CFD ANALYSES OF THE ALFRED HOT PLENUM

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Abstract

The Advanced Lead Fast Reactor European Demonstrator (ALFRED) is a pool-type lead-cooled fast reactor of up to 300MW(th). The purpose of ALFRED is to demonstrate the viability of reliable electricity production of a European Lead Fast Reactor (LFR) system as a next-generation Small Modular Reactor (SMR) based commercial power plant. ALFRED is cooled with pure lead in forced circulation, having a nominal core inlet temperature between 390-400 °C and an outlet temperature of 430-530 °C, depending on the reactor power level.

The conceptual design of ALFRED has been developed in the frame of the European LEADER project, coordinated by Ansaldo Nucleare. Recently, this concept has been revised, responding to main issues identified in a critical review of the previous configuration. Currently, different optimization studies are underway to further improve the robustness of the reactor coolant system configuration, taking into account the most recent technology advancements.

The paper describes the approach followed by NRG to model the flow and temperature distribution in the ALFRED hot plenum using the Computational Fluid Dynamics (CFD) code STAR-CCM+. The CFD results provide detailed information on the upward lead flow in and in-between the fuel assemblies of the core, the cross flow from the core to the core outlets and the flow inside the core outlet regions. The flow field and predicted temperature distribution are an important indicator of the mixing behavior in the core and provide relevant feedback to the designers of ALFRED.

1. INTRODUCTION

The Advanced Lead Fast Reactor European Demonstrator (ALFRED) is a pool-type lead-cooled fast reactor demonstrator of up to 300MW(th) [1][2] developed with the support of the FALCON consortium between Ansaldo Nucleare, ENEA and RATEN-ICN [3]. The purpose of ALFRED is to demonstrate the viability of reliable electricity production of a European Lead Fast Reactor (LFR) system as a next-generation Small Modular Reactor (SMR) based commercial power plant. ALFRED is cooled with pure lead in forced circulation, having a nominal core inlet temperature between 390-400°C and an outlet temperature of 430-530°C, depending on the reactor power level.

The conceptual design of ALFRED has been developed in the frame of the European LEADER project, coordinated by Ansaldo Nucleare [1]. Recently, this concept has been revised, responding to the main challenges identified in a critical design review of the previous configuration. Currently, different optimization studies are underway to further improve the robustness of the reactor coolant system configuration, taking into account the most recent technological advancements.

Computational Fluid Dynamics (CFD) analyses with STAR-CCM+ have been performed by NRG of the core outlet flow field in the updated (3 pumps) configuration of ALFRED. The domain considered, starts above the heated core section and models the flow of liquid lead in and in-between the fuel assemblies (FAs), and the cross flow from the core to the pump pipe. This CFD work has been performed as part of a cooperation between FALCON and NRG, and is based on NRG's expertise on thermal hydraulic analyses for fast reactors [7]. The geometry modelled in CFD is based on CAD files provided by Ansaldo Nucleare. In the CFD model only the flow and heat transfer of the liquid lead is considered. Heat transfer and heat loss across walls are neglected.

The CFD results provide detailed information on the upward lead flow in and in-between the fuel assemblies of the core, the cross flow from the core to the pump pipe and the flow in the pump pipe. The flow field and predicted temperature distribution are an important indicator of the mixing behaviour in the core and provide relevant feedback to the ALFRED design team. In chapter 2, the ALFRED core outlet region model developed by NRG in the CFD code STAR-CCM+ is described. Next, in chapter 3, the simulation results are presented and discussed.

2. CFD MODEL

The ALFRED reactor vessel of the updated (3 pumps) configuration is about 10m high and 8.3m in diameter and consists of three symmetrical portions of 120°, each containing one pump and one steam generator (SG) [1]. On the left in FIG. 1, a schematic drawing of the complete ALFRED reactor coolant system is provided. On the right in FIG. 1, one symmetrical part of the ALFRED core is shown, visualizing part of the inner vessel with its internals and one of the three pump pipes.

