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CFD Analysis of an Infinite Wire-Wrapped LBE-Cooled Fast Reactor Sub-channel

I. K. Umezu[1], A.L. Costa[1] and A.A.C. Santos[1,2]

[1]ivkeum@ufmg.br, antonella@nuclear.ufmg.br, Programa de Pós-Graduação em Ciências e Técnicas Nucleares, Departamento de Engenharia Nuclear - DEN
Universidade Federal de Minas Gerais - UFMG, Belo Horizonte, Brazil
[2]aacs@cdntn.br, Centro de Desenvolvimento de Tecnologia Nuclear - CDTN, Belo Horizonte, Brazil

1. Introduction

In the new context of Generation IV technologies, liquid metal cooled fast reactors (LMFR) are in a promising position, given their inherent safety, nuclear waste reduction and fuel consumption sustainability. One of the most distinguishing engineering features of LMFR is the employment of wire-wrapped fuel assemblies, which consist in wires revolved around the fuel rods, making it a compact and stiff assembly. However, due to the large amount of contact points and tight gaps, wire-wrapped fuel assemblies are considered to be complex in geometry, which makes analytical predictions practically impossible and highlights the importance of a consistent Computational Fluid Dynamics (CFD) modeling approach, such as developed in recent years by [2], [3], [4] and [5]. In this work, an infinite wire-wrapped fuel assembly CFD analysis is carried out evaluating the results for stream-wise velocity, fluid temperature and turbulent kinetic energy. The geometry was based on the current fuel assembly design of the MYRRHA project and the calculation code used was Ansys Fluent. The main goal of this work is to compare the results of a low-cost RANS-based calculation with a high-fidelity quasi-Direct Numeric Simulation (q-DNS) database developed by [3] and to compare with the work of [4], in which RANS-based simulations were validated. The authors emphasize that, in this extended summary, only the preliminary results are presented and analyzed, once the study is still under development.

2. Methodology

In this work, the infinite wire-wrapped computational domain used is based on the current MYRRHA design, detailed in Table I. The infinite domain consists of a sub-channel with a central rod and 6 surrounding rods, with a length equal to one wire-wrap pitch, thus making it possible to be modeled with periodic boundary conditions in 3 radial and in the axial directions. Figure 1 (a) presents the geometrical representation of the sub-channel. The use of an infinite domain is justified by the impracticality of simulating a whole MYRRHA fuel assembly, which is made up of 127 wire-wrapped fuel pins. The coolant employed in this analysis is Lead-Bismuth Euthetic (LBE), at an inlet temperature of 340 °C (613.15 K), [1]. The main properties for LBE at the inlet temperature are shown in Table II. Regarding the thermal boundary conditions, a heat flux of 152 kW/m^2 is applied to the fuel rod walls, and the wire walls are considered to be adiabatic. Three translational periodic boundary conditions were applied to the opposite boundaries of the cross section, shown in Figure 1 (b) as matching color arrows, and also one inlet-outlet periodic boundary condition, with a fixed mass flow rate, was imposed.

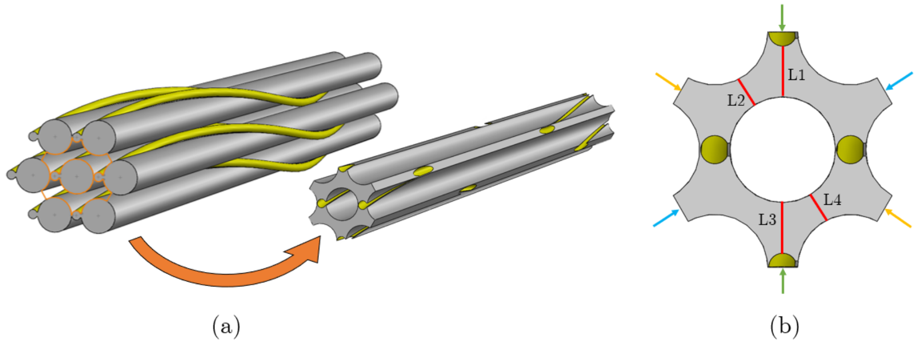


Figure 1: (a) Infinite wire-wrapped sub-channel extracted volume. (b) Sub-channel cross section

Table I: Dimensions of the infinite wire-wrapped assembly [1].

