Flow visualization for a natural convection in a horizontal layer of water over a heated smooth and grooved surfaces

Sudhakar Subudhi[1,*], Jaywant H Arakeri[2]

[1]Department of Mechanical and Industrial engineering, IIT Roorkee, Roorkee, India
[2]Department of Mechanica engineering, IISc, Bangalore, India
*corresponding author: subudfme@iitr.ac.in

Abstract

The present paper deals with the flow visualization of free convection on the horizontal surfaces with and without V grooves. The experimental setup consists of a tank of dimensions 265×265×300 (height) containing water. The bottom surface was heated and free surface of the water was left open to the ambient. In the experiments, the bottom plate had either a smooth surface or a grooved surface. We used 90^0 V-grooved rough surfaces with two groove heights, 10 mm and 3 mm. The experiment was done with water layer depths of 90 mm and 140 mm, corresponding to values of AR equal to 2.9 and 1.8 respectively. *Thymol blue* ($C_{27}H_{30}O_5S$), a pH sensitive dye, was used to visualize the flow near the heated plate. The enhanced heat transport in the grooved cavities cannot be ascribed to the increase in the contact area, rather it must be the local dynamics of the thermal boundary layer that changes the heat transport over the grooved surface & this dynamics of thermal boundary layer is directly connected to the detachment of thermal plumes from the tips of the grooves. But for the smooth surface, there is no detachment of plumes from surface.

Keywords: Natural convection, Plumes

1 Introduction

Free convection or natural convection is an important branch of fluid mechanics and heat transfer. Flow structures due to free convection over the heated surface influence the transfer of heat from the surface to the core of the fluid layer. This transport may be either due to thermals or due to plumes according to the various studies. According to Howard [1] and Sparrow et al. [2], the eruption of thermals is the medium for the convective heat transfer. Howard [1] proposed a one-dimensional model of periodic growth and eruption of conduction layer, whereas Sparrow et al. [2] verified this model by conducting experiments over heated copper plates of square and circular planform placed in a large tank of water. The periodic eruption of thermalswas observed and the period of a periodic temperature signal matched with Howard's prediction. However, according to recent studies, plumes are the main mechanism for the turbulent convective heat transfer. Adrian et al. [3] had carried out experiments in a wide horizontal layer of water heated from below and insulated at the top. They had observed line plumes moving in a random fashion and the thermals were only identified at the beginning of the experiments.

Du and Tong [4] had carried out experiments for the turbulent thermal convection in a cylindrical cell containing water with pyramidical rough elements of height 3.175 mm and 9 mm on both top and bottom surfaces. Detachment of thermal plumes from the roughness tips by the interactions between large scale circulation and a secondary flow (eddies) in the groove region was observed from the side views of the flow structures. Verzicco et al. [5] studied turbulent thermal convection over grooved plates using direct numerical simulations (DNS) for Prandtl number (Pr) of 0.7. Their computational model is a cylindrical cell vertically confined by plates with circular grooves, the lower being hotter than the upper. The grooves of the horizontal plates are V-shaped with a tip angle of 90° and height of 0.025 h, where h is the height of the enclosure. They observed the formation of point plumes from the tips of the V-shaped grooves of the horizontal plates.

From the previous studies, it is observed that visualization of flow structures for both side and top view of convection has not been carried out and also there are only few comparative visualization studies for both smooth and rough or grooved surfaces. Theerthan and Arakeri [6,7] had already carried out detailed study for the top view of flow structures of convection over smooth surface using liquid crystal sheet and electro-chemical dye technique for the above papers respectively. So, in present paper, both top and side view of flow structures over both heated smooth and grooved surfaces using electrochemical dye technique using the same experimental setup have been discussed.

