# A QUALITATIVE STUDY OF UNSTEADY NON-PENETRATIVE THERMAL CONVECTION FROM NON-UNIFORM SURFACES

Richard D. Keane and Ronald J. Adrian
Department of Theoretical and Applied Mechanics
University of Illinois at Urbana-Champaign
Urbana, IL 61801
USA

## INTRODUCTION

To model the planetary boundary layer in atmospheric sciences, there have been many experimental studies of unsteady penetrative and non-penetrative highly turbulent thermal convection in a wide layer of fluid bounded below by a thermally conducting heated plate and from above by a thermally insulating upper plate. Adrian et al. (1986) have performed experiments for unsteady non-penetrative convection in water to determine mean temperature profiles and joint statistics of temperature and velocity for the core region of the convection layer. These results were compared with earlier results in Rayleigh convection and penetrative convection by Willis and Deardorff (1974) as well as with results obtained by direct measurement of the planetary boundary layer by Telford and Warner (1964) and Lenschow (1970, 1974). The experimental results were consistent with a physical model in which buoyant thermals and plumes are responsible for most of the convective flow field as they rise through relatively quiescent fluid. In this regard, unsteady non-penetrative thermal convection is easier to visualize than Rayleigh convection because the only source of buoyant fluid is the heated lower boundary.

Although a more accurate model of ground topography would indicate the influence of variations in terrain on thermal convection within the boundary layer, there has not been much experimental research upon the effect of heterogeneity of the lower boundary surface on the coherent structures in convective turbulence on the temperature and velocity field statistics. Laminar convection has been analyzed theoretically by Kelly and Pal (1978) for Raleigh-Bénard convection between wavy surfaces with small amplitude variation, in order to determine stable equilibrium solutions. Using direct numerical simulation, Krettenauer and Schumann (1989) investigated unsteady, non-penetrative, thermal convection where the lower surface varies sinusoidally in one horizontal direction while remaining constant in the other. They concluded that for turbulent Reynolds numbers, the convection exhibited little sensitivity to the wavy surface for a 10% amplitude, although roll cells did develop over the wavy surface.

In a later paper, Krettenauer and Schumann (1992) used large-eddy simulation to determine that the wavy lower surface did not significantly change the volume-averaged kinetic energy. The coherent structures of motion were comprised of large-scale primary rolls with axes parallel to the lower surface wave crests and secondary rolls with axes perpendicular to the wave crests and which became more pronounced for steep surface waves. They concluded that the wavy surface does enforce three-dimensional motions such as the rolls perpendicular to the wave crests but has rather small effects on the mean turbulence profiles and heat exchange at the surface. Their results agree approximately with field observations over more irregular terrain by Kaimal et al. (1982) which show similarity to observations over homogeneous surfaces.

## EXPERIMENTAL APPARATUS AND PROCEDURE

To understand the mechanism of turbulent thermal convection over rough surfaces, the coherent structures of the flow have to be identified and studied to determine the most important parameters in their production, transport and dissipation. A set of one-dimensional grooved plates for a rough surface in the convection test section which consists of a square container 510 mm x 510 mm in horizontal dimension and 400 mm in depth with plexiglass sidewalls 10 mm thick and an upper plexiglass sheet 13 mm thick. The lower heat conducting boundary is an aluminum plate of total thickness 19 mm into which has been cut artificial rectangular roughness elements screwed into close thermal contact with a second flat aluminum plate of thickness 19 mm. The third and lowest plate is bonded to a wire heating mat which provides the heat flux. Seven different lower plates were used ranging from the smooth plate to the plate with the largest roughness amplitude and wavelength. The heat supply to the lower surface was varied by choosing three input voltages and by varying layer depth, a range of flux Rayleigh numbers, $Ra_f$, from $2.3 \times 10^9$ to $8.3 \times 10^9$ was obtained.

