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STUDY OF ENHANCED ENTRANCE PRESSURE LOSSES IN A ROD BUNDLE EXPERIMENT EMPLOYING HEAVY LIQUID METAL COOLANT

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Abstract

Innovative nuclear reactor concepts like accelerator driven systems (ADS) or the lead cooled fast reactor LFR employ lead bismuth eutectic (LBE) as a coolant. Within the framework of the EU project THINS (thermalhydraulics of innovative nuclear systems) a rod bundle experiment in LBE is performed employing characteristic dimensions at the Karlsruhe Liquid Metal Laboratory (KALLA)l of Karlsruhe Institute of Technology (KIT). In a first measurement campaign it is observed that the pressure drop across the first spacer in the rod bundle experiment is noticeable larger than at the subsequent spacers. We speculate that this is due to blockage of the very narrow spacer channels and numerically investigate whether there are substantially enhanced entrance effects. The present numerical study investigates the whole rod bundle including the entrance region in order to show possible mechanisms which can increase the pressure drop of the first spacer even if no blockage is present. The extra pressure loss compared to simulations with uniform inflow is found to be very small which supports the speculation of blockage. Since rod bundle flow is known to depend very sensitive on turbulence models and mesh resolution we carefully verify that our simulations use an adequate computation domain, mesh resolution and turbulence model.

1. Introduction

At the Karlsruhe Liquid Metal Laboratory (KALLA) a series of experiments are performed which aim at providing high quality experimental data on the generic liquid metal thermohydraulics of typical components of innovative nuclear reactors at prototypical dimensions. For this purpose the large liquid metal loop THEADES (190-450°C operation temperature, 47m³/h maximum flow rate, 4m³ LBE inventory) has been set up and hosts various experiments including a 19 pin rod bundle experiment. Pin to pitch ratio as well as the axial dimensions exactly correspond to the dimensions of the XT-ADS fuel bundle considered in the IP-EUROTRANS, see [1]. Since liquid metal experiments do not allow for optical measurement techniques the liquid metal experiments are accompanied by water experiments with identical test sections. The combination of numerical simulations, water experiments with comprehensive instrumentation and liquid metal experiments with global and local measurements provides an optimal environment to gain profound basic understanding of relevant phenomena.

In the present study the 19 pin rod bundle test are considered. The test section shown in figure 1 consists of a foot piece, flow equalizer and straightener, a Venturi nozzle, the rod bundle, and a head piece. The pins are held in their position by a pin fixer downstream of the venture nozzle and 3 spacer grids which are shown in figure 2.