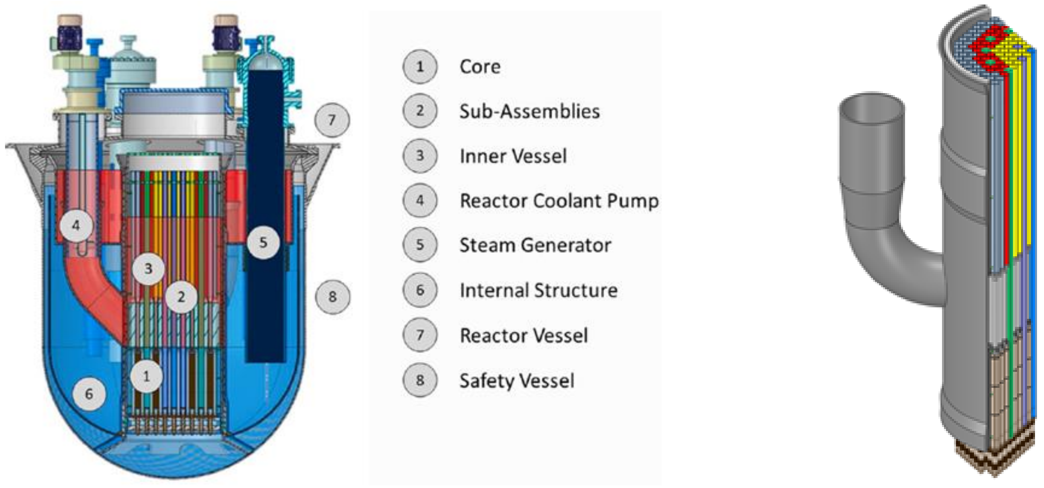

FIG. 1. Schematic drawing of the ALFRED reactor coolant system (left) and one symmetrical part of the ALFRED core with pump pipe (right).

2.1. CFD domain

As shown in FIG. 2, the modelled CFD domain starts just above the heated section of the core, and extends up to the lead free level. Boundary conditions are imposed on the horizontal cross sections shown by the dashed lines indicated as 'INLET' and 'OUTLET'.

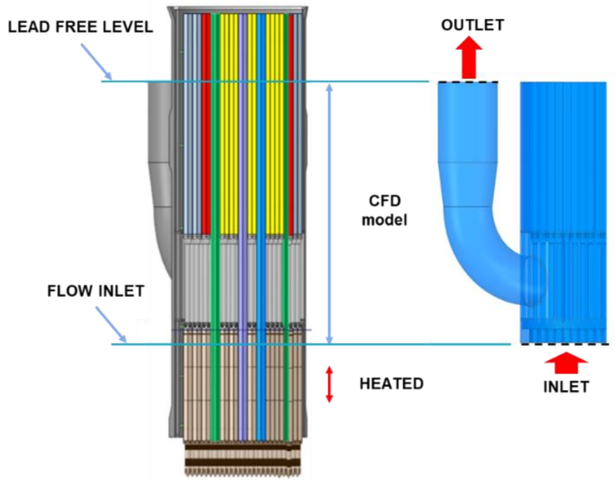

FIG. 2. ALFRED core outlet region modelled with CFD.

In the CFD model, only 1/3rd (120°) of the core outlet region is considered by making use of the symmetry planes. The geometry of the 1/3rd section of the ALFRED core outlet region is provided by Ansaldo Nucleare as

CAD files of the solid parts. The left picture in FIG. 3 shows the solid parts after importing the CAD files into the ANSYS Space Claim software. The Control Rods (CRs), Safety Devices (SDs) and In-Pile Section (IPS) are not included in the CAD files, as indicated by the empty positions in FIG. 3, and are not considered in the CFD model. Since only a small (leak) flow of lead is going through these positions (< 0.5% of the total flow), little effect is expected from the CRs, SDs and IPS on the nominal flow and temperature of the lead in the steady case studied here. This model simplification seems, therefore, justified for the present work.

