MERGING OF SHEET PLUMES IN TURBULENT CONVECTION

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Abstract— The predominant coherent structures near the hot or cold wall in turbulent convection are sheet plumes. We present results from a visualization experiment in turbulent free convection in water over a horizontal heated surface at moderately high Rayleigh number (Ra=10^5 to 10^9). We observe the random initiation of sheet plumes very close to the heated surface at regular intervals. These sheet plumes move horizontally in the direction of the bulk flow and merge with the neighbouring plumes. Two merging plumes are being often found to be parallel. We study the merging dynamics of two parallel sheet plumes by measuring the lateral velocities at different times of their merging, at different heat flux.

Keywords— turbulent convection, sheet plumes, merging.

I. INTRODUCTION

Natural convection over horizontal surfaces has been studied in simple geometries to investigate the dynamics of buoyancy driven flows. Due to the large unsteady density gradients created over the heated surface, convection with continuous rising columns of buoyant fluid called "plumes" occur. Many models [1], [2] & [3] claim to explain the near wall flow dynamics. However, visualization results presented [4] on high Rayleigh number (Ra) unsteady turbulent free convection in the high Prandtl number (Pr) regime showed that, the near wall coherent structures are sheet plumes Fig.1. The number of sheet plumes increases with increase of Rayleigh number. Sheet plumes are continuous rising of columns of buoyant fluid in the form of sheets due to the instabilities created along lines on the natural convection boundary layer. They also showed that the effect of near wall shear was to restrict the horizontal movement and merging of sheet plumes.
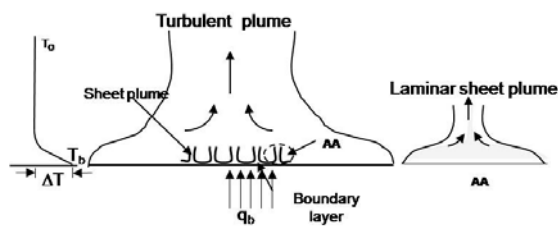

Fig. 1 The schematic of turbulent convection over horizontal surface

A model of an array of laminar sheet plumes predicted the average plume spacing, the mean temperature distribution and fluctuations of r.m.s temperature and vertical velocity [5]. Visualizations [7] also showed that coherent structures are assumed to be produced by pairs of counter rotating stream wise vortices that are aligned with the mean flow. Numerical simulation conducted [8] also confirmed the formation of sheet plumes near the wall. Studies on the temperature and velocity distributions in individual plumes abound. In turbulent convection, very little is known about interacting plumes. Since merging plumes are the dominant near wall mechanism in turbulent convection, understanding their dynamics is crucial in clarifying many unresolved issues.

Present study tries to understand the near wall dynamics in natural convection over horizontal heated surface. An electro-chemical technique [9] is used to observe the variation of plume spacing and the merging mechanism.

II. EXPERIMENTS

The set up for the horizontal plate convection is shown in the Fig.2. It consists of an open tank of size 300x300x250 mm with four glass side walls. The bottom hot plate is of 10mm thick and made of copper. The top surface of the copper plate is coated with chromium of 30 micron thick to avoid corrosion due to the acidic dye solution used for the visualization experiment. Below the copper plate are the layers of plates Fig. 2(a). A glass plate of 10mm thick is placed in between the copper and 5 mm thick aluminium plate. The heat is supplied by the Ni-Cr wire kept below the Aluminium plate. Having known the thermal conductivity of the glass plate, the heat flux supplied to the copper plate is calculated using the temperature difference measured across the glass plate. To reduce the air gap resistance, heat sink compound (Anabond) was spread between the plates. The bottom and side losses are reduced to less than 2% by insulating the sides and the bottom with Styrofoam. Water is used as the working fluid in all the experiments. Different fluid (water) layer depth such as 50, 100, 150 and 200mm corresponding to the AR 6, 3, 2 and 1.5 were used during the experiment. The heat flux supplied through the Ni-Cr mesh heater were kept at 260, 585, 1039, 1625 and 2340 W/m^2.
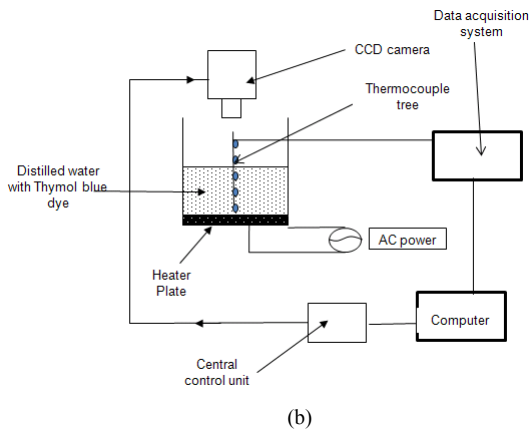

