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Design optimization and experimental testing of the High-Flux Test Module of IFMIF

D. Leichtle [a,*], F. Arbeiter [a], B. Dolensky [a], U. Fischer [a], S. Gordeev [a], V. Heinzel [a], T. Ihli [a], A. Moeslang [b], S.P. Simakov [a], V. Slobodchuk [a], E. Stratmanns [a]

[a] Association FZK-EURATOM, Forschungszentrum Karlsruhe, Institut für Reaktorsicherheit, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[b] Association FZK-EURATOM, Forschungszentrum Karlsruhe, Institut für Materialforschung, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

ABSTRACT

The design of the High-Flux Test Module of the International Fusion Material Irradiation Facility has been developed continuously in the past few years. The present paper highlights recent design achievements, including a thorough state-of-the-art validation assessment of CFD tools and models. Along with design related analyses exercises on manufacturing procedures have been performed. Recommendations for the use of container, rig, and capsule materials as well as recent progress in brazing of electrical heaters are discussed. A test matrix starting from High-Flux Test Module compartments, i.e. segments of the full module, with heated dummy rigs up to the full-scale module with instrumented irradiation rigs has been developed and the appropriate helium gas loop has been designed conceptually. A roadmap of the envisaged experimental activities is presented in accordance with the test loop facility construction and mock-up design and fabrication schedules.

1. Introduction

The International Fusion Material Irradiation Facility (IFMIF) [1] is a deuterium–lithium neutron source for irradiation tests of candidate fusion reactor materials. Within the High-Flux Test Module (HFTM) a testing volume of 0.5 l filled by qualified small scale specimens will be irradiated at displacement rates of 20–50 dpa/fpy in structural materials. The Engineering Validation Engineering Design phase (EVEDA) [2] of IFMIF is devoted to the development of a detailed, integrated, cost and time assessed, engineering design of IFMIF, through the associated prototypical component tests.

Within the subsystem Test Facilities, comprising the so called "Target and Test Cell", lithium target assembly and technology rooms, several tasks will be performed including design, manufacturing and experimental testing of a full-size HFTM. The present paper summarizes recent design achievements in Chapter 2, accompanying validation and design analyses (Chapter 3) in preparation of the experimental programme foreseen in EVEDA phase (Chapter 4).

2. Design optimization

The reference design of the HFTM [3] consists of 12 identical flat plate rigs housed in 4 compartments of the container, made of austenitic steel (see Fig. 1). The container also integrates reflectors for the improvement of dpa level and gradients in the test section volume. The irradiation rigs (Fig. 2) have outer dimensions of 50×17 mm; cooling channels of 1 mm at the longer side and 0.6 mm at the smaller side are established by spacers on rig and container walls. The HFTM is cooled by helium at low pressure and low temperature (0.3 MPa, 50 °C at the inlet). Helical ohmic heaters brazed on the irradiation capsule are used to achieve the desired irradiation temperatures (300–650 °C) and to compensate axial and radial temperature gradients as well as short beam drops. The capsules are inserted into rigs, forming a narrow isolation layer filled by stagnant helium between the two components.

A continuous effort is devoted to design refinements based on concurrent nuclear, thermo-hydraulic and thermo-mechanical analyses (see e.g. [4,5]. They have been focused recently on the general mechanical stress and deformation situation of the container, on hot spots and peak stresses, as well as a major revision of the lateral reflector system.

It has been realized that the high temperature samples (at 650 °C) require introducing several design changes due to local temperature hot spots and stress concentrations. Hot helium gas passing the heated capsule zone will cause hot fanes (up to 220 °C) in the compartment stiffening walls. The small cooling channels of 0.5 mm width proved to be insufficient. After increasing the gap width to 0.6 mm the maximum wall temperatures drop down to ca. 166 °C and the corresponding Von-Mises stresses are well below the yield strength of 195 MPa (see Fig. 3). In addition, a safety margin is provided, since the mass flow rate could be increased due to the larger flow cross section.

Peak stresses at the container edges have been addressed by softening the container structure near the helium inlet and

* Corresponding author.
E-mail address: leichtle@irs.fzk.de (D. Leichtle).