2 Experiments

The schematic of the setup is shown in Fig. 1. The experimental setup was earlier used in the laboratory Theerthan [6,7] for studies on free convection on a smooth surface. The setup consists of a tank of dimensions 265 mm×265 mm cross-section and 300 mm height. The side walls are made of glass for visualization. The top surface of the water was left open to the ambient. For the experiments with a smooth surface, the bottom plate (hot plate) is 10 mm thick and made of brass. This plate was fixed to the tank. The rough surfaces had parallel straight 90° V-grooves with groove height of 10mm. The lateral separation between adjacent grooves is twice the groove height. The cross-section dimensions of each plate are 260 mm×260 mm and are 20mm thick. During the grooved surface experiment, the grooved plate was kept on the smooth surface. The open convection was studied at water layer depth of 90 mm, corresponding to value of AR equal to 2.89 (AR is lateral dimensions of the convection layer divided by height of convection layer). Ten thermocouples were used to measure various temperatures in the smooth surface experiments; fourteen thermocouples were used in the grooved-surface experiments. Four thermocouples were placed in semi-circular grooves of 2 mm diameter in the aluminum plate next to the heater. Two thermocouples were placed in 2 mm diameter, 10 cm long holes drilled in the center plane of the smooth brass plate. For the rough brass plates, four thermocouples were placed in 2 mm diameter, 6.5 cm long holes. One thermocouple was traversed in the vertical direction to obtain temperature profiles. Three thermocouples were used to obtain the bulk temperature in the middle of the water layer, two of which were near the side walls and one was in the center. One thermocouple was kept touching the top evaporating surface. The temperature from these thermocouples was recorded in a data acquisition system (Agilent 34970A) which was connected to a computer. Visualization was done using the electrochemical dye technique of Baker [8] using thymol blue. Thymol blue, a pH indicator, is mixed with a few drops of 1 N Sodium hydroxide solution to increase its solubility in water and dissolved in water, approximately 0.015% by weight. This solution is basic and is blue in color. Then this solution is titrated against 1 N hydrochloric acid, adding drop by drop, till the solution just turns yellow orange. At this point the solution is slightly acidic (pH<7). When a dc voltage 10 volts is applied between two electrodes, pH of the fluid changes near the negative (positive) electrode due to the removal of hydroxyl (hydrogen) ions. The color changes locally near the negative electrode and this “dye” marks the fluid motion. The bottom surface (on which dye is produced) is the negative electrode and the positive electrode is kept at some distance so as to minimize disturbance to the flow and also produce uniform dye on the test surface. The test section was illuminated by two 250W Sodium vapor lamps and the side and top views were recorded using a digital video camera (SONY DCR-PC9E). The Sodium vapor lamps were used to obtain maximum contrast as the parent solution is orange yellow and the dye is blue. The experiment was started by varying the input ac voltage from 0 volt in steps using a variac so as to avoid large thermal stresses on the bottom glass plate. In all the experiments, the temperature measurements or the visualization commenced after about 2 hours from the time the final voltage was set. For all the plates, we have taken readings for 3 hours with the sampling time of 1 minute.

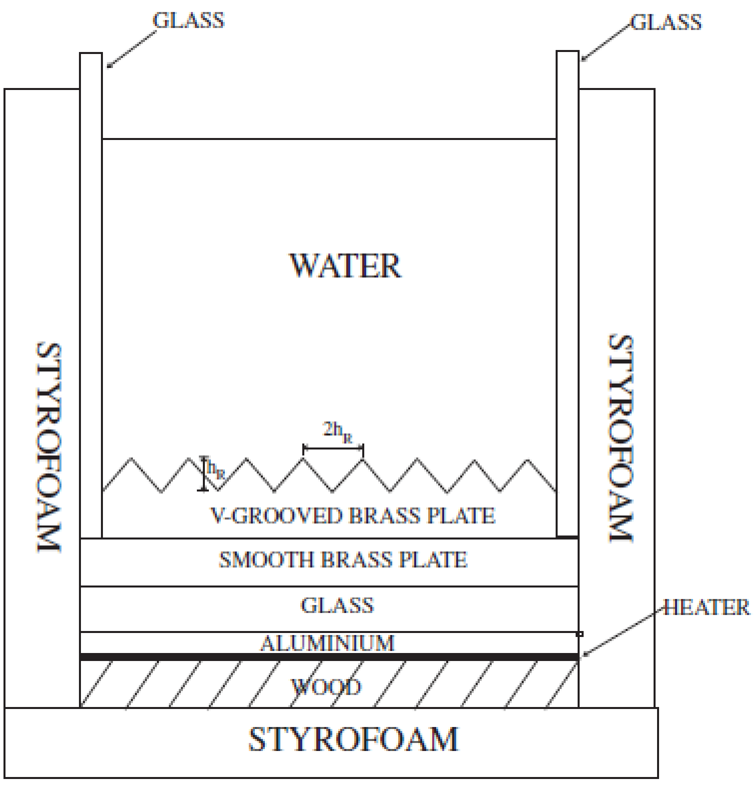

Fig.1. Experimental setup.

