MERGING OF SHEET PLUMES IN TURBULENT CONVECTION

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ABSTRACT
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 formation of sheet plumes very close to the heated surface. The rising sheet plumes also merge laterally, presumably due to the entrainment flow into the plumes. We study the merging dynamics of two parallel sheet plumes by measuring the lateral velocities at different times of their merging, at different heat fluxes and aspect ratios. We observe that the merging rate increase with the increase in heat flux. The effect of aspect ratio on merging rate is found to be negligible for constant heat flux. Due to the local shear created by the large scale flow the merging rates decreased.

Key words: turbulent convection, sheet plumes, merging.

INTRODUCTION
Natural convection over horizontal surfaces has been studied in simple geometries to understand the nature of buoyancy induced turbulence. These flows abound in nature and have major technological applications. Effectiveness of many engineering processes such as electronics cooling and chemical vapour deposition is decided by the natural convection dynamics near the horizontal heated surfaces. Due to the strong density gradients created over the heated surface, convection with continuous rising columns of buoyant fluid called “plumes” occur. Various theories of turbulent natural convection approximate the near-wall region as turbulent shear boundary layer [Castaing et al, 1989], mixing zone [Siggia, 1990], Balsius boundary layer [Grossmann & Lohse, 2000]. The Rayleigh number (Ra = gβΔT^3/ν), a ratio of buoyancy to dissipative effects and the Prandtl number (Pr= ν/α), a fluid property defined as the ratio of momentum to thermal diffusivity characterize such flow regimes. Here g = the acceleration due to gravity, β = the thermal expansion coefficient, ΔT = the temperature difference between the walls, D = the height of the fluid layer, α = the thermal diffusivity and ν = the kinematic viscosity. However, visualization results presented [Puthenveettil and Arakeri, 2005] 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.
Figure 1 shows one such planform obtained at $Ra = 2 \times 10^{11}$. The lines in the figure are the top view of these rising sheets of lighter fluid. It was also observed that the instantaneous structures formed due to the dynamics of these sheet plumes at different Ra number have a common multi-fractal nature. 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. The number of sheet plumes increases with increase of Rayleigh number. Figure 2 shows the schematic diagram of turbulent convection over a horizontal heated surface. Visualizations [Haramina. T & Tilgner. A., 2004] 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 [Kerr, 1996] also confirmed the formation of sheet plumes near the wall. The rising sheet plumes also merge laterally, presumably due to the entrainment flow into the plumes. Puthenveettil and Arakeri also showed that the effect of near wall shear was to restrict the horizontal movement and merging of sheet plumes. The near-wall transport and the distribution of velocity and temperature in turbulent convection are critically dependent on this plume dynamics. The problem of interest is to quantitatively understand this sheet plume dynamics, and its dependence on the relevant non-dimensional parameters Ra, Pr and AR so as to predict the phenomena in turbulent convection in a better way. 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 merging dynamics of sheet plumes in natural convection over horizontal heated surface. An electro-chemical technique [Baker, 1966] is used to observe the variation of plume spacing with time. This paper is organized as follows. ‘Experiments’ heading gives the details of experimental setup and the conduct of experiments. Experimental results followed by discussions are presented in ‘Results and Discussion’ heading.

EXPERIMENTS

The set up for the horizontal plate convection is shown in the Fig 3. It consists of an open tank of size 300x300x250 mm with four glass side
walls. The bottom hot plate is 10mm thick and made of copper. The top surface of the copper plate is coated with a chromium layer of 30 micron thickness to avoid corrosion due to the acidic dye solution used for the visualization experiment. 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. Knowing 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 layer depths of 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 are kept at 260, 585, 1039, 1625 and 2340 W/m^2. A total of 14 T type 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). From these thermocouples, a maximum deviation from uniformity of surface temperature of 0.05°C is observed. 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

![Diagram of the experimental setup](image-url)
used to get the average data for every minute. The heat flux supplied to the bottom plate is calculated using the temperature difference across the glass plate. Since the convection in open tank is unsteady, the heat flux transferred to the convecting water layer is calculated using the temperature difference ($\Delta T$) between the plate $T_w$ and the ambient fluid $T_\infty$ after it reaches a steady state (Fig. 4).

**Visualization**

The visualization of near-wall coherent structures, the sheet plumes, is done using an electro chemical dye technique [Baker, 1966]. 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, located at 5 cm away from the bottom plate, 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 planforms 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.

**RESULTS AND DISCUSSION**

The top view of the near-wall structures for different heat flux supplied ($q$) and water level ($D$) are shown in Fig. 5.

