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Helium-cooled Divertor: Design and DEMO Integration Studies

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The development of novel materials for fusion applications with better ductile properties under irradiation has led, in the recent years, to rethink the helium cooled divertor design under development at KIT. In particular, the availability of pipes and plates made of tungsten laminates that show very good mechanical properties under fusion relevant conditions has triggered a new search for concepts in which such materials can be used. The present work is introducing the newly developed helium-cooled divertor concept including an analysis of the integration into a divertor target. The experimental qualification plan is discussed afterwards, and some details on thermal-hydraulic performances of the first testing mock-up under a high heat flux loading conditions is presented.

Keywords: helium-cooled divertor, DEMO, W-laminate, CFD, jet-impingement cooling.

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1. Introduction

Modern tokamaks and stellarators use divertors to implement the particle exhaust function which is essential for the plasma operation. However, the particle exhaust process is associated with concentrated high surface loads on the divertor targets and requires substantial power exhaust capabilities, way superior to that of the first wall components. This makes the development of the divertor targets one of most challenging tasks in the designing of ITER and future power plants, including DEMO. On the technology development side, as part of the sustained efforts in providing solutions that could be integrated into a fusion power plant like DEMO, Karlsruhe Institute of Technology (KIT) is developing a helium-cooled divertor; using helium at high temperatures as coolant, such a concept would allow an efficient conversion of the divertor power into electricity. Combining the high heat removal capabilities of the jet impingement cooling with the use of novel materials, like tungsten laminate, the new concepts aim at providing a design that operates at temperature levels at which, on one side, the structural materials maintain a suitable level of ductility and mechanical strength and, on the other side, it allows integration into a heat transport system that would operate at temperature levels as the one used in the high temperature gas cooled reactors. With earlier divertor concepts developed at KIT able to cope with surface heat fluxes of 10MW/m^2 as experimentally demonstrated in [1], the current efforts focus on addressing some of the weak points of the earlier concepts while maintaining the cooling performances. The aim of the present work is to introduce the newly developed helium-cooled divertor concept including an analysis of the integration of such a concept into a divertor target. The experimental qualification plan will be discussed as well, and some details on thermal-hydraulic performances of the first testing mock-up under a high heat flux loading conditions will be presented.

2. Helium-cooled divertor concept for DEMO

In the recent years, there has been a significant progress in the manufacturing and characterization of tungsten laminates. These novel materials show improved ductility as compared with monolithic-coarse grained tungsten parts obtained through established industrial routes. Using severally cold rolled ultrafine-grained tungsten sheets as building blocks, these newly developed materials behave better than its hot-rolled or recrystallized counterparts [2]. Pipes made of a W-Cu laminate, with length up to 1m and diameters of 16mm, have been already manufactured and successfully tested under high pressure, high temperature conditions. High-heat flux tests performed on water-cooled laminate pipes showed that they can withstand heat fluxes in excess of 20MW/m^2 [2].

In order to make use of these promising features of the W-laminates, a novel divertor concept has been proposed [3]. The concept uses an ITER-like divertor geometry: the divertor target is made of cooling rows, each row having the amour, made of tungsten blocks, installed on a W-laminate pipe that contains the coolant; the heat deposited on the surface of the amour being removed using a jet-impingement cooling scheme similar to the one used in the de-icing of wings leading edges of the modern airplanes (Picolo tube). Thus, the jets are created using a coolant distribution manifold in the form of a pipe-cartridge installed inside the W-laminate pipe. In Fig. 1, a cross-section through an early manufacturing mock-up is shown: the coolant, helium at 10MPa and 500°C, enters the mock-up from the left side, and it is jettisoned out through the holes present in the distribution cartridge, a 6mm diameter pipe. After impinging on the upper side of the 16mm W-Cu laminate pipe, the helium streams-out through the right opening of the mock-up.

