Enhanced Heat Transport in Turbulent Convection over a Rough Surface

Y.-B. Du and P. Tong*
Department of Physics, Oklahoma State University, Stillwater, Oklahoma 74078

(Received 19 February 1998)

A novel convection experiment is conducted in a cell with rough upper and lower surfaces. The heat transport across the rough cell is found to be increased by more than 76%. Flow visualization and near-wall temperature measurements reveal new dynamics for the emission of thermal plumes. The discovery of the enhanced heat transport has important applications in engineering and atmospheric convection. [S0031-9007(98)06763-5]

PACS numbers: 47.27.Te, 05.60.+w, 44.25.+f, 47.27.Nz

Turbulent flows over a rough surface are ubiquitous in nature. An example is convection in the atmosphere and oceans, where the underlying surfaces are almost always rough. The study of turbulence over a rough surface is of fundamental interest for understanding the structure and dynamics of turbulent boundary layers and is also relevant to many practical applications, ranging from effective heat transfer for a reentry vehicle to turbulent drag reduction of a commercial aircraft. Our current knowledge about the roughness effect on turbulent flows comes largely from experiments in wind tunnels and other open systems [1], where the disturbance flow produced by a rough wall is confined in the near-wall region and is quickly discharged to the downstream. Because of these reasons the surface roughness usually does not perturb the turbulent bulk region very much, and its effect can often be described by rescaling the relevant parameters with the surface roughness height k [2]. This situation is changed completely for flows in a closed cell, in which the disturbances produced by the boundaries are inevitably mixed into the turbulent bulk region.

Turbulent Rayleigh-Bénard convection is an example of such a closed system, which has attracted much attention in recent years [3]. Intermittent bursts of thermal plumes from the thermal boundary layers and the coherent large-scale circulation, which modifies the boundary layer via its shear, are found to coexist in the convection cell. These salient features are directly related to the heat transport across the cell, and have been adopted in several theoretical models [3–5] to explain the observed scaling laws in the heat flux and temperature statistics [4,6]. In this Letter, we describe a novel convection experiment in a closed cell with rough upper and lower surfaces. It is found that when k becomes much larger than the thermal boundary layer thickness δ, the heat transport across the rough cell is increased by more than 76%. Flow visualization and near-wall temperature measurements reveal that the large-scale circulation interacts with the surface roughness and produces more thermal plumes from the tip of the rough elements. The striking effect of the surface roughness provides new insights into the nature of convective turbulence, and also has a myriad of applications in engineering, geography, and meteorology.

The experiment is conducted in a cylindrical cell filled with water. Details about the apparatus have been described elsewhere [7], and here we mention only some key points. The rough upper and lower surfaces are made from identical brass plates and have woven V-shaped grooves on them. The grooves have a vertex angle of 90° and their spacing is such that a square lattice of pyramids is formed on the surface. The height of the pyramids is $k = 9.0$ mm and their spacing is $2k$. The sidewall of the cell is a cylindrical ring made of transparent Plexiglas. Two cylindrical rings with the same inner diameter of 20 cm but having different heights of 20 and 40 cm, respectively, are used. The corresponding aspect ratios (A = diameter/height) are 1.0 and 0.5. The upper plate is cooled by passing cold water through a cooling chamber fitted on the top of the plate. The lower plate is heated uniformly with an electric heating film attached on the back side of the plate. The temperature difference ΔT between the two plates is measured by two thermistors imbedded in the two plates. A small movable temperature probe is installed inside the cell in order to measure the local temperature $T(z)$ of the convecting fluid near the central axis of the cell as a function of distance z from the upper (cold) plate. The control parameter in the experiment is the Rayleigh number $\mathrm{Ra} = \alpha g h^3 \Delta T/(\nu\kappa)$, where g is the gravitational acceleration, h is the height of the cell, α, ν, and κ are, respectively, the thermal expansion coefficient, the kinematic viscosity, and the thermal diffusivity of the fluid. In the rough cells, h is measured from the base of the grooves.

