Development of Helium-Cooled Tungsten Divertor Systems

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Background and Current Status

A major challenge in plasma-material interactions (PMI) is to develop ways to effectively remove the extremely high heat fluxes incident on plasma-facing surfaces in magnetic fusion energy (MFE) power plants. In most cases, the target plates of the divertor are subject to the most extreme conditions, with steady-state incident heat fluxes as great as 10 MW/m². Several solid tungsten (W) divertor designs, cooled by arrays of impinging helium (He) jets, have been proposed for these conditions. A nine-module assembly of the helium-cooled modular jet (HEMJ) design developed by the European Union (EU) and proposed for the EU DEMO has already been experimentally shown to withstand steady-state heat fluxes of 10 MW/m² over more than 1000 heating cycles [1], with current efforts focused on developing W alloys that can be used at lower temperatures [2].

Helium-cooled heat sinks have made remarkable progress starting from the first American experiments in 1993, and, at the time of the ReNeW report, were already as effective as water-cooled heat sinks, albeit in small-scale devices—a major accomplishment given that He has a thermal mass less than 1% that of water. Helium is considered to be an inherently safe coolant because of its chemical inertness and lack of neutron activation; moreover, “helium is the fluid of choice for a highly efficient, high-temperature Brayton cycle … and the closed cycle helps contain any tritium reaching the coolant” [3].

Over the last decade, a number of studies have shown that the steady-state thermal and structural performance of individual modules for a variety of divertor designs can be evaluated with reasonable accuracy under prototypical conditions using a combination of numerical simulations and experimental studies [4]. Moreover, initial studies suggest that significant heat transfer enhancement may be possible by incorporating porous materials, using new jet impingement designs, and increasing the area cooled by jet impingement using fins and grooves, for example, although these modifications may also increase coolant pumping power requirements.

Specific Proposal

There remain many questions and challenges for He-cooled W divertors, and a variety of alternative concepts, including sacrificial liquid-metal protection schemes [5; 6], have been proposed. Nevertheless, He-cooled W divertors, which are to date the only designs proven to have the required thermal performance, are at a stage where we should start to evaluate these designs in terms of their technological (vs. scientific) feasibility, and address the question posed in Thrust 11, Improve power handling through engineering innovation, of the ReNeW report: “How do we develop better PFC designs that operate at higher temperatures and can remove higher heat loads with adequate design margin?”
Evaluating the technological and scientific feasibility of helium-cooled solid-tungsten divertors will require research in three major areas:

**New materials and fabrication:** Manufacturing these modules with their complex geometries in tungsten, a brittle metal that is notoriously difficult to machine, on a massive scale—several hundreds to several hundred thousands for a single MFE reactor, depending on the actual design—poses major challenges. Developing new W composite materials and new methods for bonding such materials to structural materials (e.g. SiC, steel) could significantly improve the ductility of W-based armor without increasing its activation, or reducing its thermal conductivity. Emerging advanced manufacturing techniques (e.g. additive manufacturing, spark plasma sintering) could enable mass production of functionally graded W alloys in complex geometries, including grooved jet impingement surfaces or surfaces with monolithic fins. Investigating how such techniques could be used to improve current He-cooled W divertor designs—and simplify their manufacture—should be a priority of this effort.

**Large-scale thermal and structural performance:** Designing manifolds that will evenly distribute and supply coolant to a large number—again, in quantities ranging from several hundreds to several hundred thousands—of modules is also a major challenge. Moreover, there may be significant variations in the He flow rate between different modules due to flow instabilities, which would of course result in large variations in thermal stresses and cooling for different target plates. At present, the American fusion community has no helium flow facilities suitable for testing large arrays of heat sinks under conditions relevant to a MFE reactor (with mass flow rates exceeding 500 g/s and heating at prototypical incident heat flux values). Yet high-heat flux testing, especially of neutron-irradiated materials, and sub-components, is required to develop and evaluate new materials and advanced manufacturing techniques.

**Transient thermal and structural performance:** Although the steady-state thermal performance and resulting thermal stresses of these modules have been evaluated at prototypical conditions (albeit in the absence of neutron irradiation), there has been far less testing of these modules at higher transient heat flux values. Given that off-normal events may expose the divertor target plates to heat fluxes as great as 50 MW/m² over very short times, evaluating the potential damage to divertor modules, and arrays of such modules, due both to transient thermal loads and the resulting thermal stresses is an important factor in evaluating the feasibility of He-cooled W divertors.

**Anticipated Impact**

Developing divertor designs that can withstand extremely high heat fluxes is a major engineering challenge in PMI. Helium-cooled tungsten divertors, which have already been successfully tested at 10 MW/m², are the leading candidate for the EU DEMO. An engineering evaluation of these designs, focusing on incorporating new materials, developing advanced manufacturing techniques, and large-scale high heat flux testing, is required to determine if these designs have the long-term performance required for the next generation of fusion facilities and MFE power plants.
References