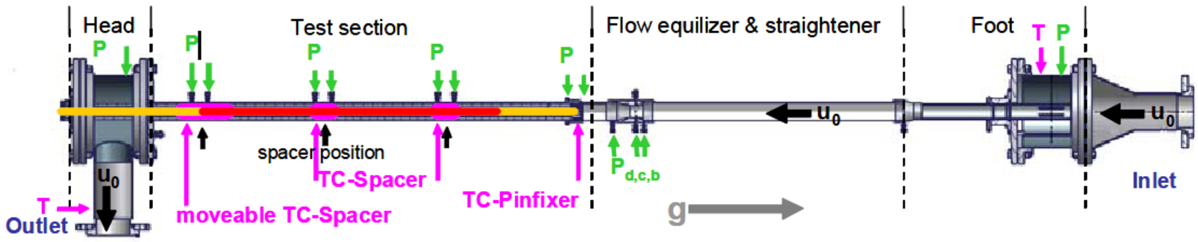

Figure 1   Instrumentation of the LBE rod bundle experiment

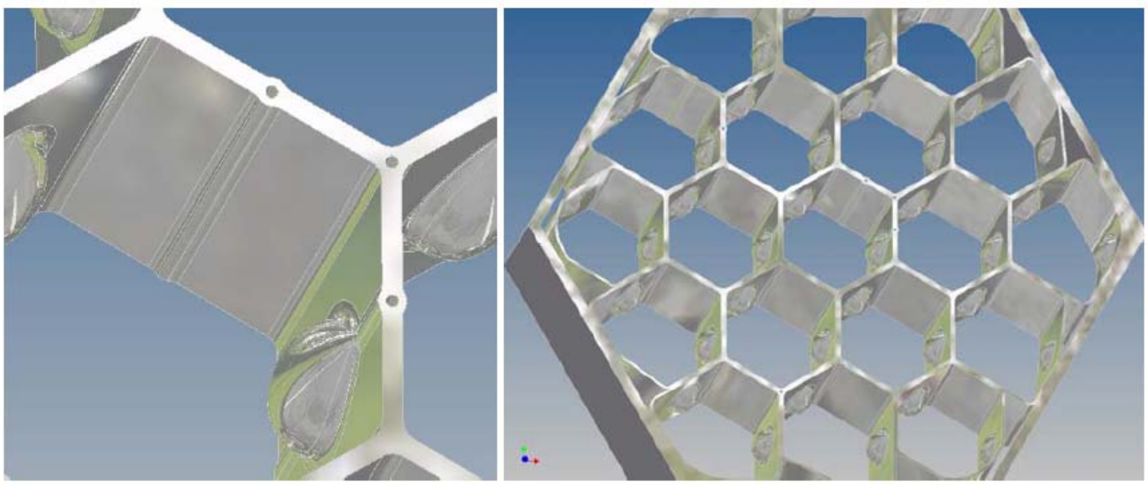

Figure 2: Design of used Spacer for equipment with thermocouples for the LBE rod bundle experiment (p/d=1.47, d=8.2mm, small holes on left figure are installed with thermocouples**)**

The foot piece and flow equalizer have been numerically optimized [2] to provide uniform inflow. This has been experimentally verified in the water experiment, so that the present study assumes uniform flow prior to the Venturi nozzle. Figure 3a shows measured axial velocity profiles at the lowermost window position in the test section just upstream of the rods [2]. Figure. 3b shows the optical access of the water test section. The water experiment was accompanied by numerical simulations [1] which showed that the three spacer grids have near identical pressure drop. The reason for the small effect of developing flow is the strong acceleration due to the reduced flow cross section within the bundle. Therefore, we expect the same situation in the liquid metal experiment. In the first measurement campaign of the liquid metal rod bundle experiment a strongly enhanced pressure drop was found at the first spacer which also increased in time. This observation leads to the speculation of blockage. Yet there may be some small pressure drop enhancements due to the developing flow that might explain at least part of the additional pressure drop found between the first and successive spacers. In our previous studies of successive spacers [1] we assumed uniform inflow which we claimed a fair approximation. Other studies like [3,4] investigates the experiment based on subchannel codes. The enhanced pressure drop at the first spacer grid in the experiments drove us to reconsider this approximation and we started a new series of simulations which include the Venturi nozzle and pin fixer so that flow development can be analyzed. Also we take account of the known sensitivity on turbulence models, mesh resolution and wall treatment.

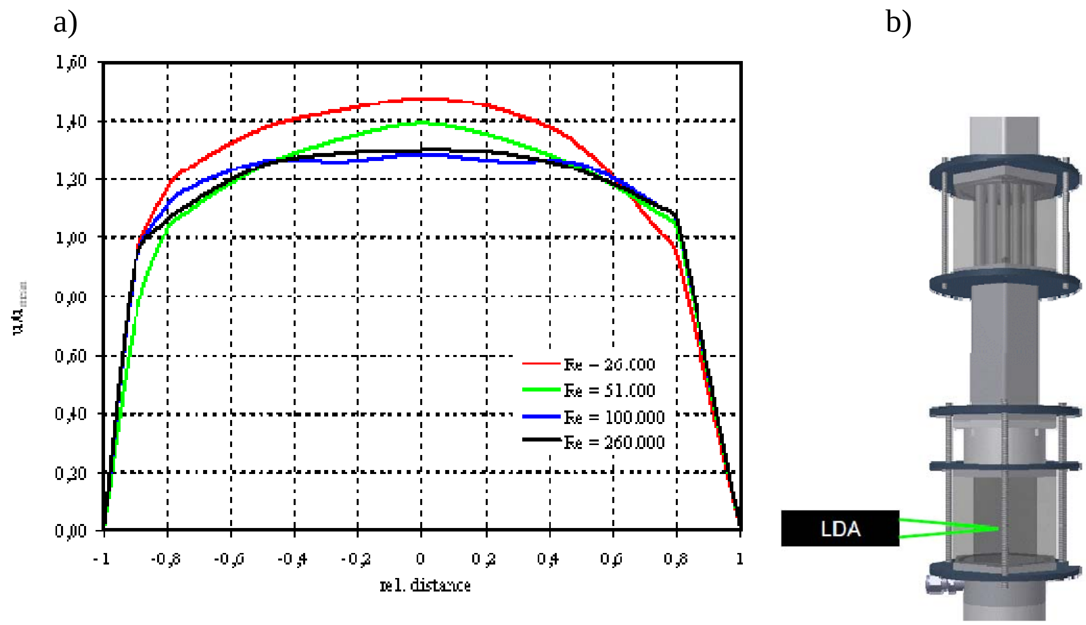

Figure 3 Axial velocity profile at beginning of the test section measured by LDA

The structure of the present investigation is as follows. First we compare a simulation of the full geometry (360° sector) including venturi, pin fixer and first spacer to a greatly simplified geometry with 60° sector uniform inflow and a single spacer. This verifies our assumption of no significant pressure drop enhancement. We also check lateral transport and symmetry assumptions. The sensitivity study of turbulence models and wall treatment and a mesh refinement study are performed o the 60° sector geometry. These simulations include unsteady simulations which allow analysing potential instabilities enhancing lateral mass flow between neighbouring subchannels.

