A Tokamak Scrape-off Layer Model Based on Turbulent Thermal Convection

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The control of tokamak SOL heat flux is one of the most important issue in magnetic confinement fusion research. To make the heat flux tolerable for divertor targets, the heat flux width λ_q, defined as the radial position where the parallel heat flux reduces to $1/e$ of its value at separatrix, is expected to be large enough. A well-known model for λ_q is Goldston's heuristic drift (HD) model[1], which agrees well with experiments[2] and predicts a discouraging value of $\lambda_q \sim 1mm$ for future devices such as ITER. However, HD model does not take SOL instability and turbulence into account, which may not be the case for future devices with higher SOL influx. A more comprehensive study of SOL modelling is certainly needed.

We note that the scenario of SOL is similar to the boundary layer of Rayleigh-Benard convection, i.e., they both have sharp temperature gradients, and the centrifugal force induced by magnetic curvature is analogous to gravity. If the boundary layer is turbulent, the perpendicular convective heat transport is expected to widen the heat flux width. We adopt a flux-driven reduced fluid model containing the evolution of vorticity and temperature under Boussinesq approximation:

$$\frac{\partial T_0}{\partial t} + C_2\langle \tilde{\boldsymbol{v}}_E \cdot \nabla \tilde{T}\rangle = \nabla_\parallel^2 T_0 + \nabla \cdot \boldsymbol{S} \qquad (1)$$

$$\frac{\partial \tilde{T}}{\partial t} + C_2\left[\boldsymbol{v}_E \cdot \nabla \tilde{T} + \tilde{\boldsymbol{v}}_E \cdot \nabla T_0 - \langle \tilde{\boldsymbol{v}}_E \cdot \nabla \tilde{T}\rangle\right] + C_2 \frac{\partial \tilde{\phi}}{\partial y} \cdot \frac{\mathrm{d}T_0}{dx} = \nabla_\parallel^2 \tilde{T} \qquad (2)$$

$$\frac{\partial}{\partial t}\tilde{\omega} + C_2[(\boldsymbol{v}_E \cdot \nabla)\tilde{\omega}] = -C_1 \frac{\partial}{\partial y}\tilde{T} + Pr\nabla_\perp^2 \tilde{\omega} \qquad (3)$$

where T_0 is the mean temperature, a tilde stands for perturbation, $< \cdots >$ denotes poloidal average, C_1 and C_2 are constants due to normalization, $Pr = \nu/\chi_\parallel$ is the Prandtl number and $\boldsymbol{S}$ is the source term. Note that we only consider parallel temperature dissipation since it is much larger than the perpendicular one. Also, $\boldsymbol{v}_E = \boldsymbol{v}_{E0} + \tilde{\boldsymbol{v}}_E$ where $\boldsymbol{v}_{E0}$ is the shear flow induced by sheath boundary condition at the divertor target, i.e., $v_{E0} = -d\Phi_0/dx = 3dT_0/dx$.

First, we analyze the linear stability of this system and give a threshold for instability or turbulence to occur, similar to Rayleigh number in classical Rayleigh-Benard convection. Then we obtain some scaling laws of temperature and vorticity using similar methods in classical turbulent boundary layer theory [3]. To verify these scaling laws, we perform numerical simulations where the initial mean temperature profile is exponentially decaying and the dissipation coefficients are chosen to be the typical values in SOL. Results show that the final stationary mean temperature profile can be divided into a viscous layer where T_0 falls linearly and a turbulent layer where T_0 follows log-law. The convective heat flux is significantly enhanced in turbulent boundary layer, indicating the widening of a properly defined heat flux width.

References

[1] R.J. Goldston, Nucl. Fusion 52 (2012), 013009.
[2] T. Eich et al, Nucl. Fusion 53 (2013) 093031.
[3] R. H. Kraichnan, Phys. Fluids 5, 1374 (1962).

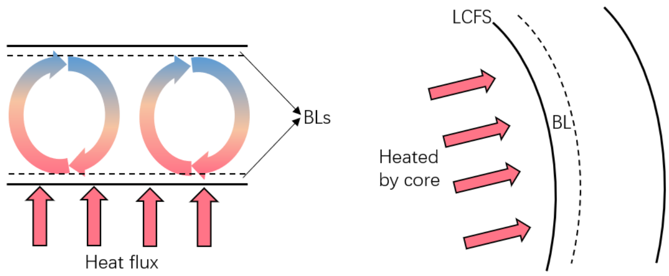

Figure 1. A comparison between classical Rayleigh-Benard convection (left) and SOL (right).

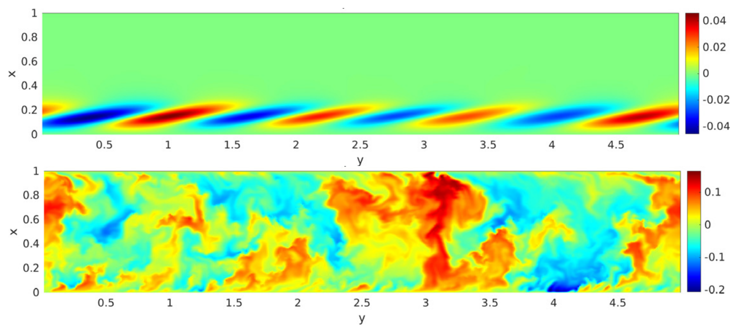

Figure 2. Simulation results of temperature perturbation contour where x is the radial coordinate and y is the poloidal direction. Top: linear growing phase, the modes are tilted by shear flow. Bottom: nonlinear turbulent state, where the ejection of plumes and the significant increase of convective heat transport are observed.