(a)

(b)
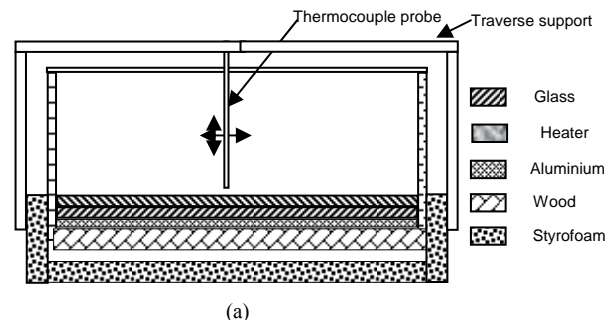
Fig.2. (a) Schematic diagram of the bottom plate and heater assembly (b) The schematic of the experimental set used for the visualization.

T type thermocouples were used to measure the temperatures, which were calibrated using constant temperature bath.

A total of 14 thermocouples were used to measure the temperatures at various locations both in the plate assembly as well as in the fluid inside the tank. Three thermocouples were placed at the bottom of the copper plate keeping one at the center (at 150mm from the edge) and two on the opposite edges (at 20mm from the edge). Similarly, three more thermocouples were placed above the aluminium plate exactly at the same location as in the copper plate so that the temperatures across the glass plate were recorded at three different locations, to calculate the actual heat flux supplied to the copper plate. This also ensures a constant heat flux boundary condition to the bottom plate. A thermocouple tree was used to measure the temperature of the fluid at different height. The temperatures from these thermocouples were recorded using a data logger (Agilent, model 34970A) with scanning interval of 1 minute. A sampling time of 1 second is used to get the average data for every minute.
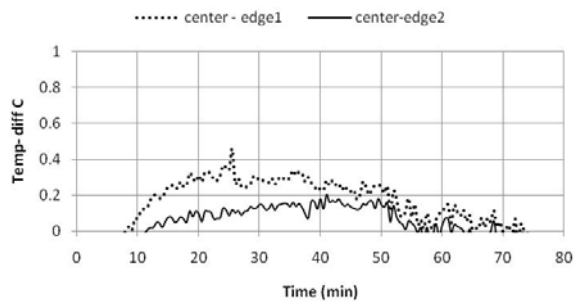

Fig.3. Variation of surface temperature difference on the copper plate with time.

Before starting the experiment, the surface temperature of the copper plate was checked for the uniformity with an accuracy of ±0.1°C Fig. 3.

Since the convection in open tank is unsteady, the heat flux transferred to the convecting water layer is calculated using the temperature difference between the plate and the ambient fluid after it reaches a steady state Fig.4.
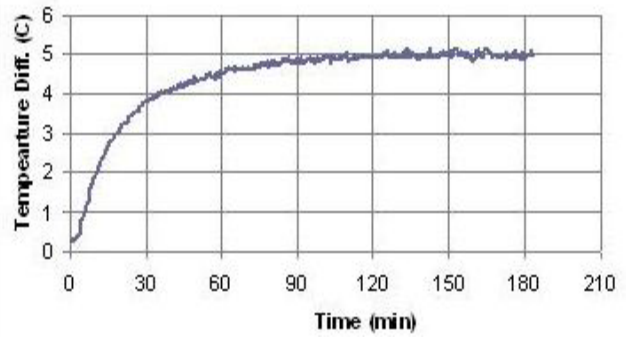

Fig.4. Variation of temperature difference between the bottom plate and water when the heat flux (Q) supplied to the heater is 4150 Wm^{-2} and water level at 200 mm.

