SETUP OF A HEAVY LIQUID METAL COOLED ROD BUNDLE EXPERIMENT FOR THE INVESTIGATION OF TURBULENT HEAT TRANSFER

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In the framework of accelerator driven sub-critical reactor systems (ADS), heavy liquid metals (HLM) like lead or lead bismuth eutectic (LBE) are considered as coolant for the reactor core and the spallation target due to their efficient heat removal properties and high neutron production rate. The excellent heat conductivity of LBE-flows characterized by its low molecular Prandtl number leads to a violation of the analogy of turbulent heat and momentum transfer so that modelling of the turbulent heat transfer in heavy liquid metals is still quiet inaccurate. Although various models for thermal hydraulics of LBE flows are existing, reliable heat transfer correlations for ADS-relevant conditions are still missing. In order to validate sub-channel codes and computational fluid dynamics (CFD) packages used to design fuel assemblies comparison with experimental data is inevitable.

In this paper the setup of a scaled LBE cooled rod bundle experiment planned at the KArlsruhe Liquid metal LAboratory (KALLA) for the experimental study of a thermally developing turbulent LBE flow in an electrically heated hexagonal rod bundle is discussed. Measurements of the local temperature and velocity distribution are planned by means of traversable thermocouples and pitot-tubes. A priori calculations with sub-channel analysis and commercial CFD codes are used to optimize the setup of the geometry and sensor equipment of the experiment.

I INTRODUCTION

Liquid metals are often considered as coolant for an efficient heat removal of thermally high loaded surfaces. Due to their high thermal conductivity heavy liquid metals allow rather simple geometries of the heat transfer unit employed.

However, the high conductivity leads to a violation of the analogy of turbulent heat and momentum transfer. The spatial extension of viscous and thermal boundary layer is different and the concept of a constant turbulent Prandtl number does not apply. While for momentum transport the turbulent contribution is dominant, the molecular contribution is of equal or even stronger importance for heat transfer. The common turbulence models in commercially available code packages (like k-ε model, Reynolds stress model, k-ω model) lead to considerable errors compared to the experimentally obtained temperatures.

Only the detailed knowledge of the convective-diffusive heat transport phenomena in laminar and turbulent liquid metal flows enables an adequate design of heat transfer units near highly heat loaded surfaces such as fuel bundles. This problem is particularly prominent in the weakly turbulent Reynolds number regime, where buoyancy plays a non-negligible role. Moreover, in most technical applications the flows are thermally developing so that the heat exchange trough the boundary layer plays a significant role. Only the detailed knowledge of the momentum and energy transfer in the thermal boundary region allows the understanding of the discrepancies between computational results and the experimental observation.

Therefore, a series of experiments has been initiated at the KArlsruhe Liquid metal LAboratory (KALLA) of the Forschungszentrum Karlsruhe. In order to quantify and separate the individual phenomena occuring in the momentum and the energy transfer domain of a fuel assembly the experimental program is composed of three major experiments.

In the LBE single rod experiment a single electrically heated rod is placed in a hydraulically developed turbulent LBE pipe flow in the regime of forced, mixed and buoyant convection. Radial and axial temperature fields are measured with a thermocouple rake and a movable thermal probe that also contains a pitot tube for pressure measurements. The experimental data are compared to numerical simulations simultaneously conducted by various groups in the context of the EUROTRANS program. Furthermore, this experiment allows to test the heater performance and the validation and qualification of the used measurement techniques.

In the second experiment an isothermal hexagonal rod-bundle is placed in a turbulent water flow where the flow distribution and the pressure drop in the sub-channels is measured by Laser Doppler Anemometry (LDA), Ultrasonic Doppler Velocimetry (UDV) and a movable pitot tube. This experiment also serves as a test for flow induced vibrations of the setup because the same experimental geometry is used for the LBE setup.