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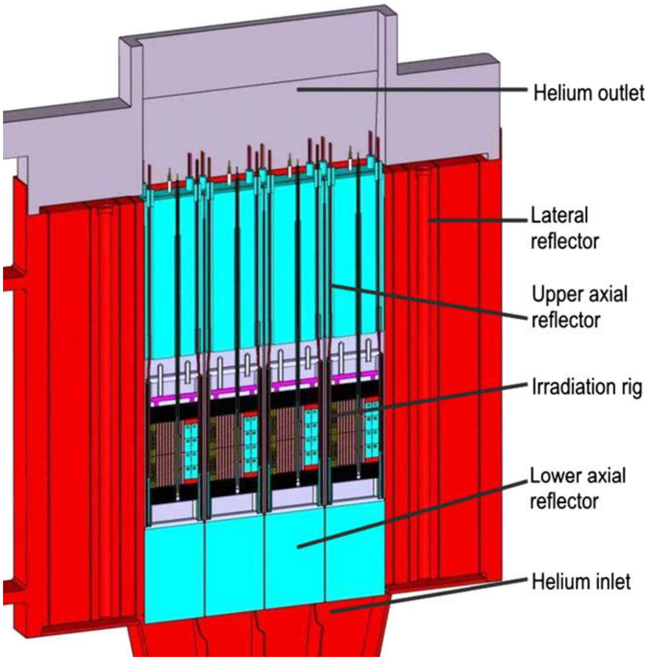

Fig. 1. High-Flux Test Module with main components.

relieving notches at the top of the compartment stiffening walls. Without plastification the maximum stresses are about 300 MPa. Further optimisation to reduce further the stress level is in progress.

Based on the general problems of the compartment walls, in particular the deformation situation of the lateral reflector inner walls, a new concept has been proposed for the lateral reflectors.

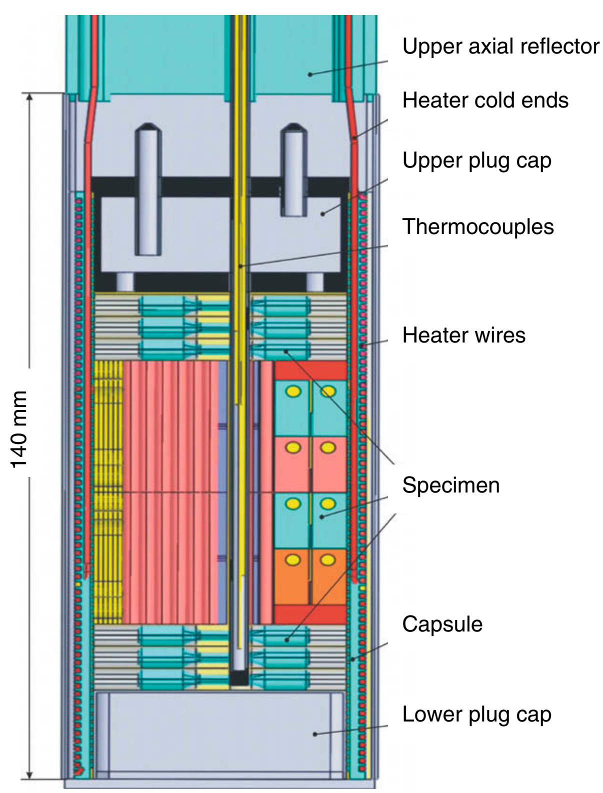

Fig. 2. Vertical cut through a HFTM irradiation rig.

