

Near-wall velocity field in turbulent Rayleigh-Bénard convection with rough surface

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We present measurements of the near-wall velocity field in turbulent Rayleigh-Bénard convection with a partially rough horizontal surface. These measurements cover Rayleigh numbers ranging from $Ra = 5.8 \times 10^{10}$ to $Ra = 8.0 \times 10^{11}$, while the Prandtl number was fixed at $Pr = 0.7$. The measurements have been undertaken in the large-scale convection experiment “Barrel of Ilmenau,” which provides a very high resolution in space and time. The measurements confirm the prominent role of the ratio between the thickness of the boundary layer δ_{th} and the height of the roughness elements h , although transition effects only appear below $\delta_{th}/h \approx 0.6$ in our experiments. In addition, we calculated the ratio between the turbulent kinetic energy and the average kinetic energy in the boundary layer. This ratio remains virtually constant up to $Ra = 4.2 \times 10^{11}$ and increases beyond this value. This is another indication of a qualitative transition of the boundary layer flow field. We observed this transition above both the TOP and above the VALLEY regions of the rough surface, concluding that both regions may contribute similarly to an increase in heat flux. The transition in the flow field is purely induced by viscous effects. The Richardson number, based on the thickness of the boundary layer and the velocity of the mean wind, is much smaller than one for all Rayleigh numbers investigated. This indicates that viscous effects dominate the near-wall flow field, and buoyancy does not play any role in the variation of the flow field here. We have also analysed time series of the wall-normal velocity component w in the plane where the temperature fluctuates at its maximum. The distribution of the fluctuations of w deviates from a normal distribution for all investigated Rayleigh numbers. In particular, the distributions exhibit broader tails on both sides. However, the distributions show just a little asymmetry, which we would expect as a signature of thermal plumes.

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I. INTRODUCTION

Thermal convection in nature or in engineering applications quite often occurs on nonsmooth surfaces. Despite significant progress in computational fluid dynamics over the last decade, simulating such processes remains challenging. In particular, the spatial and temporal resolution required to simulate convection combining both a rough surface and a high Rayleigh number exceeds the capabilities of even the most powerful computers. Well-controlled laboratory experiments, ideally

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on a large scale, can help to overcome these limitations and provide velocity, temperature, or heat flux data that go beyond the Rayleigh number range accessible by computation. In this paper, we present velocity data, measured in a large-scale Rayleigh-Bénard experiment with a partially rough heating plate.

Recently, we have studied the near-wall temperature field in turbulent Rayleigh-Bénard convection (RBC) with a rough horizontal surface [1]. In this paper, we focus on the near-wall velocity field using the same experimental setup. We start with a brief reminder of the basic facts of this widely used model flow. RBC occurs in a fluid layer that is heated from below and cooled from above. The temperature and density gradients between the warm and light fluid at the bottom of the fluid layer and the cold and heavy fluid on top of it trigger recirculation, transporting heat much more effectively than pure Brownian motion. The RB system with smooth walls is determined by four dimensionless parameters: the Rayleigh number Ra and the Prandtl number Pr as inputs, and the Nusselt number Nu and the Reynolds number Re as the system's responses. These parameters are defined as follows:

$$Ra = \frac{\beta g \Delta T H^3}{\nu \kappa}, \quad Pr = \frac{\nu}{\kappa}, \quad (1)$$

$$Nu = \frac{\dot{q}_c}{\dot{q}_d}, \quad Re = \frac{UH}{\nu}. \quad (2)$$

The variables in this definition are β (thermal expansion coefficient), g (gravitational acceleration), ΔT (temperature difference across the fluid layer), H (thickness/height of the fluid layer), ν (kinematic viscosity), and κ (thermal diffusivity), $\dot{q}_c$ (convective heat flux), $\dot{q}_d$ (conductive heat flux), U (typical velocity). An important concept when studying turbulent RBC is that of the boundary layer, which divides the entire fluid layer into two distinct regions. Region I is the so-called bulk. Here, the fluid is well mixed due to the turbulent motion, and the temperature is almost uniform. Region II is the boundary layer. It develops close to the walls and is characterized by strong velocity and/or temperature gradients. Here, we consider the boundary layers on the horizontal walls, one on the heated side and one on the cooled side of the fluid layer. The thickness of these layers, δ_{th} , is usually defined as $\delta_{th} = H/2Nu$. In highly turbulent RBC ($10^9 < Ra < 10^{12}$), δ_{th} is very small, lying between 1% and 0.1% of the height of the fluid layer. Furthermore, it is also well known that they determine the total heat flux across the fluid layer, which is true for RBC with both smooth and rough plates. For more details, please refer to one of these reviews [2–4].

Until now, very little has been known about the characteristics of the velocity field in the vicinity of a non-smooth surface, since most previous studies have focused on the global/local heat transfer coefficient [5–12]. Only a few authors have reported direct measurements of the velocity field in turbulent RBC with rough surfaces or analyzed velocity data obtained from direct numerical simulations (DNS). One of the first reports of such measurements dates back to 2005. Qiu *et al.* report measurements of the viscous boundary layer over a pyramid-shaped rough conducting surface [13]. They used dual-beam intensity cross-correlation spectroscopy to measure local profiles of the velocity components parallel to the wall. Their working medium was water with a Prandtl number $Pr \approx 7$. Compared to a smooth surface, the authors found an increase in heat flux, which they attributed mainly to the formation of small vortices inside the roughening grooves. In 2016, Liot *et al.* conducted Particle Image Velocimetry (PIV) measurements in a cubic Rayleigh-Bénard cell with a base area of 2.50 m by 0.625 m and a height of 2.50 m [14]. The working fluid was air with a Prandtl number $Pr = 0.7$, and the measurements covered Rayleigh numbers $Ra = 4.7 \times 10^9$, $Ra = 2.8 \times 10^{10}$, and $Ra = 4.0 \times 10^{10}$. The main conclusion of Liot *et al.*'s work is that a transition of the velocity field in the vicinity of the roughness elements, as well as a transition of the wall heat flux occurs when the Rayleigh number exceeds a critical value Ra_c . More precisely, they found that the fluid in the roughening grooves remains at rest as long as $Ra < Ra_c$. In this regime, the flow structure above the obstacles is very similar to that above a smooth surface. However, when Ra becomes larger than Ra_c , the fluid in the grooves begins to move and interact with the fluid flow

above the obstacles. This leads to a modification of the velocity boundary layer and eventually to an increase in local wall heat flux. However, the same authors in collaboration with another group, reported similar measurements in a Rayleigh-Bénard cell of cylindrical shape with water ($Pr = 4.4$) as working fluid [15]. These measurements confirmed the observations made in their 2016 work. Furthermore, they demonstrated that the velocity fluctuations increase in the vicinity of the rough surface and the center of the RB cell (when compared to a RB cell with smooth plates). The authors also observed a variation in the longitudinal velocity structure function for the rough cell, inferring a potential transition of the boundary layer to turbulence. Other PIV measurements of the local velocity field in close proximity to pyramidal rough surface have been reported by Xie and Xia [16]. They used RB cells of cylindrical shape but various sizes to cover a Rayleigh number domain as wide as possible ($7.5 \times 10^7 \leq Ra \leq 1.3 \times 10^{11}$). They also varied the Prandtl number between $Pr = 3.6$ and $Pr = 23.3$ by changing the working fluid. Furthermore, they varied the ratio of the height to the base width of the pyramids in their experiments. The main conclusion of this work is the classification of the RB flow with rough horizontal surfaces into three regimes: (i) Regime I: the system is in a dynamically smooth state, and the heat flux is the same as in RBC with smooth plates. (ii) two Regimes II and III in which the heat flux is larger than in RBC with smooth plates. Unlike previous studies by other researchers, which linked the enhancement of the heat flux to the ratio of the thermal boundary layer thickness δ_{th} to the roughness height h , Xie and Xia associated this transition with the ratio of the viscous boundary layer thickness δ_v to h . The authors also observed a variation of the plume dynamics originated in the boundary layer and being transported into the core region of the RB flow. This phenomenon also contributes to the enhancement of the heat transfer at the rough surface. A similar classification of the RB flow with rough surfaces has been done by Tummers and Steunebrink [17]. They conducted experiments in a cubic RB cell with water, methanol, ethanol, and acetone ($Pr = 4.2...17$) as working fluids. The heating and cooling plates were covered with cubic roughness elements with heights of $h = 1$ mm and $h = 3$ mm. They measured the global velocity field in a vertical plane using PIV with thermochromic liquid crystals. However, the spatial resolution of their measurements was inadequate to resolve the flow field in the vicinity of the roughness with sufficient detail.

