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Evaluation of Numerical Methods for Transient Thermal-Hydraulic Reactor Analysis

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ABSTRACT

Improvement in computer speeds, usage of computer networks, and availability of newer computer codes allows one to bring a large amount of computational power to the analysis of transients in reactors. Using these many resources is not always practical on a day-to-day basis. Instead one may be limited to using a system-level code which has less spatial detail. Two Computational-Fluid-Dynamics (CFD) codes STAR-CCM+ and ANSYS have been used to model the transient behavior of a twisted-pin fuel element and compared with results obtained using system-level code RELAP5-3D.

1. Introduction

When analyzing reactor transients, the analyst must sometimes choose among various methods for performing the analysis. The methods range from simple to complex. There is usually a desire to use the simplest method which will provide an adequate result.

This paper analyzes two power-increase transients: slow and fast. Results are compared among a less complex system-level code (specifically RELAP5-3D) and two more complex Computational Fluids Dynamics (CFD) codes (specifically STAR-CCM+ and ANSYS CFD).

2. Geometry and Methods

The comparison of numerical models is done using the fuel geometry for the IVG.1M reactor, located in Kurchatov-city and operated by the Institute of Atomic Energy (IAE) branch of the National Nuclear Center of the Republic of Kazakhstan (NNC-RK). The first start-up was in 1971; modernization was conducted during 1989-1990. The reactor can operate at 35 MW; however, most operation occurs below 9 MW.

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A fuel element (FE) is a two-bladed spiral rod, as shown in Fig. 2.1; the outer dimensions are 2.8x1.5 mm, 0.25 mm cladding thickness; and 30 mm pitch for twist. The fuel is U-Zr and the cladding is Zr-Nb. The current high-enriched uranium (HEU) fuel is enriched to 90% in U-235; it is technically feasible [1] to convert the reactor to low-enriched uranium (LEU) fuel using the same fuel geometry. Most FE are 600 mm long; some FE are 200 mm. A fuel assembly (FA) consists of 468 FE on triangular pitch packed into an annular-circular area; this is illustrated in Fig. 2.2, where the circles indicate the area swept by the twisting FE; there are two enrichment zones in each FA, denoted by the plain and cross-hatched circles; the black circles are two sizes of non-fuel rods used as spacer fillers. There are 30 FA in the core, arranged in 3 concentric circles. The FA (total of 12) in the inner 2 circles have a section which contains 456 FE having length 200-mm stacked on top of the 600-mm section. Coolant (water) flow through an FA is from top to bottom.

Additional information about the reactor is given in Ref.[1].