Dimensions	Value [mm]
Rod diameter (D)	6.55
Wire diameter	1.75
Wire wrapping pitch	262
Gap between wire and rod	0.1

Table II: LBE properties at 340 °C [1].

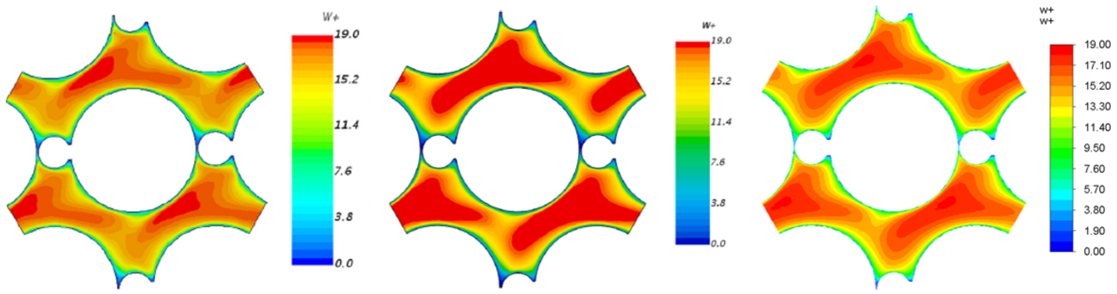
Property	Value	Units
Density (ρ)	10,285	kg/m^3
Dynamic viscosity (μ)	1.69×10^{-3}	kg/m.s
Thermal conductivity (k)	12.25	W/m.k
Specific heat (C_p)	145	J/kg.K
Prandtl number (Pr)	0.02	-

Considering the high level of complexity in the regions between the wires and rods, a refinement was employed around the walls. It consisted of 8 prism layers, with a growth rate of 1.2 and a transition ratio of 0.227. The final volume mesh was composed of 13.3 million polyhedral cells of maximum size of 0.22 mm. As mentioned, the mesh refinement process will not be addressed, once it is still under development. The calculations were run on Ansys Fluent R19.3, employing the RANS-based linear k-ω SST turbulence model, due to its robustness, relative low computational cost and, most importantly, due to its fairly good predictions when studied by [4].

3. Results and Discussion

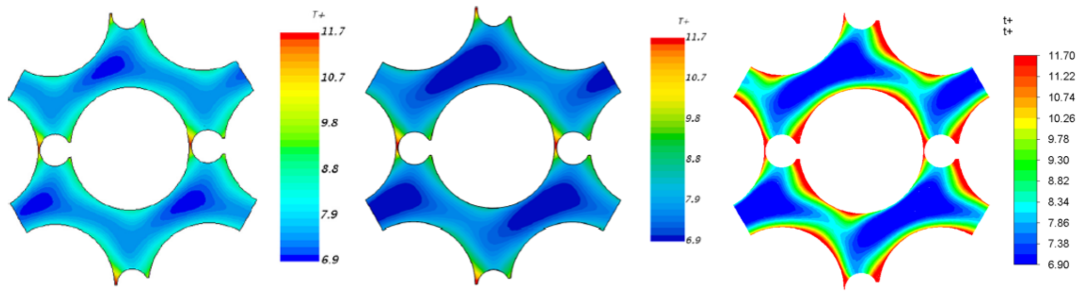
For the sake of brevity, in this extended summary, only brief results regarding line 1 (L1) will be presented and discussed in this section, Figure 1 (b). The field results evaluated were the axial velocity (W$^+$), fluid temperature (T$^+$) and turbulent kinetic energy (TKE$^+$). All the fields were non-dimensionalised using the average frictional velocity u_t, as per [3], in order to allow a direct comparison between the results. The non-dimensionalised fields were defined as: Averaged axial velocity field: $W^+ = \frac{W}{u_t}$; Averaged temperature field: $T^+ = \frac{T - T_{min}}{T_\tau}$, in which $T_\tau = \frac{Q}{\rho \cdot C_p \cdot u_t}$ and Averaged turbulent kinetic energy field: $k^+ = \frac{k}{{u_t}^2}$.