In the last few years, DNS of turbulent RBC with rough surfaces has become a viable option for realistic 3D geometries and high Rayleigh numbers up to $Ra \approx 10^{10}$. For instance, Belkadi *et al.* performed DNS of an asymmetric RB rectangular cavity with a rough bottom plate [18]. The DNS covered a domain in Rayleigh number from $Ra = 10^5$ to $Ra = 10^{10}$, while the Prandtl number was kept constant at $Pr = 4.4$, corresponding to water as the working fluid. The roughness pattern was modeled using a set of square-based blocks. The distance between neighboring blocks was equivalent to the length and width of their base. The simulations essentially confirm the existence of three distinct regimes in global heat transport, as outlined in the research conducted by Xie and Xia [16]. Belkadi *et al.* proposed the concept of dividing the horizontal plane at the roughness height into two distinct regions: the area above the solid top surface of the blocks and the area above the valleys between the blocks. The researchers found that a unique scaling law for the (dimensionless) heat flux, $Nu \propto Ra^\gamma$ with $\gamma \approx 1/3$, holds, regardless of the specific regime, if only the area above the solid top surface is considered. In contrast, when considering only the heat flux above the valleys, the exponent γ changes from $\gamma \approx 1/3$ in Regime I to $\gamma \approx 0.5$ in Regime II and then back to $\gamma \approx 1/3$, albeit with a larger prefactor, in Regime III. Belkadi *et al.* attempted to explain this behavior by considering the varying ratio between the conductive and convective fractions of the heat transfer above the valleys. While in Regime I, the conductive fraction is the dominant one, in Regime III, the convective part is much larger. Another study dealing with 3D numerical modeling of RBC with irregular conical roughness has been published by Sharma *et al.* [19] in 2024. The authors of this paper investigated RBC in a cubic box at a fixed $Ra = 10^8$. They were particularly interested in how variations in the Prandtl number influence the large-scale circulation (LSC) and the plume emission from the boundary layer close to rough surfaces, as well as the effect of these on global heat transport. They compared their new data from the 3D DNS with older data from a 2D DNS. The most significant finding of their work is the discovery that the presence of a third direction

significantly alters the emission and evolution of plumes. In the 3D configuration, they appear in a less coherent and organized way than in the 2D one. The authors demonstrated that this has a strong effect on both the structure of the LSC and the $Nu-Ra$ relation. Currently, 2D DNS is suitable for modeling RBC, albeit with some reservations. Fully 3D simulations or experiments (still) remain the preferred approach for studying turbulent RBC with non-smooth surfaces.

Finally, we will summarize the above discussion into a few key items:

(1) The ratio between the thickness of the boundary layer δ and the height of the roughness h serves as a critical indicator in determining whether convection at a rough surface differs from that at a smooth one. It is not yet clear whether the appropriate part of this criterion is the thickness of the thermal or velocity boundary layer.

(2) When the thickness of the boundary layer falls below the height of the roughness, an increase in heat flux compared to a smooth surface has been observed. This increase can be either in the prefactor C_1 or in the exponent γ in the relation $Nu = C_1 Ra^\gamma$.

(3) This increase could be caused by one or more of the following: (i) an onset of a fluid exchange between the fluid in the valley and in the bulk, (ii) a transition to turbulence in the boundary layer above the top of the roughness elements, (iii) an enhancement of the emission of plumes, and (iv) a variation of their dynamics and coherence.

In this paper, we present and discuss new measurements of the near-wall velocity field in highly turbulent RBC with a partially rough surface. These measurements were undertaken in the “Barrel of Ilmenau (BOI),” a RB experiment in which air was used as the working fluid ($Pr = 0.7$). The large size of the BOI, the maximum height of the fluid layer amounts to $H_{\max} = 6.30$ m, allows a very high Rayleigh number of $Ra_{\max} \approx 10^{12}$ to be set as well as enabling the velocity field in the vicinity of the rough surface to be resolved with an adequate spatial resolution. The velocity measurements presented and discussed here complement our recent work on the temperature field cited in [1]. The paper is structured as follows. First, we present the experimental setup and the measurement technology used. We will then describe the procedure for measuring the near-wall velocity field and the various parameters. The main part of the paper presents the measurement results and their analysis, as well as a discussion of their implications for local heat transport. The final section of the report summarizes the key findings of the work.

II. EXPERIMENTAL SET-UP AND MEASUREMENT TECHNIQUE

We used the same experimental apparatus as described in references [1,20]. For the reader’s convenience, we will give a brief summary below. For more detailed information on the apparatus itself, please refer to [20]. Details of the particular setup used for the measurements on the rough surface can be found in [1].

The experimental apparatus is designed as a classical RB experiment of cylindrical shape, in which air is heated from below and cooled from above (cf. Fig. 1). It is equipped with a heating plate at the base and a free-hanging cooling plate above. The temperature of the heating plate can be set to values between $T_h = 20^\circ\text{C}$ and $T_h = 80^\circ\text{C}$ (heating plate) and that of the cooling plate between $T_c = 10^\circ\text{C}$ and $T_c = 30^\circ\text{C}$. These temperatures are maintained with a maximum fluctuation of ± 0.02 K over time. The maximum deviation of any local temperature at the surface of the heating plate from its global mean is typically less than ± 1 % of the total temperature drop between both plates (± 1.5 % at the cooling plate). The distance H between both plates can be adjusted within the range of $0.2 \text{ m} < H < 6.3 \text{ m}$ by lifting the cooling plate up/down. The inner diameter of the cylinder is fixed at $D = 7.1$ m. The sidewall of the test section is thermally well insulated by two layers of polyurethane, each 16 cm thick. An active compensation heating system complements the passive insulation. This consists of heating elements arranged between the two polyurethane layers. These heating elements are kept at the same temperature as the inner surface of the sidewall. This system effectively minimizes heat loss to the environment, reducing it to less than 0.5 % of the convective heat flux inside the test cell.

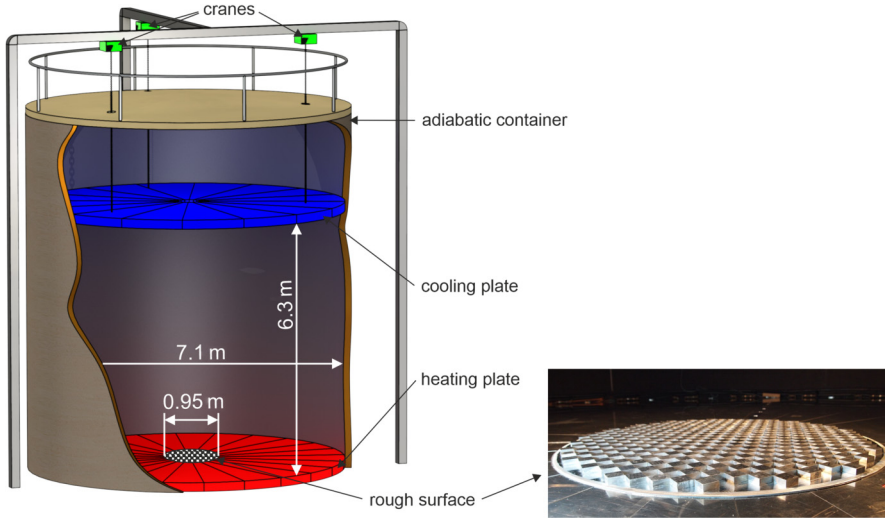


FIG. 1. Sketch of the large-scale RB experiment “Barrel of Ilmenau” (left) and photo of the rough surface with the chess-board-like pattern of cuboids (right).

In order to study the effects of roughness on the convective heat transfer, we covered a circular area with 0.95 m diameter with cuboids having a base area of 30 mm by 30 mm and a height of $h = 12$ mm. This height is of the order of the thickness of the thermal boundary layer δ_{th} . It is slightly larger at the higher Ra numbers but smaller at lower ones. The cuboids are made of aluminum and fixed to the surface of the heating plate using double-sided adhesive pads that facilitate high thermal conductivity. The cuboids are arranged in a checkerboard pattern (cf. Fig. 1). This pattern precludes the formation of long grooves in the surface structure and makes it invariant to the orientation of the flow sweeping across the surface.

We measured the velocity field in the vicinity of the rough surface using stereoscopic Particle Image Velocimetry (sPIV). SPIV is a technology that provides all three velocity components u , v , and w in an x, y plane. This plane is illuminated by laser light. Appropriate particles added to the fluid follow the fluid flow as closely as possible. The motion of these particles in the illuminated plane is captured by two cameras arranged in a stereoscopic configuration. A mathematical algorithm is then used to calculate the shift in the position of the particles between two subsequent images (with a known time interval between them). The algorithm recalculates the distance and the orientation of the particle path in the real world. It then provides all three velocity components over the time span during which the images were captured. A sketch of such a system and how we applied it at the “Barrel of Ilmenau” is shown in Fig. 2. We used a Minilite II laser with two laser tubes to illuminate the measurement plane. The tubes operated in pulsed mode and provide laser flashes lasting a few nanoseconds and delivering approximately 20 mJ of power. The laser was located outside the test section, and the light was guided into the test section using dichroic mirrors. A combination of two spherical lenses and one cylindrical lens widened the laser beam in the direction parallel to the rough surface, but focused it in the direction perpendicular to the wall. At the measurement position, the width of the light sheet was approximately 50 mm. A slit aperture limited its thickness to 1 mm.