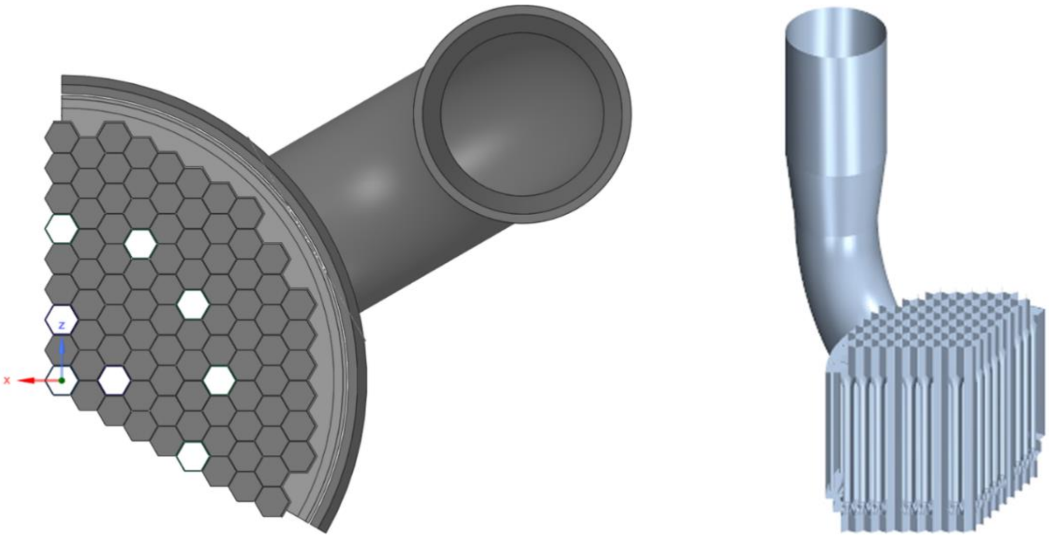

FIG. 3. On the left, a top view on the modelled 1/3rd section of the ALFRED core outlet region. On the right, a 3D view of the modelled 1/3rd section of the ALFRED core outlet region.

The CFD domain is the inverse (fluid counter-part) of the solid parts from the CAD files. The right picture in FIG. 3 shows the walls of the fluid domain after importing into the CFD software STAR-CCM+ 12.02.011 [5].

2.2. CFD setup

The objective of the current work is to study the flow field in the core outlet region and the pump pipe under nominal conditions. To this end, the steady-state flow, heat transport and turbulence in the liquid lead is solved, with the segregated 2nd order solver of STAR-CCM+. Turbulence is modelled with the realizable k-ε model with all y^+ near wall treatment and using a turbulent Prandtl number of 2.0, as recommended by Duponcheel et al. [6] to take into account the specific heat transport properties of the liquid metal coolant. Note that we have applied the above model settings also in previous CFD analyses for fast reactors [7]. A gravitational acceleration of −9.81 m/s^2 acts in the y-direction (downward). In the CFD model only the heat transfer in the liquid lead is considered. Heat transfer and heat loss across walls is neglected. The details of the applied CFD model are summarized in Table 1 below.

TABLE 1. CFD Model Settings

CFD code	STAR-CCM+ version 12.02.011 [5]
Solver	3-Dimensional, steady state, segregated, 2nd order
Approach	Single phase/fluid
Mesh	Wall modelled (y^+ > 30) mesh of 25 million polyhedral cells with prism layers near the walls
Turbulence model	Realizable k-ε with all y+ near wall treatment and Pr_t = 2.0 [6]
Buoyancy	g = -9.81 m/s^2 in vertical direction
Lead coolant	Temperature dependent properties based on the OECD handbook [4]
Walls	Adiabatic no-slip walls
Heat losses	Heat loss to environment and/or cover gas is neglected
Cover gas	Modelled as adiabatic slip boundary conditions at the lead free surface

Table 2 shows the temperature dependent properties of liquid lead taken from the OECD [4]. These correlations are implemented and used in the CFD model. The last column of Table 2 gives the properties of liquid lead at 520 °C, *i.e.* the average core outlet temperature under nominal conditions.

TABLE 2. Temperature Dependent Properties of Liquid Lead [4]

Property	Correlation	Value at 520 °C
Density	$11441 - 1.2795 \cdot T$	10426 kg/m^3
Viscosity	$4.55 \cdot 10^{-4} \cdot exp(1069/T)$	1.75E-03 Pa.s
Conductivity	$9.2 + 0.011 \cdot T$	17.92 W/m.K
Specific Heat	$175.1 - 4.961 \cdot 10^{-2} \cdot T + 1.985 \cdot 10^{-5} \cdot T^2$ $-2.099 \cdot 10^{-9} \cdot T^3 - 1.524 \cdot 10^6/T^2$	144.8 J/kg.K

A polyhedral mesh of 25 million cells is created. A base cell size of 40 mm is used, in combination with prism layers near the walls. A mesh sensitivity study has been performed to demonstrate mesh independence and to ensure a $y^+ > 30$ near wall mesh throughout the domain. In Table 3 an overview is provided of the three meshes applied in the mesh sensitivity study with their characteristics.