The third experiment is an electrically heated hexagonal rod-bundle that will be tested in a hydraulically developed turbulent LBE flow in regime of forced, mixed and buoyant convection. Measurements of temperature distribution and velocity fields are planned by means of UDV sensors and movable thermocouple rakes inside the rod bundle.

The experimentally gained data of all three experiments serves as a numerical benchmark of sub-channel analysis codes and commercial CFD software packages. The setup of two of the experiments, the water and the LBE rod bundle experiments is described in this article.

II. ROD BUNDLE DESIGN

The setup of the test rod bundle is of hexagonal shape and contains 19 electrically heated fuel pin simulators. It represents part of the fuel assembly proposed for the PDS-XADS (Preliminary Design Studies of an eXperimental Accelerator-Driven System) that contains 91 fuel pins. The active heated length is 870 mm, the power distribution is constant over the active length. The design parameters of two proposed PDS-XADS geometries together with the experimental setup are listed in table 1. The design of the rod bundle and its intended sensor instrumentation is shown together with a fuel assembly of the PDS-XADS design in figure 1. In a first step the rod bundle will be tested in a water loop at isothermal conditions to determine the pressure drops and the flow distribution in the individual sub-channels. It's also intended to investigate the occurrence of potential flow induced vibrations as a function of the flowrate.

TABLE I. Design parameters for the PDS-XADS fuel assemblies as well as the water and the electrically heated rod bundle experiment

	PDS-XADS	MYRRAH	Exp. H_2O	Exp. LBE
Geometry	hexagonal	hexagonal	hexagonal	hexagonal
Total Power	0.775 MW	1.466 MW	-	0.43 MW
Fuel pins	90	91	19	19
Pin diameter	8.5 mm	6.55 mm	8.2 mm	8.2 mm
Pitch	13.41 mm	8.55 mm	11.48 mm	11.48 mm
Pin length	1272 mm	1200 mm	1272 mm	1272 mm
Active height	870 mm	600 mm	870 mm	870 mm
Grid spacer	3	3	3	3
Mean velocity	0.42 m/s	2.5 m/s	10 m/s	2 m/s
Mass flow	~41 kg/s	~71 kg/s	~ 13 kg/s	~ 26 kg/s
Sub-ch. area	9330 mm²	2760 mm²	1260 mm²	1260 mm²
Max. heat flux	150 W/cm²	131 W/cm²	-	100 W/cm²
Inlet temp.	~ 300 °C	~ 200 °C	~ 25 °C	~ 300 °C
Outlet temp.	~ 400 °C	~ 337 °C	~ 25 °C	~ 415 °C