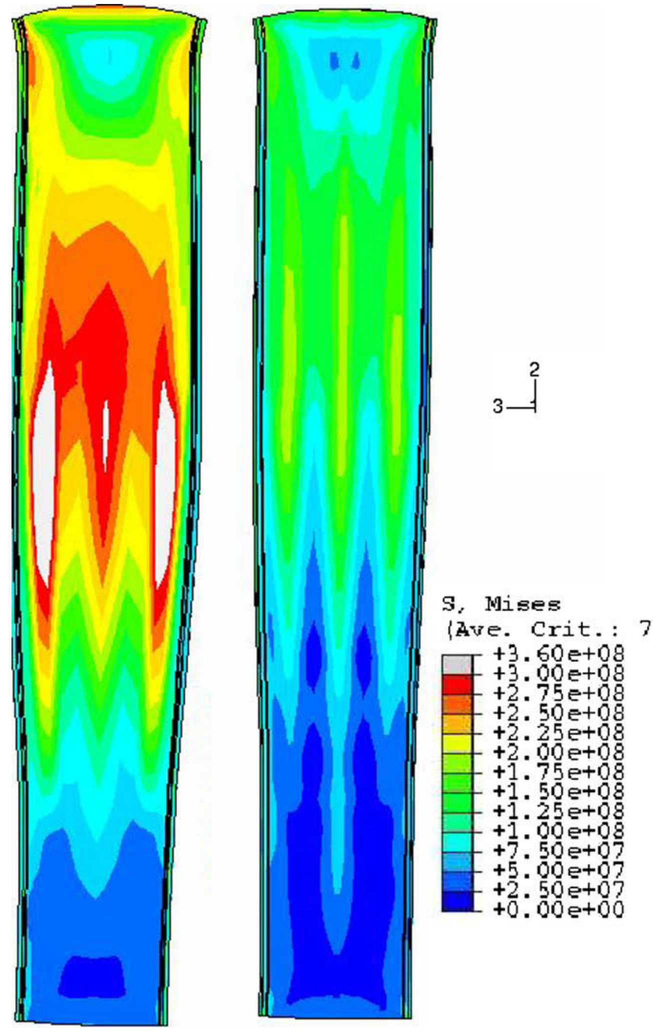

Fig. 3. Compartment stiffening wall (650 °C specimen temperature): Von-Mises stresses at 0.5 mm (left) and 0.6 mm (right) cooling channel width; deformation factor 100×.

It is based on cut-free blocks to separate the massive reflector block from the thin walled structure (Fig. 4). The hydraulic conditions should be maintained as much as possible. A stagnant helium layer dividing the reflector block from the container walls is set-up by spaceholders on the reflector block. This design will be analysed further to assure the feasibility of the concept. A preliminary thermo-mechanical analysis indicated a reduction of peak stresses by 10% (Fig. 5). Issues are connected to reduced cooling capabilities at the front wall, which have to be analysed carefully.

3. CFD validation and design analyses

The design of the HFTM relies on reliable thermo-hydraulic analyses. As the emerging flow conditions in extensively heated mini-channels at Reynolds numbers in the range of 5000–10000 are not covered previously by experimental data in the literature, a series of dedicated heat-transfer and flow-velocity measurements have been conducted in the ITHEX experimental helium loop facility [6] during the past few years. Extensive numerical analyses have been performed to study the thermal and hydraulic conditions in the HFTM test section with the main objective to investigate the feasibility of the envisaged design and possibilities for further improvements. The tool used for these analyses was the computational fluid dynamics (CFD) code STAR-CD [7]. The main

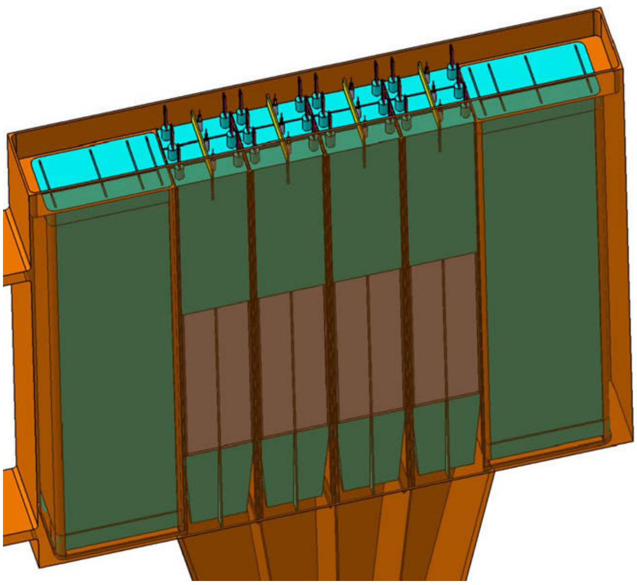

Fig. 4. CAD-model of container with cut-free lateral reflectors.

conclusions from the validation work performed in the past were the applicability of STAR-CD to perform analyses on a quarter rig using low-Reynolds number (low-Re) turbulence models and the sensitivity of the inlet geometrical configuration on the turbulence development in the minichannel (see [5,6]. The simulation of the full HFTM container is extremely demanding using a low-Re model. Therefore, a corresponding high Reynolds number (high-Re) model has been chosen based on similarity of sample temperature distributions for the design analyses of the container.

