Master Thesis Article:
Cold Moderator Hydrogen Flow and Cooling

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Abstract

In this master thesis, cold moderator flow concepts have been developed on behalf of the European Spallation Source, ESS AB in Lund. The function of the cold moderator is to slow down neutrons, generated in the spallation process. The moderation is done in liquid para-hydrogen at 15 bar and 17 K. Moderating neutrons is the primary function of the liquid hydrogen, but it also removes nuclear heat load, which is deposited in the hydrogen and the moderator aluminum vessel. The flow in the cold moderator has to therefore meet requirements for the cooling performance and limit pressure losses. In order to analyze and develop the flow in the cold moderator, commercial CFD and structural analysis codes has been used.

Key words: Conjugate Heat Transfer, Liquid Hydrogen, Cryogenic Liquid

1 Introduction

1.1 Neutron Spallation Source ESS

The European Spallation Source, ESS will be world leading spallation source in the nearest future. Generated neutrons will be used for science purposes that will help to develop future technologies within many different fields. The spallation process starts in the linear accelerator where protons are accelerated to a velocity near the speed of light. Then as a result of collision with tungsten pieces, a collection of high-energy neutrons is scattered. In the next phase, neutrons have to be moderated, which means that their kinetic energy will decrease and some of that energy will be transformed into a heat load.

2 Cold Moderator

The moderation of the neutrons takes place when high energy level neutrons collide with the liquid hydrogen, which is flowing through the cold moderator aluminium vessel at 17 K with mass flow of 0.4 kg/s.

At the same time, the fluid flow is removing the deposited heat load, which is approximated with a Monte Carlo simulation. The average heat load deposition in the aluminium, decreases from 15 W/cm^3 to 11 W/cm^3 in radial direction starting in the center of the moderator, while the liquid hydrogen has an equal deposition of 4 W/cm^3 . However, the neutron flux has a frequency of 14 Hz, which creates 3 ms long heat pulses with 69 ms breaks between them. The operating conditions in the cold moderator are close to the critical point of the liquid hydrogen, so that properties of the hydrogen will change very rapidly if the temperature will rise close to 33.18 K, [3]. During this thesis two geometry concepts has been developed. One for serial flow, Figure 1, and one for parallel flow, Figure 2.

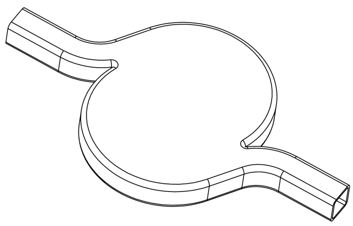

Fig. 1. Serial Flow Concept

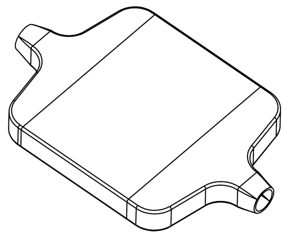

Fig. 2. Parallel Flow Concept

Both geometries have to withstand operating pressure of 15 bar and create a stable fluid flow that has an efficient cooling performance in order to avoid the critical temperature of the liquid hydrogen. Moreover, the total volume of the aluminium used for the outer shell and the fluid guides should be limited, hence aluminium decreases the brightness of the moderated neutron flux.

3 Simulation Methods

In order to evaluate requirements of the cold moderator geometries, unsteady conjugate heat transfer analyses have been performed with the CFD package ANSYS CFX. The fluid flow was simulated with several turbulence models as $k-\omega$ SST and full BSLRSM. The structure integrity was calculated with basic stress analysis performed in the ANSYS Mechanical package.

4 Results

4.1 Serial Flow Concept

Figure 3, shows the velocity field for the serial flow concept. There are two major re-circulation zones located behind U-bends with smallest radius. The size of these regions is reduced by additional guide blades introduced in the center of the channel. The total pressure drop is about 3.2 kPa.

Figure 4, shows the average temperature field of the outside aluminium vessel. It is noted that the temperature around the outlet bend is few degrees higher compared with the rest of domain. This depends on the incoming velocity profile, which is result of a combination of all previous U-bends. However, there are none fluid dead zones that might accumulate deposited heat.

The unsteady heat transfer simulation resulted in maximal peak temperatures up to 35 K in the aluminium and one degree less in the hydrogen, Figure 5. However, the average fluid temperature in time stays between 17 K and 22.5 K. This result implies that the supercritical liquid hydrogen is probably present only within the boundary layers, close to the aluminium walls.

The stress analysis for the operating pressure 15 bar, resulted in maximal stress concentration located in the corners of the channels giving about 79 MPa, Figure 6. According to [4] the maximal yield strength for the aluminium at 20 K is 380 MPa. This analysis shows that there is a good margin between maximal calculated value and the maximal yield strength value.

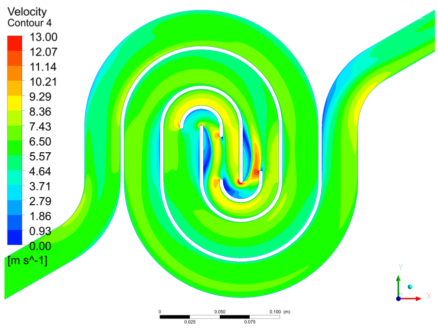

Fig. 3. The velocity field of the serial flow.