3 Results and Discussion

The turbulent convection experiments are conducted with a water layer of 90 mm, corresponding to value of AR equal to 2.89. The heat flux is varied between 150 W/m^2 and 1250 W/m^2 corresponding to a Ra in the range of $1.3\times10^7-4\times10^7$. The experiment is unsteady, i.e., the temperatures change with time; however, temperature difference between two spatial points is nearly constant about 1 hour after the start of the experiment. In particular, the temperature difference between the hot surface next to the water and the bulk water is constant for a given heater electrical power input. So we can treat these unsteady experiments as quasi-steady. Before we present results from flow visualizations, we distinguish between plumes and thermals. Plumes result when energy is supplied continuously at some location in a fluid. Thermals, on the other hand, result from a sudden discontinuous release of buoyancy. The flow patterns observed in our cases are plumes as cleared from the above definitions. Fig. 2(a) shows the top views of the convective flows over the smooth and grooved surfaces. Visualization on a smooth surface shows that the plumes are of line or sheet type; on the surface, dye accumulates along lines, representing the bases of the plumes. This phenomenon is shown in the line diagram (Fig. 2(b)). The heated fluid continuously rises along the plumes accelerating in the central stem of the plume. The rising material produces a stalk, while the deflected fluid at the end of the stalk produces a cap on top. As the pushing and deflection continue, the edge of the cap may further fold over (Fig. 2(c) and (d)). Fig. 2(c) is for heat flux of 150 W/m^2 and Fig. 2(d) is for heat flux of 1250 W/m^2. So it can be observed that structures of plumes are more inclined with increasing in heat fluxes due to the stronger large scale flow at the higher fluxes. Also, it can be seen from Fig. 3 that line plumes move randomly and merge with each other. Theerthan and Arakeri [6, 7] had also observed this phenomenon. This phenomenon may be due to the large scale flow at the core of the fluid layer. In the case of the grooved surfaces, the top views are shown in Fig. 4(a) and (b) from dye visualization and line diagram respectively. Dye is released from a point from the tip of a groove; thus the plumes are point plumes different from the line plumes seen on a smooth surface. It can be clearly confirmed from the side views shown in Fig. 4(c) and (d) for heat fluxes of 150 W/m^2 and 1250 W/m^2 respectively. So the structures of plumes are more inclined with increasing with fluxes due to the stronger large scale flow at the higher fluxes like the smooth surface case. From top views, dye can be seen to be accumulated along lines, but most of the dye (representing the hot fluid) is released from points on the tips. Also there is intermittent detachment of these plumes, especially at the higher fluxes.