TABLE 3. Mesh Sensitivity Study

Mesh	10M	24M	25M
# cells	10.4×10^6	23.9×10^6	25.4×10^6
cell type	polyhedral	polyhedral	polyhedral
cell size [mm]	80	40	40
# boundary layers	2	3	4/5
cell refinement	near walls	near walls and in (narrow) flow passages	near walls and in (narrow) flow passages
Wall y+	50 ~ 1000	50 ~ 500	30 ~ 300

On the left hand side in Fig. 4, a picture of the mesh on a vertical cut plane going through the centre of the ALFRED core and the centre of the pump pipe. On the right hand side in Fig. 4, a detailed view on the mesh inside and in-between the assemblies near the inlet of the modelled domain.

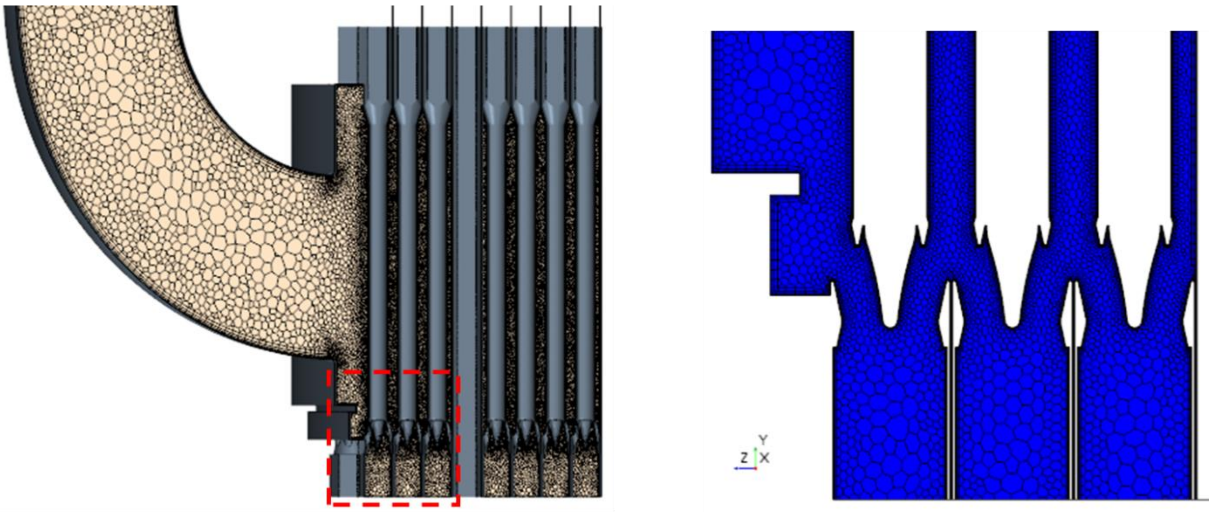

FIG. 4. Applied polyhedral mesh in the modelled ALFRED core outlet section.

2.3. Boundary conditions

Since the Control Rods (CRs), Safety Devices (SDs) and In-Pile Section (IPS) are not included in the CFD model, the inlet of the CFD domain consists of the following four regions, as illustrated in FIG. 5:

(a) Inner fuel assemblies (inner FAs).
(b) Outer fuel assemblies (outer FAs).
(c) Dummy assemblies (DAs).
(d) Inter assembly bypass (IA bypass).

