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An advanced He-cooled divertor concept: Design, cooling technology, and thermohydraulic analyses with CFD

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Abstract

At the Forschungszentrum Karlsruhe (FZK), designs of He-cooled divertor concepts are pursued for near-term reactor models like DEMO. Due to the new concept presented here, small structured tungsten parts are no longer needed for the design. In combination with new assembly and sub-module designs this results in promising characteristics regarding cooling performance, reliability and feasibility. The cooling method and conceptual design of the He-jet-cooled divertor shall be presented in this study, together with an assessment of the performance based on computational fluid dynamics (CFD) simulations.

Keywords: Divertor; Helium cooled; Jet impingement; Tungsten; CFD; Tokamak; DEMO

1. Introduction

The major challenge for the divertor of a tokamak is to handle high target heat loads. Values up to 10–15 MW/m^2 can be tolerated with the technology described in this paper. The divertor has to discharge about 15% of the total fusion thermal power into a power conversion cycle, if possible. For this, a highly effective and reliable cooling system is necessary. Nevertheless, the coolant pumping power should be kept as low as possible and thermal stresses caused by extreme temperature differences in the heat-loaded and cooled parts have to be kept below acceptable limits. Further criteria to be met by the design result from the operation temperature windows of the materials.

Helium is chosen as coolant due to its advantageous safety characteristics. It allows for a high exit temperature of 700 °C at least, which is suitable for the power conversion system based on a gas turbine cycle.

2. Cooling method

Jet impingement heat transfer is a well-known effective heat transfer enhancement technique [1]. As in the present case, where a large amount of heat has

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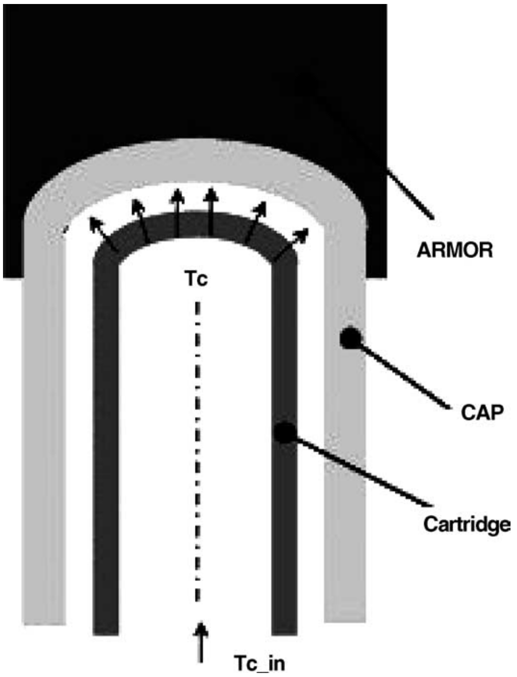

Fig. 1. Principle of a jet impingement cooling finger for the gas-cooled divertor.

to be removed from a hot surface, this technique can be employed directly due to its simple design involving a plenum chamber (thimble cartridges) and orifices (holes in the cartridges, Fig. 1).

In the stagnant core of the impinged jets, cold coolant is contacting the hot surface (Fig. 2). The outlet velocity of the jet is high (in the present case around 200 m/s), resulting in turbulent flow immediately after impingement. After impingement, the flow represents a wall jet flow. It is extremely turbulent with high velocity fluctuations and increased local turbulent mixing. As a result, a significant increase in the heat transfer performance is achieved.

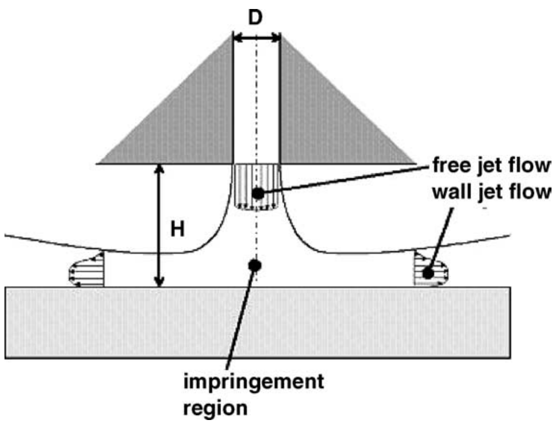

Fig. 2. Principle of jet impingement cooling.

A large number of holes and small jet-to-jet spacing of the holes permit to achieve higher heat transfer coefficients. For the first layout of the Forschungszentrum Karlsruhe (FZK) divertor cooling system, holes of at least 0.6 mm in diameter are chosen (Fig. 3) to prevent flow blockage even in the case of an incompletely filtered helium coolant.

The main parameters to be analyzed for the jet cooling system are geometrical parameters as well as heat load and flow parameters like mass flow, inlet pressure and inlet temperature.

3. Design

The ring divertor of the assumed tokamak reactor is toroidially divided into cassettes, which allows for comfortable handling and maintenance. The main divertor components are the thermally highly loaded target plates, the dome with the opening for pumping and the main structure with the manifolds for the coolant.

The surfaces of the target plates have to be made of an armor material with a high melting point, high thermal conductivity and a low sputtering rate. Tungsten seems to meet these requirements very well and is therefore used in this study. For acceptable thermal stress levels in the armor layer and the cooling system below, the W-armor layer has to be castellated. For a close package of the armor segments and the cap-like substructure below, hexagonal armor parts (tiles) are used. Thermal stress calculations have indicated that a width of 18 mm for the tiles is reasonable [2]. The tiles are not cooled directly due to the risk of cracks.

The directly cooled structure below the tiles has to withstand the high internal loading of about 10 MPa and high temperature gradients leading to high stress levels without any defects occurring, e.g. cracks or creep fatigue. This structure (cap or thimble) is made of tungsten alloy (currently in development), which has to possess a high ductility up to a temperature of about 1300 °C. The tiles are brazed onto the caps. The caps