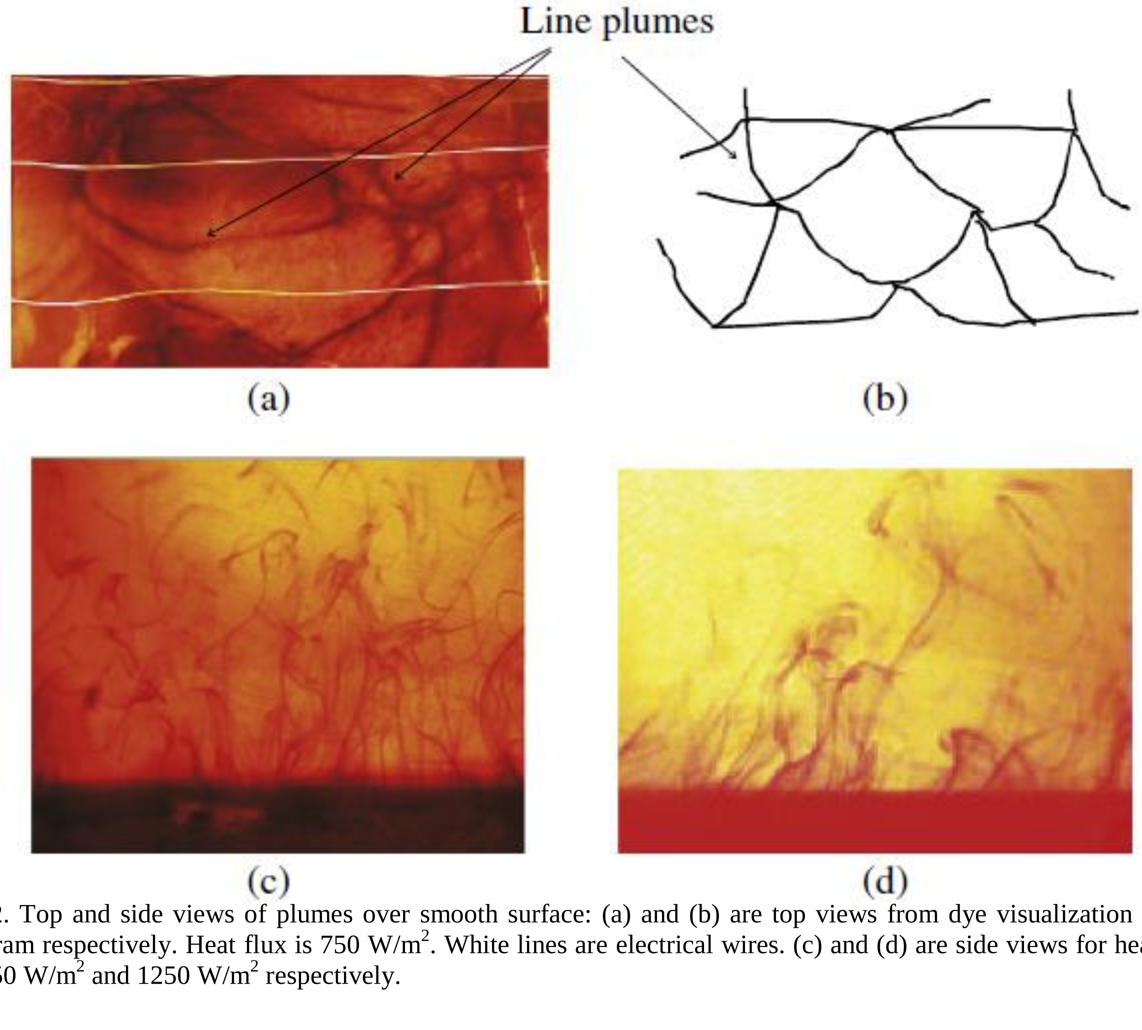

Fig.2. Top and side views of plumes over smooth surface: (a) and (b) are top views from dye visualization and line diagram respectively. Heat flux is 750 W/m^2. White lines are electrical wires. (c) and (d) are side views for heat fluxes of 150 W/m^2 and 1250 W/m^2 respectively.

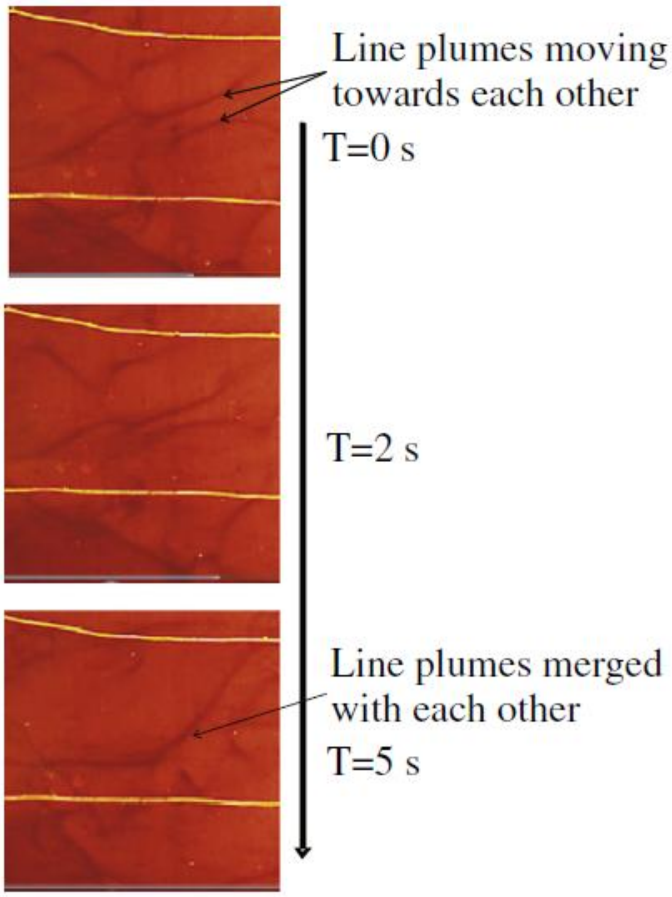

Fig.3. Merging of plumes with time over smooth surface. Heat flux is 750 W/m^2.