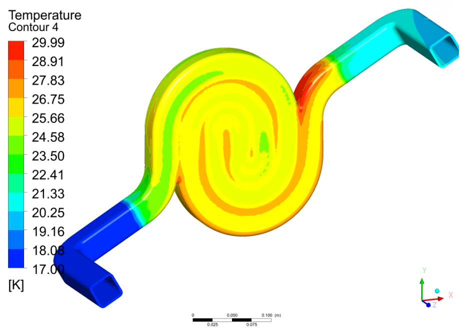

Fig. 4. The average temperature field of the outside aluminium vessel

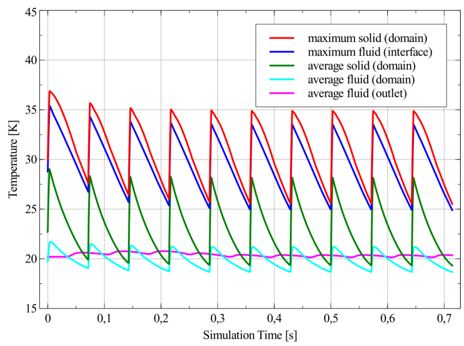

Fig. 5. The temperature monitors in time

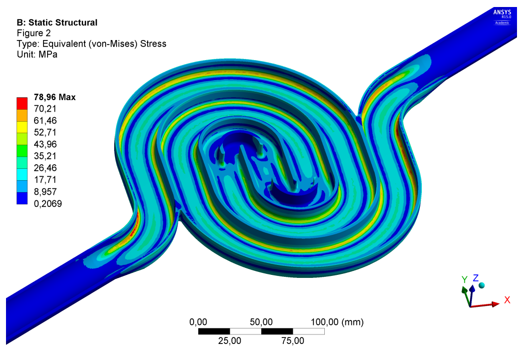

Fig. 6. The equivalent von Mises stress distribution

4.2 Parallel Flow Concept

Differently from the serial flow concept, the parallel flow divides the total mass flow into seven channels. This creates several obstacles that are not seen in the serial flow concept.

The most important one is the even distribution of the mass flow into all of the channels.

This may be difficult due to the required limitation of the aluminium volume that may be used in order to create all of the fluid guides that distribute the flow. The design that was chosen introduces a C-shaped crossbar in the front of the channels with a 1.5 mm gaps between the crossbar and the top and the bottom wall. The resulting distribution of the mass flow is presented in the Figure 7.

Figure 8, shows that this design results in regions with temperature above the critical temperature of the liquid hydrogen up to 79 K. The reason of that is the insufficient distribution of the mass flow to the outer channels of the vessel in combination with the lower flow rates in each channel.

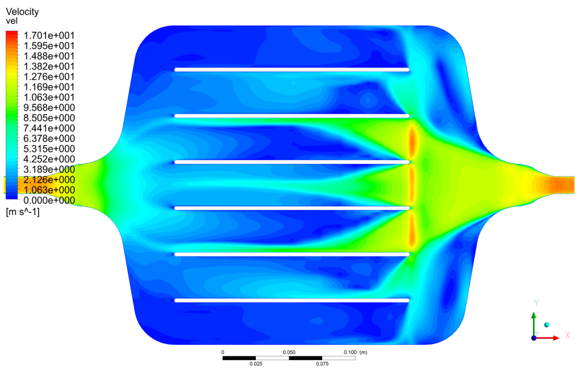

Fig. 7. The velocity field of the parallel flow.

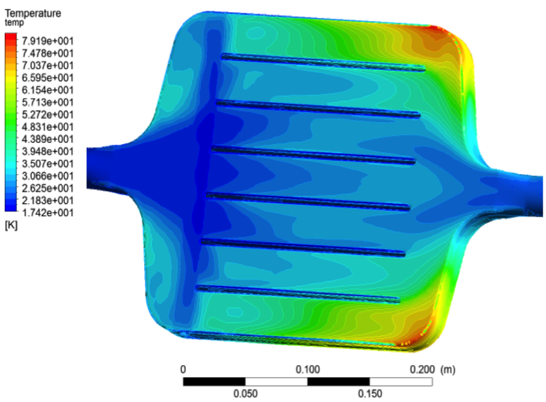

Fig. 8. Contours of temperature on the fluid-solid interface.

5 Conclusions

The proposed serial flow concept has a promising cooling performance and a well distributed velocity field with the total pressure drop of 3.2 kPa. The total removed heat load is calculated to 11.2 kW. The unsteady simulations showed that the maximum temperature of the liquid hydrogen may rise above the critical value of 33.18 K. However, the super critical hydrogen will then be present only within the boundary layers. The aluminium vessel of the serial concept should withstand the operating pressure, however a more detailed calculation is required.

Regarding the parallel flow concept, it has been shown that the current design does not satisfy the requirements of the cooling performance due to the insufficient distribution of the mass flow. This deficiency may be addressed through further development of the method for even mass flow distribution.

6 Future Work

A more advanced heat transfer simulation may take into account phenomena like expansion of the liquid hydrogen. Also, there are several geometry improvements that could be applied on the proposed geometries.

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