2. Numerical study

2.1 Study of domain effect

For the numerical study different computational domains are used. Due to size of the whole bundle we restrict our simulation to the entrance region including one spacer. As explained above for the first test two computational domains are used. The first includes all details of geometry in the bundle upstream by including venturi nozzle and pin fixer as indicated in figure 4a. The other domain is simplified and covers only a sector of 60° as indicated in figure 4d. For the current study the same cell size and mesh parameters are used in order to make the comparison of mesh independence. Domain I with a 360° sector is meshed with approximately 2 million cells where domain II with a 60° sector is meshed with 0.2 million cell. The standard k-ε model with high y+ wall treatment is used. Unsteady computations are performed leading to a steady state solution for the tested mass flow rate of 26 kg/s.

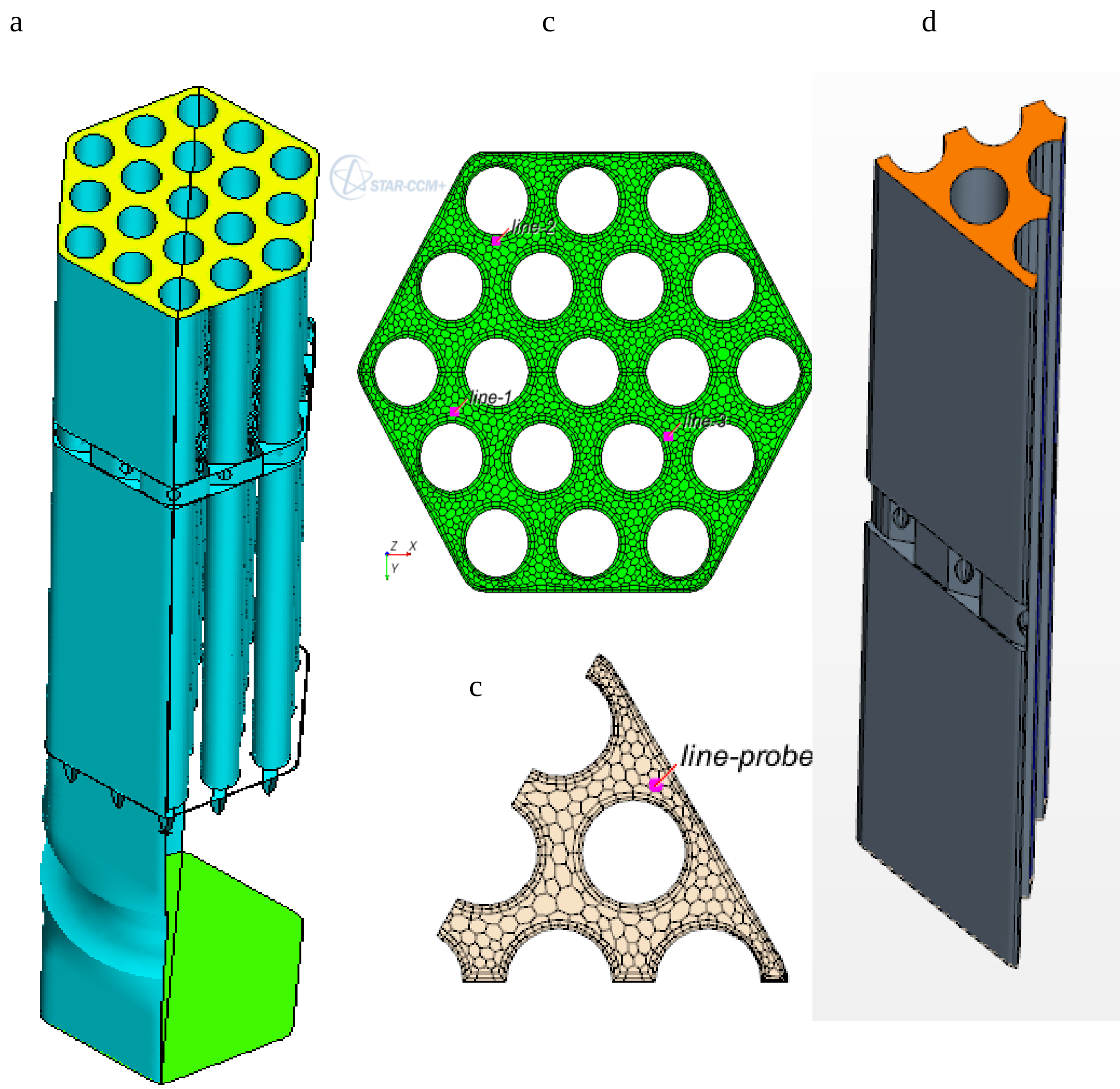

Figure 4 Computational domains for the study of the entrance region, 360° and 60° sector and mesh at outlet section.