Figure 1 shows the measured Nusselt number Nu (the normalized heat flux) as a function of Ra in the rough (circles) and smooth (triangles) cells. The vertical heat flux across the cell is determined from the power required to keep the lower plate at a constant temperature. In these measurements, the cell was well insulated to prevent heat leakage. The measured Nu(Ra) in the smooth cells is well described by the power law $\mathrm{Nu} = 0.17\mathrm{Ra}^{\beta}$ (lower solid line). The exponent $\beta = 0.29$, which agrees well with previous measurements [4,8,9]. The measured heat flux

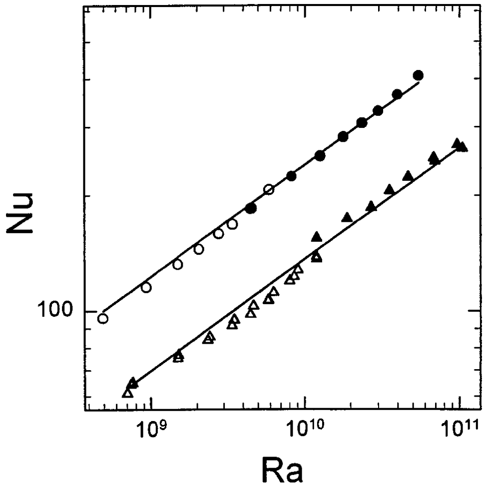

FIG. 1. Measured Nusselt number Nu as a function of Ra in the smooth (triangles) and rough (circles) cells. The solid symbols are obtained in the cells with $A = 0.5$, and the open symbols are obtained in the cells with $A = 1.0$. The solid lines are the power law fits.

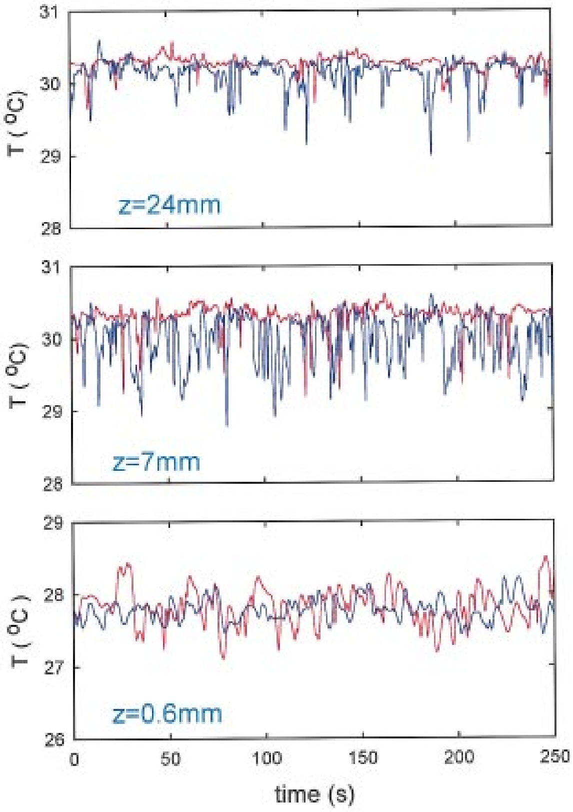

FIG. 2(color). Typical time series measurements of temperature fluctuations near the upper (cold) plate in the smooth (red curve) and rough (blue curve) cells. The distance z in the rough cell is measured from the bottom of the groove.

in the rough cells can also be described by a power law with the same exponent β, but the amplitude is changed from 0.17 to 0.30 (upper solid line) [10]. This amounts to a 76% increase in the heat transport. In a recent experiment, we have shown [7] that the effect of the surface roughness on the heat transport depends on the length ratio k/δ. When $k < \delta$ (in low Ra region), the rough elements on the surface are buried beneath the thermal boundary layer, and hence the effect of the roughness is small. In the opposite limit of large Ra, where $k > \delta$, the surface roughness can strongly affect temperature fluctuations near the surface and thereby alter the heat transport. In our working range of Ra, δ is of the order of 1 mm, which is much smaller than k. The enhanced heat transport shown in Fig. 1 cannot be explained simply by an increase in the contact area of the rough surface, because the contact area is increased only by a factor of $\sqrt{2}$.

