Theoretical evaluation of turbulent heat transfer for arc plasma in SF_6 flow

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Abstract: The quenching heat flux due to turbulence with density fluctuation (TDF) around arc plasma in a SF_6 flow is evaluated theoretically and quantitatively. Although the arc plasma has a large temperature gradient causing a large heat flux due to conduction at its fringe, that due to TDF is more dominant for transporting the thermal energy outward.

1. Introduction

SF_6 (sulfur hexafluoride) gas offers extremely short time for arc plasma extinction in high-voltage gas-blast circuit breakers. Our experiment [1] and numerical simulation [2] suggested that turbulent vortices played a significant role for arc plasma quenching by mixing cold gas into arc plasma effectively. Until now, there has been no report to evaluate the quenching heat flux due to turbulence with density fluctuation (TDF) which occurs around arc plasma.

This study evaluates it theoretically and quantitatively using the numerical data which were obtained by a two-dimensional axisymmetric simulation of an SF_6 flow including an arc plasma in a model-type cylinder [2].

2. Mathematical operation

Physical quantities fluctuate temporally with velocity fluctuation of turbulence. Herein, a general variable ϕ is separated into the time average $\bar{\phi}$ and the fluctuation ϕ' as

$$\phi = \bar{\phi} + \phi'. \qquad (1)$$

The time average of the fluctuation is zero, $\overline{\phi'} = 0$.

ϕ is also separated using the density-weighted time average $\tilde{\phi}$ defined as

$$\tilde{\phi} = \frac{\overline{\rho\phi}}{\bar{\rho}}, \qquad (2)$$

with the density ρ and the fluctuation ϕ'' as

$$\phi = \tilde{\phi} + \phi''. \qquad (3)$$

Using equations (1) and (3), taking the time averages with the relations of $\overline{\phi'} = 0$, $\bar{\bar{\phi}} = \bar{\phi}$, and $\bar{\tilde{\phi}} = \tilde{\phi} = \frac{\overline{\rho\phi}}{\bar{\rho}}$ yields

$$\overline{\phi''} = -\frac{\overline{\rho'\phi'}}{\bar{\rho}}. \qquad (4)$$

We set $\phi = C_p T u_r$; herein, C_p, T, and u_r denote specific heat at constant pressure, temperature, and radial component of velocity, respectively. The net radial heat flux due to TDF can be evaluated as

$$\dot{q}_r^{(\mathrm{TDF})} = \overline{\rho'(C_p T u_r)'} = -\bar{\rho}\,\overline{(C_p T u_r)''}. \qquad (5)$$

It is noteworthy that the net radial heat flux due to turbulence without density fluctuation is zero because of $\bar{\rho}\,\overline{(C_p T u_r)'} = 0$. Meanwhile, the net radial heat flux due to conduction is evaluated as

$$\dot{q}_r^{(\mathrm{cond})} = -\lambda\overline{\frac{\partial T}{\partial r}}, \qquad (6)$$

where λ and r stand for thermal conductivity and radial position, respectively. For these fluxes, positive values are interpreted as heat losses outward from the central region including the arc plasma.

3. Results and discussion

Figure 1 shows the instantaneous thermo-fluid field obtained by our inhouse simulation code PLASTIPC (PLasma All-Speed Turbulence with Implicit Pressure Code) [2]. Using the numerical data, the distributions of the net radial heat fluxes due to the TDF and the conduction are obtained as shown in Fig. 2. To understand better, Fig. 3 shows the one-dimensional radial profiles extracted for the axial position of z = -10 mm.

The arc plasma has a steep temperature gradient causing a large heat flux of $\dot{q}_r^{(\mathrm{cond})}$ at its fringe, it is much smaller than $\dot{q}_r^{(\mathrm{TDF})}$. In the plasma fringe and outer of r > 0.7 mm, the heat flux due to TDF $\dot{q}_r^{(\mathrm{TDF})}$ is more dominant for transporting the thermal energy outward.

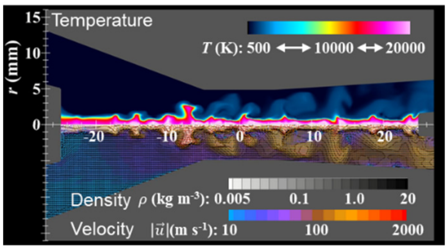

Fig. 1. Instantaneous thermo-fluid fields

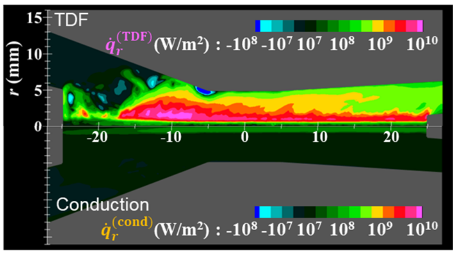

Fig. 2. Net radial heat flux distributions

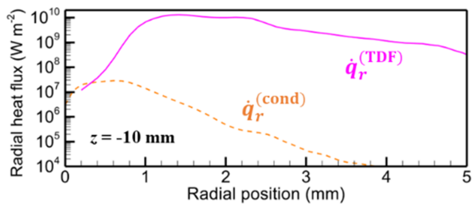

Fig. 3. Radial profiles of net radial heat fluxes

References

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