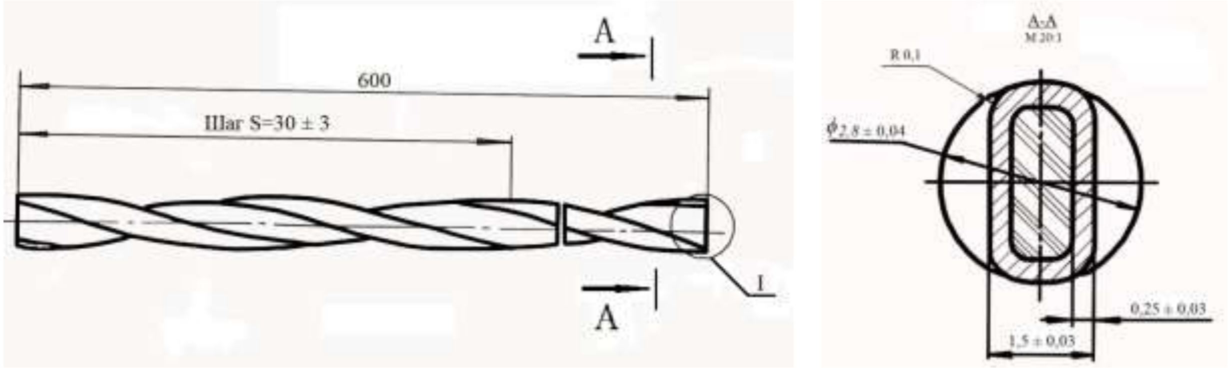

Fig. 2.1 Fuel Element (FE) Geometry

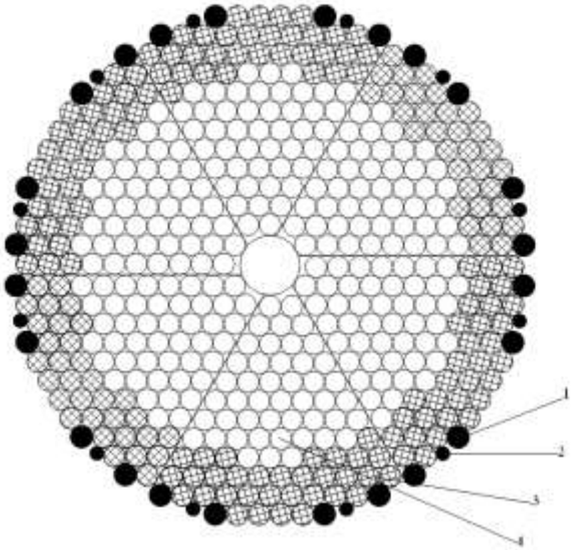

Fig. 2.2 Fuel Assembly (FA) Geometry

The various analyses to be reported in this paper modeled a single FE and its associated coolant, which is a hexagonal unit cell. The exact values are not particularly important since this is merely a comparison of analysis methods rather than an accident driven by reactor-specific safety analysis. Two power-increase transients will be studied: slow and fast. In both cases the power increase is prescribed, rather than the more-normal case of being driven by a specified reactivity perturbation. Coolant inlet temperature and flow rate are constant during each transient.

The transient analysis at ANL would normally be done using a system-level (or even simpler) computer code like RELAP5-3D [2]. (Although the code does have some limited three-dimensional capability, none of that is useful in the current analysis. To avoid being misled, the "3D" suffix is dropped from the code name for the rest of this paper.) Such a model would usually have 10-20 nodes axially in the heated zone (50-mm node height is typical), a few (5-10) nodes radially in the FE at each axial level, but only a single node radially in the coolant at each axial level. There are approximately 700 solid plus fluid nodes in the RELAP5 model for one FE. The geometry of the FE twist can not be modeled in RELAP5. The blade-type FE is treated as an equivalent hollow cylinder, shown in Fig. 2.3 (left). The outer radius of the cladding (1.24 mm) is chosen to give the same outer perimeter as the real FE; this provides the correct heat transfer area. The inner radius of the cladding (0.96 mm) is chosen to give the same cladding volume as the real FE, although this results in a cladding thickness which is 12% larger than the real FE. The inner radius of the fuel (0.44 mm) is chosen to give the same fuel volume as the real FE. There is no heat transfer at the inner surface of the fuel. There is no axial heat transfer in the solids. The heat source (in the form of power density) varies axially, and is input for each axial level in the fuel meat; and the relative axial shape is constant in time.

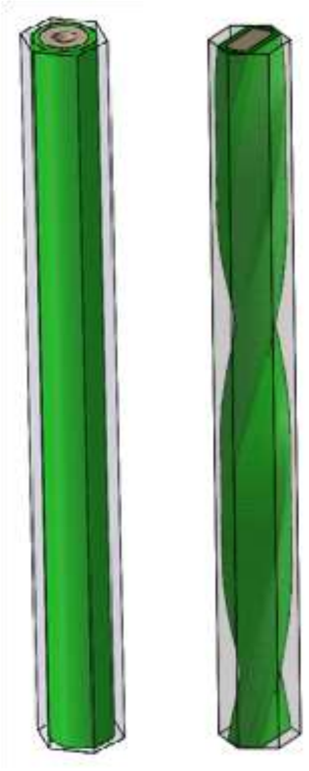

Fig. 2.3 Models: RELAP5 (left) and CFD (right)

Since ANL had never modeled a twisted FE before starting work on IVG.1M, we felt that it was worthwhile for calculations to be done with a CFD-type code like STAR [3]. STAR is in the RANS class: Reynolds-Average Navier-Stokes. STAR is able to model the exact shape of the fuel blade, including the twist, such as shown in Fig. 2.3 (right). The model includes conduction heat transfer in all three-dimensions. The axial power shape is input as a continuously varying polynomial; as in RELAP5 the relative axial shape is constant in time. There are 6.6 million solid plus fluid nodes for one FE. The effective axial node size is approximately 0.16 mm. which is a factor of 300 smaller than that being used in the RELAP5 model. Since the nominal coolant flow rate is characterized by a Reynolds number of a few thousand, which is at the low end of what is considered turbulent flow, an extensive study was performed [4] in order to be able to choose the "realizable k-epsilon 2-layer" turbulence model as being appropriate for analysis of the IVG.1M FA.