We added droplets of Di-Ethyl-Hexyl-Sebacat (DEHS), measuring approximately $5 \mu\text{m}$ to the flow. These, almost monodisperse-sized droplets were generated in a condensation aerosol generator manufactured by TOPAS GmbH. The droplets were injected through a ring of nozzles that were placed around the rough disk. We computed their Stokes number St to validate how well they follow the flow. This is defined as the ratio of the viscous relaxation time of the particle τ_v to

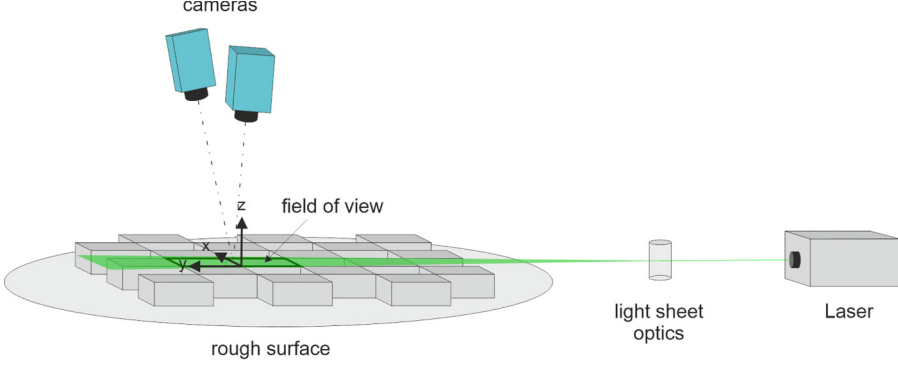


FIG. 2. Simplified sketch of the setup to measure the 3D velocity field in horizontal planes parallel to the surface of the heating plate. The position z of the plane with respect to the top surface of the cuboids can be varied starting from $z = 1$ mm. The dimensions of the cuboids are $b = 30$ mm $\times$ $w = 30$ mm $\times$ $h = 12$ mm.

the Kolmogorov time scale τ_η :

$$St = \frac{\tau_v}{\tau_\eta} \quad \text{with} \quad \tau_v = \frac{1}{18} \frac{\rho_p d_p^2}{\rho_f \nu_f} \quad \tau_\eta = (\nu/\varepsilon)^{1/2}, \quad (3)$$

where ρ_p and ρ_f are the droplet and fluid densities, ν_f is the fluid kinematic viscosity, d_p is the droplet diameter, and ε is the rate of dissipation of turbulent kinetic energy. The viscous relaxation time of our droplets amounts to $\tau_v = 0.07$ ms, while the Kolmogorov time scale ranges from $\tau_\eta = 563$ ms at $Ra = 5.8 \times 10^{10}$ to $\tau_\eta = 82$ ms at $Ra = 8.0 \times 10^{11}$. This results in Stokes numbers ranging from $St = 1.2 \times 10^{-4}$ to $St = 8.3 \times 10^{-4}$. A Stokes number much smaller than unity indicates that the droplets can follow the flow almost perfectly.

The motion of the droplets in the light sheet was captured using two JAI GO-5000M-USB cameras. These cameras are compact in size (29 mm by 29 mm by 52 mm) and have a power consumption of 3.6 W. They are equipped with a 1" progressive scan sensor chip, offering a resolution of 2560 pixels by 2048 pixels. The maximum frame rate achievable at this resolution is 30.9 frames per second. We used the cameras in reduced-size mode, which offers a resolution of 2560 $\times$ 1024 pixels and a frame rate of 99.2 frames per second. The cameras were combined with Scheimpflug adapters and KOWA LM50XC lenses with a focal length of $f = 50$ mm. The cameras were mounted on a frame bridge approximately 0.4 m high, with the optical axes at an angle of 20 degrees to the wall-normal vector. The field of view was approximately 90 mm by 40 mm, encompassing slightly more than one cuboid and one valley (see Fig. 2).

III. MEASUREMENT PROCEDURE AND IMAGE PRE-PROCESSING

In this section, we will provide a detailed overview of the experimental settings. We have summarized all parameters in Table I. We will also provide a detailed explanation of the measurement procedure and describe the algorithms used to compute the vector fields. For the velocity measurements, we set the temperature of the heating and the cooling plates to the same values as we did for our earlier temperature measurements (see [1]). This results in a Ra domain ranging from $Ra = 5.8 \times 10^{10}$ to $Ra = 8.0 \times 10^{11}$. To keep the measurement effort and the amount of data within acceptable limits, we fixed the distance between the plates to a single value $H = 6.3$ m and refrained from measuring the velocity at the smooth surface. Such measurements have previously been taken and subsequently published, see [21,22].

As with our previous measurements, we allowed sufficient time for the experiment to reach a steady state. Typically, this took two days or more after setting the temperature of the heating and cooling plates. We started the calibration procedure early in the morning, since it required us

TABLE I. Set of parameters for the velocity measurements at the rough surface. The Nusselt number Nu results from earlier measurements of the local wall heat flux at the smooth plate (see [1]). We also give the thickness of the thermal boundary layer $\delta_{th} = H/(2Nu)$ as a reference with respect to the roughness height h . $z|_{T'_{\max}}$ indicates the distance from the top surface of the cuboids where the fluctuations of the temperature are largest (see [1]).

Γ	Ra	ΔT [K]	T_b [°C]	H [m]	Nu	δ_{th} [mm]	$z _{T'_{\max}}$ [mm]
1.1	5.8×10^{10}	2.7	30.2	6.3	164.2	19.18	15.7
1.1	8.6×10^{10}	4.0	30.3	6.3	256.8	12.26	12.9
1.1	1.5×10^{11}	7.0	30.4	6.3	313.9	10.04	11.5
1.1	2.2×10^{11}	10.0	30.6	6.3	361.6	8.71	9.5
1.1	4.2×10^{11}	20.0	31.0	6.3	429.2	7.34	8.5
1.1	6.4×10^{11}	30.0	31.4	6.3	471.5	6.68	7.5
1.1	8.0×10^{11}	38.0	32.3	6.3	542.8	5.80	7.5

to access the test section. We then closed the test section and waited approximately 6 h before commencing the velocity measurement. The cameras were calibrated using a plate bearing a printed grid of lines, spaced apart. The plate was 1 mm thick and defined the z -position with respect to the top of the cuboids. For measurements $z > 1$ mm, we used distance pieces. The $x = 0$ mm and $y = 0$ mm positions were set to the corner of one cuboid (see Fig. 2). After positioning the calibration plate correctly, we aligned the laser light sheet accordingly. Having completed these steps, we captured 10 images with each camera, which we used in the subsequent calibration process. We performed calibration and processing of the particle images using the commercial software package DaVIS 10 (LaVision GmbH). We used the pinhole model taking into account the radial distortion caused by the lenses. After successfully completing the calibration, we started recording the particle images. Each velocity measurement consists of a series of approximately 36 000 double images, taken at a rate of 10 frames per second. The resulting set of images covered a period of 1 h, corresponding approximately 1 200 free-fall time units $t_f = H/\sqrt{\beta g \Delta T H}$. These settings were a compromise between achieving the longest possible measurement time, ensuring an adequate resolution of the velocity data over time, and keeping the data volume manageable. Using these settings, one data set consists of 720 GB. After acquiring the particle images, we applied the planar self-calibration scheme to refine the calibration [23]. This scheme adjusts the $z = 0$ mm plane exactly to the center of the laser light sheet and corrects for possible camera misalignment. Before applying the PIV algorithm, the raw images had to be pre-processed. This procedure includes removing background reflections and spurious noise. This was achieved by subtracting a sliding average over 15 images. After completing this procedure, we ran a PIV algorithm with five iterations and a decreasing interrogation window size. The final resolution was $\Delta x, \Delta y = 0.8$ mm. The final step in this process was to obtain instantaneous vector plots of all three velocity components u , v , and w in the horizontal plane, which form the basis of the following discussion.

IV. RESULTS

A. The plane $z = 1$ mm

In this section, we will evaluate the various items addressed at the end of Sec. I. We start with the evaluation of item 3(a), the heat flux at a rough surface begins to exceed that at a smooth surface, when the thickness of the thermal boundary layer δ_{th} falls below the roughness height h . Liot *et al.* have identified a qualitative change in the near-wall flow field at this transition. When $\delta_{th} > h$, the flow sweeps over the top of the cuboids and the fluid in between them is at rest. As Ra increases and the δ_{th} falls below h , the bulk flow begins to penetrate the valleys and push the fluid out of

TABLE II. Selection of measurement results of the velocity measurements at the rough surface. The time and space averaged velocity in the two measurement planes are denoted as $\bar{U}_{\text{hor}}|_{z=1\text{mm}}$ and $\bar{U}_{\text{hor}}|_{z|_{T'_{\text{max}}}}$. TKE_{top} , AKE_{top} , TKE_{valley} , and AKE_{valley} are both the turbulent and the average kinetic energies, respectively, at $z = 1$ mm. The indices denote the position (TOP or VALLEY). Ri is the boundary layer Richardson number [for definition see Eq. (8)].

Γ	Ra	$\bar{U}_{\text{hor}} _{z=1\text{mm}}$ [mm/s]	$\bar{U}_{\text{hor}} _{z _{T'_{\text{max}}}}$ [mm/s]	$TKE_{\text{top}} \times 10^{-4}$ [mm ² /s ²]	$AKE_{\text{top}} \times 10^{-4}$ [mm ² /s ²]	$TKE_{\text{valley}} \times 10^{-4}$ [mm ² /s ²]	$AKE_{\text{valley}} \times 10^{-4}$ [mm ² /s ²]	Ri
1.1	5.8×10^{10}	21.48	123.27	1.0	1.6	2.1	3.7	0.039
1.1	8.6×10^{10}	22.08	139.52	0.9	1.5	2.5	4.6	0.036
1.1	1.5×10^{11}	42.54	170.84	5.0	7.0	8.5	13.2	0.039
1.1	2.2×10^{11}	60.90	205.79	10.9	15.5	16.2	24.5	0.032
1.1	4.2×10^{11}	95.11	246.53	28.9	39.6	40.0	55.9	0.042
1.1	6.4×10^{11}	109.17	273.20	47.7	52.1	65.2	72.8	0.046
1.1	8.0×10^{11}	106.53	318.34	48.5	47.5	74.6	74.1	0.040

them (see Figs. 4 and 5 in [14]). This increases the local heat flux. We will verify this observation by analyzing the 3D velocity field measured in a horizontal plane directly above the top of the cuboids at $z = 1$ mm. Our measurements cover Rayleigh numbers from $Ra = 5.8 \times 10^{10}$ to $Ra = 8.0 \times 10^{11}$. Unlike Liot's slender cubic cell, our cell is an upright cylinder. To give the reader an idea of the ratio between δ_{th} and h for the various Rayleigh numbers in our experiment, we have listed these values in Table I.