**Fig. 4.** Variation of temperature difference between the bottom plate ($T_B$) and water ($T_\infty$) when the heat flux ($q$) supplied to the heater is $2340 \text{ Wm}^{-2}$ and water level at $200 \text{ mm}$.

**Fig. 5.** Plan view of near wall sheet Plume structure for different Rayleigh Numbers

(a) $q = 65 \text{ W/m}^2$, $AR = 6$, $Ra = 4.63 \times 10^5$,
(b) $q = 260 \text{ W/m}^2$, $AR = 6$, $Ra = 2.70 \times 10^6$,
(c) $q = 2340 \text{ W/m}^2$, $AR = 6$, $Ra = 1.1 \times 10^7$,
(d) $q = 585 \text{ W/m}^2$, $AR = 3$, $Ra = 5.1 \times 10^7$,
(e) $q = 1040 \text{ W/m}^2$, $AR = 2$, $Ra = 2.14 \times 10^8$ and
(f) $q = 4150 \text{ W/m}^2$, $AR = 1.5$, $Ra = 1.1 \times 10^9$
Fig. 6 Plume merging sequence at $q = 65 \text{ Wm}^{-2}$, AR= 6 and Ra=4.63x10^5. The arrow indicates the direction of merging. (a) $t = 0\text{s}$, (b) $t = 40\text{s}$ and (c) $t = 70\text{s}$

Fig. 7. Plume merging sequence at $q = 260 \text{ Wm}^{-2}$, AR= 6 and Ra=2.7x10^6. (a) $t = 0\text{s}$, (b) $t = 12\text{s}$ and (c) $t = 18\text{s}$

The Aspect Ratio (AR) corresponding to the planforms shown in the caption is defined as the ratio of width of the tank to liquid layer height.

Fig. 8. Plume merging sequence at $q = 2340 \text{ Wm}^{-2}$, AR=6 and Ra=1.1x10^7. (a) $t = 0\text{s}$, (b) $t = 4\text{s}$ and (c) $t = 8\text{s}$.

It is seen clearly from the images that at lower Ra, cell type of structures are formed which then transform to aligned line like structures at higher Ra. The alignment of plumes is in the direction of the large scale flow [Puthenveettil and Arakeri, 2005]. Figures 6, 7 and 8 show the sequence of few images taken during the merging of plumes when the heat fluxes ($q$) are 65Wm^{-2}, 260Wm^{-2} and 2340Wm^{-2} respectively and water level at 50mm. In the cell type structure Fig.6, the sheet plumes move randomly in the horizontal direction to merge with the neighbouring plumes. In aligned line structures Fig.8, the sheet plumes are aligned in the direction of the large scale flow and merge with the nearby plume. From the recorded video, merging of two nearly parallel plumes separated initially by some minimal distance $\lambda$ was identified. The video clip was then split into frames of known time intervals. From each frame the coordinates of the plumes were fed using mouse clicks into a Matlab code to determine the plume
spacing at different interval of time. 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 variation of plume spacing ($\lambda$) with respect to time for different heat flux. It is evident from the graph that for the same initial spacing the plumes merged faster at higher heat flux.

![Graph showing change of plume spacing with time for different heat flux at AR=6.](image)

Fig.9. Change of plume spacing with time for different heat flux at AR=6. The planforms of the merging sequence are given in Fig.6, 7 and 8.

It is also observed that for a given Aspect Ratio (AR=6) the merging rate is proportional to the supplied heat flux. Figure.10 shows the alignment of plumes due to the local shear created by the large scale flow. These large scale flows are driven by plume columns rising from a corner or side towards which the plumes are swept by the large scale flow itself. It is also observed that the predominant motion of the plume due to the mean shear occurs along the plume length. Change in the position of the plumes apart from lateral merging, relative to the wire mesh seen as thin lines in the image, confirms the existence of local shear. The planforms showing the merging sequence of nearby parallel plumes with and without the mean shear for the heat flux 2340 Wm$^2$ and AR=6 are shown in Fig.11.

![Alignment of plumes due to local shear created by large scale flow at q=2340 W/m$^2$, AR=1.5 and Ra=1.19x10$^9$.](image)

Fig.10. Alignment of plumes due to local shear created by large scale flow at q=2340 W/m$^2$, AR=1.5 and Ra=1.19x10$^9$. The arrows in the image show the direction of local shear due to the large scale flow.