The qualitative contour results are presented from Figure 2 to Figure 4 and the quantitative results are shown in Figure 5. The (a) contours are from the q-DNS high-fidelity reference results from [3], the (b) contours are from the reference k-ω SST simulation from [4] and the (c) contours are the preliminary k-ω SST simulation results obtained so far in this work. The quantitative results are plotted in a Cartesian plane along the normalized axis $s^+ = s/D$, the data is measured along the lines 1 through 4, using the same coordinates as [3]. One important indicator of mesh refinement necessity is the difference in data points between these preliminary results and the cited references. Following the results presented in Figures 2 through Figure 5,



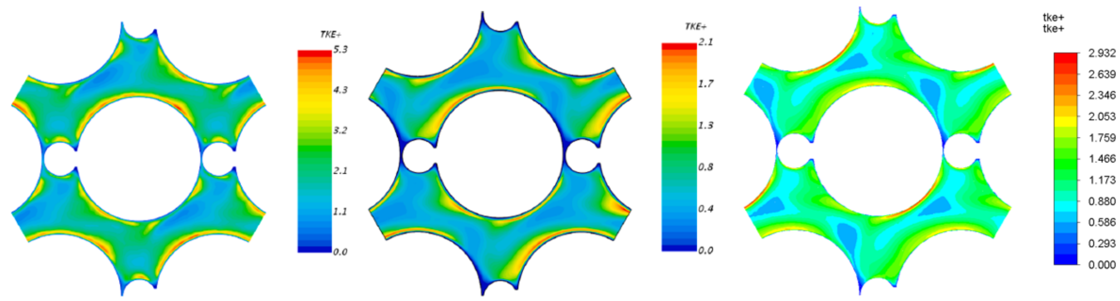
(a) q-DNS, Shams et. al. (2018) (b) k-ω SST, Dovizio et. al. (2019) (c) k-ω SST, preliminary result

Figure 2: Compared averaged axial velocity field.



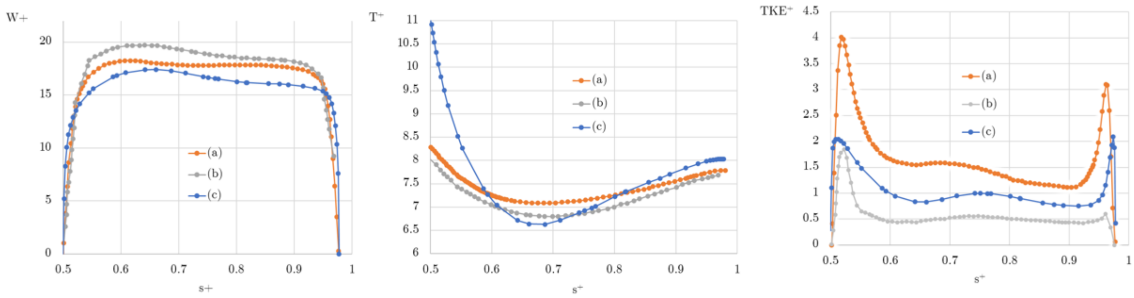
(a) q-DNS, Shams et. al. (2018) (b) k-ω SST, Dovizio et. al. (2019) (c) k-ω SST, preliminary result

Figure 3: Compared averaged temperature fields.



(a) q-DNS, Dovizio et. al. (2019) (b) k-ω SST, Dovizio et. al. (2019) (c) k-ω SST, preliminary result

Figure 4: Compared averaged turbulent kinetic energy fields.



(I) (II) (III)

Figure 5: Quantitative results comparison along L1: (I) W^+, (II) T^+, (III) TKE^+ .

it can be noted that the preliminary axial velocity (W^+) contours and plots fit the reference results the better. The preliminary TKE^+ plots have an equivalent shape, but noticeable offset from the k-ω SST results from [4], as seen in Figure 5 III. However, it can also be noted that the T^+ preliminary plots are the most divergent, in L1's $s^+ = 0.5$ (Figure 5 II). These discrepancies are likely related to the mesh refinement around the walls. This discrepancy is expected to be solved once the mesh refinement process is carried out.

4. Conclusions

This short summary presented the main aspects of the authors' current work on the CFD analysis and results comparison with existing references. Although the work is still in its early development stages, promising results are already present. Special attention will be given to the mesh refinement and sensitivity processes, as they are expected to improve both the qualitative and quantitative results. Once this work is completed, it is expected to obtain verified and validated results from this infinite wire-wrapped sub-channel CFD modeling approach, including the software used and computational expense reduction, when compared to the reference works that employ RANS-based calculations.

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