The flow visualizations of the temperature field are obtained for quasi-steady heating conditions in which the test-section is heated until the rate of temperature increase in the core of the convecting fluid is constant. The flow visualizations of thin light sheets of thickness 2mm to 5mm are recorded on both photographic colour film

and slide film showing the colour change of micro-encapsulated chiral nematic liquid crystals and of the velocity field by following the motion of the liquid crystal spheres over a known time interval. The liquid crystals were selected to undergo a complete colour change from red to blue from $31^0C$ to $34^0C$, which was within the quasi-steady range. The white light sheet has been oriented vertically, perpendicular to the roughness elements to observe the effects of the amplitude and wavelength of the roughness upon production of plumes and thermals and to compare the results for the rough plates with those from smooth plates. Plan views of the temperature field close to the lower plate and in the core region have also been obtained.

For each set of experimental parameters, independent realizations of the flow field are photographed to identify the thermal plumes and the large scale eddies within the isothermal central region. These parameters include the dimensions of the roughness elements, which distinguish the lower surface from the plane surface used in previous experiments on non-penetrative thermal convection, the layer depth, $z*$, the dimensions of the test section and the kinematic heat flux, $Q$, into the fluid layer. The layer depth and the horizontal dimensions of the test section are related through the aspect ratio which is fixed at 5.1:1 throughout the experiments. The heat flux is measured by the non-dimensional flux Rayleigh number. As outlined previously, four lower plate profiles have been considered, one being planar and the other three having a constant amplitude to wavelength ratio of 1:5. Although the input voltage for the heat supply was designed to allow three separate heat fluxes to be chosen, the flux Rayleigh number for each experiment has been determined by measuring the rate of temperature increase within the isothermal core layer. The kinematic heat flux determined by measuring the power input to the heating mat is not a reliable method of determining $Ra_f$ as defined in equation (1) because this overestimates the heat flux as there are heat losses to the walls of the test section, the base and the insulation, and these losses increase as the heat input rate increases. Thus, the flux Rayleigh number is calculated from the measured, constant rate of temperature increase in the isothermal layer during recording, namely:

$$Ra_f = (\beta g Q(z*)^5/\kappa^2 \nu) \cdot \partial T/\partial t \tag{1}$$

where it is assumed that the heat flux is heating the core of the fluid layer at a uniform rate given by

$$Q = z* \, \partial T/\partial t \tag{2}$$

## RESULTS

Each group of flow visualizations for a given parameter set has been analyzed to determine the influence of the rough surface on plume production and transport from the lower surface through the isothermal layer to the insulated upper plate in the presence of large scale eddies in the central core. From visualizations of vertical light sheets, the relationship between plume production and surface wavelength has been studied to learn if the plumes are generated over entire roughness elements or over more than one element. As the bouyant plumes arise from the lower surface and interact with large scale motions within the core, the likelihood of amalgamation of neighbouring plumes has been examined. The location of plumes has been examined in relation to large scale eddies within the core layer to see how the presence of downflows or quiescent fluid determines the location of thermal plumes. Furthermore, the existence of horizontal mean flows or long time transitory flows has been examined for all visualizations in both horizontal and vertical planes.

### Existence of horizontal mean flow.

In previous works by Krishnamurti and Howard (1983) and Howard and Krishnamurti (1986), it has been found by laboratory experiments and mathematical modelling, that spontaneous generation of a large horizontal flow occurred in a horizontal layer of fluid heated below and cooled above. Yao (1983) showed that the presence of mean flows in an inclined test section did not extrapolate to zero mean flow when the test section was horizontal. In an attempt to determine whether any mean flows were visible in the flow visualizations, horizontal and vertical light sheet recordings were made with both long and short periods of time between successive images. The rapidly recorded images were made to discern possible preferred directions of mean flow by recognizing the same large scale structures moving horizontally between succesive exposures. The longest periods of recording images were limited by the temperature range for which the thermochromic crystals were visible. For the lowest kinematic heat flux, the maximum time was 12 minutes. Any large scale horizontal motions with a time constant larger than this value, would be difficult to detect from the flow visualizations recorded as they would be dominated by the eddies within the central region.