We start by examining the time-averaged velocity field. Its components $\bar{u}(x, y)$, $\bar{v}(x, y)$, and $\bar{w}(x, y)$ have been computed according to:

$$\begin{aligned}
 \bar{u}(x, y) &= \frac{1}{N} \sum_{i=1}^N u_i(x, y) \\
 \bar{v}(x, y) &= \frac{1}{N} \sum_{i=1}^N v_i(x, y) \\
 \bar{w}(x, y) &= \frac{1}{N} \sum_{i=1}^N w_i(x, y).
 \end{aligned} \tag{4}$$

We plot the components for three different Rayleigh numbers $Ra = 5.8 \times 10^{10}$, $Ra = 1.5 \times 10^{11}$, and $Ra = 8.0 \times 10^{11}$ in Fig. 3. To make the vector plots at the different Rayleigh numbers comparable, we have normalized the velocity field by the mean horizontal velocity $\bar{U}_{\text{hor}} = \sqrt{\bar{u}^2 + \bar{v}^2}$ with u, v being the two horizontal velocity components (see Table II). This type of normalization ensures comparability between different Rayleigh number cases and indicates how strong the wall normal velocity component is relative to the components parallel to the wall. The plots in the figure are ordered with the lowest Rayleigh number case at the top and the highest one at the bottom. According to these Rayleigh numbers, the thickness of the thermal boundary layer is $\delta_{th} = 19.2$ mm ($\delta_{th} > h$), $\delta_{th} = 8.7$ mm ($\delta_{th} < h$), and $\delta_{th} = 5.8$ mm ($\delta_{th} \ll h$). All three plots show a flow region slightly larger than that occupied by one cuboid (TOP) and one valley (VALLEY). The

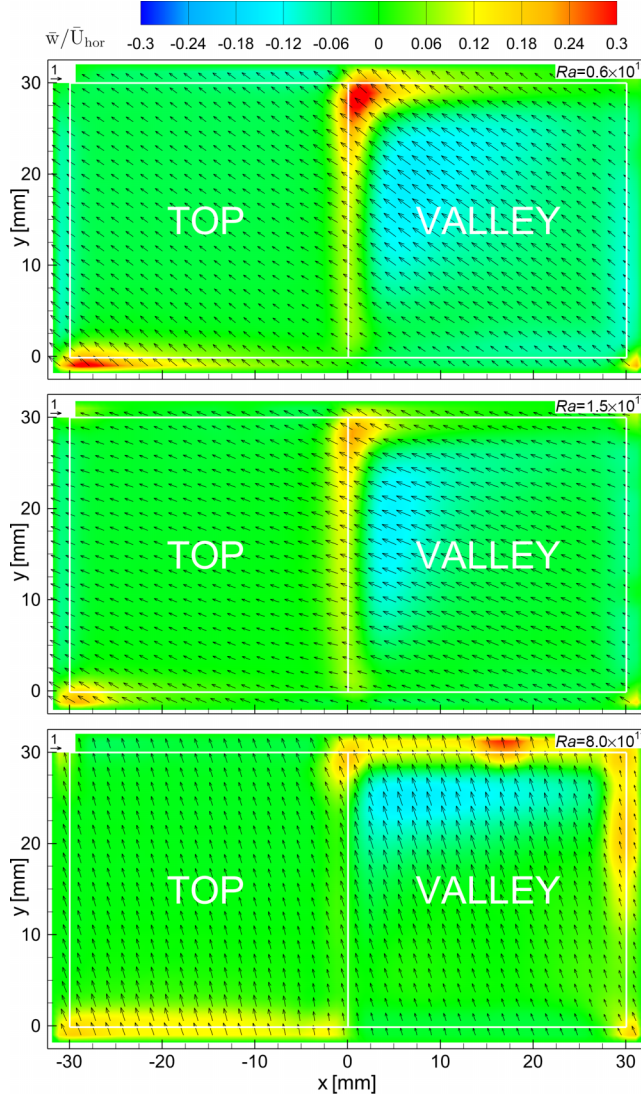


FIG. 3. Time-averaged velocity field at $z = 1$ mm directly above the top of the cuboids for three different Rayleigh numbers $Ra = 0.6 \times 10^{11}$ (top), $Ra = 1.5 \times 10^{11}$ (middle), and $Ra = 8.0 \times 10^{11}$ (bottom). The arrows represent the two horizontal components $\bar{u}/\bar{U}_{\text{hor}}$ and $\bar{v}/\bar{U}_{\text{hor}}$, while the wall-normal component $\bar{w}/\bar{U}_{\text{hor}}$ is encoded by color. All components are scaled by the mean horizontal velocity $\bar{U}_{\text{hor}}$ in the plane $z = 1$ mm.

arrows indicate the horizontal velocity components $\bar{u}/\bar{U}_{\text{hor}}$ and $\bar{v}/\bar{U}_{\text{hor}}$, while the color represents the wall-normal velocity component $\bar{w}/\bar{U}_{\text{hor}}$. To verify Liot's observation, we focus on $\bar{w}/\bar{U}_{\text{hor}}$. Above the cuboids (TOP), it is virtually zero for all the Rayleigh number cases we investigated (including those not shown in the figure). More interesting things happen above the VALLEY, especially at the intersection between the TOP and the VALLEY regions. For all Rayleigh numbers, the flow significantly penetrates the valley (blue areas), which clearly contradicts Liot's earlier observation that the fluid is at rest in the valleys as long as $\delta_{th} > h$. The area of the penetration decreases slightly with increasing Rayleigh number ($4.7 \times 10^9 < Ra < 4.1 \times 10^{10}$ in Liot's work), but the difference is marginal. At the windward edges/corners of neighboring cuboids, the fluid accelerates away from the surface (yellow and red areas).

While the time-averaged velocity field remains virtually unchanged over the range of Rayleigh numbers we investigated, the fluctuating field does change. We compute this as the standard deviation of its three components:

$$\begin{aligned} u'(x, y) &= \sqrt{\frac{1}{N} \sum_{i=1}^N (u_i(x, y) - \bar{u}(x, y))^2}, \\ v'(x, y) &= \sqrt{\frac{1}{N} \sum_{i=1}^N (v_i(x, y) - \bar{v}(x, y))^2}, \\ w'(x, y) &= \sqrt{\frac{1}{N} \sum_{i=1}^N (w_i(x, y) - \bar{w}(x, y))^2}. \end{aligned} \quad (5)$$

The most interesting component is the wall-normal one w' , since it is directly linked to the wall-normal heat flux $\dot{q}_z$:

$$\dot{q}_z = -\lambda \frac{\partial T(z)}{\partial z} + \rho c_p \langle w' T' \rangle. \quad (6)$$

In this equation, λ , ρ , and c_p denote the thermal conductivity, the density, and the isobaric specific heat capacity of the fluid, respectively. We plot w' at $z = 1$ mm in Fig. 4. Once again, we have scaled it with $\bar{U}_{\text{hor}}$ to emphasize the magnitude of w' with respect to the mean horizontal velocity. We have selected the same Rayleigh numbers as in the plots in Fig. 3. While the fluctuating field appears virtually unchanged for $Ra = 0.6 \times 10^{11}$ and $Ra = 1.5 \times 10^{11}$, it exhibits an increase in the fluctuations at higher Rayleigh numbers. To analyze this increase more quantitatively and for all Rayleigh numbers, we have calculated the average of $w'/\bar{U}_{\text{hor}}$ over 25 mm by 25 mm areas above the TOP and VALLEY regions. This data is plotted against the Rayleigh number in Fig. 5. Above the TOP and the VALLEY regions, $w'/\bar{U}_{\text{hor}}$ remains constant up to $Ra = 4.2 \times 10^{11}$. The thickness of the thermal boundary layer at this Rayleigh number is $\delta_{th} = 7.34$ mm. Even beyond this Rayleigh number, $w'/\bar{U}_{\text{hor}}$ increases above both the TOP and the VALLEY regions. This is remarkable in two respects. Firstly, according to Liot's hypothesis, the transition should occur at $Ra \approx 8.6 \times 10^{10}$, where $\delta_{th} \approx h$ (see Table I). However, this is not the case. It is possible that the Nusselt number-based thermal boundary layer thickness is not the best indicator for this transition and, consequently, of the onset of a steeper increase in heat flux with respect to the Rayleigh number as observed in earlier experiments (see [8, 24]). Secondly, the increase in $w'/\bar{U}_{\text{hor}}$ occurs above both the TOP and the VALLEY regions. This also contradicts Belkadi's observation that the VALLEY region mainly contributes to the enhancement of the local heat flux in turbulent RBC with rough horizontal surfaces [18].