Visualization

The visualization of near-wall coherent structures, the sheet plumes, is done using an electro chemical dye technique [9]. The pH indicator thymol blue solution, of 0.01 % by weight is prepared and titrated initially with 1 n NaOH solution to the end point followed by 1 n HCl so that, it is acidic and orange yellow in colour. The bottom copper plate formed the negative electrode and a copper wire mesh formed the positive electrode. When the two electrodes are connected to a d.c supply (3-9V), the thymol blue indicator solution changes its colour from orange yellow to deep blue locally near the negative electrode through an induced proton transfer reaction. These deep blue coloured dye solution are accumulated by the flow in the wall boundary layer feeding the plume from either side to form a dark thick line. The dark thick line forms the base of the sheet plume when it is visualized from the top. The flow patterns describing the formation, merging and alignment of sheet plumes were recorded using a CCD camera.

Experiments were conducted by varying the input voltage (ac) supplied to the heater using a variac. In all the experiments, recording of images were started after the steady state is reached.

III. RESULTS AND DISCUSSION

The top view of the near-wall structure showing sheet plumes for different heat flux supplied and for different water level is shown in Fig.5. Here Rayleigh number (Ra) is defined as

$$Ra = \frac{g\,\beta\Delta T D^3}{\alpha\nu}$$ where g is the acceleration due to gravity, β thermal expansion coefficient, ΔT the temperature difference between the plate and the ambient fluid, D height of the fluid level, α thermal diffusivity and ν the kinematic viscosity.
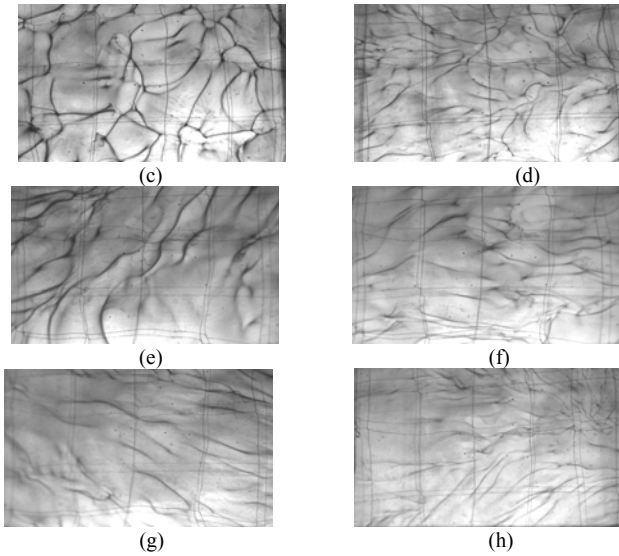

(a) (b)

(c)   (d)

(e)   (f)

(g)   (h)
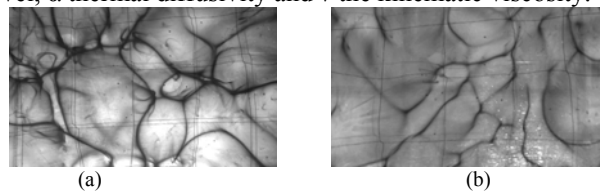
Fig.5. Plan view of near wall sheet Plume structure for different Rayleigh Number (a) Ra = 4.63×10^5, (b) Ra = 2.7×10^6, (c) Ra = 5.7×10^6, (d) Ra = 1.1×10^7, (e) Ra = 5.1×10^7, (f) Ra = 9.1×10^7, (g) Ra = 8.32×10^8 and (h) Ra = 1.1×10^9

It is seen clearly from the images that at lower Ra, cell type of structures are formed which are then transformed to aligned line like structures at higher Ra [6]. The alignment of plumes is in the direction of the large scale flow. In cell type structure, the sheet plumes move randomly in the horizontal direction to merge with the neighbouring plumes.
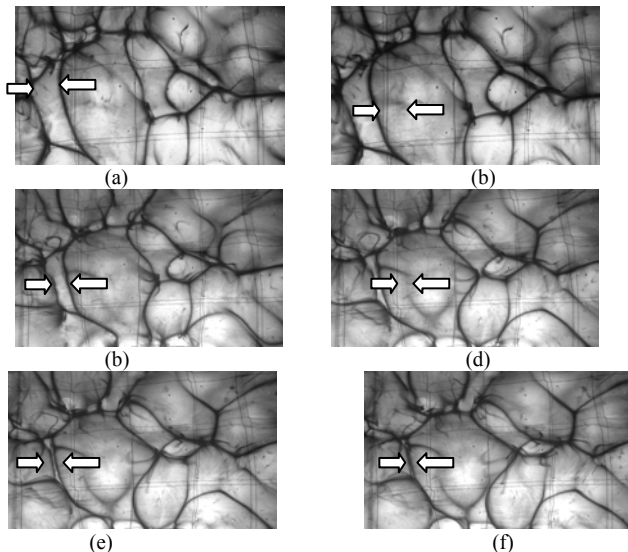

