Non-equilibrium Turbulence Effect on Plumes

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Plumes are persistent vertical fluctuating motions originated from localized buoyancy source, and ubiquitously observed convective elements at high Rayleigh numbers. The plume flow direction is along the large-scale gradient of density and temperature, in this sense, plumes are similar to streamers in fusion plasmas.

In the stellar convection, negatively buoyant plumes generated by the surface cooling play a crucial role in turbulent mixing of mass and heat. The properties of turbulence and its transport are fairly different between the convection locally driven by the entropy gradient in the whole region (locally-driven convection) and the counterpart non-locally driven by the strong cooling at the surface (non-locally-driven convection).[1,2] The horizontal structure of the convective cells is much larger in the locally-driven case, and the plume motions are prominent at the near-surface region in the non-locally driven case (Figure 1).

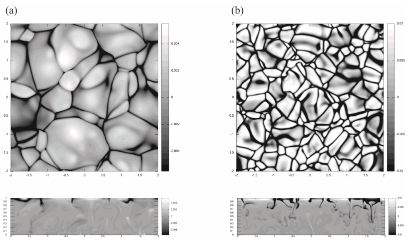

Figure 1: Entropy contours obtained from DNSs for (a) the locally driven and (b) the non-locally driven convections. Horizontal cut (upper) and vertical cut (lower).

The direct numerical simulations (DNSs) showed that the turbulent transport represented by the turbulent mass and turbulent internal-energy fluxes is much larger as a whole, and much localized in the near surface region in the non-locally driven cases.[2] These properties of turbulence and its transport could not be reproduced by the usual turbulence model based on the gradient diffusion approximation with mixing-length theory.

Temporal variation of turbulence properties along the mean motions is one of the representative non-equilibrium effects. In the framework of the multiple-scale direct-interaction approximation, where the response-function formulation is adopted, the non-equilibrium effect is incorporated through the advective or Lagrangian derivative of the velocity fluctuations. In this framework, the length scale of turbulence is expressed in terms of K and ε and their Lagrangian derivatives. With this non-equilibrium effect, for example, the eddy viscosity is expressed as

$$\nu_{\rm T} = \nu_{\rm E} \left(1 - C_{\rm N} \frac{1}{K} \frac{D}{Dt} \frac{K^2}{\varepsilon} \right), \qquad (1)$$

where $\nu_{\rm E}$ is the equilibrium eddy viscosity.

In order to capture the plume motions, we adopt a time-space double averaging procedure, With this formulation, a field quantity f is divided into three components: the spatial average of the time average $\langle \overline{f} \rangle$, coherent fluctuation $\widetilde{f}$, and incoherent fluctuation f'' as

$$f = \overbrace{\langle \overline{f} \rangle + \underbrace{\widetilde{f}}}^{\overline{f}}\underbrace{+ f''}_{f'}. \qquad (2)$$

The energy transfer between the coherent and incoherent fluctuation energies are mediated by

$$P_{K''} = - \left\langle \widetilde{u''^j u''^j} \frac{\partial \widetilde{u}^i}{\partial x^j} \right\rangle = - P_{\widetilde{K}}, \qquad (3)$$

where $P_{K''}$ and $P_{\widetilde{K}}$ are the gains of the incoherent and coherent fluctuation energies due to the transfer. Equation (3) shows that *the shear of the coherent or plume motions* coupled with the incoherent or random fluctuations determines the energy transfer between the plume and random fluctuations (Figure 2).

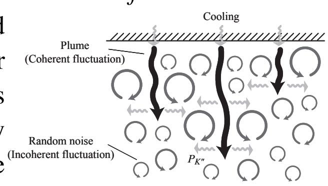

Figure 2: Interaction between the coherent and incoherent fluctuations.

The turbulent internal energy flux is modeled as

$$\langle e' \mathbf{u}' \rangle = -\kappa_{\rm E} (1 - C \langle \overline{\rho} \rangle^{-1/3} \Lambda) \nabla E, \qquad (4)$$

where $\langle \overline{\rho} \rangle$ is the ambient mean density, C is the model constant, and Λ is the non-equilibrium effect factor defined by

$$\Lambda = (\widetilde{\mathbf{u}} \cdot \nabla) \langle \overline{\mathbf{u}'^2} \rangle. \qquad (5)$$

Here, $\kappa_{\rm E}$ is the equilibrium turbulent internal-energy diffusivity.

In Figure 3, the spatial distributions of the turbulent internal-energy flux $\langle e' \mathbf{u}' \rangle$ obtained from the DNSs and the turbulence model with the non-equilibrium effect are shown. We see that the non-equilibrium model well reproduces the DNS result for the non-locally driven convection, which cannot be reproduced by the standard gradient-diffusion model with the mixing-length theory.

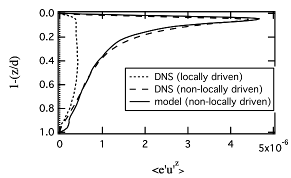

Figure 3: Spatial distribution of the turbulent internal-energy

References

[1] N. Yokoi, Y. Masada, and T. Takiwaki, Mon. Not. Roy. Astro. Soc., **516**, 2718 (2022)
[2] N. Yokoi, Atmosphere, **14**, 1013 (2023)