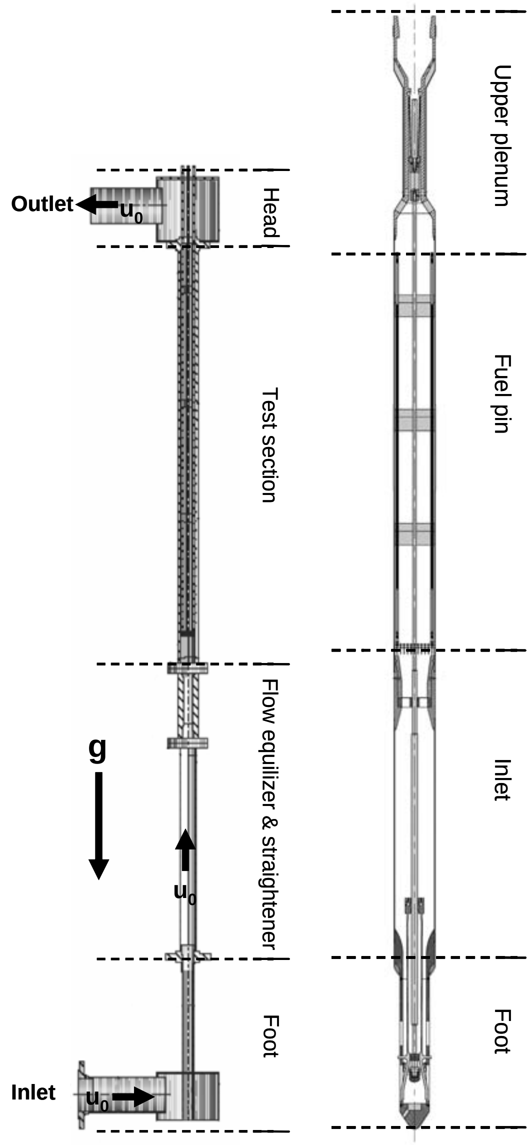

Fig. 1. Setup of the heated rod bundle experiment inserted into the LBE-Loop (left) and original fuel assembly of the PDS-XADS design (right).

The heated rod bundle experiment will be carried out at the THEADES LBE loop in KALLA to characterize the heat transfer characteristics of different operation conditions in the LBE-flow.

The entire fuel bundle simulator is composed of four modules flanged to each other and is fabricated from stainless steel. For the LDA measurements in the water experiment some parts of the test section are replaced by windows made of polymethylmethacrylate (PMMA).

The first part is the foot where at low velocity the incoming fluid is guided into a vertical tube through 6 vertical slits of 70 mm height and 6.5 mm width at fuel bundle conditions. The second part is the flow equalizer and straightener containing a venturi nozzle generating a hydraulically fully developed flow. The third part is the test section containing the 19 fuel pin simulators in a hexagonal arrangement. The transverse position of the pins is fixed by 3 vertically equal positioned spacers and an entrance guide. The spacer design is identical to that proposed for the XADS. The fourth part at the top is a head collector which is flanged to the test section and guides the fluid sidewards to the outlet. This is necessary in order to mount the simulators to the electric power supply.

III NUMERICAL CALCULATIONS

III.A Sub-Channel Analysis

By means of sub-channel analysis of the test section the expected pressure losses are calculated and the wall distance is optimized to provide a homogenous temperature distribution for all sub-channels in the rod bundle.

For this purpose, the thermalhydraulic analysis code MATRA (Multi-channel Analyzer for steady states and Transients in Rod Arrays) based on the sub-channel analysis tool COBRA-IV-I, was used. It was initially developed at the Korean Atomic Energy Research Institute (KAERI) to provide an improved structure, additional functions and models, a convenient user environment and increased numerical accuracy.

For the analysis of heavy liquid metal cooled fuel assemblies several modifications to the MATRA code were necessary as the original code does not include the thermophysical properties of liquid metals.

Therefore, the thermophysical properties of the used heavy liquid metal LBE was implemented into the MATRA code using the properties given by Sobolev in the OECD Handbook[1].

For the heat transfer in rod bundles the correlation of Subbotin was used[2]. For pitch to pin diameter ratios larger than 1.3 it reads

$$Nu = 7.55 \cdot \frac{P}{D} - 20 \cdot \left(\frac{P}{D}\right)^{-13} + \frac{3.67}{90} \cdot \left(\frac{P}{D}\right)^{-2} \cdot Pe^{0.19 \cdot \frac{P}{D} + 0.56},$$

where Nu is the Nusselt number, P is the pitch, D the fuel pin diameter and Pe the Peclet number.

Neutronic calculations performed within the EUROTRANS project suggest an optimal performance for a P/D ratio of 1.4. For this particular case the Nu-calculation in the bundle simulator reduces to

$$Nu = 10.3 + 0.0208 \cdot Pe^{0.826}.$$

Note that this equation results in Nusselt numbers much higher than those of the heat transfer correlation of LBE in circular tubes.

The single phase turbulent friction factor is obtained using the Rehme correlation for triangular rod arrays[3]. Detailed knowledge about turbulent mixing in-between adjacent sub-channels in LBE flows is still missing. A CFD based systematic study of the turbulent mixing in heavy liquid metal cooled rod bundles conducted by Cheng[4] showed that the turbulent mixing, i. e. the velocity fluctuation across the gap, is proportional to the mean axial flow velocity with a factor of 0.02.