To find out the real cause of the enhanced heat transport, we measure temperature fluctuations of the convecting fluid near the upper plate. Figure 2 shows typical time series measurements of the local temperature T in the smooth (red curve) and rough (blue curve) cells. The measurements were made at $\text{Ra} = 1.5 \times 10^9$, and the corresponding value of δ is 1.5 mm. The temperature probe was placed at a distance z away from the bottom of the groove. The values of z are $z = 24$ mm (outside the rough surface), $z = 7$ mm (inside the groove but outside the thermal boundary layer), and $z = 0.6$ mm (inside the thermal boundary layer). In Fig. 2 the cold fluctuations are seen superposed on an average base line. The downward going spikes are associated with cold thermal plumes detached from the upper boundary layer, and they are carried through the temperature probe by the large-scale circulation. Figure 2(b) clearly shows that the emission of the (cold) thermal plumes is greatly enhanced in the rough cell. From the flow visualization (see Fig. 3), we find that near the upper rough surface many thermal plumes are carried away horizontally by the large-scale circulation. Therefore, moving the temperature probe farther away from the boundary will reduce the probability of detecting the thermal plumes. Nevertheless, there are still some energetic thermal plumes, as shown in Fig. 2(a), which can penetrate vertically into the bulk region. In contrast to Figs. 2(a) and 2(b), Fig. 2(c) shows that temperature fluctuations inside the boundary layer are reduced in the rough cell.

An important question one might ask is where do the thermal plumes come from? Are they detached from the "valley" inside the grooves or from the tip of the pyramids? To answer this question, we use a photographic technique which allows simultaneous visualization of the temperature and velocity fields near the upper rough surface. Small thermochromic liquid crystal (TLC) spheres of diameter ~15 μm are suspended in the convecting fluid at a low concentration. These particles are purchased from Hallcrest (R29C4W) and have been used previously to visualize the temperature field in different flow systems [9,11]. A 3-mm-thick, vertical sheet of white light is shone through the central region of the convection cell. The orientation of the light sheet is adjusted such that it coincides with the rotation plane of the large-scale

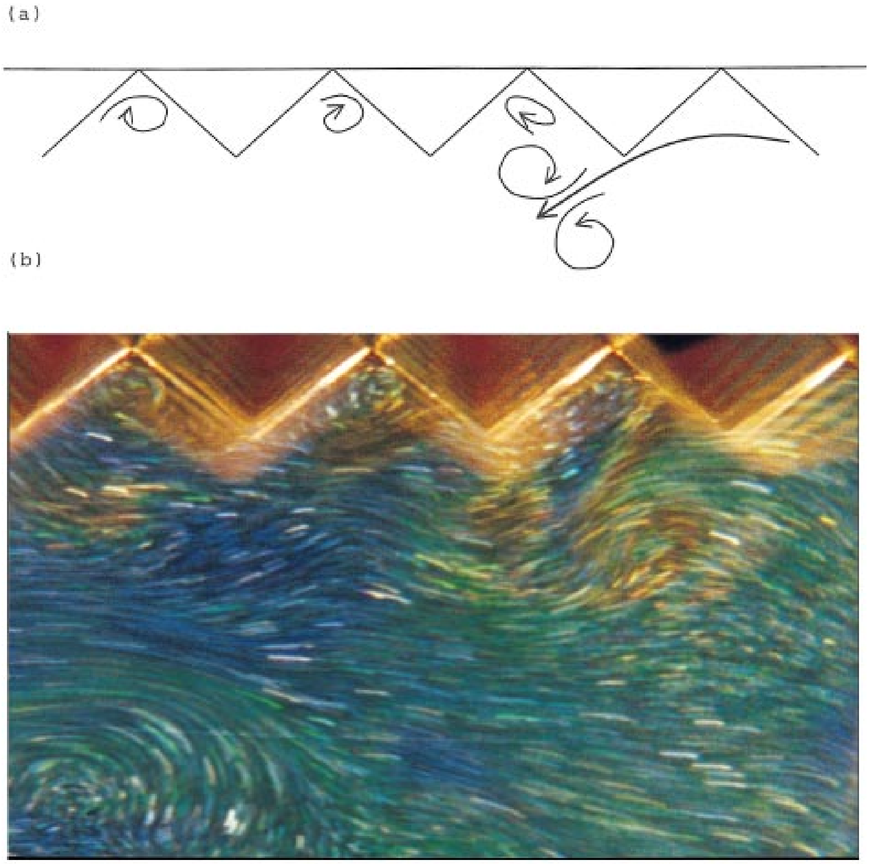

FIG. 3. (a) Sketch of the flow field near the rough surface. (b) (color) A typical streak image of the TLC spheres taken near the cold rough surface at $\mathrm{Ra} = 2.6 \times 10^9$. The cold eruptions are red-brown; green and blue regions are warmer. The displayed region is approximately 6.3 cm by 3.8 cm.

circulation and along a groove on the rough surface. The Bragg scattered light by the TLC spheres changes color from red to blue in a temperature range from 29 °C to 33 °C. The temperature of the bulk fluid is adjusted such that strong Bragg scattered light can be imaged from the side. A long exposure time of 0.5 s is used to obtain a streak image of the TLC spheres.