Another hypothesis states that the boundary layer above the TOP becomes turbulent if the Rayleigh number is sufficiently high [25]. However, temperature measurements such as those reported in [1, 26] are not meaningful enough to answer this question unambiguously. However, analysis of the time-resolved, 3D-velocity field can. To this end, we plot the ratio between the turbulent kinetic energy (TKE) and the average kinetic energy (AKE) against the Rayleigh number in Fig. 6. TKE is a measure of the kinetic energy per unit mass associated with eddies/fluctuations in turbulent flow, while AKE is a measure of the kinetic energy of the flow averaged over time. They

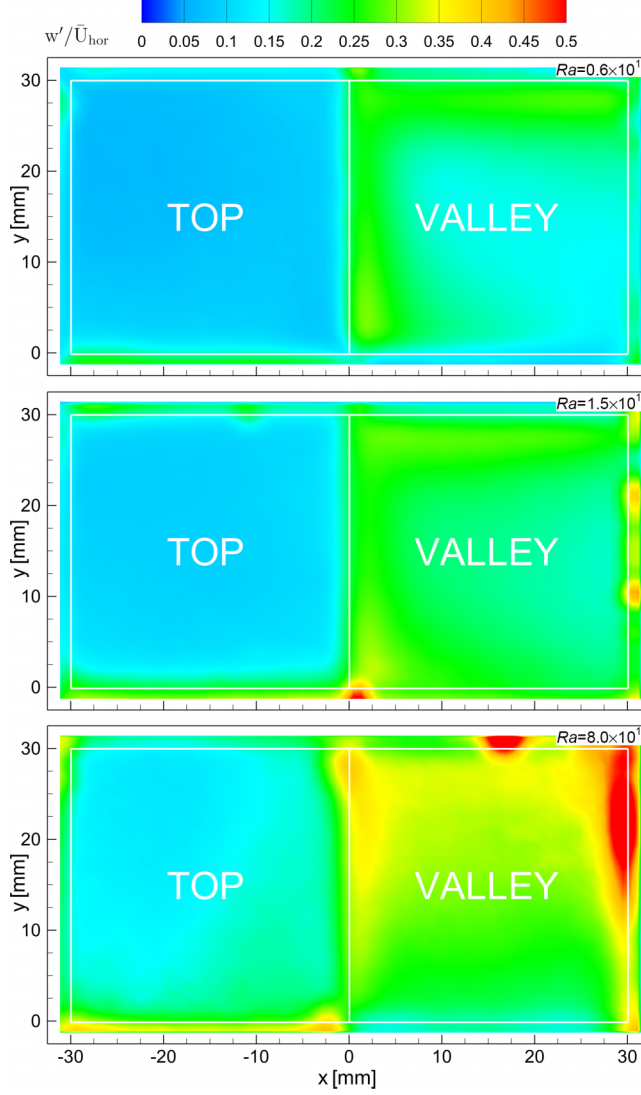


FIG. 4. Standard deviation of the wall-normal velocity component w' at $z = 1$ mm directly above the top of the cuboids for three different Rayleigh numbers $Ra = 0.6 \times 10^{11}$, $Ra = 1.5 \times 10^{11}$, and $Ra = 8.0 \times 10^{11}$. w' is scaled by the mean horizontal velocity $\bar{U}_{\text{hor}}$ in the plane $z = 1$ mm.

are defined as follows:

$$TKE = \frac{1}{2} (\overline{(u')^2} + \overline{(v')^2} + \overline{(w')^2}) \quad \text{with} \quad \overline{(x'_i)^2} = \frac{1}{N} \sum_{j=1}^N (x_j - \bar{x})^2$$

$$AKE = \frac{1}{2} (\overline{u^2} + \overline{v^2} + \overline{w^2}) \quad \text{with} \quad \bar{x}_i = \frac{1}{N} \sum_{j=1}^N (x_j). \quad (7)$$

Their ratio indicates the level of turbulence in the flow. The behavior of TKE/AKE with respect to the Rayleigh number is very similar to the fluctuations of the wall-normal velocity component. It remains almost constant up to a Rayleigh number of $Ra \leq 4.2 \times 10^{11}$ and then increases. For

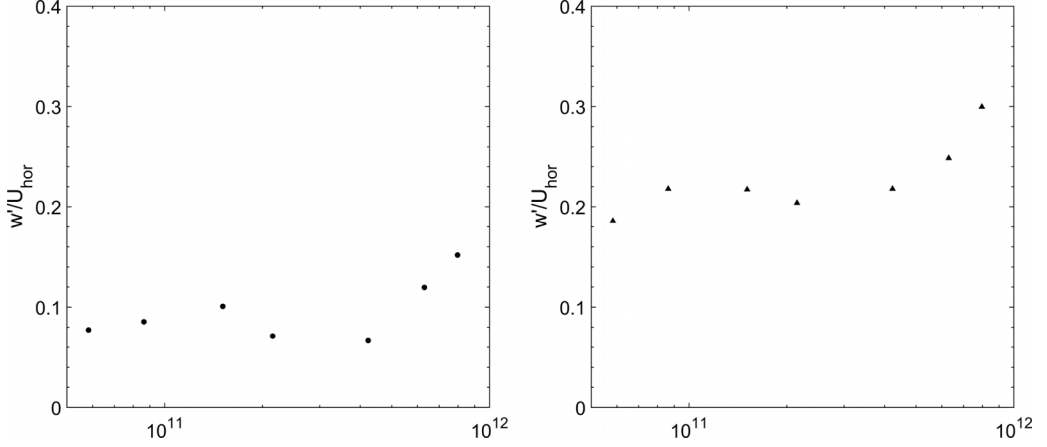


FIG. 5. Standard deviation of the wall-normal velocity component w' in the plane $z = 1$ mm above the top of a cuboid (left sub-figure) and above a valley in between the cuboids (right sub-figure) versus the Rayleigh number Ra . The fluctuations are averaged over areas of 25 mm by 25 mm above the TOP and the VALLEY regions. The presented quantity w' is scaled by the mean horizontal velocity $\bar{U}_{hor}$ in the plane $z = 1$ mm.

our highest Rayleigh number $Ra = 8.0 \times 10^{11}$, TKE becomes even larger than AKE . This is true for both the TOP and the VALLEY regions. In our view, this indicates that the boundary layer on the rough surface becomes turbulent when the Rayleigh number exceeds a certain value and/or the boundary layer thickness falls below the roughness height. In this sense, the TOP and VALLEY regions contribute equally to the increase in heat flux at the rough surface.

At the end of this section, we wish to discuss the question of whether the aluminum blocks generate a specific rough surface dynamics rather than they just disturb the flow of the mean wind over a smooth plate. To this end, we calculate the Richardson number of the boundary layer which

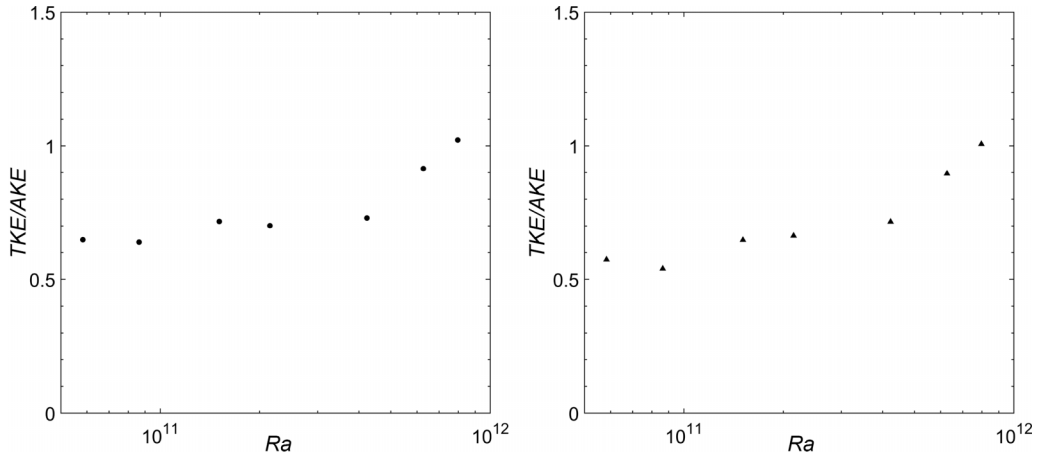


FIG. 6. Ratio of the turbulent kinetic energy (TKE) to the average kinetic energy (AKE) in the plane $z = 1$ mm above the top of a cuboid (left sub-figure) and above a valley in between the cuboids (right sub-figure) versus the Rayleigh number Ra .