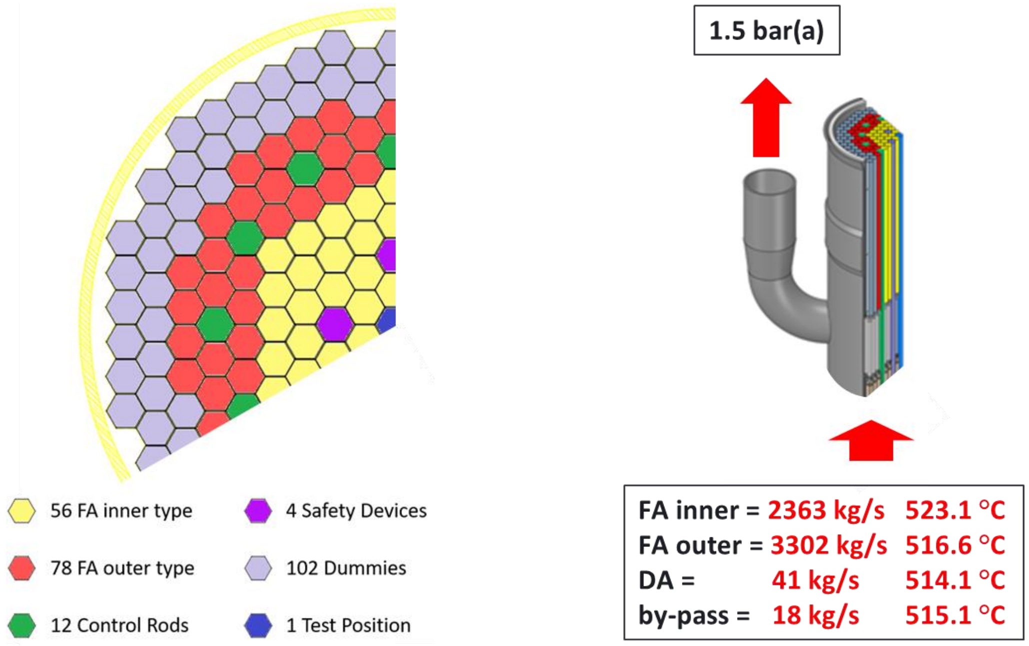

FIG. 5. Inlet regions (left) and imposed boundary conditions in the CFD model (right).

The flow rate and temperature at each inlet region have been provided by Ansaldo Nucleare. Because the CRs, SDs and IPS are not included in the CFD model, it was decided to add the leak flow through the CRs (0.35% of total flow) to the outer FAs mass flow rate and the leak flow through the SDs (0.1% of total flow) and IPS (0.02% of total flow) to the inner FAs mass flow rate.

The inflow temperature at the outer and inner FAs is adapted accordingly. The temperature at the inlet of the outer FAs is defined as the mass flow averaged temperature over the outer FAs and the CRs. The temperature at the inlet of the inner FAs is defined as the mass flow averaged temperature over the inner FAs, the SDs and the IPS. The model is finally provided with an outlet boundary condition of 1.5 bar absolute pressure at the top of the pump pipe. The imposed (nominal) boundary conditions at the inlets and the outlet of the CFD domain are shown in FIG. 5 and listed in Table 4.

TABLE 4. Imposed boundary conditions in the CFD model.

	Inlet inner FA	Inlet outer FA	Inlet DA	Inlet IA bypass	Outlet
Mass Flow Rate [kg/s]	2363.22	3302.10	41.21	17.75	-
Temperature [°C]	523.10	516.63	514.11	515.11	-
Pressure [bar(a)]	-	-	-	-	1.50

3. CFD RESULTS

FIG. 6 gives a view inside the modelled ALFRED core outlet region and pump pipe, showing the flow patterns and contours of velocity magnitude under nominal conditions. The liquid lead enters, mainly, through the inlets of the inner and outer FAs. First, the liquid lead flows straight up inside the FAs until it is pushed out at the FA exit holes, entering the inter assembly (IA) region. In the IA region the liquid lead is pulled towards the pump pipe. Highest velocities are observed at the exit holes of the FAs and at the upper end of the bend in the pump pipe.

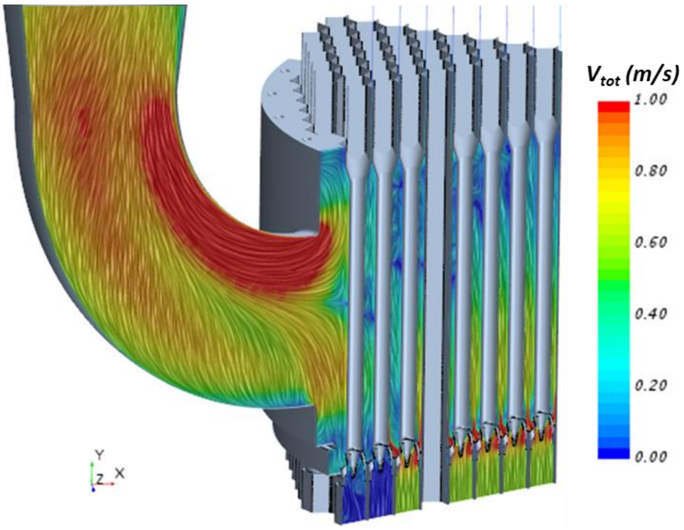

FIG. 6. 3D view of the modelled ALFRED core outlet section, cut in half at the vertical plane through the centre of the pump pipe to give a view inside. The contours of velocity show the flow path of the liquid lead.