Figure 3(b) shows how a red-brown, mushroom shaped thermal plume is erupted from the (upper) cold rough surface. It is seen that the large-scale motion in the near-wall region is well characterized by a simple shear flow (from right to left). However, the mean flow is modulated by the rough surface, a situation very much like a steady flow passing over bluff obstacles on a wall [12]. The mean flow is forced to become divergent from the surface when it meets with the upstream side of a pyramid. On the downstream side of the pyramid, an adverse pressure gradient region is formed inside the groove. This adverse pressure gradient produces an eddy whose vorticity is opposite to that of the large-scale circulation. The interaction between the upstream divergent flow and the downstream backflow causes the thermal boundary layer to detach near the tip of the pyramid [see the sketch shown in Fig. 3(a)]. The detached thermal boundary layer becomes a thermal plume, which is sheared to the downstream by the mean flow.

Besides their effect on the detachment of the thermal boundary layer, the small eddies trapped inside the grooves also produce a strong mixing, which affects the local temperature near the boundary. Figure 4(a) compares the normalized mean temperature profiles in the rough cell (circles) and in the smooth cell (triangles). It is seen that the measured $T(z)$ increases linearly with z for small values of z (the solid line). After it reaches a maximum value T_m, the measured $T(z)$ remains constant throughout the bulk region. The measurement indicates that turbulent mixing creates on average an isothermal fluid in the bulk region and the temperature gradient across the rough cell is concentrated in the upper and lower thermal boundary layers, which follow the contour of the rough surfaces. The thickness δ of the boundary layer can be defined as a distance at which the extrapolation of the linear part of $T(z)$ equals T_m. From Fig. 4(a) we find that the value of δ near the bottom of the groove is 2.0 mm, whereas in the smooth cell $\delta = 1.5$ mm. Another interesting feature shown in Fig. 4(a) is that the mean temperature inside the groove $(z < k)$ is reduced by approximately 0.5 °C when compared with the smooth cell. This is caused by

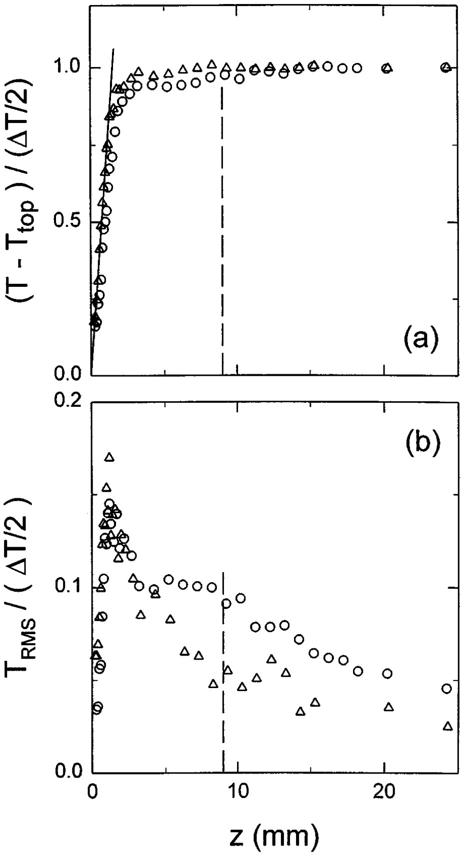

FIG. 4. Measured (a) mean temperature profile and (b) RMS profile in the rough (circles) and smooth (triangles) cells at Ra $= 1.5 \times 10^9$. The distance z in the rough cell is measured from the bottom of the groove. The mean temperature $T - T_{\rm top}$ relative to the top plate temperature $T_{\rm top}$ and the RMS temperature fluctuation $T_{\rm RMS}$ are both normalized by one-half of the temperature difference ΔT across the cell. The vertical dashed lines indicate the roughness height k.