IAE staff have performed CFD-based analysis of transients using ANSYS CFD[5]. In terms of these example problems the ANSYS and STAR capabilities can be considered the same. IAE staff are also developing their own code for transient analysis. This work is reported in more detail in a separate paper [6] at this meeting.

3. Slow Transient

The slow transient is characterized by somewhat arbitrary choices made by ANL staff for the purposes of code comparison. The case uses the peak power FE in the HEU core; this FE generates 1.217 kW when total reactor power is 10 MW. The transient starts at 50% power, and the power increases to 100% linearly over 10 s. The coolant flow rate is 4.3 g/s/FE and the inlet temperature is 293.15 K (20°C); both of these values are held constant during the transient.

Although not an essential part of the discussion, we note for completeness that constant but different material properties were used in the fuel and in the cladding for this transient.

Figure 3.1 shows the maximum coolant, cladding surface, and fuel temperatures as a function of time. Solid lines are for RELAP5 and the chain-dot lines are for STAR with a continuous-form polynomial description of the axial power distribution. As an overall assessment, there is quite good agreement between the two codes. The coolant temperature is the same in the two codes at the beginning and at the end, signifying (since the coolant flow rate is the same) that both calculations have the same rate of heat removal from the FE. The cladding and fuel temperatures from RELAP5 are slightly higher than those from STAR; given that the two codes have quite different levels of geometry representation and fluid-solid heat transfer modeling, some difference might be expected. The agreement between the two codes can be improved if the STAR calculation is performed using a step-function for axial power distribution, changing from one step value to the next every 50-mm in order to simulate the approximation used in the RELAP5 calculation; the results from this STAR calculation are shown using dotted line in Fig. 3.1.

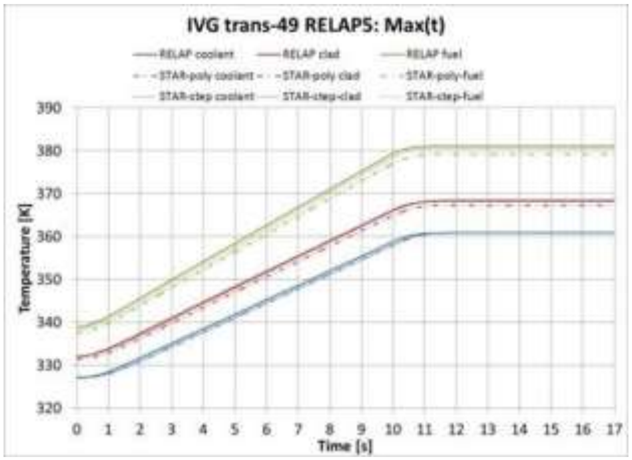

Fig. 3.1 Maximum Coolant, Clad Surface, and Fuel Temperatures Calculated Using RELAP5 and STAR for Slow Transient

Another aspect of the results is the change in axial distribution of cladding surface temperature during the transient. This is shown in Figs. 3.2 for RELAP5 (left) and STAR (right). The agreement between the two codes is quite good. Denoted by vertical black line at 0.6 m in these figures is the location of a spacer grid which separates the 200-mm FE section from the 600-mm FE section. The presence of this spacer has a large impact on the fluid flow pattern, which impacts the heat transfer; these effects are realizable in a CFD-type code such as STAR but not in the 1-D RELAP5 code.