Although there were downflows in the test section down the face of optical access for the light sheet from the slide projector, there was no conclusive evidence for any large scale horizontal flow in any group of visualizations of vertical light sheets for either the flat or the rough lower surfaces. From plan views of the fluid flows just above the lower surfaces, polygonal cells produced by the interaction of large slow-moving downflows did not possess any regular lateral displacement to indicate the presence of a mean flow.

The absence of a mean horizontal flow may be due to the nature of the upper surface, which is thermally insulated and does not produce plumes to enhance the plume production of the lower surface. Hence, in non-penetrative thermal convection, unlike Rayleigh-Benard convection, the lack of mean flows may be due to the lack of thermal plumes from the upper surface and may necessitate a much higher $Ra_f$ before such flows are achieved.

### Rough surface length scales.

For a fixed kinematic heat flux into the test section and fixed $Ra_f$, the effect of rough surface wavelength and amplitude upon the coherent structures of the flow field can be ascertained by statistically examining features on the photographs and slides of both horizontal and vertical light sheets for each lower surface profile. The generation of thermal plumes from the lower surface has been studied by determining the width of the plumes relative to the roughness elements i.e. do the roughness elements limit the width of the plumes or are the plumes generated from an area which is independent of roughness lengthscale ? In addition, the average linear density of the plumes transverse to the roughness axis has been calculated to determine the effect of roughness

lengthscale on the distribution of plumes. Finally, the amalgamation of plumes has been investigated to find the conditions under which neighbouring plumes join as they rise.

It can be seen from Figs. 1(a), (b), (c), and (d), when $Ra_f$ is held constant, that the plume width is independent of the roughness lengthscale, for the plumes generally extend over more than one roughness element for the lowest wavelength of plate 1, while they originate from a single roughness element for plate 2, which has a larger wavelength. In many instances for plate 3, the plumes originate from sections and edges of the roughness elements. Although realizations for plate 1 show multiple and single element plumes and amalgamation of plumes are common, it can be seen that the plumes for plate 3 arise from sections of the upper surface, the vertical faces and the lower surface of the roughness elements. Similar results occur when the kinematic heat flux is doubled and quadrupled with little significant change occurring in the plume dimensions for these increases in turbulence.

The average linear transverse plume density from the lower plate has been estimated by counting the number of plumes in each realization of experimental parameters. It has been found that the density of plumes is independent of the roughness lengthscale and is only marginally affected by increasing $Ra_f$. For the lowest $Ra_f$ considered here, ( $2.5 \times 10^9$), it has been estimated that plumes originate for plates 0, 1, 2 and 3 at intervals of 50, 47, 46 and 50mm respectively. When the heat flux is maximized, with $Ra_f = 6.5 \times 10^9$, the plumes originate at intervals of 55, 60, 44 and 45mm respectively, which is not substantially lower than for the lower heat flux case.

The extent of plume penetration and amalgamation of neighbouring plumes is determined by the large scale convective eddies within the core region. Warm buoyant plumes, generated on the lower plate, penetrate the fluid layer above them until they collide with the upper surface, provided that large scale downflows from the upper surface do not interact with them and destroy them. The amalgamation of plumes from neighbouring surface elements occurs when the large scale downflows sweep them together between counter rotating eddies in adjacent downflows.

### Geometry of downward flowing polygonal convective cells.

While the vertical light sheet visualizations provide a clear understanding of the relationship between the bouyant plumes and the lengthscale of the rough surface, they do not give any three-dimensional information about the structure of the large scale eddies and the bouyant plumes. Thus, a horizontal thin light sheet, located as closely as possible to the lower plate's upper surface reveals the interaction and polygonal structure of the downflows at the lower surface.

For a flat plate, the upward bouyant plumes are formed at the boundary between adjacent cells of downward moving fluid. There, the downflows upon reaching the lower plate spread radially, pushing fluid across the lower plate until they meet another similar flow, at which point the fluid which has been heated crossing the plate becomes buoyant and rises. Thus, the plumes visible in the flow visualizations of vertical light sheets are predominantly not isolated, circularly symmetric plumes but are frequently the thin sheets of bouyant upflow at the edges of polygonal cells of downflow. For the flat plate, there is some evidence of penetration of axisymmetric thermal plumes into the isothermal layer in regions of quiescent flow, but the main source of buoyant upflow results from the intersection of downflows in adjacent polygonal cells.