The numerical results obtained for the velocity distribution show that the flow is almost homogeneously approaching the pin fixer as shown in figure 5. This behaviour of the flow downstream of the Venturi nozzle was verified in the water experiment depicted in figure3. Accordingly, the working assumption of substantially enhanced pressure drop for the first spacers compared to the other spacers as a consequence of substantial flow concentration downstream of the Venturi nozzle cannot be confirmed by simulations.

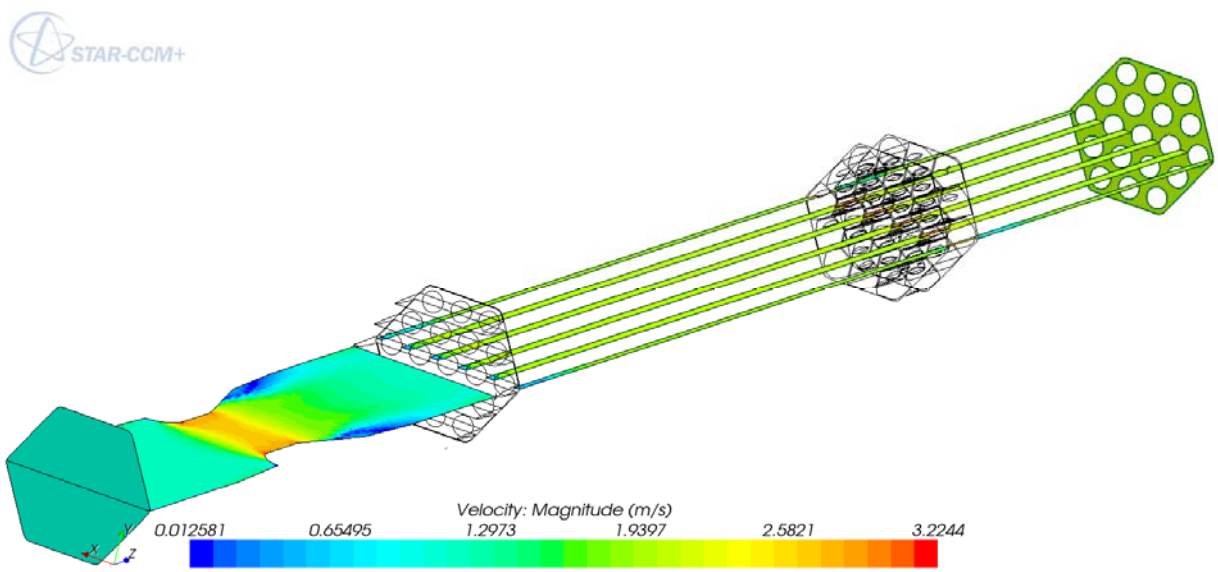

Figure 5. Velocity magnitude at a symmetry plane in the middle of the bundle

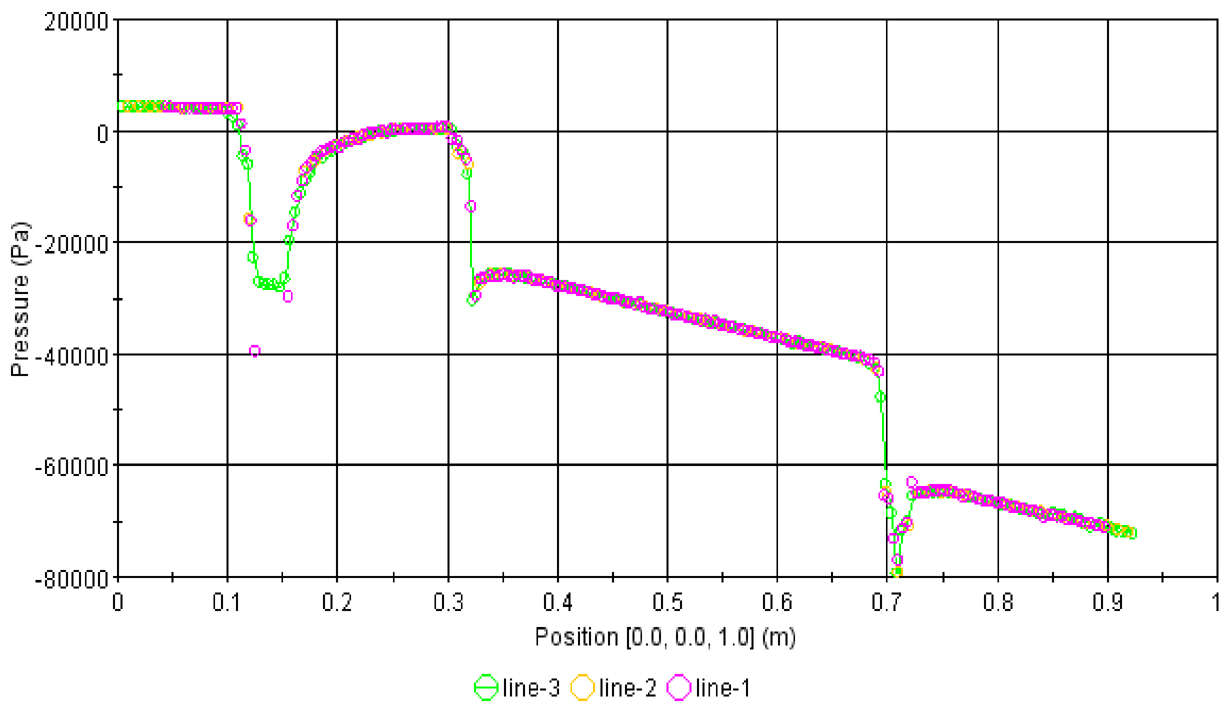

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Figure 6. Axial pressure along 3 lines in the bundle for the 360° sector domain. Positions of lines are indicated in figure 4b.

Moreover, in figures 6 and 7 the results for the axial pressure drop obtained for the 60° sector domain indicate that the computed pressure drop across all spacers are of similar magnitude. Accordingly, the measured higher pressure of the first spacer in the first measurement campaign performed at KALLA should be attributed to effects which are not reproduced by our simulations such as possible blockage of spacers. The possible enhancement of the pressure drop in the first spacer compared to the second and third spacer was also investigated in [1,2].

