DYNAMICS OF SHEET PLUMES IN TURBULENT CONVECTION

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Summary We present experimental measurements of merging velocities of sheet plumes near horizontal surfaces in turbulent convection. We show that the mean velocities of merging increase with increase in near-wall Rayleigh number (Ra_w) . The mean merging velocities are shown proportional to the plume rise velocities, i.e. the dimensionless rate of merging $\frac{d\lambda}{dt}(\frac{Z_w}{\nu})$, equal to a near-wall Reynolds number (Re_w) is a constant for a given Pr.

INTRODUCTION

Rising sheets of hot fluid, often described as sheet plumes or line plumes, are the commonly observed near-wall coherent structures in turbulent convection over hroizontal surfaces [1],[2]. These sheet plumes form and merge over the horizontal surface and at any instant result in a complex pattern of coherent structures [1]. These plume structures exhibit a common fractal nature [1] implying a possible commonality in their dynamics at all Rayleigh number (Ra). The external shear created by the large scale circulation modifies these dynamics by aligning the plumes in the direction of shear. Understanding this predominant near-wall dynamics in turbulent convection, is important in defining wall functions in turbulence modelling. In addition, since the line plumes transport most of the heat from the plate [5], quantifying the dynamics of these structures near the wall will help in understanding the flux scaling in turbulent convection. In the present study, we present measurements of merging velocities of sheet plumes near the horizontal surface in turbulent convection in the range of $10^5 < Ra < 10^9$ for $Pr = 0.74$ and 5.2. We then propose scaling laws for the mean merging velocities of near-wall sheet plumes.

PLUME MERGING RATES

Figure(1) shows the planforms of sheet plumes observed near the wall in temperature driven convection in water and air at $Ra_w = 1.1 \times 10^7$ and $Ra_w = 2.5 \times 10^8$ respectively. Here, $Ra_w = \frac{g\beta\Delta T_w H^3}{\alpha\nu}$ is the Rayleigh number based on the near-wall temperature difference ΔT_w and is equal to $Ra/2$. The dark lines seen in the images are the sheet plumes. The planforms in water are obtained by electrochemical visualization [4] from unsteady, temperature driven, convection in a 30cm $\times$ 30cm tank. The planforms in steady, temperature driven, convection of air confined between two 250cm $\times$ 50cm horizontal plates are obtained due to the scattered light from smoke particles when a horizontal laser sheet is passed grazing the bottom plate. Figure 1(a, b and c) shows the stages of plume merging in water for $\xi = 6$ where, ξ is the aspect ratio defined as the ratio of length (L) of the tank to the height(H) of the fluid layer and heat flux $q = 2340W/m^2$. Figure 1(d,e and f) shows a similar sequence in air for $\xi = 5$ and heat flux $q = 57.64W/m^2$. In such planforms, two adjacent and parallel plumes that are merging are identified and the change in spacing between the two plumes as a funcion of time is measured. The measurement is made by using a program that takes the coordinates of the line plumes from successive image frames from mouse clicks and then estimates the rate of change of spacing between the merging plumes. Similar sequences of plume merging are identified at the same Ra_w at different times or different locations in the planforms, using which multiple measurements of merging velocities at the same Ra_w are obtained.

Figure 2(a) shows the mean velocity of merging of sheet plumes $\bar{V_m} = \frac{\bar{d\lambda}}{dt}$ as a function of Ra_w; the mean being calculated from the multiple measurements at the same Ra_w. Here, $\frac{d\lambda}{dt}$ is the rate of change in spacing between the two merging plumes. This figure shows that the mean velocities of merging increase with increase in Ra_w for a given fluid. It could also be noticed that the plumes merge faster in air compared to that in water at the same Ra_w. We assume that the mean velocity of merging $\bar{V_m}$ is proportional to the vertical centerline velocity V_c of the plume at a height of $40Z_w$ given by the expression $V_c = C_0(\frac{g\beta q}{C_p})^{2/5}(\frac{Z_w}{\mu\rho})^{1/5}$, Gebhart et al.(1969); where $Z_w = (\frac{\alpha\nu}{g\beta\Delta T_w})^{1/3}$ is a near wall length scale. This characteristic velocity V_c, which is a function of heat flux, indirectly determines the merging velocities of sheet plumes. Using the expressions $Nu = 0.07Ra^{1/3}Pr^{-0.02}$ and $\frac{\bar{\lambda}}{H} = 47.5\frac{Pr^{0.1}}{Ra_w^{1/3}}$, Puthenveettil et al.(2011), the near-wall Reynolds number $(Re_w = V_c Z_w/\nu)$, is then obtained as $Re_w = 3.99Pr^{-0.75}$. Figure 2(b) shows that the non-dimensional mean merging velocity of plumes $\bar{V_m}Z_w/\nu = 1.176Pr^{-0.75}$ obtained from the measurements is a constant for the two fluids at all Ra_w. Note that the measured $\bar{V_m}Z_w/\nu$ equal to the near-wall Reynolds number Re_w has the same Pr dependence as that of the derived Re_w but with slightly different prefactor . Since $Z_w = H/Ra_w^{1/3}$, the Reynolds number $(Re_H = V_c H/\nu)$ is obtained as $Re_H = 3.16Ra_w^{1/3}Pr^{-0.75}$. Figure 2(c) shows the variation of $\bar{V_m}H/\nu$ with Ra_w and the expression based on the measurements is given as $\bar{V_m}H/\nu = 0.97Ra_w^{1/3}Pr^{-0.7}$. It is seen that $\bar{V_m}H/\nu = Re_H$, scales as $Ra_w^{1/3}$ and has the same Pr dependence. Using the flux relation [6], the expression for Nu obtained in terms of Re_H is $Nu = 0.025Re_H Pr^{0.73}$. Figure 2(d) shows the dependence of dimensionless mean velocity of merging of plumes on Nu. This figure showed that $\bar{V_m}H/\nu = Re_H$ is proportional to the flux supplied for a given fluid. The resulting expression from the experiment $Nu = 0.12Re_H Pr^{0.73}$ is found to match with the derived relation with slightly higher