From the foregoing analysis of the frequency and source of the plumes, it can be seen that the flux Rayleigh number and the surface roughness have little influence on the average spacing of the plumes and consequently, on the size of the large-scale eddies with the isothermal layer.

Above the flat plate, the polygonal cells show no preferred orientation, but, in the presence of roughness elements, the polygonal cell walls become more complex and become aligned with the roughness axis. This can be understood by considering the effect of the roughness elements upon the horizontal flow of the downflows across the lower plate. A horizontal flow along the axis parallel to the roughness elements will not be significantly affected by the surface roughness, but when the flow moves across the roughness elements, it is influenced by thermal plumes which originate within the depressions of the surface, where they are unaffected by horizontal flows until they have sufficient buoyancy to leave the lower surface. At the edges of the convection cells, the horizontal flows interact with the upward buoyant flow from the lower surface to produce a less uniform boundary of adjacent downflows due to their increased buoyancy of the fluid in the channels. Thus, the presence of isolated, bouyant thermal plumes can be noted where these plumes penetrate the fluid above the upper surface of the lower plate and are visible by their circular temperature profile within the upflow between two adjacent downflows. Such isolated plumes may not be apparent for a three- dimensional rough surface where there is less protection of individual plumes from horizontal flows near the lower plate. Thus, further rough surface profiles, such as circular or sinusoidal waveforms, need to be tested to determine the dependence of the coherent structures of thermal convection upon their dimensions and for comparisons with numerical experiments performed by Krettenauer and Schumann (1989, 1992).

## SUMMARY

A qualitative study of the velocity field and the temperature field has been carried out using flow visualization techniques. The test section contained a set of lower surface plates which featured two-dimensional square waves with 2 fixed amplitude-wavelength ratios. Use of encapsulated thermochromic crystals enabled temperature fields to be visualized during quasi-steady non-penetrative thermal convection, in vertical planes parallel to the roughness axis and in horizontal planes above the lower surface.

There was an absence of conclusive evidence of any large scale mean flows in the flow visualizations which may indicate that higher $Ra_f$ is necessary before such flows are achieved. By determining the spatial density of thermal plumes, it has been found that the density of such plumes is independent of the surface roughness lengthscale and only weakly dependent upon $Ra_f$. The planform flow visualization revealed the interaction of the rough surface with the large-scale convective eddies in the isothermal region and the interaction of these eddies

with buoyant plumes generated in the grooves of the lower plate.  Further analysis using lower surfaces with smoother profiles and three-dimensional profiles is anticipated.

## REFERENCES
Adrian, R. J., R. T. D. S. Ferreira, and T. Boberg,  1986.  Turbulent thermal convection in wide horizontal fluid layers, *Experiments in Fluids*, **4**, 121-141.

Howard, L. N. and R. Krishnamurti,  1986.  Large scale flow in turbulent convection: a mathematical model, *Journal of Fluid Mechanics*, **170**, 385-410.

Kaimal, J. C., R. A. Eversole, D. H. Lenschow, B. B. Stankov, P. H. Kahn, and J. A. Businger,  1982.  Spectral characteristics of the convective boundary layer over uneven terrain, *Journal of the Atmospheric Sciences*, **39**, 1098-1114.

Kelly, R. E. and D. Pal,  1978.  Thermal convection with spatially periodic boundary conditions : resonant wavelength excitation, *Journal of Fluid Mechanics*, **86**, 433-456.

Krettenauer, K. and U. Schumann,  1989.  Direct numerical simulation of thermal convection over a wavy surface, *Meteorological and Atmospheric Physics*, **41**, 165-179.

Krettenauer, K. and U. Schumann,  1992.  Numerical simulation of turbulent convection over wavy terrain, *Journal of Fluid Mechanics*, **237**, 261-299.

Krishnamurti, R. and L. N. Howard,  1983.  Large scale flow in turbulent convection: Laboratory experiments and a mathematical model, *Papers in Meteorological Research*, **6**, 143-159.