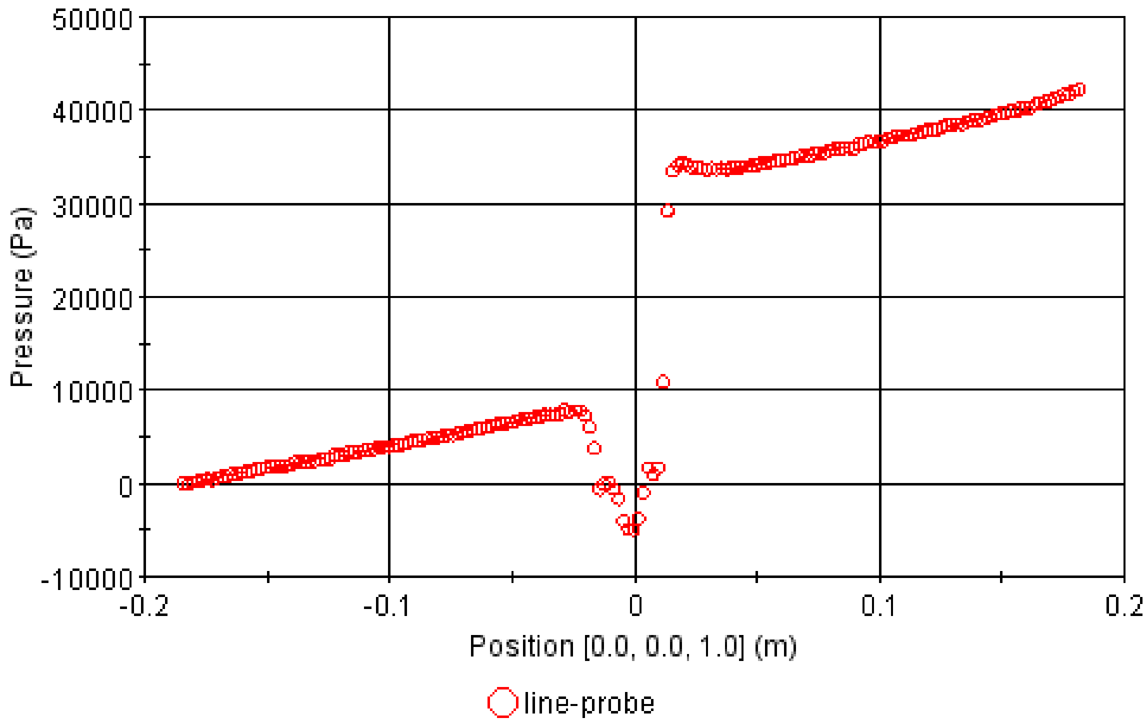

Figure 7. Axial pressure along axial lines through the bundle for the 60° sector domain. Positions of lines are indicated on figure 4d.

2.2 Sensitivity study of mesh and turbulent models

In this section the sensitivity of computed pressure drop across the grid spacer is considered. The mesh effect and turbulent models including different wall treatments are the most important parameters in the current study. Earlier studies of the water bundle indicate a strong dependent of the computed pressure drop on the computational mesh. Taking account of mesh resolution guidelines derived in [2] two well resolved fine meshes are considered in this study. The present study investigates different wall treatments available in the CCM+ code which was employed for the simulation. The "high y+ wall treatment", "two-layer all y+ wall treatment" and quadratic pressure-strain model of Sarkar, Speziale and Gatski [5] are tested. In all cases unsteady computations finally lead to stable steady state solution. Figures 8-9 show the resulting y+ values and mesh density at a cross section in the middle of the spacer. Figure 10 compare local mesh density in the spacer region at the symmetry plane for meshes I and II.

