τ_D . This agglomeration increased the sedimentation rate of the particles. Owing to the low concentration and size of the particles, a thin layer of heat-conducting sediment formed in the thermal boundary layer. The conductive flux in the lower thermal boundary layer increased locally, resulting in an asymmetry in the temperature profile between the top and bottom of the cavity. This asymmetry made convective rolls unstable and allowed hexagonal cells to coexist. This increase in the conductive flow increased the mean temperature of the fluid, which resulted in a lower effective Prandtl number than that of pure water, and therefore a higher effective diffusivity. A lower Prandtl number increased the contribution of nonlinear terms and secondary hydrodynamic instabilities. This is why the mean wavelength decreased and the propagation velocity grew with increasing concentration. We have shown that the colloidal stability and sedimentation of particles in a nanofluid play a major role in flow dynamics and increase the efficiency of heat transfer.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [39].

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