The CFD simulations done for such a configuration [4] indicate that a heat flux of 10MW/m^2 could be removed while keeping the materials within their thermal operating limits. These simulations were done simply to estimate the thermal-hydraulic performances of the mock-up as-built, without any dedicated optimization. As a consequence, the calculations showed that the cooling of only one single block with a plasma facing surface of 31mm×23mm requires around 20g/s of helium. For a full divertor outboard vertical target (OVT) with a high heat flux length of 645mm in poloidal direction, around 50 blocks will be needed to cover that length. Thus, such a row of tungsten blocks using a single module of 645mm length would require a flow rate of 1kg/s. Given the pipes dimensions, in particular the diameter of the distribution manifold, it would be difficult to distribute uniformly such a large amount of helium. In addition to that, considering a DEMO reactor configuration and a power distribution as presented in [5], such an OVT divertor target row would receive 34kW of power (here it is assumed that 2/3 of the power radiated from the core towards divertor is deposited on the OVT); thus, the overall helium temperature increase would be close to 7K which is a rather modest value for an efficient integration into a power conversion system.

Fig. 1. Mock-up of a helium-cooled divertor.

To address this, a configuration using several modules in series has been considered. In order to decide in how many modules should we split the 645mm long row, let us have a look at the power distribution along the target (in poloidal direction). Since the OVT is the target with the highest loading, hereafter, we will focus our discussion only on this particular target. Thus, using the power distribution from [5], a single OVT row will subject to a surface power input of 24.7kW (here a row width and, implicitly, a W-block width of 23mm is assumed); this power is not uniformly distributed but has a peak near the strike point. Assuming that the divertor target load has a profile as indicated by [6] and [7] and, that the maximum heat flux is close to 10MW/m2, we get a surface heat flux distribution along the target with a peak heat flux of 9.99MW/m^2 at 4.69mm away from the strike point (see the continuous distribution in Fig. 2). The heat flux outside this region is low, being mostly determined by the background heat flux which is estimated to be 0.95MW/m2.

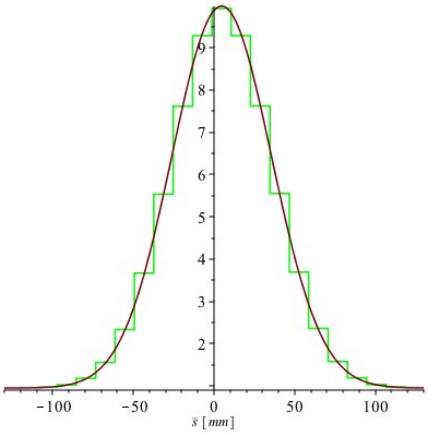


Fig. 2. Estimated heat flux distribution (in MW/m^2) on the OVT as a function of the relative position to the strike point (brown line); green line: discrete distribution assuming that the strike point lies in the middle of a 12mm thick W-slab.

In fact, for distances larger than 80mm left from the strike point and larger than 60mm on the right side, the averaged heat flux is close to 1MW/m^2 while near the strike point (between -80mm and 60mm) the averaged heat flux is 5.74MW/m^2.This means that, if we take 5 segments in series, each having a length of 125mm, and adjust our mass flow rate to have a segment temperature increase of 10K for each MW/m^2 of heat flux we would expect to have an overall temperature increase close to 100K. Taking in account the power deposited on a single row, such an overall temperature rise would require a flow rate of 65.6g/s.

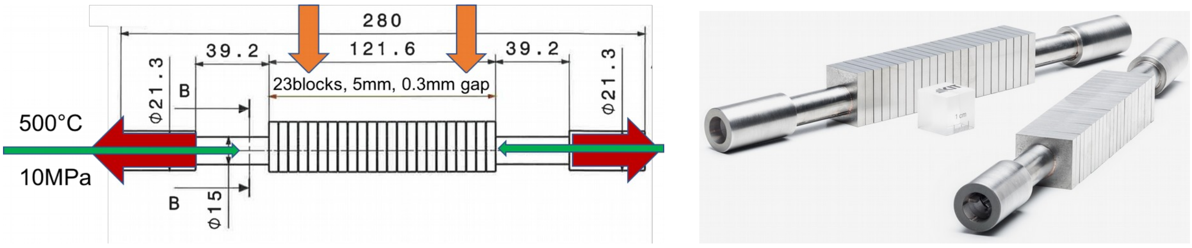


Fig. 3. Helium-cooled divertor mock-up.