(a)   (b)

(b)   (d)

(e)   (f)

Fig.6. Plume merging sequence at Ra=4.63×10^5. The arrow indicates the direction of merging. (a) t = 0s, (b) t = 10s, (c) t = 30s, (d) t = 40s, (e) t = 60s and (f) t = 70s

Whereas in aligned line structure, the sheet plumes are aligned in the direction of the large scale flow and during the process of alignment they merge with the nearby plume.
From the recorded video, merging of two nearly parallel plumes separated initially by some distance λ was identified.

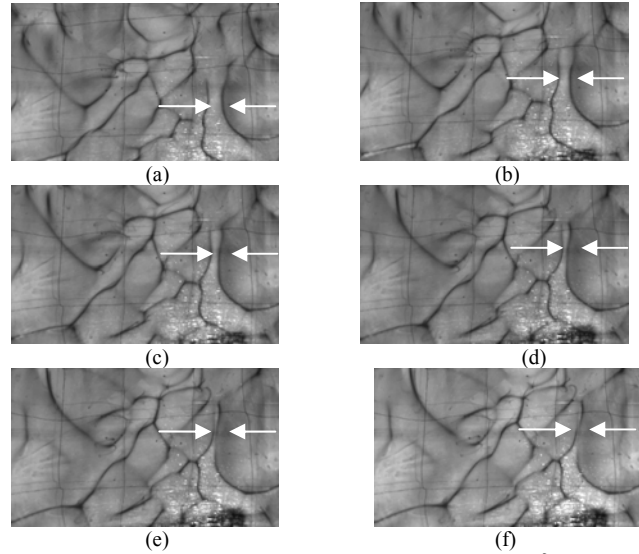The video clip was then split into frames of known time intervals.

(a)   (b)

(c)   (d)

(e)   (f)

Fig.7. Plume merging sequence at Ra=2.7×10^6. The arrow indicates the direction of merging. (a) t = 0s, (b) t = 4s, (c) t = 8s, (d) t = 12s, (e) t = 16s and (f) t = 18s
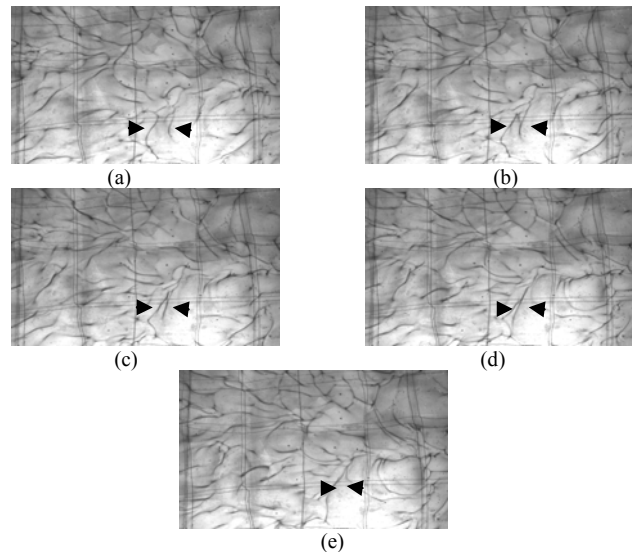

(a)   (b)

(c)   (d)

(e)

Fig.8. Plume merging sequence at Ra=1.1×10^7. The arrow indicates the direction of merging. (a) t = 0s, (b) t = 2s, (c) t = 4s, (d) t = 6s, and (e) t = 8s

Figure 6.shows the sequence of few frames taken during the merging of plumes when the supplied heat flux (Q) is 65Wm^{-2} and water level at 50mm. Using a Matlab code, the change in distance between the plumes was estimated.
Figure 7 and 8 also shows the sequence of merging when the supplied heat fluxes are 260Wm^{-2} and 2340Wm^{-2} respectively and water level at 50mm. It is also observed that for a given Aspect Ratio (AR=6) which is defined as the ratio of tank width to liquid height, the merging rate is proportional to the supplied heat flux.
From the known time difference between the frames, the change in distance between the two parallel merging plumes

was plotted as a function of time. For AR=6, Fig.9 shows the change in plume spacing (λ) with respect to time for different heat flux supplied. It is evident from the graph that at higher heat flux the plumes merged faster when the initial spacing is nearly the same.