The results are summarized in table 1 for the tested meshes and used wall treatments. In addition results for the quadratic pressure-strain model are shown which is restricted to "High y+ Wall Treatment".

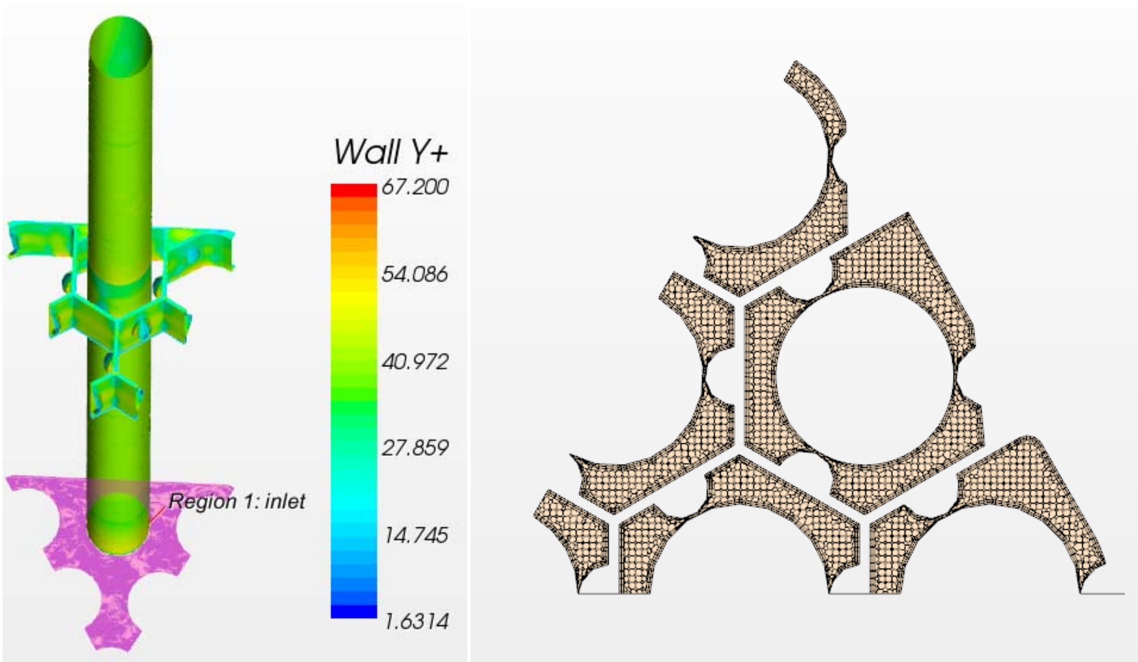

Figure 8 y+ values for mesh I and mesh density at spacer mid-plane.