The rod bundle layout is shown in figure 2a. Sub-channel calculations are performed for different wall distances w in the range between 5.1 mm and 8.1 mm. Constant mean LBE flow velocity of 2.0 m/s and a channel inlet temperature of 300 °C is assumed. The channel exit temperatures of all channels for three different values of w are shown in figure 2b.

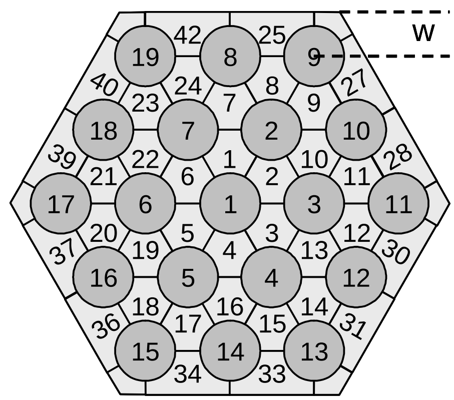

Fig. 2a. Rod bundle layout with modeling parameter wall distance w.

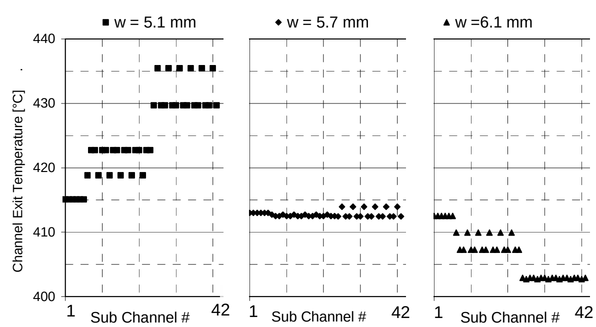

Fig. 2b. Channel exit temperatures of the sub-channels for three different wall distances w.

Due to the constant mean flow velocity the average temperature decreases with increasing wall distance w. Obviously the outer channels 25 to 42 are highly affected while the temperature for the inner channels 1 to 24 remains nearly constant. Simulation for a wall distance of

5.1 mm (squares) shows an about 20 K higher channel exit temperature for the outer channels, while for a wall distance of 6.1 mm (triangles) the temperature is about 10 K lower.

The optimized wall distance of 5.7 mm leads to a minimal temperature difference between all channels. This reduces thermal stresses and minimizes differential elongation. An average pressure loss of 0.20 MPa and an average channel exit temperature of 413 °C is computed. The maximum temperature variation among all rods over the test section is as low as 4.9 K, while the variation of the sub-channel temperature shows a much higher value of 9.2 K. This is due to the high temperature in the corner channels with the smallest channel area. The maximum temperature difference between the rods and its corresponding sub-channel at a given height does not exceed a value of 33 K.