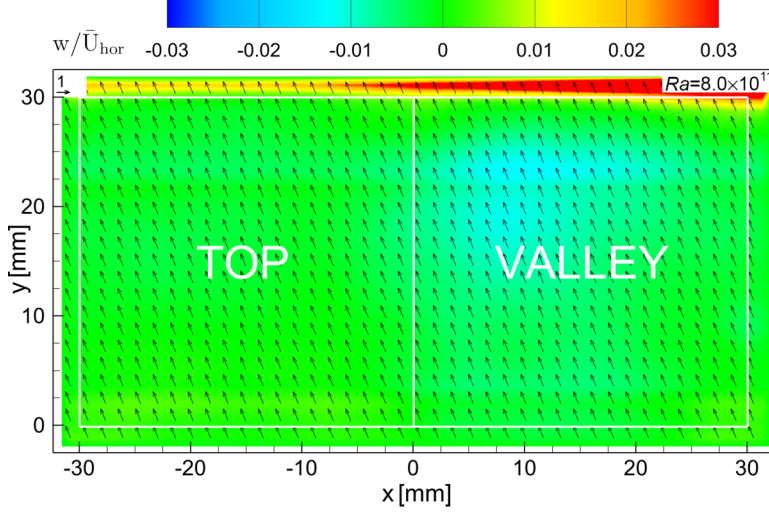


FIG. 7. Time-averaged velocity field at $z = 7.5$ mm above the top of the cuboids for $Ra = 8.0 \times 10^{11}$. The arrows represent the two horizontal components $\bar{u}/\bar{U}_{\text{hor}}$ and $\bar{v}/\bar{U}_{\text{hor}}$, while the wall-normal component $\bar{w}/\bar{U}_{\text{hor}}$ is encoded by the color. All components are scaled by the mean horizontal velocity $\bar{U}_{\text{hor}}$ in the plane $z = 7.5$ mm.

expresses the ratio of buoyancy to shear forces:

$$Ri = \frac{\beta g \Delta T \delta_{T'}}{U_{\text{hor}}^2}. \quad (8)$$

If the Richardson number is less than 0.1, shear forces dominate the boundary layer and the aluminum blocks merely disturb the flow of the mean wind. For Richardson numbers larger than 10, buoyancy is the dominating force. For its calculation, we use the mean horizontal velocity $\bar{U}_{\text{hor}}$ in the plane $z|_{T'_{\text{max}}}$, the temperature difference ΔT between the surface of the heating plate and the bulk (see Table I), and the thickness of the boundary layer $\delta_{T'} = z|_{T'_{\text{max}}}$ (see Table I) for this computation. The results are listed in Table II. For all Rayleigh numbers, the Richardson number is smaller than 0.1, indicating that local buoyancy effects above the rough surface can be neglected. Shear forces induced by the mean wind dominate the boundary layer flow, and insofar, the roughness elements just disturb the flow.

B. The plane $z|_{T'_{\text{max}}}$

Having analyzed and discussed the local velocity field directly above the top surface of the cuboids, we will now do the same in the plane where the temperature fluctuations are at their maximum. This region is often referred to as the mixing zone [27], where the boundary layer becomes unstable. Plumes develop, detach from the boundary layer, and move into the bulk. On their way, they transport a disproportionately large amount of heat relative to the turbulent background (see Grossmann and Lohse's unifying theory [28]), thus contributing significantly to the global heat flux. As thermal plumes are accompanied by large temperature fluctuations, we have selected this particular plane (obtained from the measurements in [1]) for a second set of velocity measurements. This set of measurements helps us to understand the role of plumes on a rough surface. The exact distances of this plane from the top surface of the cuboids, which vary according to the Rayleigh number, are listed in Table I.

Again, we start with a brief discussion of the mean velocity field. In Fig. 7, we plot the time-averaged velocity field at $z = 7.5$ mm for the maximum Rayleigh number $Ra = 8.0 \times 10^{11}$, which is representative of all Rayleigh numbers. As in Fig. 3, the arrows represent the two horizontal

components $\bar{u}/\bar{U}_{\text{hor}}$ and $\bar{v}/\bar{U}_{\text{hor}}$, while the wall-normal component $\bar{w}/\bar{U}_{\text{hor}}$ is encoded by the color. Readers may notice that the color scale differs by a factor of 0.1 from that in Fig. 3. Unlike in the plane directly above the top of the cuboids ($z = 1.0$ mm), the two horizontal velocity components $\bar{u}/\bar{U}_{\text{hor}}$ and $\bar{v}/\bar{U}_{\text{hor}}$ are very uniform over the TOP and VALLEY regions in the $z|_{T'_{\text{max}}}$ plane. The vertical velocity component $\bar{w}/\bar{U}_{\text{hor}}$ is less than 0.01, and thus, negligible. This typical behavior of the mean velocity field is true for all Rayleigh numbers investigated. Please also note that the small red region at the top right edge of the plot is an error resulting from an inadequacy in the measurement technique.

Next, we examine the fluctuations of the wall-normal velocity component w' in order to answer two questions: how large are they (with respect to the mean horizontal velocity $\bar{U}_{\text{hor}}$), and are there differences above the TOP and the VALLEY regions? To this end, we plot w' at $z|_{T'_{\text{max}}}$ for three different Rayleigh numbers $Ra = 0.6 \times 10^{11}$, $Ra = 2.2 \times 10^{11}$, and $Ra = 8.0 \times 10^{11}$ in Fig. 8. Since the amplitude of the fluctuations would be biased by the increasing Rayleigh number, we scale w' again by the mean of the horizontal velocity $\bar{U}_{\text{hor}}$, but now, in the plane $z = z|_{T'_{\text{max}}}$. For the lowest Rayleigh number $Ra = 0.6 \times 10^{11}$, the (scaled) fluctuations are $w'/\bar{U}_{\text{hor}} \approx 0.09$ and equal above the TOP and the VALLEY regions. As the Rayleigh number increases, the value of $w'/\bar{U}_{\text{hor}}$ increases to a value of $w'/\bar{U}_{\text{hor}} = 0.14$ above the VALLEY region. As in the $z = 1$ mm plane, the fluctuations above the TOP region are weaker than those above the VALLEY region.

Since thermal plumes are known to be short and very dynamic events with a main velocity component normal to the wall, they should be visible in the time series of the wall-normal velocity component. We extracted such a time series $w(t)$ at the centers above the TOP and VALLEY regions. We also tested other positions, but the results were qualitatively the same. To illustrate the typical amplitudes and timescales at which $w(t)$ fluctuates, and to facilitate a comparison between the TOP and VALLEY regions, we have plotted the time traces of w in Fig. 9. Again, $w(t)$ is scaled by the mean horizontal velocity $\bar{U}_{\text{hor}}$ in the plane. The figure contains time series for the lowest and highest Rayleigh numbers $Ra = 0.6 \times 10^{11}$ and $Ra = 8.0 \times 10^{11}$ respectively. Not much can be seen with the naked eye. The time series differ slightly in the width of the band of medium-scale fluctuations as well as in the amplitude of the stronger excursions. Both are smaller at the lower Rayleigh number. We will analyze this behavior in more detail below for the TOP and VALLEY regions and for all Rayleigh numbers.

We start with the standard deviation/fluctuations w' , skewness $\text{skew}(w)$, and kurtosis $\text{kurt}(w)$. These quantities are plotted in Fig. 10. Once again, the fluctuations w' are scaled by the mean horizontal velocity $\bar{U}_{\text{hor}}$. Other than in the $z = 1$ mm plane, the fluctuations of the wall-normal velocity component in the $z|_{T'_{\text{max}}}$ plane are almost equal above the TOP and the VALLEY regions. At both locations $w'/\bar{U}_{\text{hor}} \approx 0.1$ which is quite similar to the value above the TOP region in the $z = 1$ mm-plane. It is also worth noting that the fluctuations steadily increase with the Rayleigh number, unlike the trend observed in the $z = 1$ mm plane. The plot of the skewness of the wall-normal velocity fluctuations shows a weak tendency towards negative values, with $0 < \text{skew}(w) < -0.2$. This is surprising, since we had expected massive positive excursions in the wall-normal velocity component due to the formation of thermal plumes. However, this is not the case. Insofar, we can conclude that the flow region in which the temperature fluctuates to a maximum is not the one where the plumes originate. They must develop further away from the rough surface; therefore, it is doubtful whether their rate or their size is affected by the roughness of the surface. This applies to the investigated Rayleigh numbers and is independent of the ratio between δ_{th} and h . The kurtosis of w starts with $\text{kurt}(w) = 5.8$ at $Ra = 0.6 \times 10^{11}$ and runs in a plateau with $\text{kurt}(w) \approx 4.3$ for $Ra \geq 4.2 \times 10^{11}$.

