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Hydraulic modeling of the Jules Horowitz Reactor: Mass flow split between 36 fuel elements

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HIGHLIGHTS

- A Computational Fluid Dynamics model of the JHR is presented.
- Hydraulic simulations with realistic assumptions are performed.
- Results are analyzed and the main findings are introduced.
- Mass flow heterogeneities in core between the 36 fuel elements are small.
- Potential improvements for the future work are proposed.

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ABSTRACT

The newest European high performance material testing reactor, the Jules Horowitz Reactor, is under construction at the CEA Cadarache research center in southern France. The reactor will support existing and future nuclear reactor technologies and the first criticality is expected to be achieved at the end of this decade. This paper presents Computational Fluid Dynamics hydraulic calculations of the reactor and some results of the side thermal-hydraulic simulation of the fuel element. The main objective of this work is to improve the hydraulic knowledge of the reactor and to present the mass flow distribution between 36 fuel assemblies. Potential improvements for future work are proposed.

1. Introduction

The newest European material testing reactor (MTR), the Jules Horowitz Reactor (JHR), is currently under construction at CEA Cadarache research center in France and is expected to start operation at the end of this decade. JHR will meet the requirements of the latest safety standards and will support current and future nuclear reactor technologies and it will replace the current over half a century old aging fleet.

The high performance of the reactor (e.g. high neutron fluxes, high power densities) and its design (e.g. narrow flow channels in the core) render the reactor modeling somewhat challenging when compared to more traditional reactor. One possibility to get a better insight of the reactor is to use the thermal-hydraulic or solely hydraulic Computational Fluid Dynamics (CFD) simulations. This approach is utilized in this paper.

This paper is a fourth step of an ongoing four year project aiming at development of an improved JHR CATHARE2 model. It should be noted that in all these steps a CEA 36 fuel assembly configuration is used and the location of the hot fuel element and its hot channel are configuration dependent.

In the first step (Pegonen et al., 2014), the current CEA methodology for thermal-hydraulic modeling of the reactor using the system code CATHARE2 and the core analysis code FLICA4, was described. In addition to identifying the need for specific CFD calculations, other possible ideas for improvement to the methodology current at that time were discussed. In the second (Pegonen et al., 2015) and third steps (Pegonen et al., 2016), the CFD simulations of the reactors hot fuel element were carried out using the code STAR-CCM+ version 9.06 (CD-adapco, 2014). Moreover, a conjugate heat transfer analysis was carried out for the hot channel.

The purpose of this fourth step is to investigate the full reactor by conducting CFD hydraulic studies. This is a purely theoretical exploratory study considering realistic assumptions. This study is put forward in order to identify the mass flow split between the 36 fuel elements and to explain the flow field in the upper and

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lower plenums. As an aside study a thermal-hydraulic calculation, similar to those accomplished in previous steps was carried out, utilizing the outcome of hydraulic study. To date, the research published in steps two and three are the only CFD thermal-hydraulic publications available on the JHR fuel elements and this paper is the first publication involving CFD hydraulic study of the full reactor.

This paper first gives a short overview of the JHR and describes the computational model. Next a hydraulic analyses of the flow within the JHR are discussed, following a thermal-hydraulic side analysis of the flow within the hot fuel element. Finally, the main conclusions are presented and potential improvements for the future work are proposed.

2. The Jules Horowitz Reactor

The Jules Horowitz Reactor is a new high-performance material-testing reactor currently under construction at the CEA in Cadarache, France. The JHR project involves several European and international industrial and institutional partners. This pool-type reactor will have a maximum core power of 100 MW$_{th}$ and will use light water for cooling and for moderation (CEA, 2013). The first criticality is expected to be achieved at the end of this decade.

The JHR will be used to investigate the behavior of nuclear materials and fuels under irradiation and to produce radioisotopes for medical purposes (e.g. ^{99}Mo) Dupuy et al., 2005; Bignan et al., 2011. The reactor's flexible high-performance experimental capacity will meet the industry's needs related to generations II, III and IV nuclear reactors (Iracane et al., 2008). The JHR will provide a high neutron flux- twice as large as the maximum available today in European MTRs (Bignan et al., 2011).