For the optimized design a comprehensive inter-comparison exercise on the thermo-hydraulic properties of a quarter rig model has been performed. As the detailed design and analysis of the heat contact between capsule and rig walls have not been addressed, in the present CFD model the depth of the stagnant helium isolation layer has been assigned as 1.35 mm on the long side and 1.0 mm at the short side. Also the model uses 316-L steel instead of EUROFER. As previous analyses have shown, that the choice of material does not change the overall situation significantly and the higher thermal conductivity of EUROFER will reduce thermal gradients in the structure, the present exercise will give a conservative estimation of the real situation.

Table 1
Results from quarter rig simulation: T_s^{max} maximum sample temperature, T_w^{max} maximum rig wall temperature, T_{fl}^{max} maximum fluid temperature, W_{max} maximum fluid velocity, ΔP pressure drop.

Turbulence model	T_s^{max} (°C)	T_w^{max} (°C)	T_{fl}^{max} (°C)	W_{max} (m/s)	ΔP (bar)
High-Re					
Standard k–ε	520.1	122.7	105.8	243.9	0.315
k–ε quadratic	521.8	123.8	107.0	251.4	0.312
Chen	519.8	122.6	105.4	239.7	0.313
RNG	521.9	125.9	107.2	243.0	0.294
k–ε Suga quadratic	520.1	122.9	106.0	244.0	0.316
k-omega	514.6	117.2	114.4	272.2	0.440
v2f	522.3	129.9	126.9	253.3	0.292
Low-Re					
Standard k–ε	528.5	156.8	155.0	293.5	0.235
k–ε quadratic	527.6	153.1	151.2	300.9	0.236
k–ε Suga quadratic	548.1	172.8	171.2	308.7	0.217
k-omega SST	521.8	131.1	129.3	262.1	0.329

A series of low- and high-Re models have been compared (cf. Table 1). The temperature distribution in the test section volume is hardly affected by the choice of the turbulence model, with an exception found for the low-Re k–ε Suga models. Also all models predict the hot spots in the compartment walls at similar locations and similar temperature levels. However, there is still a large discrepancy in the flow properties, i.e. maximum velocity and pressure drop, between high-Re and low-Re models. Taking into account the experiments on ITHEX (see e.g. [6,8] and the present analysis, the v2f model seems to be the proper choice for the layout analyses of the full container due to its applicability tu use coarse meshes compared to other low-Re models. Further work investigating a three-rig compartment is foreseen in combination with thermo-mechanical analyses.

4. Manufacturing and experimental testing EVEDA

An assessment of a material selection guideline for in-test-cell components [9] is currently performed with the objective to provide designers with basic guidelines and recommendations for structural material selection based on available experimental data.

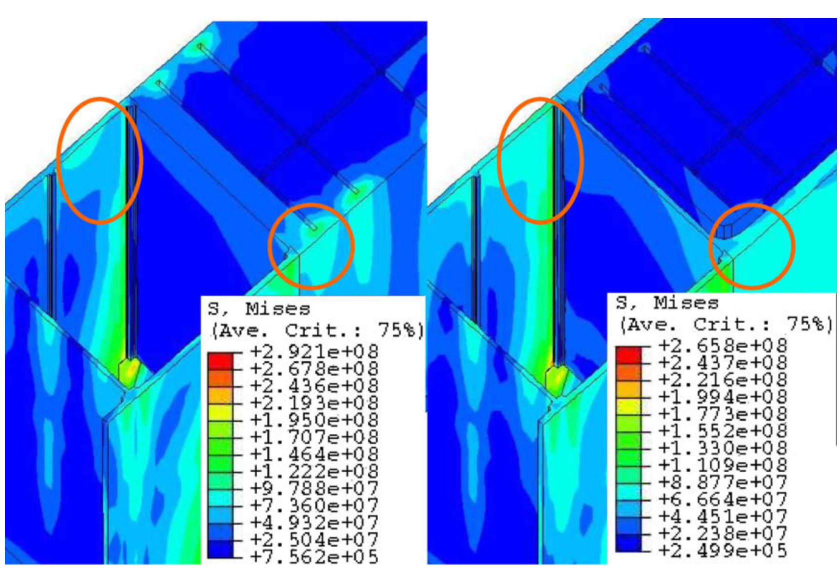

Fig. 5. Von-Mises stresses: integrated reflector (left), cut-free reflector (right).