3. Evaluation of the thermal-hydraulic performances

In the previous section, it has been shown that, when using a helium flow rate of 65.6g/s together with a row segmentation with 5 modules cooled in series we would expect that the coolant overall temperature will rise with 100K. However, this analysis, so far, does not look into the operating limits of the armor and structural materials and makes no assumption on the cooling performances. Thus, to evaluate the thermal-hydraulics performances and validate such a configuration both experimental and CFD investigations are needed. Hereafter, the experimental strategy for the qualification of the KIT helium cooled divertor will be outlined, followed by the presentation of the current CFD modeling activities with focus on the thermal-hydraulic aspects.

3.1 Experimental qualification strategy

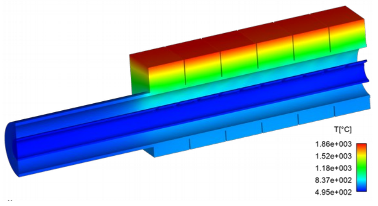
The manufacturing of the small mock-up introduced in the previous section gave us the possibility to address and solve various aspects related to the assembly of such a concept, define a proper manufacturing route and give us the possibility of a better estimation of the difficulties to be faced when moving towards larger mock-ups. Due to its reduced dimensions, it has been considered as less suitable for investigating the concept thermal-hydraulic performances. For this, a mock-up with a heated length comparable with the length of a single segment has been proposed (see Fig. 3). This mock-up uses the same 16mm in diameter W-laminate pipe as in the previous mock-up due to its availability at the time when the manufacturing started; the coolant distribution manifolds is done out of a 6mm in diameter pipe. For the armor, tungsten blocks made of a 5mm thick plate have been used, the width of the blocks being 23mm, slightly reduced as compared to previous concept.

The other difference as compared with the first mock-up is the fact that the coolant will stream in through both sides of the mock-up (the green arrows in Fig. 3), the inlets being coaxial with the outlets. This has been done to decrease the coolant inlet velocity which, in case of a one-through configuration as previously used, would reach values around 500m/s. Such velocities will increase the compressibility effects having a strong impact on pressure losses. For the following mock-ups, the possibility of an inlet with an increased cross-section will be considered.

It is foreseen to manufacture and test several mock-ups of this length in order to find the most appropriate configuration as well as to test various manufacturing technologies. These tests will be then followed by experiments where a full-length row (5 segments) will be investigated. For a complete qualification of the concept, divertor target mock-ups will be tested. Given the capabilities of KIT helium experimental facilities, it would be possible to test up to 3 rows in parallel, under design operating conditions (10MPa and 500 to 600°C), using KATHELO facility [8] or, test up to 15 rows in HELOKA [9] under slightly reduced pressure and temperature conditions (9MPa and 400 to 500°C).

3.2 CFD modelling and analysis

In parallel with the mock-up design and manufacturing activities, a numerical investigation of the heat transfer characteristics and pressure losses has been performed. This analysis has two main objectives: on one side, as part of the model validation process, we need the results of the numerical simulations to compare it with the experimental data; on the other side, these investigations are used to understand the behavior of the mock-up and better define the experimental set-up and the experimental matrix. In addition to that, these models give us the possibility to look into design alternatives that could improve the divertor performances.



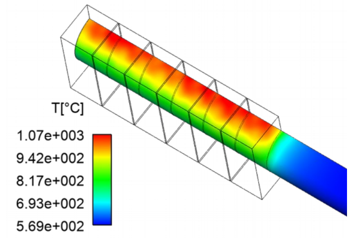


Fig. 4. Mock-up temperature field (top) and pipe outer wall temperature (bottom)

Taking in account the existing mock-up symmetries, only a quarter of it has been modelled. As compared to the manufactured mock-up, the model considers 10mm thick W-blocks which was the reference at the time the simulations were performed; however, the laminate pipe and the geometry of the distribution manifold, including the jet pattern, is the same as in the experiment. As the current focus is mainly on the pipe wall temperature, this change should not impact on the results. The simulation was done assuming that the "plasma-facing" side of the tungsten armor receives a uniform heat flux of 10MW/m^2, while the cooling is done with 17g/s (68g/s for the full mock-up) helium at 10MPa and 500°C. In Fig. 4 the temperature field in the pipes and tungsten are shown (top picture). The results show that the pipe outer wall temperature (Fig. 4 bottom picture) is higher than in the previous simulations mostly due to a lower flow rate as well as due to jet-to-jet interaction. Additional simulations show that this value can be improved by using ribs on the inner side of the pipe which help regularizing the flow pattern after the jet impingement. In Fig. 5 a comparison between the pipe temperature in the reference case and the case with ribs on the inner side of the pipe (rib height 1mm and a thickness 0.5mm) is shown. Thus, the peak temperature decreases from 1070°C down to 920°C.

