Assessing The Efficacy Of Inhomogeneous Thermal Conductivity To Enhance Heat Transfer Within Fusion Reactor Blankets

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Abstract

Poloidal blanket modules within magnetic confinement fusion reactors must generate tritium fuel and exhaust large thermal loads, while exposed to extreme temperatures at the plasma-facing wall. This necessitates the use of liquid metals, which exhibit rapid rates of thermal diffusion (Prandtl numbers of order 10^{-2}). As thermal energy is preferentially diffused, rather than advected, this work focuses on thinning the thermal boundary layer, by disrupting its formation, through inhomogeneity in the thermal conductivity of the wall. This also avoids any increase in viscous pressure drop.

The plasma-confining magnetic field introduces a great deal of complexity. The electrically conducting breeder liquid experiences a Lorentz force, $\boldsymbol{j} \times \boldsymbol{B}$, where $\boldsymbol{j}$ represents the current density, and $\boldsymbol{B}$ the magnetic field. The Lorentz force greatly increases the pressure drop, and equalizes velocities within the core of the duct, which results in a flat, slug flow velocity profile. To the further detriment of heat transfer, the Lorentz force suppresses turbulent mixing. Hence, within fusion reactor blankets, improving the efficiency of conduction may be more effective at enhancing heat transfer, as attempts to increase the convective velocity must overcome the strength of the magnetic field.

However, the heat flux directly applied by the plasma, as well as from absorption of neutrons into the breeder liquid, can locally drive high-velocity buoyant flows. Although the pressure drop still scales with the strength of the magnetic field, strongly buoyant flows provide an excellent means of highlighting the capabilities of inhomogeneous thermal conductivity. It is also highly relevant to the design of reactor blankets. The Richardson number, which quantifies the ratio of buoyant to inertial forces, may be of the order of magnitude of 10^{-4} (strongly inertial) to 10^{2} (strongly buoyant) for various blanket designs.

Simulations were performed with a spectral element solver employing the SM82 model, proposed for quasi-two-dimensional flows. Such an approximation is valid for reactor blankets as the strength of the magnetic field, and hence Lorentz force, causes rapid diffusion of momentum along magnetic field lines, enforcing two-dimensionality. The relative strengths of forced and natural convection were varied, in the Rayleigh number and interaction parameter ranges of $10^2 < Ra < 10^4$ and $100 < N < 1600$, which respectively govern the strength of buoyant to viscous, and electromagnetic to inertial, forces.

It was found that heat transfer was promoted when buoyant forces were sufficiently stronger than electromagnetic forces (low N, high Ra), when comparing a duct with reduced conducting area, to an unmodified duct, at the same blanket conditions (N, Ra). A peak Nusselt number ratio of $Nu_R = 3.5460$ was observed at $N = 100$, $Ra = 10^4$, with *6.25%* of the heated face conducting (*93.75%* insulating). As the natural convective velocity was found to linearly scale with the ratio of conducting to total area, this indicates that the efficiency of conduction requires significant improvement before convective effects (streamwise velocities) become the limiting condition. Furthermore, the effect of inhomogeneous thermal conductivity on pressure drop was also considered. The increase in pressure drop for a flow directed against gravity exactly matched that for a flow directed with gravity (with the same fraction of conducting area). For blankets with multiple ducts, this makes the system highly efficient. Overall, the application of inhomogeneous thermal conductivity can provide significant benefits to heat transfer; however, it remains highly dependent on the working conditions.

Key notice & instructions: oral presentation by C. J. Camobreco

Brief Biography

C. J. Camobreco is a first year PhD student, under the supervision of G. J. Sheard and A. Pothérat. He graduated from Monash University in 2017, with H1 Honours in a Bachelor of Aerospace Engineering. His PhD work is an extension of his FYP.

G. J. Sheard is an Associate Professor of Mechanical and Aerospace Engineering, and Director of the Sheard Lab at Monash University. He received his PhD from Monash University in 2004, winning the Faculty of Engineering Kenneth Hunt Medal and Monash Universities' Mollie Holman Doctoral Medal for the year's best PhD thesis, before securing an Australian Postdoctoral Fellowship. Dr. Sheard has authored over 150 research publications, editorials and patents, and has secured over $1.7 million in nationally competitive grant funding, including extensive time allocations on national high performance computing facilities.