![Plume merging sequence at q = 2340 W/m$^2$, AR = 6 and Ra=1.1x10$^7$. Images (a) t = 0s, (b) t = 3s and (c) t = 5s show the variation of plume spacing without local shear where as images (d) t = 0s, (e) t = 6s and (f) t = 10s show the variation of plume spacing with local shear.](image)

Fig.11. Plume merging sequence at q = 2340 W/m$^2$, AR = 6 and Ra=1.1x10$^7$. Images (a) t = 0s, (b) t = 3s and (c) t = 5s show the variation of plume spacing without local shear where as images (d) t = 0s, (e) t = 6s and (f) t = 10s show the variation of plume spacing with local shear.
Images (a), (b) and (c) of Fig.11 shows the merging of two neighbouring plumes where the effect of mean shear is negligible. It is seen from the images that there is no lengthwise movement of the merging plumes with reference to the wire mesh. Whereas, images (d), (e) and (f) shows the plume movement in the lengthwise direction due to the local shear created by the large scale flow apart from merging. This also confirms that mean shear affects the near wall structure for Rayleigh numbers (Ra>10^7) when the cell like structure is transformed to aligned plume like structure [Theerthan & Arakeri, 2000].

Figure.12 shows the change in plume spacing with time during merging for three different AR= 6, 3 and 2 when the supplied heat flux is 2340W/m^2. For nearly the same initial plume spacing, the rate of change of λ is the same for all the three AR. Hence, for constant heat flux the effect of AR on the near wall structure is negligible.

The change of plume spacing λ with time due to mean shear is shown in Fig.13. As mentioned in the earlier studies [Puthenveettil and Arakeri, 2005] it is shown in the Fig.13, that the mean shear created by the large scale flow restricts the horizontal movement of the plumes there by delaying the merging of plumes at higher Ra. Figure.14 shows the log-log plot of the variation of plume merging rate \((\lambda_{\text{int}} - \lambda_{\text{fin}}) / \Delta t\) with Rayleigh number (Ra) for different heat fluxes q = 65W/m2, 585W/m2, 2340 W/m2 and 4150W/m2 and aspect ratios AR = 6, 3, 2 and 1.5 respectively. The plume merging rate is found to increase with the increase in Rayleigh number.

The correlations based on the power law fit are \(\dot{\lambda} = 0.0024Ra^{0.27}, \dot{\lambda} = 0.001Ra^{0.33}\). The inset shows the variation of \(\dot{\lambda} * Zw/\nu\) with Ra.
From the power-law fit, correlation for the plume merging rate with Rayleigh number was obtained as $\lambda = 0.0024 \text{Ra}^{0.27}$. As the plume merging rate is mostly dependent on the heat flux, the experimental merging rate data was also checked for $\text{Ra}^{1/3}$ fit. $\lambda = 0.001 \text{Ra}^{0.33}$ correlation obtained from above fit matched with the flux scaling of $\text{Nu} \sim \text{Ra}^{1/3}$ from the theory. The inset in Fig.14 shows the variation of normalized merging rates with Rayleigh number. From the non-dimensional momentum equation, the plume merging rate $\lambda$ was found to scale as plume velocity $V_c$. This velocity scale $V_c$ is obtained from the plume vertical velocity expression given by the similarity solution of Gebhart, 1969. When the plume velocity $V_c$ is normalized by $v/\text{Z}_w$, it gives the near wall Reynolds number which is a constant for a given fluid. As $\lambda$ is proportional to $V_c$, the normalized $\lambda$ with $v/\text{Z}_w$ was also found to be constant and scale as $\text{Ra}^{1/3}$. However, it is seen from the graph that normalized $\lambda$ is constant only at lower Ra but increase slightly at higher Ra. This could be due to the other effects of mean shear in the direction perpendicular to the plume length axis. Even though it contradicts the earlier statement that mean shear retards the merging rate, it is observed from the visualization that there are regions on the plate where the mean shear created by the large scale flow sweeps the plume in the lateral (perpendicular to plume length) direction also.

**CONCLUSIONS**

Visualizations showed that, plumes are generated randomly over the horizontal heated surface. At lower Ra=$10^5$ cell like structures are formed near the wall which are transformed to aligned line structure at moderately high Ra=$10^7$. Plumes move horizontally and merge with the neighbouring plumes. The merging rate increased with increase in heat flux. However, at higher flux, due to the mean shear created by the large scale flow, the horizontal movement of the plumes was restricted in most of the regions which delayed the plumes merging rate. In some regions where the merging plumes are oriented perpendicular to the direction of mean shear, the plumes merged faster as they are swept away by the mean shear. However, this needs further analysis considering the magnitude of the local shear created locally by the large scale flow. Since the effect of aspect ratio is negligible on the near-wall structure, their effect on plume 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.

**REFERENCES**