As it has been shown from the earlier experiments [4], for constant heat flux the effect of AR on the near wall structure is negligible.
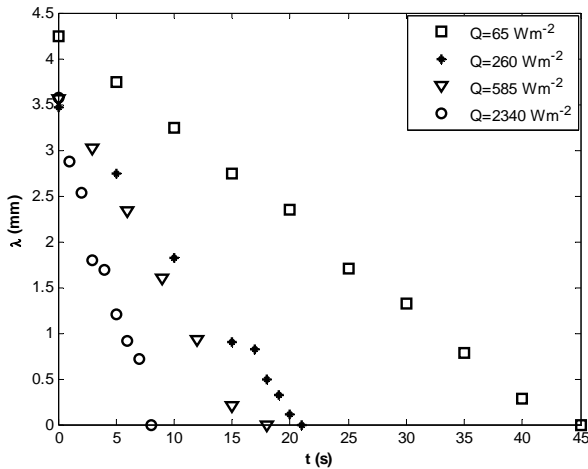

Fig.9. Change of plume spacing with time for different heat flux supplied.

Figure.10 shows the change in plume spacing with time during merging for three different AR= 6, 3 and 2 when the supplied heat flux is 2340Wm^{-2}. For nearly the same initial plume spacing, the rate of change of λ is the same for all the three AR. The change of λ with time for different Ra is shown in Fig.11. As mentioned in the earlier studies [4] it was observed from the visualization that the large scale flow restricts the horizontal movement of the plumes there by delaying the merging of plumes at higher Ra.
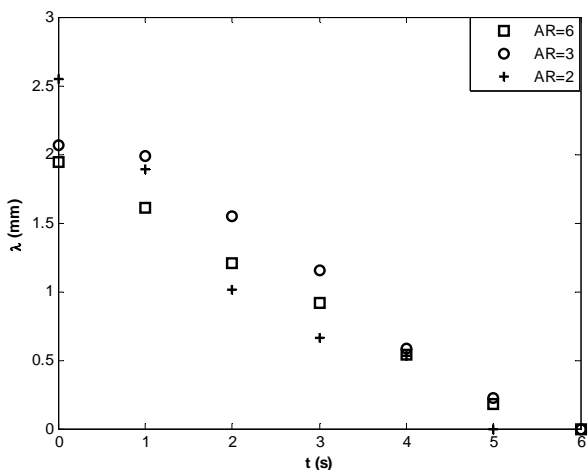

Fig.10. Change of plume spacing with time for three different Aspect ratio (AR=6, 3 and 2) when the supplied heat flux is 2340Wm^{-2}.
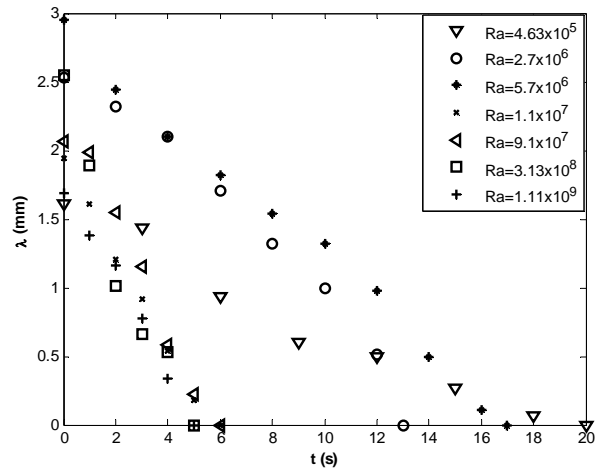

Fig.11. Change of plume spacing with time for different Ra.

IV. CONCLUSIONS

Visualizations showed that, plumes were created randomly over the heated surface at periodic intervals and moved horizontally in the direction of the bulk flow to align themselves. During alignment, the plumes moved closer and merged with the neighbouring plumes. We have observed that the merging rate increased with the increase in heat flux. However, due to the local shear, the merging rate was decreased even at higher heat flux. As the effect of AR is insignificant with respect to the near-wall structure, their effect on merging rate was also found negligible. Though it was expected that the induced flow created between the plumes was the reason for the plumes horizontal movement, the actual cause needs to be investigated.

V. REFERENCES

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