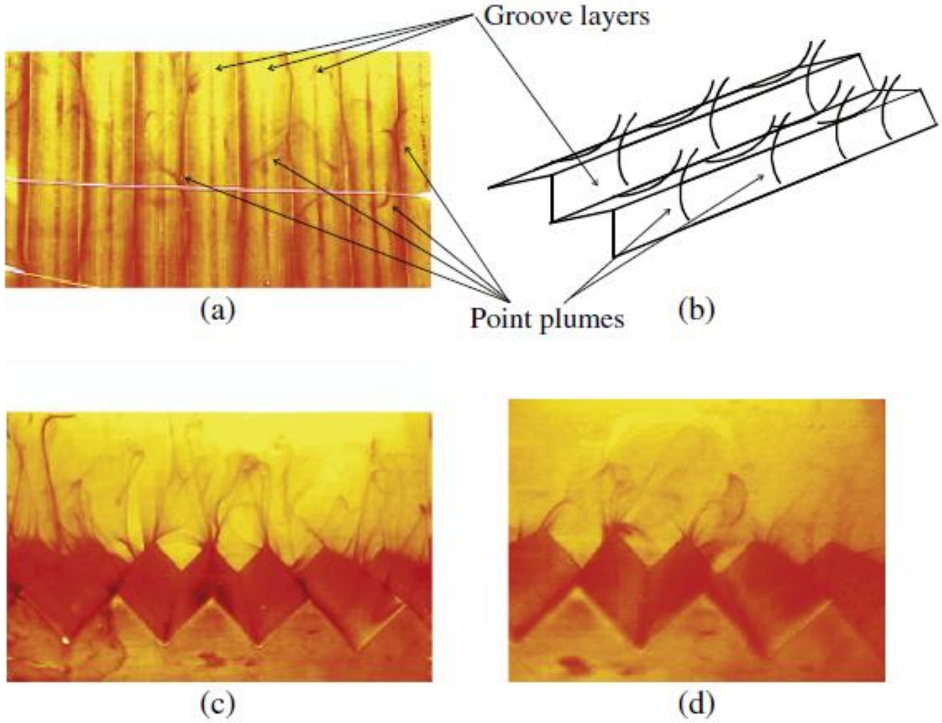

Fig.4. Top and side views of plumes over grooved surface: (a) and (b) are top views from dye visualization and line diagram respectively. Heat flux is 750 W/m^2. (c) and (d) are side views for heat fluxes of 150 W/m^2 and 1250 W/m^2 respectively.

4 Conclusions

In this paper, we have studied turbulent free convection over a horizontal surface having 90^0 V-grooves; two groove heights, 10 mm & 3 mm, were used. The experiment was done with water layer depths of 90 mm and 140 mm, corresponding to values of AR equal to 2.9 and 1.8 respectively. The heat flux was kept at four different values of 150 W/m^2, 300 W/m^2, 750 W/m^2 and 1250 W/m^2. Randomly moving line plumes are the dominant mechanism of heat transport for the smooth surface whereas point plumes are the mechanism of heat transport for the grooved surfaces. Also for the case of smooth surface, line plumes move randomly and merge with each other. We believe that the enhanced heat transport on the grooved surfaces is due to both a larger surface area and change in the plume dynamics.

References

[1] L.N. Howard (1966) Convection at high Rayleigh number. Proceedings of Eleventh Int. Congress of Applied Mech., p. 1109.

[2] E.M. Sparrow, R.B. Hussar, R.J. Goldstein (1970) Observations and other characteristics of thermals. *Journal of Fluid Mechanics*, vol. 41, pp 793-800.

[3] R.J. Adrian, R.T.D.S. Ferreira, T. Boberg (1986) Turbulent thermal convection inwide horizontal fluid layers. *Experiments in Fluids*, vol.4, pp 121-141.

[4] Y.-B. Du, P. Tong (2000) Turbulent thermal convection in a cell with ordered rough boundaries, *Journal of Fluid Mechanics*, vol. 40, pp 57-84.

[5] G. Stringano, G. Pascazio, R. Verzicco (2006) Turbulent thermal convection over grooved plates. *Journal of Fluid Mechanics*, vol.557, pp 307-336.

[6] S. Theerthan, J.H. Arakeri (1994) Planform structure of turbulent Rayleigh–Benard convection. *International Communications in Heat and Mass Transfer*, vol. 21, pp 561-572.

[7] S. Theerthan, J.H. Arakeri (2000) Planform structure and heat transfer in turbulent free convection over horizontal surfaces, *Physics of fluids*, vol.12, pp 884-894.

[8] D. James Baker (1966) A technique for the precise measurement of small fluid velocities. *Journal of Fluid Mechanics*, vol. 26, pp 573-575.