III.B CFD

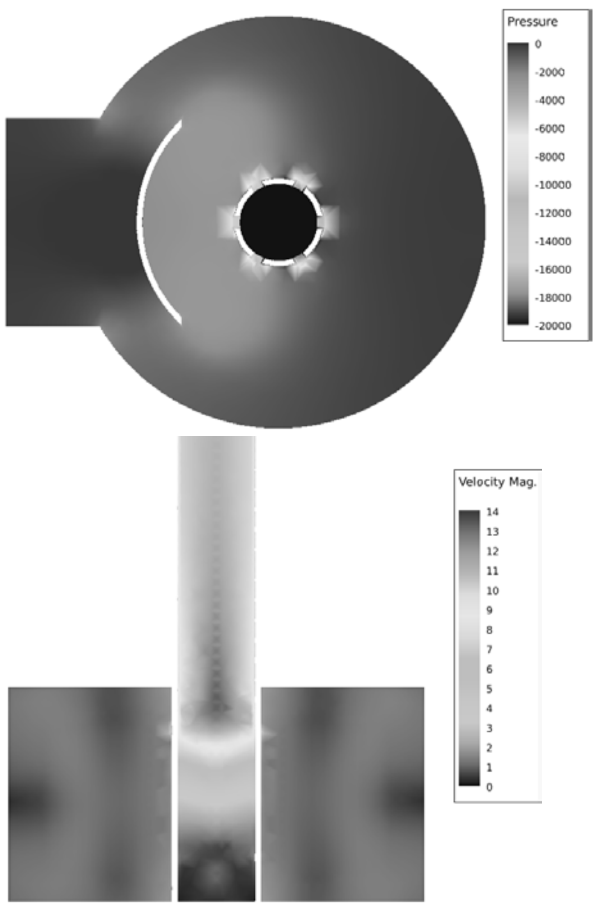

Fig. 3. Results of a CFD aided optimized foot module geometry showing pressure loss (top) and velocity distribution (bottom). (Calculations use a hybrid unstructured mesh with 200.000 cells and a high Reynolds number k-ε turbulence model)

CFD-calculations with the commercial software package STAR-CD 3.26 have been carried out for the foot section, the flow equalizer and the head section. The geometry of these parts has been optimized with respect to a minimial pressure loss while requiring a homogeneity of the flow of 98%.

For the lower vessel part of the foot several designs were discussed to homogenize the flow in the upstream tube. In the original PDS-XADS design this vertical tube ends directly in the lower part of the reactor vessel where the fluid is almost stagnant. By means of a deflector plate low uniform fluid velocities and uniform pressure conditions as shown in figure 3 could be obtained.

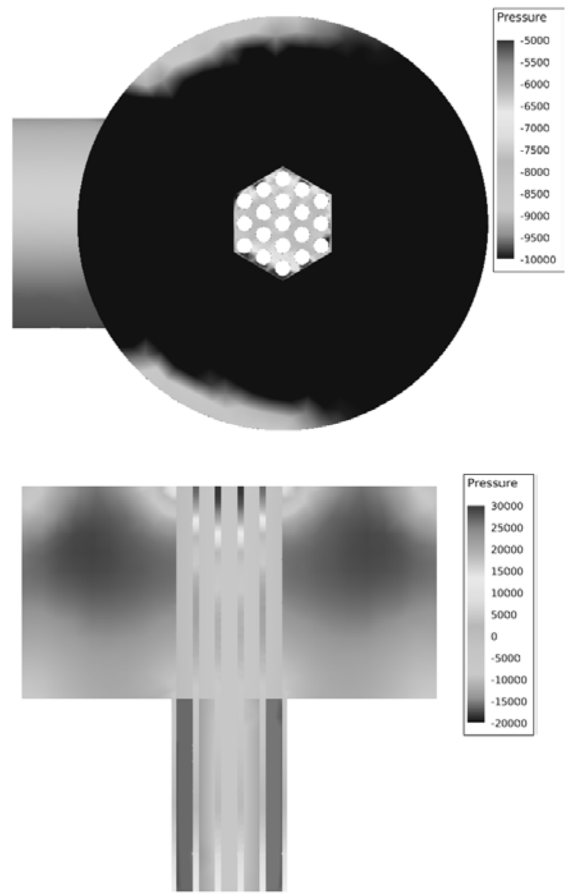

Fig. 4. Results of a CFD aided optimized head geometry showing pressure loss in the head section at test section exit (top) and side view (bottom) (Calculations use a hybrid unstructured mesh with 480.000 cells and a high Reynolds number k-ε turbulence model)

For the head collector design a big difference between the rod bundle experiment and the original fuel assembly arises since the original fuel assembly does not require an electrical connection in contrast to the simulator.

In the bundle experiment the power input is realized by means of an electric connection using a DC supply for each pin with 75 volts and 300 ampere. This requires to guide the heated rods trough the upper head.