the mixing effect of the eddies trapped inside the cold grooves. The eddy mixing also creates large temperature fluctuations. As shown in Fig. 4(b), the root mean square value $T_{\rm RMS}$ of temperature fluctuations is increased by approximately 100% in the groove region. It is also seen from Fig. 4(b) that the influence of the surface roughness extends well into the bulk region, in which the measured $T_{\rm RMS}$ is still considerably larger than that in the smooth cell. From the measurements at the center of the rough cell ($z = 100$ mm) [13], we find that the temperature histogram remains the same exponential form as that for the smooth cell and the measured $T_{\rm RMS}$ obeys the same Ra$^{-1/7}$ scaling law. However, the power law amplitude is increased by ~36% in the rough cell.

Because the local heat transport is proportional to δ^{-1} [14], Fig. 4(a) suggests that the local heat transport in the groove region is reduced. The local heat transport near the tip of the pyramids, on the other hand, is found to be increased greatly. The measured $T(z)$ as a function of distance z away from the tip is found to have approximately the same form as that in the smooth cell, but the value of δ is reduced from 1.5 to 0.85 mm [13]. It is also found that temperature fluctuations at $z = 0.6$ mm away from the tip (inside the thermal boundary layer) are stronger than those in the smooth cell. This is contrary to the situation shown in Fig. 2(c). From both the global (visualization) and local temperature measurements, we conclude that the interaction between the horizontal shear flow and the rough surface creates a secondary flow (eddies) in the groove region. This secondary flow together with the large scale circulation enhance the detachment of the thermal boundary layer from the tip of the pyramids. The extra thermal plumes detached from the rough elements are responsible for the enhanced heat transport shown in Fig. 1. In the groove region, the secondary flow produces a strong eddy mixing effect, which suppresses the emission of the thermal plumes deep inside the groove, and at the same time creates large temperature fluctuations outside the boundary layer.

We thank H. J. Swinney, J. R. Herring, J. Werne, and A. Belmonte for useful discussions. The assistance of M. Lucas and his team in fabricating the convection cells is gratefully acknowledged. This work was supported by the National Science Foundation under Grant No. DMR-9623612.

---

*Email: ptong@osuunx.ucc.okstate.edu

[1] M. R. Raupach, R. A. Antonia, and S. Rajagopalan, Appl. Mech. Rev. **44**, 1 (1991).
[2] H. Tennekes and J. L. Lumley, *A First Course in Turbulence* (MIT Press, Cambridge, MA, 1972).
[3] E. Siggia, Annu. Rev. Fluid Mech. **26**, 137 (1994), and references therein.
[4] B. Castaing *et al.*, J. Fluid Mech. **204**, 1 (1989).
[5] B. I. Shraiman and E. D. Siggia, Phys. Rev. A **42**, 3650 (1990).
[6] F. Heslot, B. Castaing, and A. Libchaber, Phys. Rev. A **36**, 5870 (1987); X.-Z. Wu, L. Kadannoff, A. Libchaber, and M. Sano, Phys. Rev. Lett. **64**, 2140 (1990).
[7] Y. Shen, P. Tong, and K.-Q. Xia, Phys. Rev. Lett. **76**, 908 (1996).
[8] H. Tanaka and H. Miyata, Int. J. Heat Mass Transfer **23**, 1273 (1980).
[9] T. H. Solomon and J. P. Gollub, Phys. Rev. Lett. **64**, 2382 (1990); Phys. Rev. A **43**, 6683 (1991).
[10] In the fitting, we have used all the data points and ignored the small effect due to the different aspect ratio of the cells. The conclusion remains the same if one uses only the data points from a single convection cell.
[11] D. Dabiri and M. Gharib, Exp. Fluids **11**, 77 (1991); G. Zocchi, E. Moses, and A. Libchaber, Physica (Amsterdam) **166A**, 387 (1990).
[12] T. E. Faber, *Fluid Dynamics for Physicists* (Cambridge University Press, Cambridge, England, 1995).
[13] Y.-B. Du and P. Tong (to be published).
[14] A. Belmonte, A. Tilgner, and A. Libchaber, Phys. Rev. E **50**, 269 (1994).