The core is located in an aluminum rack with 37 possible positions for fuel elements, 34–37 occupied by fuel elements. Experimental devices can be placed either in the core or in the reflector, which allows for approximately 20 simultaneous experiments. In the core, a maximum of 10 experimental devices can be placed either in a central hole of a fuel element (7–9 locations, Ø $\approx$ 32 mm) or can replace a fuel element (3–1 locations, Ø $\approx 70 - 90$ mm) (Gonnier, 2013). Research presented in this paper was conducted on the JHR core containing 36 fuel elements implying one test devise in place of a fuel element.

3. Computational model

In this work, the commercial computer-aided design (CAD) tool SolidWorks was used to create the complex geometry for the liquid-filled regions. Thereafter, the CFD code STAR-CCM+ was utilized for generating a mesh, describing the physics to be modeled, solving and post-processing the results.

3.1. CAD geometry

The geometry used in the numerical model was generated by manually creating the fluid domain primarily for this analysis, based on the CATIA CAD model of the JHR (see Fig. 1). Several simplifications were introduced during this process, the most significant of these were: (i) inside the test devices and the control rod guide tubes, the complex geometry mandated simplification into tubes with a diameter defined as the hydraulic diameter used in the JHR's CATHARE2 model described in Pegonen et al. (2014), and (ii) two perforated cylinders in the lower plenum (colored orange in Fig. 2) and the 36 fuel assemblies (colored red in Fig. 2) were modeled as porous media (described in Section 3.5). Other simplifications included neglecting extremely small irrelevant details/gaps (e.g. part markings, filling internal structures irrelevant to the flow) and smoothing immensely complicated details. It is impossible to model only 1/2 of the geometry due to the asymmetry of the design. The geometry utilized in this research can be seen in Fig. 2 with some of its cross-section views shown in Fig. 3.

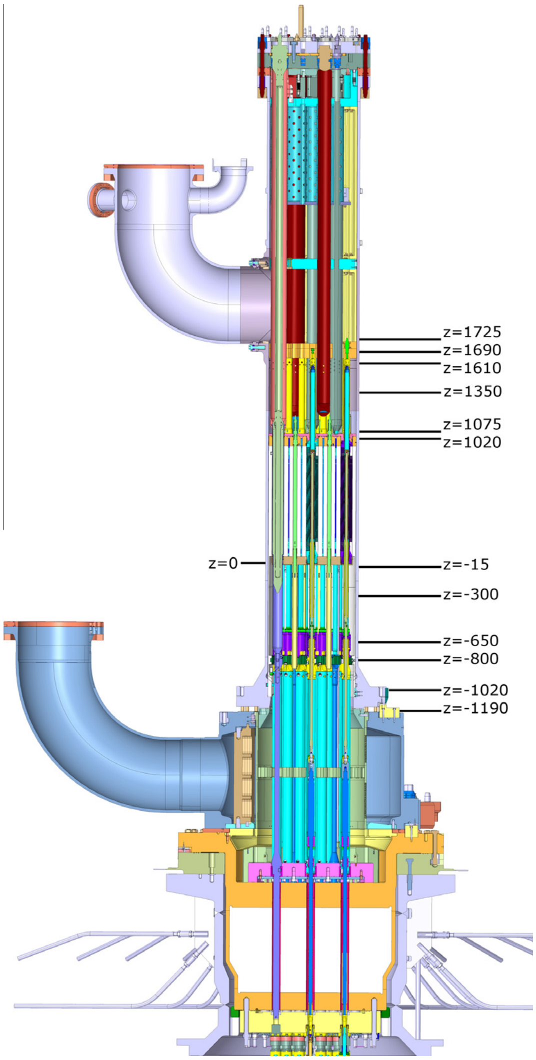

Fig. 1. Cut view of the JHR reactor with vertical positions of the cross-sections illustrated in Figs. 10 and 11 (dimensions in millimeters). Courtesy of CEA.

The geometry had to be split into four sections due to the limited computational resources available for meshing and solving. The cutting strategy is illustrated in Fig. 2 by the various coloring: (i) section one- blue, orange and green, (ii) section two- yellow, (iii) section three- light gray and red, and (iii) section four- dark gray. Splitting is done in a way to have an overlapping region between two subsequent sections, see Fig. 4. It is done in order to retrieve inlet boundary conditions to the next section (taken 15 cm below the outlet), without having significant influence of the outlet boundary conditions applied in this section. Coupling is explained in more detail in Section 3.3.

3.2. Mesh

The meshing procedure for the complex geometry should be fully automatic to produce an optimal mesh and to save time. Therefore, in this study an unstructured polyhedral mesh with