CFD was used to find an optimal compromise for the head length. On one hand large head length reduces feedback on the pressure and the flow distribution of the outlet to the test section and on the other hand a minimized head length yields better measurement access for Ultrasonic Doppler Velocimetry (UDV) from the head top into the undisturbed sub-channel area. The optimized height was found to be 110 mm. The pressure distribution of the optimized head area is shown in figure 4.

The CFD based optimization yields the geometric dimensions and pressure losses at nominal operating conditions that are shown in table 1. A summarization of the results is given in table 2.

TABLE II. Results of optimization of experimental geometry by means of sub-channel analysis and CFD calculations at nominal operating conditions.

	Foot	Test Section	Head
Length	110 mm	1272 mm	110 mm
Diameter	213 mm	59.1 mm	213 mm
Pressure loss $H_2$0 at 25 °C	1.15 bar	1.98 bar	0.10 bar
Pressure loss LBE at 200 °C	0.86 bar	2.10 bar	0.06 bar
Pressure loss LBE at 400 °C	0.85 bar	2.04 bar	0.06 bar

IV CONSTRUCTIONAL DETAILS

IV.A. Spacer

A crucial element of a rod bundle is the spacer which ensures at all operational conditions a constant P/D ratio and thus guarantees a defined neutronic and thermalhydraulic performance of the reactor system.

The spacer design is kept as close as possible to the original developed in the context of the PDS-XADS and is shown in figure 5. It is composed of a honeycomb structure requiring 4 different sub-channel types to fit into the hexagonal shape of the rod bundle cross section. The rods are focused by point contacts embossed in the honeycombs to compensate lateral and axial expansion of the rods. Moreover, the point contact reduces the extend of the hot spot. Optimizations regarding enhanced flow conditioning have not been evaluated as these are not regarded to be necessary for liquid metal flows.

In contrast to the original design which suggests bending and welding of steel plates, the spacers fabrication employs by selective laser melting. An additional surface treatment reduces surface roughness from 30µm to 15µm after polishing. This is of the same order as the laminar viscous sub layer thickness in the liquid metal sub-channel flow.

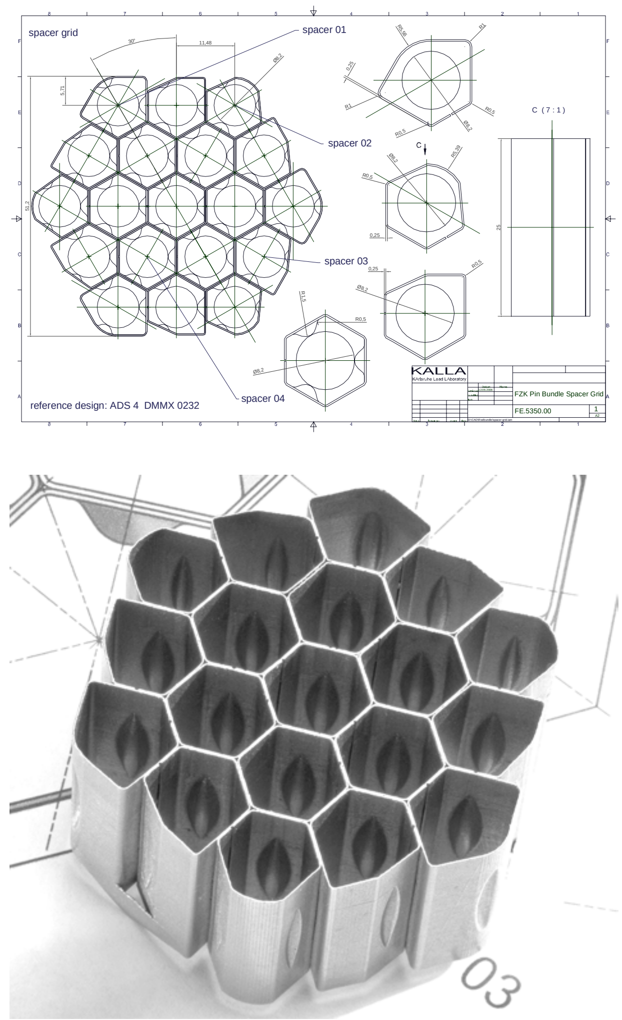

Fig. 5. Construction details of the used spacer design (top) and picture of a fabricated spacer by selective laser melting method (bottom).