FIG. 7 shows contour plots of velocity, pressure and temperature in the modelled core outlet region. A maximum pressure drop of 0.13 bar is observed from the inner-FA inlets to the outlet. The mean pressure at the inner-FA inlets, outer-FA inlets, DA inlets and IA bypass inlet is respectively 1.63 bar, 1.62 bar, 1.54 bar, and 1.54 bar. The maximum velocity stays below 2 m/s in major part of the domain, except in a small region at the upper end of the entrance to the pump pipe where velocities up to 2.65 m/s are observed. The temperature of the lead in the inner FA region stays close to the inlet temperature of 523°C and does not seem to vary much. In top of the core, the velocity is low and temperatures stay close to the maximum temperature of 523 °C, *i.e.* the inlet temperature of the inner FAs.

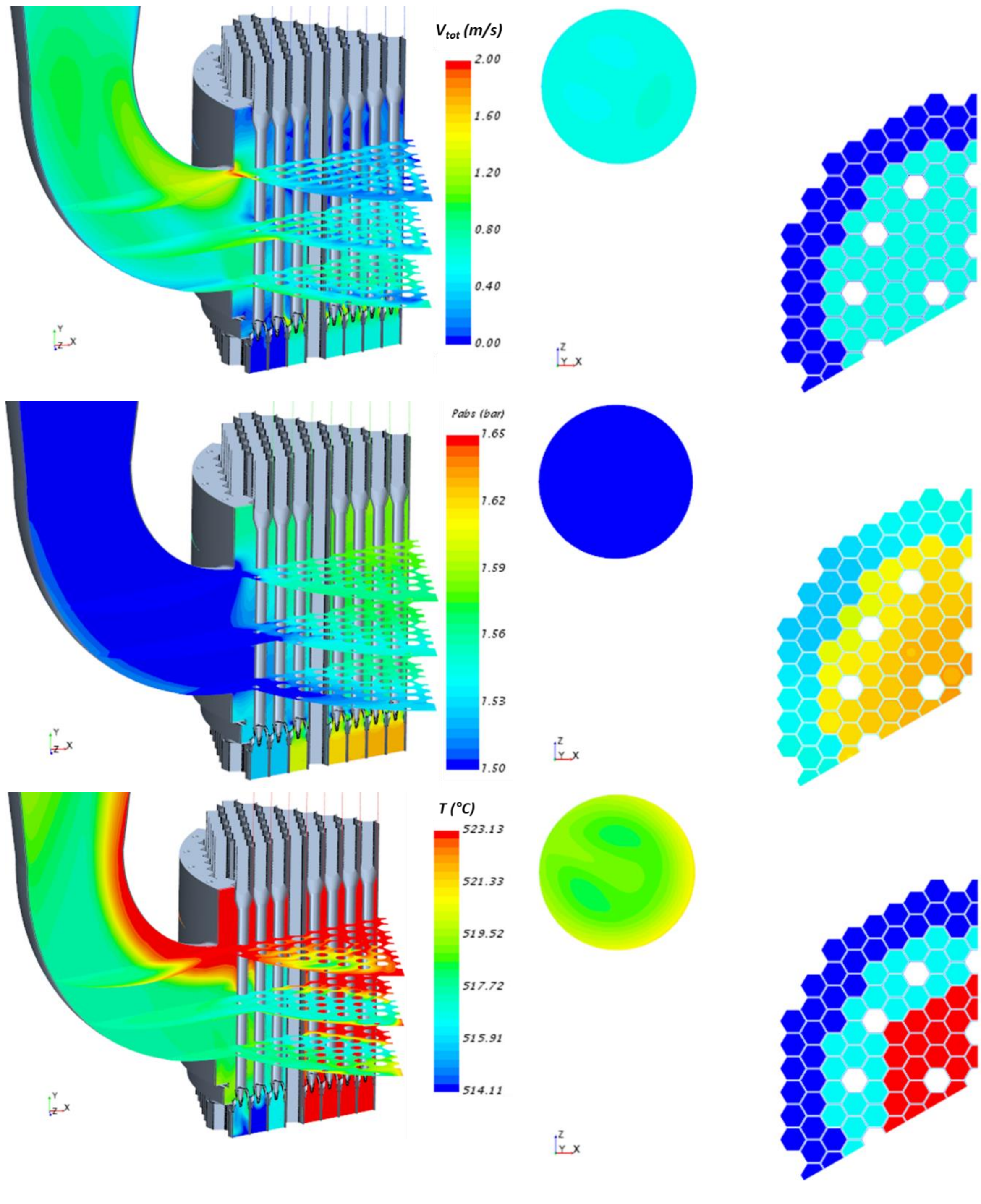

FIG. 7. Predicted velocity (top row), pressure (middle row) and temperature (bottom row). On the left, a 3D view giving a look inside the modelled ALFRED core outlet section. The horizontal cut planes are located at a height of resp. -6.8m, -6.4m and -6.0m. On the right, the contour plots on the inlets and the outlet of the modelled domain.