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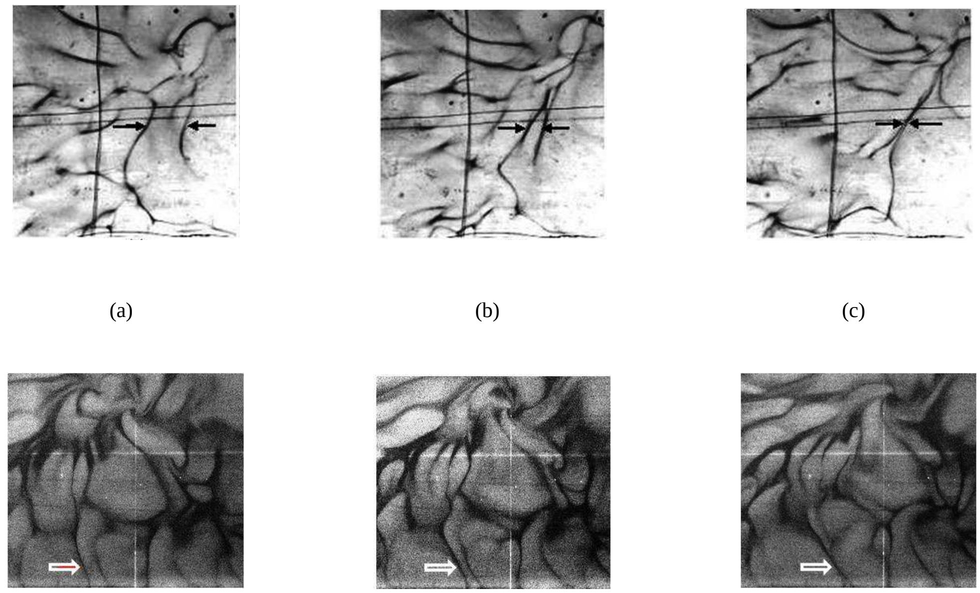
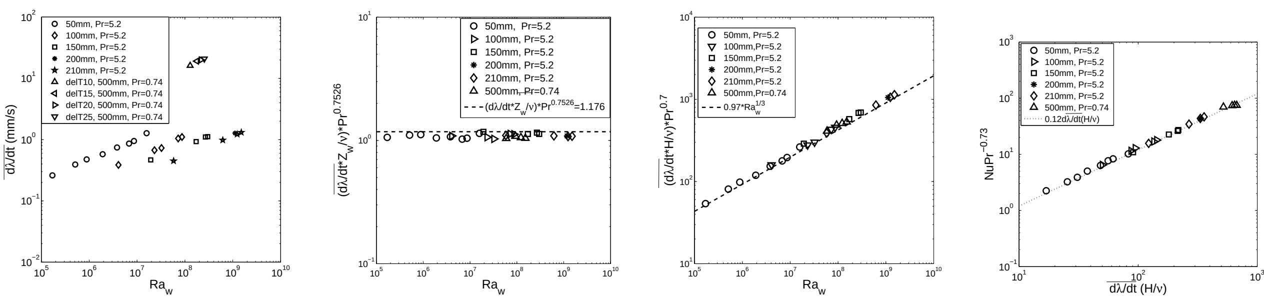


(a) (b) (c)

(d) (e) (f)

Figure 1. Sequence of plume merging indicated by arrow for $Pr = 5.2$ at $Ra_w = 1.1 \times 10^7$ and $q = 2340W/m^2$;(a) t=0s, (b) t=4s and (c) t=8s and $Pr = 0.74$ at $Ra_w = 2.542 \times 10^8$ and $q = 57.64W/m^2$; (d) t=0s, (e) t=2.5s and (f) t=4.5s.



(a) (b) (c) (d)

Figure 2. (a) Variation of mean velocities of merging of plumes with Ra_w for $Pr = 0.74$ and 5.2 (b) Variation of dimensionless mean merging velocities $\bar{V_m}$ with the near-wall Ra_w for $Pr = 0.74$ and 5.2 (c) Variation of Reynolds number Re_H with Ra_w (d) Dependence of Nusselt number Nu on Re_H

prefactor. We expect that the differences in the prefactors between the measured and the derived relations to be due to the uncertainities in the prefactor values used in the flux and the mean plume spacings relations.

CONCLUSIONS

Mean velocities of merging of plumes increase with increase in Rayleigh number. The mean merging velocities is proportional to the vertical centerline velocity of laminar sheet plumes. The near-wall Reynolds number Re_w is a constant and while Re_H scales as $Ra_w^{1/3}$. The dimensionless mean velocity of merging of plumes are directly proportional to the Nusselt number for a given fluid.

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