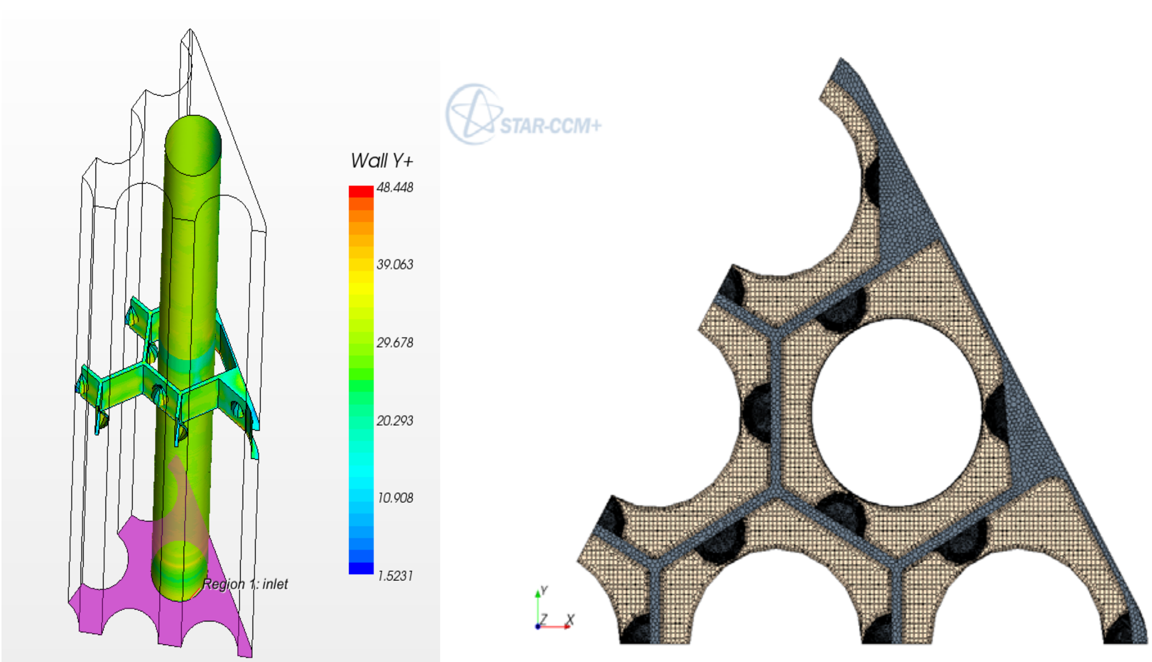

Figure 9 y+ values for mesh II and mesh density at spacer center.

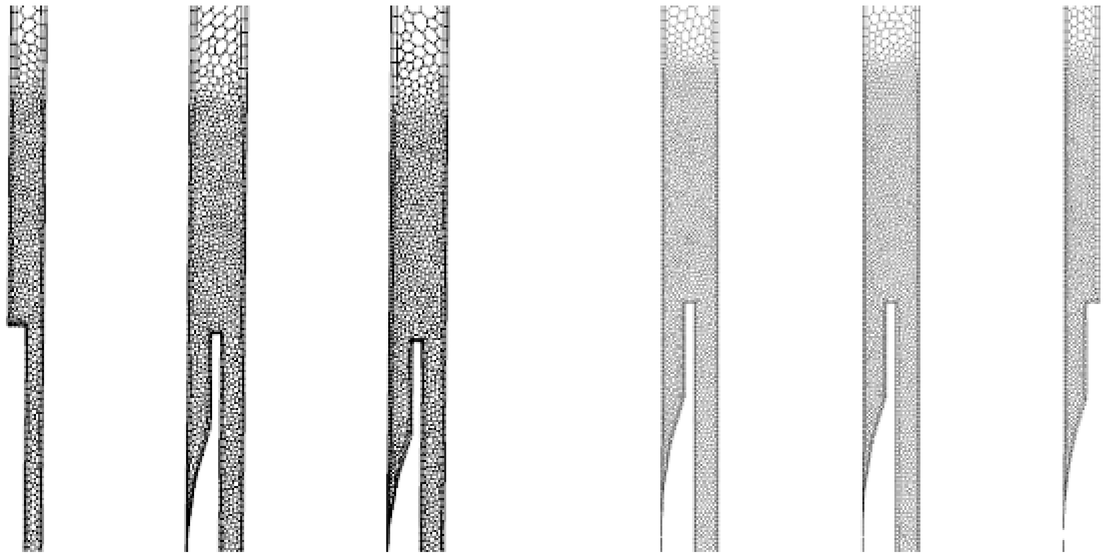

Figure 10. Right side is mesh density near spacer for mesh I and left is mesh density near spacer for mesh II

Table 1 summarizes the average pressure drop across the spacer grid calculated by variety of different models and mesh sizes.

	Wall treatment	Pressure drop in spacer kPa
Mesh 0 , .2 million cell		22
Mesh1, 1.2 million cell	k-ε high y+ treatment	17.2
	k-ε all y+ treatment	16.2
	URANS quadratic pressure strain	16.7
Mesh2 2.8 million cell	k-ε all y+ treatment	15.0

The axial pressure drop along the probe lines shown in figure 4c is given in figure 11 and 12 for the two different meshes. In figure 11 the results of mesh I with k-ε "high y+ treatment" is presented. In Figure 12 the results of mesh II with k-ε "all y+ treatment" is shown. It can be seen that the mesh 2 delivers about 10% smaller pressure drop compared to mesh I. The results shown in table 1 indicates that the mesh effect is most important since all results obtained from mesh I and II show approximately 16 kpa pressure drop while mesh 0 yields about 22 kPa pressure drop. The sensitivity of results on wall treatments and turbulence models is quiet weak which indicates that complex phenomena which require specific turbulence models such as recirculation and unsteadiness are not pronounced for the spacer geometry considered.