IV.B. Sensor Instrumentation

The intended sensor instrumentation for pressure, temperature and fluid velocity measurements of the rod bundle experiments is shown in figure 6.

To ensure the comparability of both water and LBE rod bundle measurements, the geometrical design and material used are identical except for the windows made of polymethylmetacrylate (PMMA) that are required in the water experiment for the Laser Doppler Anemometry (LDA) measurements determining the velocity distribution. For the isothermal water experiment the temperature measurements in the sub-channels are not necessary. In case of the LBE experiment LDA measurements are not possible due to the opaqueness of the fluid.

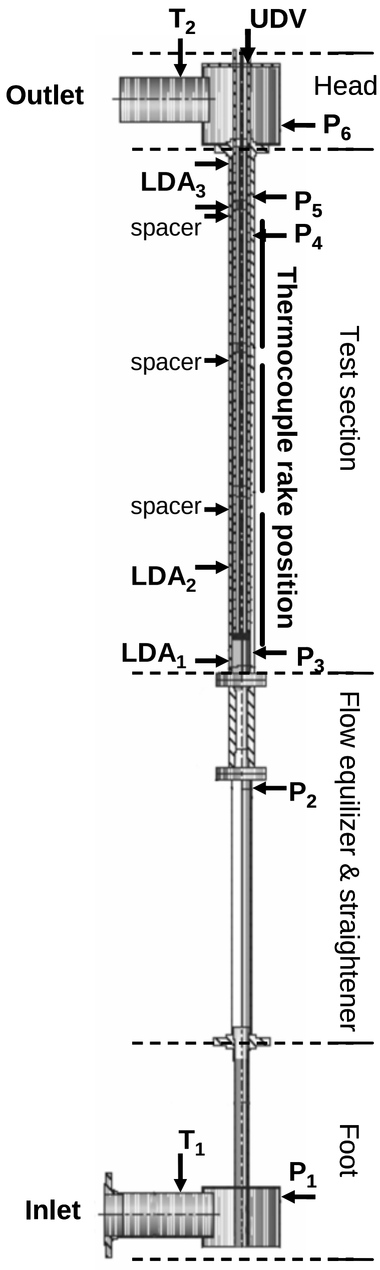

Fig. 6. Setup for the rod bundle experiment inserted into the LBE-loop with the intended sensor instrumentation.

Pressure and temperature measurements are foreseen at positions T1, T2, P1 and P6 to characterize the overall inlet and outlet conditions. Additionally pressure sensors are planned to measure the calculated pressure losses of the foot and upstream tube (P2-P1), flow equalizer (P3-P2), overall rod bundle loss (P6-P3) and the spacer induced pressure loss (P5-P4). To characterize the pressure distribution in each individual sub-channel, it is planned to integrate a movable pitot tube into the collector head. Due to the small distance of the rods a maximum diameter of 1.7 mm is allowed to reach the inner sub-channels. This domain is not accessible with a Prandtl tube that would allow for more precise measurements.