The histograms shown in Fig. 11 provide a more detailed insight into the distribution of the fluctuations of the wall normal velocity component w . To keep the results clear, we selected data sets at three different Rayleigh numbers $Ra = 0.6 \times 10^{11}$, $Ra = 2.2 \times 10^{11}$, and $Ra = 8.0 \times 10^{11}$ and again, we have scaled w by $\bar{U}_{\text{hor}}$. The most peaked distribution was observed at the lowest Rayleigh number with maximum excursions up to $w/\bar{U}_{\text{hor}} \approx \pm 0.4$. As the Rayleigh number increases, the

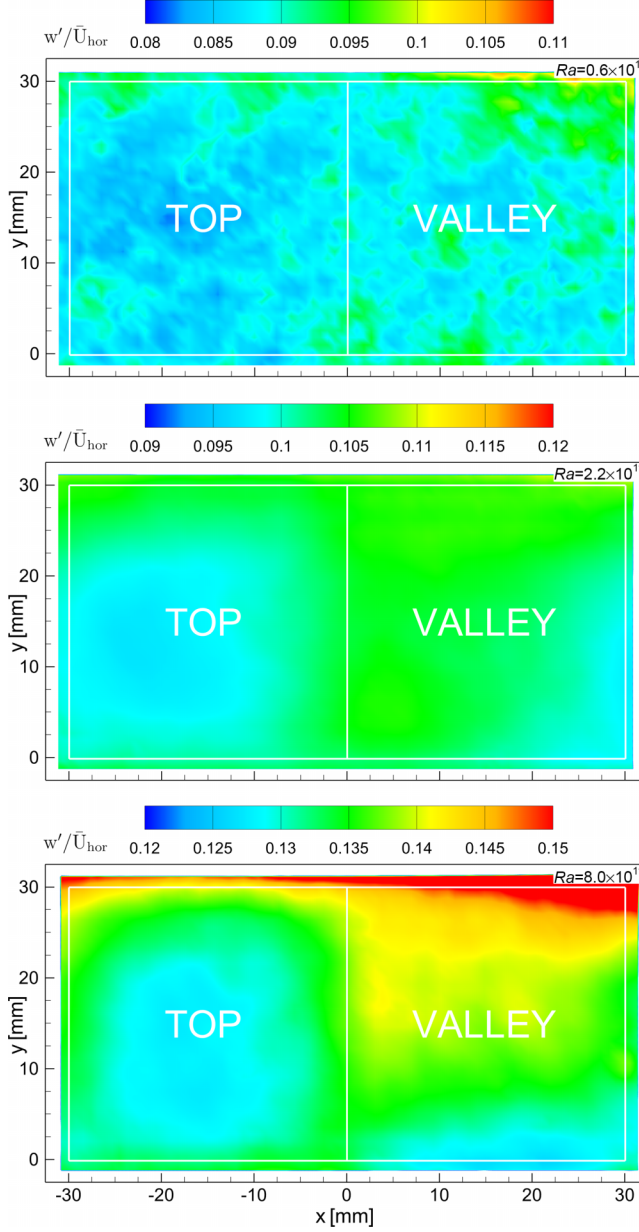


FIG. 8. Standard deviation of the wall-normal velocity component w' (for definition see Eq. (5)) in the plane of the maximum temperature fluctuations $z|_{T'_{\max}}$ for three different Rayleigh numbers $Ra = 0.6 \times 10^{11}$, $Ra = 2.2 \times 10^{11}$, and $Ra = 8.0 \times 10^{11}$. w' is scaled by the mean horizontal velocity $\bar{U}_{\text{hor}}$ in this plane.

distribution becomes flatter and the maximum excursions increase to $w/\bar{U}_{\text{hor}} \approx \pm 0.6$. This pattern is consistent in both TOP and VALLEY regions.

Finally, we want to check whether the distribution of the fluctuations in the wall-normal velocity component satisfies a normal (Gaussian) distribution or not. To do this, we plot the probability density functions (PDF) of the data from Fig. 11 in Fig. 12, this time in units of the standard deviation, $\sigma = w'$. For comparison, we have added the normal (Gaussian) distribution to each

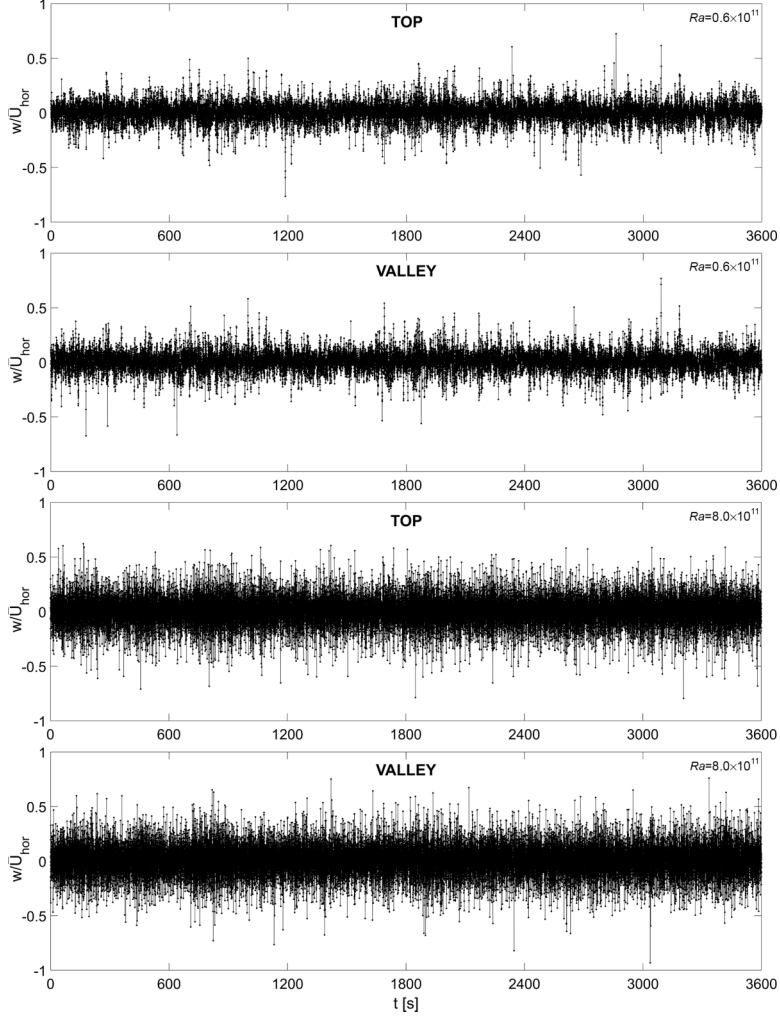


FIG. 9. Time series of the wall-normal velocity component $w/\bar{U}_{\text{hor}}$ at $z|_{T'_{\text{max}}}$ above the centers of the TOP and the VALLEY region. The upper two subplots show the data at $Ra = 0.6 \times 10^{11}$, the lower ones at $Ra = 8.0 \times 10^{11}$. $\bar{U}_{\text{hor}}$ is the mean horizontal velocity in the plane $z|_{T'_{\text{max}}}$.

sub-plot. All three PDFs virtually collapse into a single distribution. However, none of them is a normal distribution. Notably, the tails of the PDFs of the velocity fluctuations are broader than those of the normal distribution, a typical property of turbulent flows. This particular property applies to all PDFs above the TOP and the VALLEY regions, and to all Rayleigh numbers. There is no indication of any qualitative change in the flow field in the $z|_{T'_{\text{max}}}$ plane, when the Rayleigh number exceeds $Ra = 4.2 \times 10^{11}$. This applies to both a potential laminar-turbulent transition of the flow and a potential change in plume formation.

V. CONCLUSION

We have experimentally studied the near-wall velocity field in turbulent Rayleigh-Bénard convection with a partially rough surface of the bottom plate surface. Our study covers Rayleigh numbers $5.8 \times 10^{10} < Ra < 8.0 \times 10^{11}$, with a fixed Prandtl number of $Pr = 0.7$. A circular section with

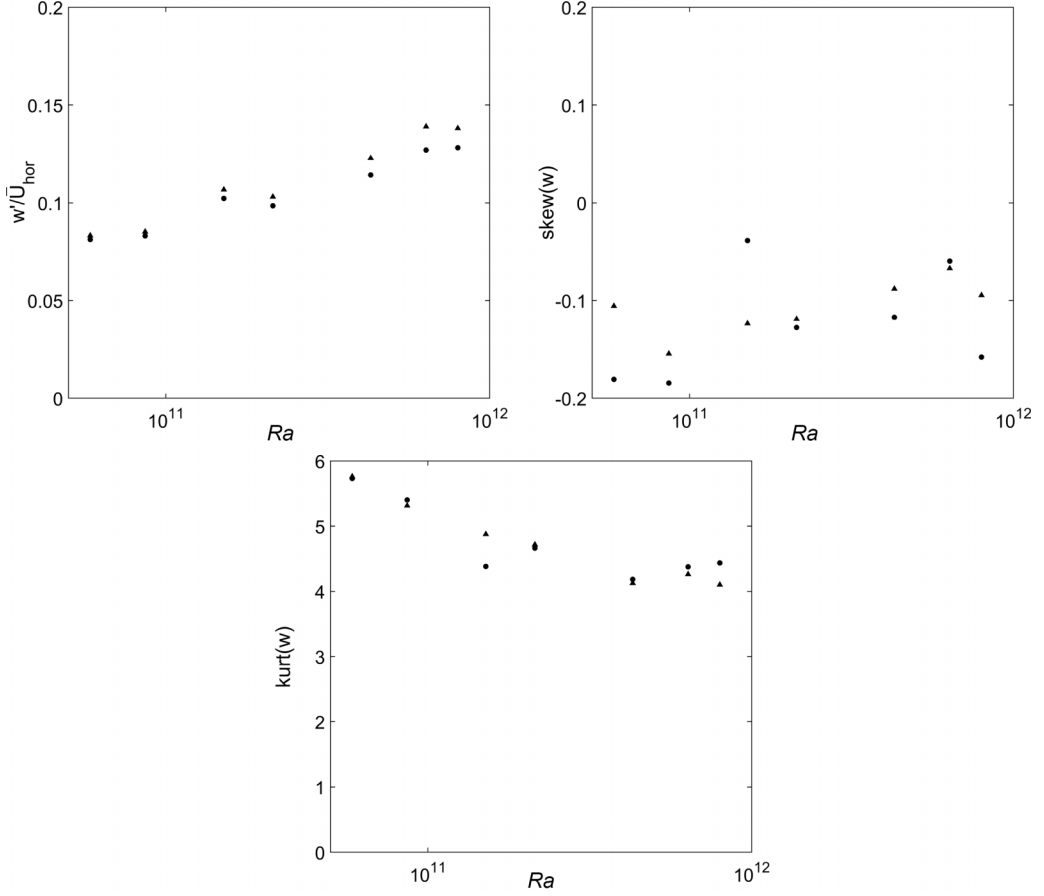


FIG. 10. Standard deviation $w'/\bar{U}_{\text{hor}}$, skewness $\text{skew}(w)$, and kurtosis $\text{kurt}(w)$ of the wall-normal velocity component at $z|_{T'_{\text{max}}}$ above the centers of the TOP ($\circ$) and the VALLEY ($\triangle$) region versus the Rayleigh number Ra .