FIG. 8 shows the velocity and temperature distribution on a horizontal planes at a height of -6.4 m (middle of entrance to pump pipe). High velocities are observed at the wall of the core inner vessel and at the wall of the bend in the pump pipe. This indicates that the liquid lead first tends to flow radially towards the inner vessel wall of the core, and next tangentially along the inner vessel wall towards the entrance to the pump pipe. The relatively hot lead from the inner FAs seems to flow straight up to the upper part of the core and leaves the core inner vessel via the upper end of the pump pipe.

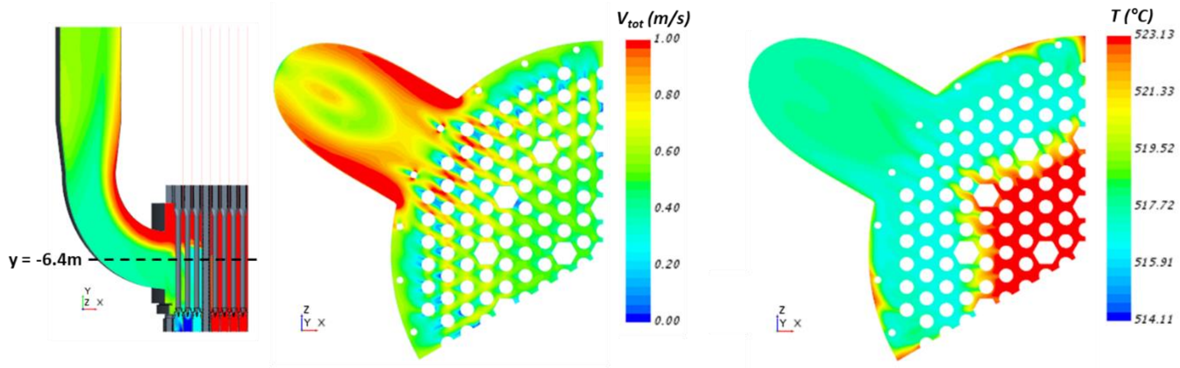

FIG. 8. Predicted velocity distribution (middle) and temperature distribution (right) on a horizontal cut plane at -6.4m through the modelled ALFRED core outlet section.

To get more insight in the flow patterns in the core outlet region, the velocity components and the temperature are plotted on horizontal and vertical probe lines. FIG. 9. shows the velocity and temperature on two radial lines at -6.4m high, one positioned in-between the FAs near the mid plane and one positioned in-between the FAs near the symmetry plane. In the IA region (0 m < r < 1.4 m) the radial velocity increases with radial position and the vertical velocity stays more or less constant around 0.5 m/s. The tangential velocity fluctuates between -0.2 and 0.2 m/s in the IA region as the liquid lead flows zigzag-wise in-between the FAs in radial direction. All velocities drop between 1.3 m < r < 1.4m when the liquid lead moves out of the IA region, where a lot of space is occupied by the FAs, into a region without FAs and with a larger flow area. From r = 1.4 m to the centre of the pump pipe at r = 2.0 m, the radial velocity dominates. In the annular region along the inner vessel wall (1.4 m < r < 1.6 m), the radial and vertical velocity both decrease. Close to the inner vessel wall the vertical velocity even becomes negative, *i.e.* downward flow. The downward flow close to the inner vessel wall brings down relatively hot lead from the upper part of the core.