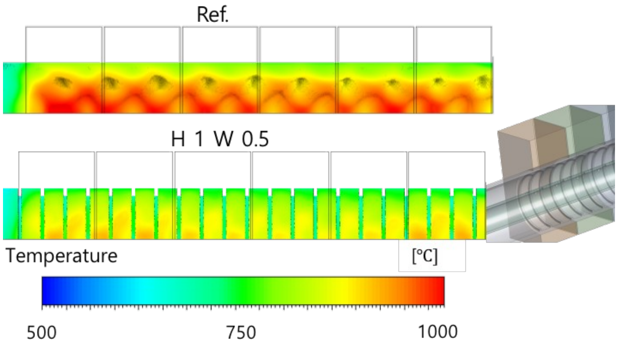


Fig. 5. Pipe temperature for the reference case (bottom) and a configuration using inner ribs (top)

In Fig. 6, the radial component of the velocity is plotted for the reference case without ribs and a simulation where ribs are present on the inner side of the pipe (the coordinate system is associated with the cylindrical part of the manifold on which the jet holes are). For the latter, the heat transfer is improved due to the reduction of the jet tilting as well as to a better mixing in the area between the jets caused by the side jets.

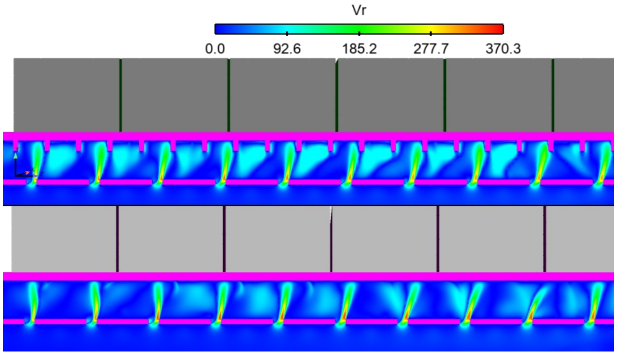


Fig. 6. Impingement jet pattern for the reference case (bottom) and a configuration using inner ribs (top).

From the previous results it can be seen that, due to the significant axial velocity component in the inlet manifold, there is a tilting of the jets, such a tilting being associated with a diminution of the heat transfer in the stagnation zone [10]. For the present mock-up, we have a counter-current configuration, the helium leaving the heated zone flowing in opposite direction as the inlet flow, therefore, this will result in to a reduced tilting effect as opposed to a co-current configuration. Since for a divertor target we have rather the latter configuration than the former, a simulation of two divertor segments in series has been performed. In order to be consistent with the power loading of the divertor, a heat flux distribution like the one shown in Fig. 2 has been used. The power peak is assumed to occur on the second segment, such a configuration being considered as more demanding, the coolant temperature being already increased after passing the first segment.

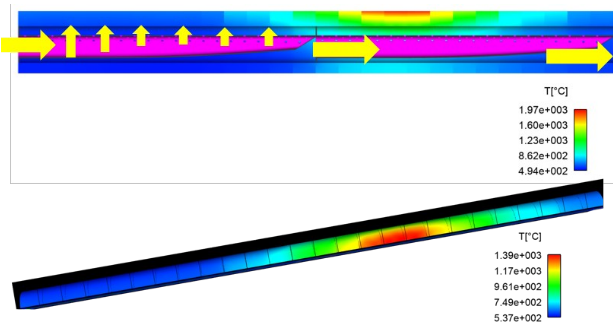


Fig. 7. Armor temperature (top) and outer pipe temperature (bottom) for the DEMO like configuration.