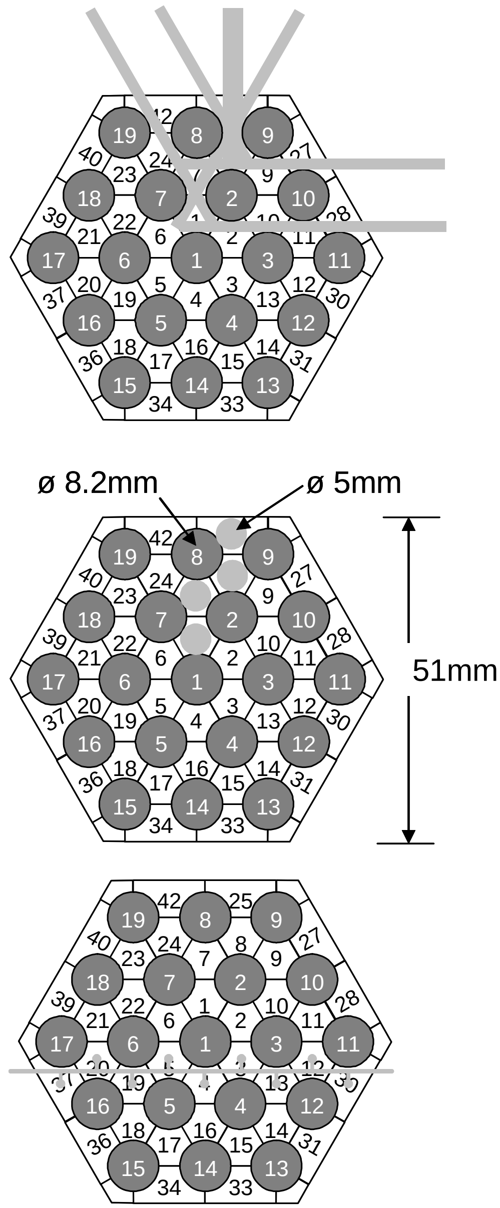

Fig. 7. Rod bundle test section with LDA measurement capabilities (top), positions for UDV sensor instrumentation (middle) and thermocouple rake (bottom). Size of the thermocouple rake is exaggerated in this view and will be much smaller in reality.

In the water experiment, fluid velocities can be easily and accurately measured by LDA. Therefore, optical access is foreseen by PMMA windows planned at positions LDA1 to LDA3 shown in figure 6. The velocity distribution is measured in the rod bundle downstream the venturi tube to characterize the inlet conditions (LDA1), upstream the first spacer to characterize the lateral flow distribution due to the bundle (LDA2), downstream the last spacer, and at the test section exit to characterize the spacer induced pressure loss and lateral flow redistribution (LDA3). Due to the rod bundle geometry only for the outer sub-channels the full area is optically accessible as shown in the top drawing of figure 7.

In the LBE experiment sub-channel temperature measurements over the whole heated test section are necessary to gather information regarding the thermalhydraulic behavior of the flow. For this purpose, three traversable thermocouple rakes are installed in the test section. They are movable along the assembly between the spacer positions as shown in figure 1. The lateral position of the thermocouple rake is depicted in figure 4.

Ultrasonic Doppler Velocimeter (UDV) measurements are carried out for both water and LBE experimental setup. For this purpose small UDV-transducers of 3 mm diameter will be positioned between the rods at the head exit position as shown in figure 1.

However, capturing of the flow rate is limited because of the beam divergence of the ultrasonic measurement signal. In this setup the maximum depth is 100 mm from the top so that it will be possible to determine the flow rate at the test section exit.

V. SYNOPSIS AND TIME HORIZON

In this paper a scaled liquid metal cooled fuel rod bundle simulation experiment performed within the IP-EUROTRANS project is presented. Its modular design admits measurements in water and liquid metal flows with minimized modifications of the experimental setup. CFD and sub-channel analysis aided geometry optimization leads to an optimal setup with minimized pressure losses.

The first part of the experiment, the single rod experiment in a LBE pipe flow is currently conducted [5]. The water rod bundle water setup is almost finished, the experiment is scheduled within the next year. The LBE rod bundle experiment will be completed within the context of the EUROTRANS contract.

ACKNOWLEDGMENTS

The work is supported in the framework of the IP-EUROTRANS project; contract number FI6W-CT-2004-516520

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