Lenschow, D. H.,  1970.  Airplane measurements of planetary boundary layer structure, *Journal of Applied Meteorology*, **9**, 874-884.

Lenschow, D. H.,  1974.  Model of the height variation of the turbulence kinetic energy budget in the unstable planetary boundary layer, *Journal of the Atmospheric Sciences*, **31**, 465-474.

Telford, J. W. and J. Warner,  1964.  Fluxes of heat and vapor in the lower atmosphere derived from aircraft observations, *Journal of the Atmospheric Sciences*, **21**, 539-548.

Willis, G. E. and J. W. Deardorff,  1974.  A laboratory model of the unstable planetary boundary layer, *Journal of Atmospheric Sciences*, **31**, 1297-1307.

Yao, C. S.,  1983.  High Reynolds number, unsteady thermal convection in a shallow layer, Ph. D. thesis, University of Illinois at Urbana-Champaign, Urbana, IL.
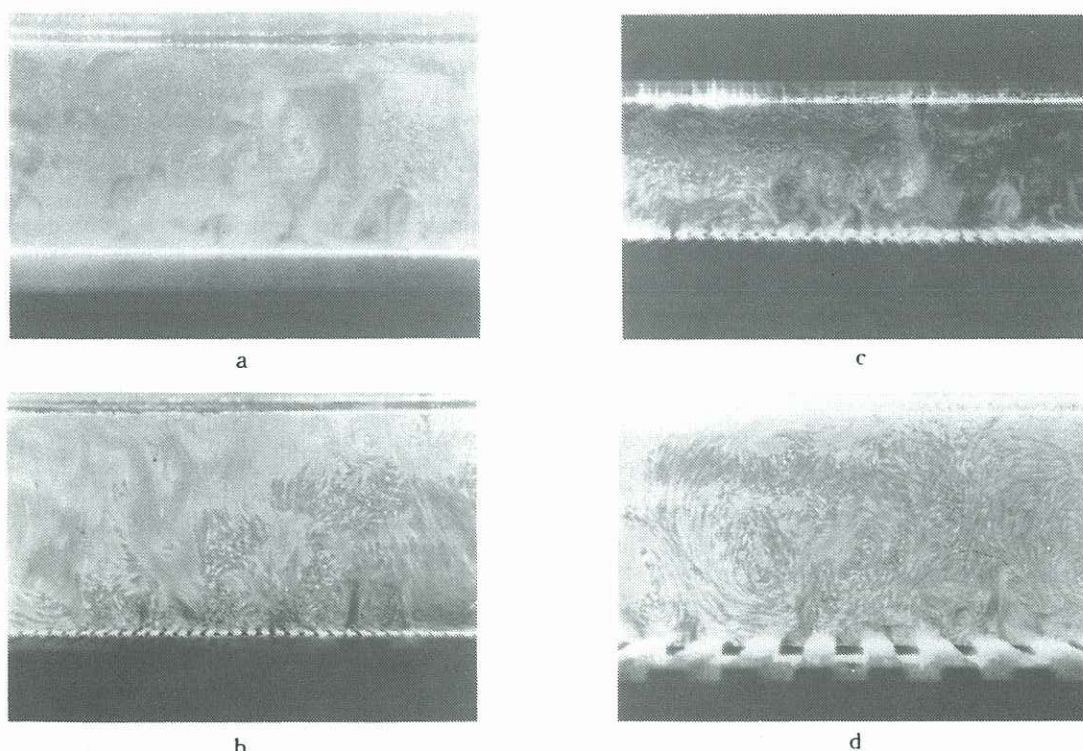
Fig. 1   Flow visualization of non-penetrative thermal convection above rough surfaces illustrating the dependence of plume width on increasing roughness lengthscale, for the smooth plate with $Ra_f = 2.4 \times 10^9$, (b) plate 1 with $Ra_f = 2.9 \times 10^9$, (c) plate 2 with $Ra_f = 2.5 \times 10^9$ and (d) plate 3 with $Ra_f = 2.7 \times 10^9$.