For this simulation, an inlet manifold with a variable cross-section has been used to reduce the axial velocity. Thus, the coolant, helium at 500°C and 10MPa, enters the module through the left side, is distributed along the first segment, impinging on the top side of the laminate pipe, flowing sidewise and towards the bottom of the pipe before going to the next segment where a similar path is followed. In Fig. 7 the temperature field in the tungsten armor and the laminate pipe are shown (top picture) together with the temperature field on the outer wall of the laminate pipe. From these results, it can be seen that the pipe temperature is with 300K higher than in the previous case under the high heat flux zone. The fact that the difference in tungsten temperature is only 110K can be explained by the fact that, for this model, the thickness of the tungsten block between the pipe and the “plasma-facing-side” is smaller.

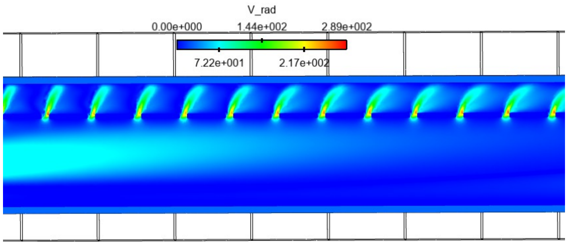


Fig. 8. Radial velocity under the high heat flux area.

The large difference in pipe (peak) temperature can be explained by two main factors: the use of a coarser grid to keep the mesh size within the limits of the machine and, the more pronounced tilting of the jets. The mesh size studies, done on a single module, show that mesh refining would reduce the peak temperature with about 100K. Concerning the jet tilting, if we look at the radial component of the velocity field (Fig. 8) and compare with the velocity from the manufactured mock-up we can see that the peak velocity is smaller and the tilting is more pronounced, the impingement angle being close to 60°. For a ratio of 5 between the nozzle-to-surface distance and the jet diameter, such a tilting would reduce the stagnation Nusselt number with about 20% [10] which, added to the difference due to the coarse grid, is consistent with the temperature increase that we observe.

4. Summary and conclusions

The development of novel materials for fusion applications with better ductile properties has led, in the recent years, to rethink the helium cooled divertor design and a somewhat simpler concept has been proposed. The present paper has looked into the possibilities of applying such a concept to a full divertor target and an arrangement with 5 segments in series has been proposed. For the evaluation of the thermal-hydraulic performances as well as for the qualification of the new divertor concept, an experimental plan has been proposed, starting from the design and manufacturing of a row-segment mock-up going up to divertor target mock-ups that could be tested in the existing facilities.

CFD investigations have been done for the singular segment mock-up as well as for larger future mock-ups comprising two segments in series. The simulation results show that the structural material, namely the pipe containing the coolant, reaches locally temperatures above the optimal operating range. Adding ribs on the inner side of the pipe helps improving the heat transfer allowing, in the case of the one-segment mock-up, to stay within the specified operating domain.

The availability of the divertor mock-up in the same size as a singular segment gives us access, in the near future, to experimental data that would allow the validation of the numerical models.

The cooling scheme using 5 segments in series helps reducing the flow rates to values that are manageable at the level of a divertor target, however, for the current size of the inlet manifold, the inlet velocities are found to be too high. One way to address this issue, while keeping the outer pipe dimensions unchanged, is to use a variable cross-section manifold as it has been done in the case of the simulation of two segments in series. The manufacturing of such a complex manifold still needs to be investigated. Another way to reduce the axial velocity in the manifold is to enlarge the pipe and manifold dimensions. While the lateral size is fixed based on optimization studies of the tungsten armor stresses (23mm is the current dimension), the pipes could be elongated in the other direction increasing thus the cross section. For the manifold the manufacturing is rather straightforward, simply cutting the pipe in two halves and welding between them straight walls of variable height. In case of the outer pipe the situation is more complex, the manufacturing of a laminate pipe with an ellipsoidal cross-section being considered as a next step in the optimization of the divertor design.

The numerical modelling of such a cooling scheme, where a train of two cooling segments was investigated, show that the concept is viable provided that the cooling performances are recovered to the level demonstrated by the initial investigations. The main issue here is the deterioration of the heat transfer coefficient caused by the tilting of the jets. Various solutions for this problem are currently being looked at, the insertion of ribs on the inner side of the laminate pipe being one of them.

Acknowledgments

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