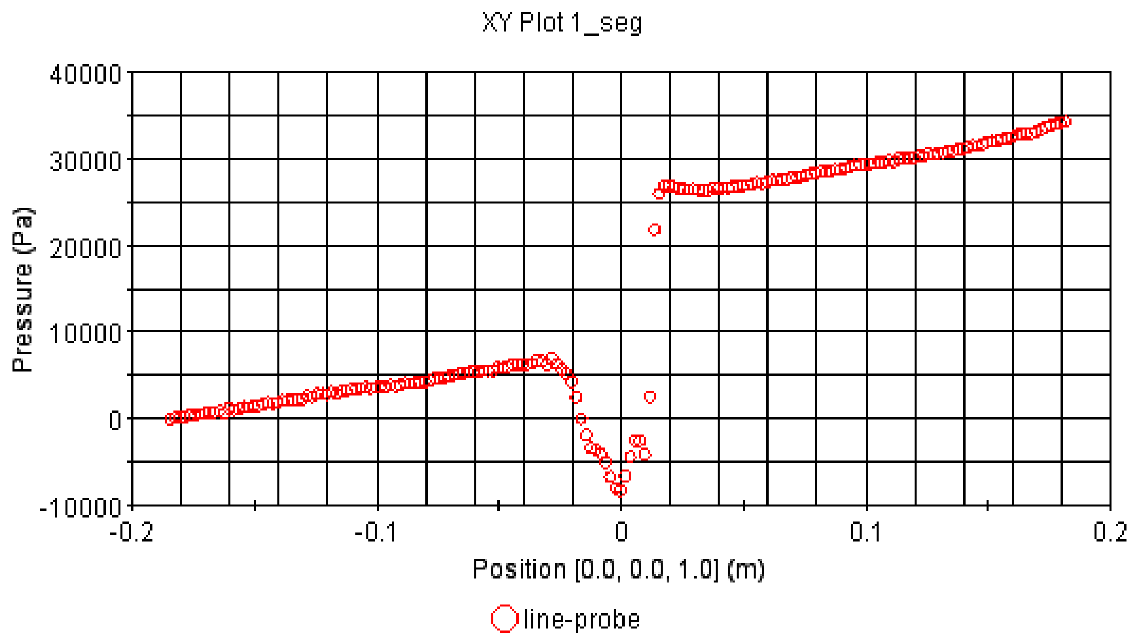

Figure 11 Axial pressure along probe line, mesh I with k-ε "high y+ treatment"

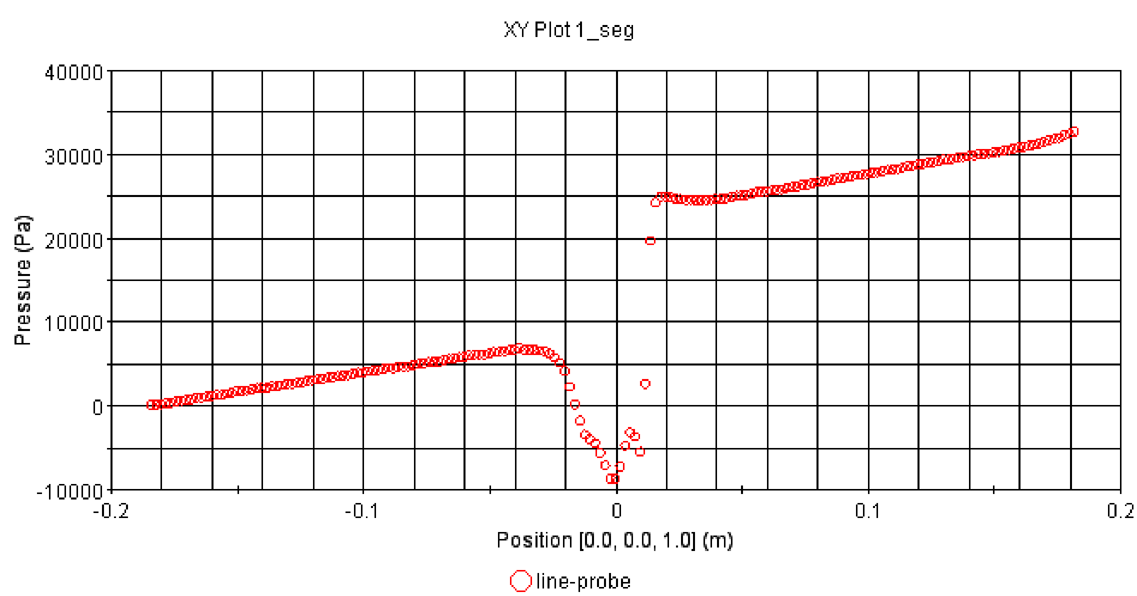

Figure 12   Axial pressure along probe line mesh II with k-ε "all y+ treatment"

3. Conclusion

Our study of different domains ranging from a 360° sector including the flow conditioner to a 60° sector with uniform inflow indicates that the smallest computational domain which exploits all possible symmetries delivers comparable results to the full domain. The comparison of the pressure drop obtained from the two domains indicates a very weak effect of the entrance region on the computed pressure drop across the spacer. The measured high pressure drop in the experiment could not be explained based on our work hypothesis which attributes additional pressure drop to developing flow effects. We rather assume that effects which are not reproducible by our simulation such as possible blockage in the spacer are responsible for the found pressure drop.

Our sensitivity study using different meshes and different models shows that the mesh effect is more pronounced than the effect of the tested wall treatment and turbulence models. This indicates that complex effects such as flow recirculation which require specialized turbulence models are not very pronounced in the considered bundle geometry.

4. References

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