a diameter of 0.95 m was covered with cuboids measuring 30 mm by 30 mm in base area and 12 mm in height. These are arranged in a checkerboard pattern. The height of the cuboids was chosen to be smaller than the thickness of the thermal boundary layer at the lowest Rayleigh number studied and larger at the highest one. We measured the two velocity components parallel to the rough surface and the component normal to it using stereoscopic Particle Image Velocimetry. Based on existing knowledge of convection at a rough surface, we selected two planes for our measurements, $z = 1$ mm the plane directly above the top of the cuboids, and $z|_{T'_{\text{max}}}$ the plane where the temperature fluctuates to a maximum. For each Rayleigh number and each plane, we measured a time series of 36,000 snapshots at a rate of 10 s^{-1} . This corresponds to a period of $1200t_f$, where $t_f = H/\sqrt{\beta g \Delta T H}$ is the free-fall time.

Our measurements confirm that the ratio of the boundary layer thickness to the height of the cuboids plays a prominent role in the structure of the near-wall velocity field and, consequently, in the heat transport from the solid surface to the surrounding fluid. Provided this ratio remains above one, the fluctuations in the wall-normal velocity component do not increase faster with the Rayleigh number than the mean horizontal velocity. However, when this ratio falls below one, the increase in wall-normal velocity fluctuations exceeds that of the mean horizontal velocity. However, this transition occurs in our experiment only at a ratio of the Nusselt-based thickness of the thermal

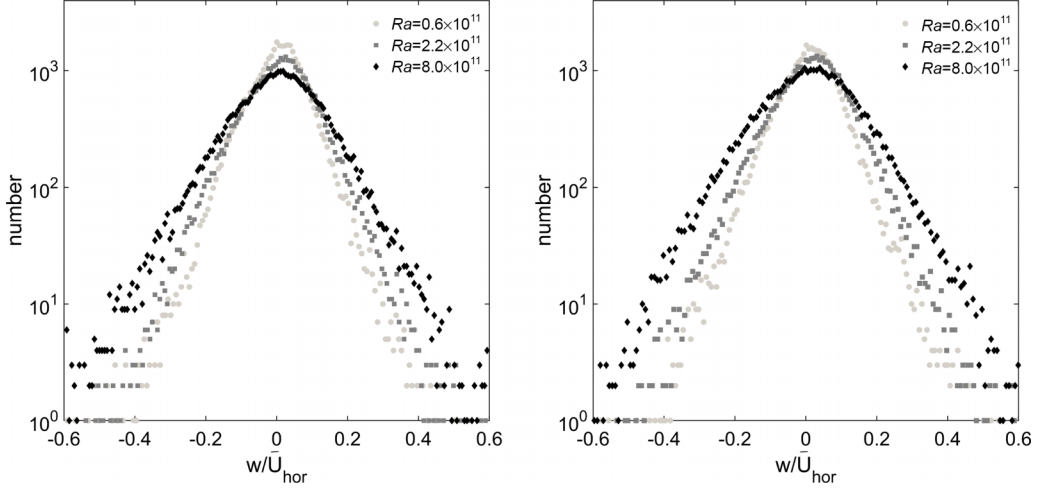


FIG. 11. Histograms of the wall-normal velocity component $w/\bar{U}_{\text{hor}}$ at $z|_{T'_{\text{max}}}$. The left sub-figure shows the data above the center of the TOP, the right sub-figure shows the data above the center of the VALLEY region. Each histogram comprises 36 000 data points.

boundary layer δ_{th} to the height of the cuboids h of 0.6. The corresponding Rayleigh number is $Ra = 4.2 \times 10^{11}$, which is five times higher than the Rayleigh number at which the thermal boundary layer thickness is approximately $\delta_{th} \approx 12$ mm. Alternatively, we calculated a boundary layer-based Richardson number. This is $Ri = 0.039$ for the lowest and $Ri = 0.040$ for the highest Rayleigh number. It indicates that shear dominates in the boundary layer, and that the roughness elements merely disturb the flow.

We could not verify Liot *et al.*'s observation that the flow sweeps over the obstacles, when $\delta_{th} > h$ and penetrates the valleys in between when $\delta_{th} < h$. In our experiment, the time-averaged

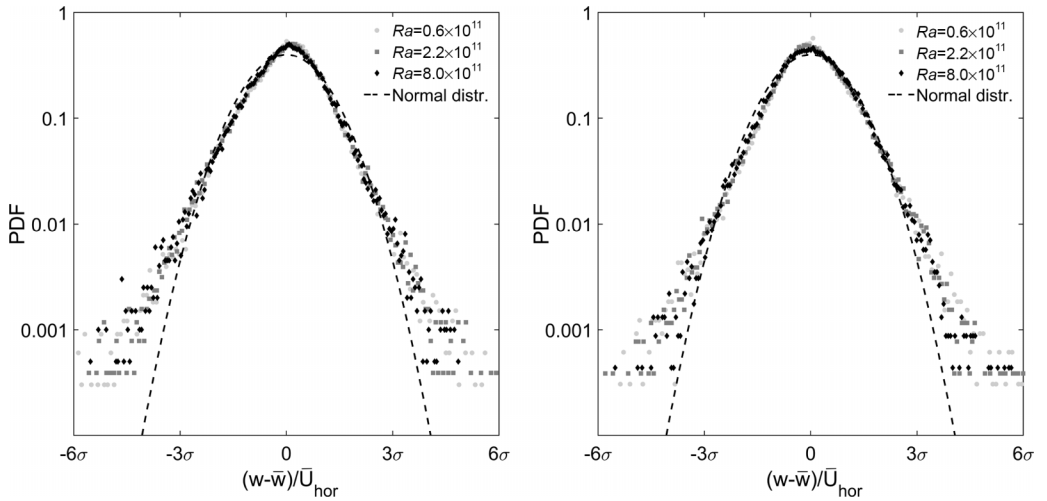


FIG. 12. Probability density function (PDF) of the wall-normal velocity component $(w - \bar{w})/\bar{U}_{\text{hor}}$ at $z|_{T'_{\text{max}}}$. The left sub-figure shows the data above the center of the TOP, the right sub-figure shows the data above the center of the VALLEY region. The data are plotted in units of the standard deviation σ . The dashed line represents a normal (Gaussian) probability density distribution with zero mean and a standard deviation of 1σ .

flow field always penetrated the valleys regardless of the ratio δ_{th}/h , and of the Rayleigh number. This discrepancy may be due to the shape of the RB cell, which was an upright cylinder in the experiments reported here and a slender cubic cell with a length-to-width ratio of 4 in Liot *et al.*'s experiment. This shape results in a different global flow pattern, a large single roll with multiple 3D modes (torsional [29], sloshing [30,31]) in the cylinder, but a fixed quasi-2D roll in the cubic cell. Additionally, the roughness pattern differed slightly: a checkerboard-like pattern without grooves in the present experiment and a pattern with continuous grooves in Liot *et al.*'s experiment.

We demonstrated that the ratio of turbulent kinetic energy to average kinetic energy in the plane directly above the cuboids ($z = 1$ mm) changes from a nearly constant value of $TKE/AKE \approx 0.7$ for Rayleigh numbers $Ra \leq 4.2 \times 10^{11}$ to a value of $TKE/AKE \approx 1.0$ for $Ra = 8.0 \times 10^{11}$ the highest Rayleigh number we investigated. This suggests that the near-wall flow field may transition to a higher turbulence intensity and, consequently, more efficient heat transfer at the rough surface. Once again, the critical Rayleigh number for this transition is higher than expected according to the ratio δ_{th}/h .

We have also studied the emission of plumes by analyzing time series of the velocity in the plane where the temperature fluctuates at a maximum $z|_{T'_{\max}}$. Our measurements show that the differences in the flow field between the TOP and VALLEY regions almost disappear for all investigated Rayleigh numbers. The same is true of the fluctuating field for all Rayleigh numbers up to $Ra = 2.2 \times 10^{11}$. Beyond this Rayleigh number; however, the fluctuations in the wall-normal velocity component increase more quickly above the VALLEY region (with respect to the mean horizontal velocity in this plane) than above the TOP region. We extracted time series of w at the centers of both the TOP and VALLEY regions and analyzed their distribution. This clearly deviates from a normal distribution with broader tails on both sides - another indication of turbulent flow. There is no specific signature of plumes in this layer, even though they originate here. So far, our work does not contribute significantly to a better understanding of the formation, specific dynamics, and coherence of thermal plumes at the rough surface. Such studies require the flow field to be measured even further from the rough surface than in our experiment.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [32].

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