The temperature window for the HFTM container is between 50 and 150 °C where austenitic steels are recommended mainly due to low helium embrittlement. On the contrary, the irradiation capsules temperatures are between 250 and 650 °C, which is not recommended for austenitic steels but more suitable for ferritic steels. The reduced activation ferritic-martensitic (RAFM) steels like EUROFER and F82Hmod show significant improvements in irradiation hardening and toughness. Therefore the present choice for rig and capsule material is a RAFM steel.

Crucial manufacturing techniques for the parts of the HFTM have been tested extensively to assure a reliable and reproducible manufacturing route for the final procurement of the HFTM. Major efforts have been devoted recently to refinement of the brazing procedure for the ohmic heater wires. Based on several tests with mock-ups, resembling the groove structure and filling height of real capsules, the temperature field have been homogenised and the brazing procedure has been shortened considerably. After 25 min hold time the braze samples have been tested by inspection of cuts and by thermography of the heated surface. No major flaws, deteriorating the temperature field, have been detected so far.

Within the EVEDA phase of IFMIF two strongly inter-correlated task areas are devoted to the manufacturing of a full HFTM assembly and the construction of a helium test loop for the experimental testing of HFTM mock-ups up to the full-sized component.

Forschungszentrum Karlsruhe has set up a work programme and schedule for this EVEDA baseline activity. Starting from the existing design of the HFTM the critical points are examined in detail. Based on the results of these analyses a revision of the concept is made and analyzed again. Results from corresponding experimental investigations, which are conducted in the ITHEX facility, are considered for further improvement of the configuration. The requirements, boundary conditions and results from other tasks, like remote handling of the test cell, target design and neutronics, sequentially will become available and will be considered within the ongoing design phases.

The experimental program in the initial design consolidation phase will be performed in ITHEX. It will comprise experiments on the flow conditions due to the entrance geometry of the HFTM inlet and in a variable gap-width channel. Flow fields will be measured by Laser Doppler Anemometry (LDA). In addition a single-rig compartment will be examined to determine the heat-transfer at heated channels. Pressure losses and temperature distributions are measured.

For the testing of the full HFTM a dedicated helium experimental loop (HELOKA-LP: Helium Loop Karlsruhe – low pressure) will be constructed. The technical specifications have been fixed with a helium mass flow rate up to 0.12 kg/s at a maximum pressure of 0.6 MPa with 0.12 MW heat and power supply. Inlet temperature could be adjusted to 25 °C to 100 °C. The estimated pressure drop at the test section is around 0.05 MPa. A call for tender has been issued, and the start of construction is scheduled for beginning of 2008.

A series of experiments is foreseen to be conducted during the EVEDA phase till the final testing of the HFTM prototype. A first important input to the concurrent design and manufacturing task is expected from experiments with single compartment mock-ups, consisting of three sample rigs. The results of these investigations will deliver input to the construction of an optimized HFTM, which is foreseen to be experimentally examined in the middle of 2011. The 1:1 prototype of the HFTM will be built at the beginning of 2012 and the functional tests will be performed till 2013.

5. Conclusions

The design of the High-Flux Test Module of IFMIF has been optimized for high temperature (650 °C) samples, and the container has been optimized with respect to the overall thermo-mechanical loads. In parallel, the manufacturing technology for the procurement of a prototype HFTM to be tested in the EVEDA phase of IFMIF has been supported by a successful brazing procedure of the capsule walls. Dedicated thermo-hydraulic validation experiments are considered as significant steps for the consolidation of the design in 2008. The EVEDA tasks on manufacturing and experimental validation of a full-scale HFTM are strongly interconnected. Experiences gained in the previous years of design and validation analyses will be a strong backbone for the future activities.

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