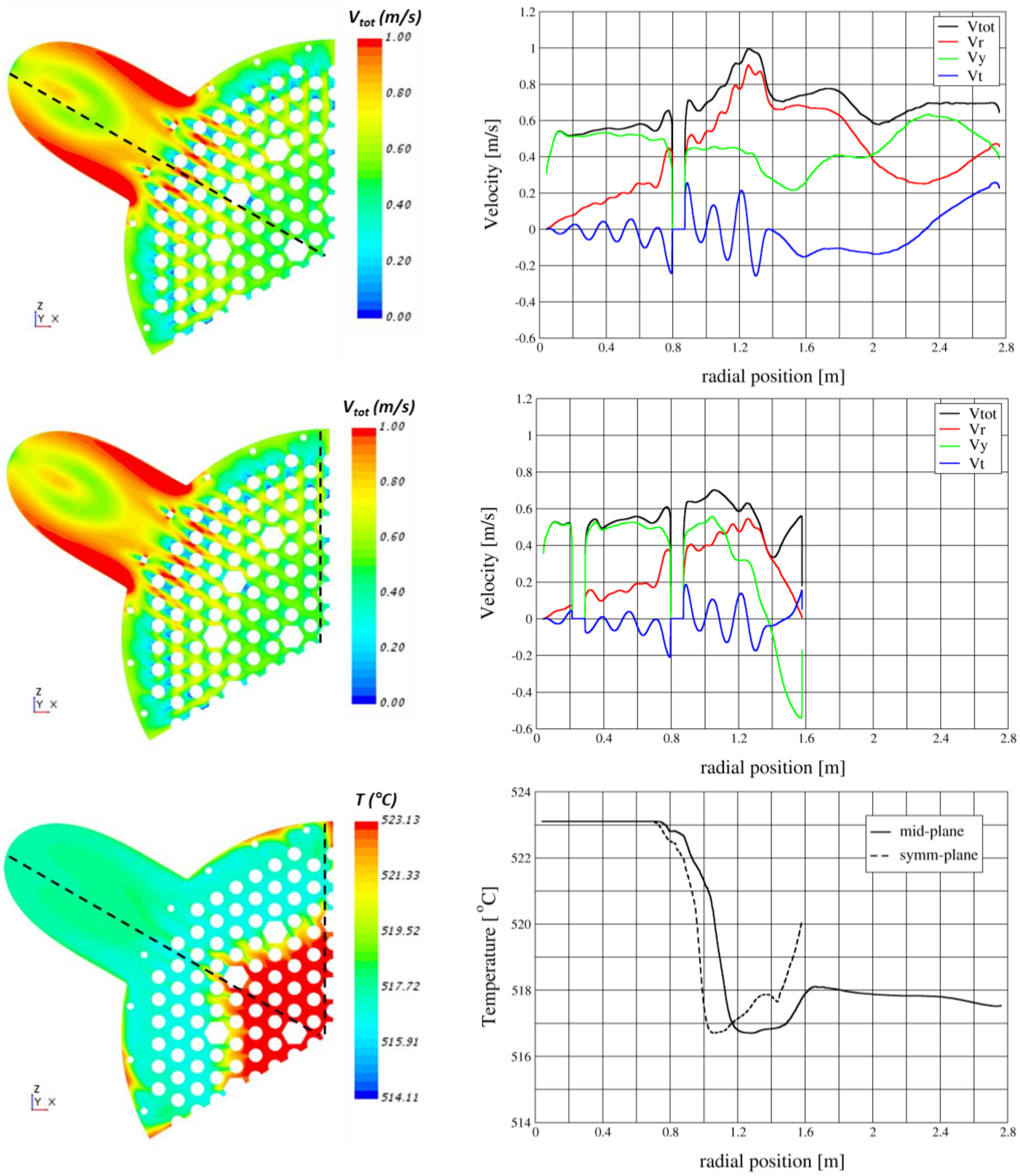

FIG. 9. Velocity components and temperature on radial probe lines through the modelled ALFRED core outlet section.

4. SUMMARY

A 1/3rd model of the ALFRED core outlet region is developed within the CFD code STAR-CCM+, making use of symmetry planes. The geometry and nominal boundary conditions have been specified in cooperation with Ansaldo Nucleare.

The steady state CFD results give a good picture of the flow paths and temperature distribution in the ALFRED core outlet region under nominal conditions. The flow and temperature in the core outlet region are driven by the imposed boundary conditions. The main flow of the liquid lead is in and in-between the inner and outer FAs. The relatively hot lead from the inner FA flows up in-between the inner FA and creates a relatively hot layer in top of the core with a temperature close to the inner FA inlet temperature of 523 °C. Even further downstream in the pump pipe the relatively high temperatures are still noticeable. The overall temperature difference of 10°C in the core outlet region seems to show a good mixing capacity of the studied configuration. The maximum velocity stays well below the 2 m/s in major parts of the core outlet region, except in a small region at the upper end of the entrance to the pump pipe, which might require further investigation. A maximum pressure drop of 0.13 bar is predicted from inlet to outlet of the core outlet region.

A possible next step could be to extend the symmetrical model to a full 3D model, opening up the opportunity to investigate asymmetric transients or accidental conditions.

ACKNOWLEDGEMENTS

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