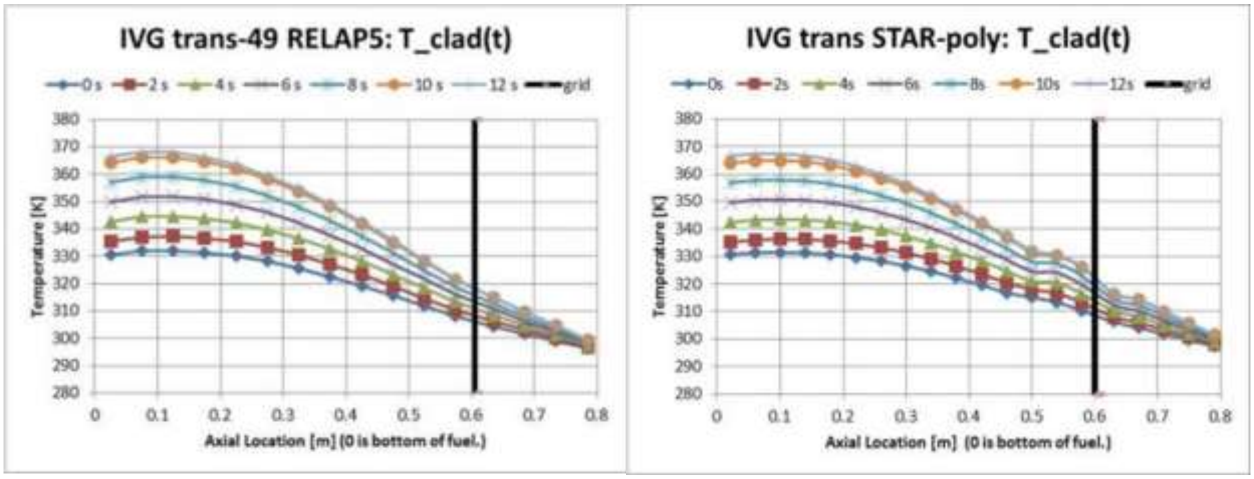

Fig. 3.2 Axial Distribution of Clad Surface Temperature at Selected Times as Calculated Using RELAP5 (left) and STAR (right) for Slow Transient

4. Fast Transient

IAE staff proposed considering a fast transient. The power is based on an average FE in the core. Initial core power is 1.72 MW, meaning an average FE power of 123 W. The core power is assumed to increase suddenly to 0.5 MW at the beginning of the transient. The initial power and amount of increase are not to be ascribed to any mechanistic set of reactor-specific conditions. The coolant flow rate is 4.3 g/s/FE and the inlet temperature is 309.25K (36.1°C); both of these values are held constant during the transient.

Although not an essential part of the discussion, we note for completeness that the fuel and cladding have temperature-dependent properties in this case. The fuel meat was modeled using cladding properties. Due to the way in which results were going to be compared, the RELAP5 model had 10-mm axial nodes (a factor of 5 smaller than used in the slow transient).

Figure 4.1 shows the maximum coolant, cladding surface, and fuel temperatures as a function of time. Solid lines are for RELAP5 and the dotted lines are for STAR with a continuous-form polynomial description of the axial power distribution. As an overall assessment, there is quite good agreement between the two codes for coolant, cladding and fuel. The apparent closeness of the agreement is affected by the coolant temperature rise across the length of the FE being so low (i.e., only 7 K). The temperatures in RELAP5 are responding slightly faster than those in STAR. A new steady state is reached about 1.4 s after the step power change.

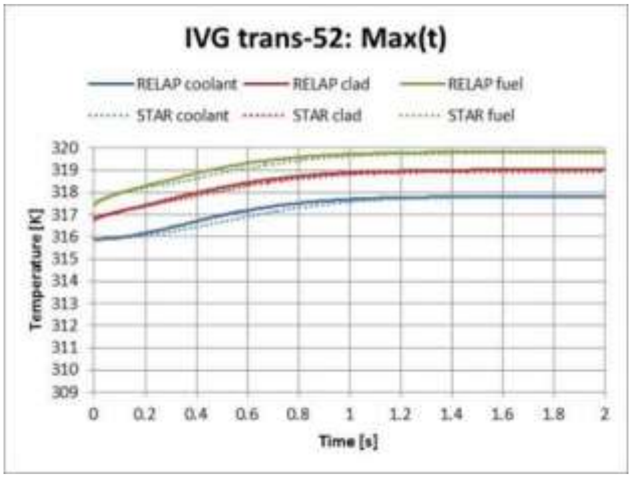

Fig. 4.1 Maximum Coolant, Clad Surface, and Fuel Temperatures Calculated Using RELAP5 and STAR for Fast Transient

Figures 4.2, 4.3, and 4.4 show additional results from RELAP5, STAR, and ANSYS, respectively. The coolant outlet temperature (orange line) shows good agreement among the three codes. The other curves in each figure are cladding temperatures at 4 axial locations; for RELAP5 and STAR these are temperature on the outer cladding surface; for ANSYS these are average over the cladding thickness. The clad surface temperatures from RELAP5 are higher than those from STAR. The clad surface temperatures from STAR are similar to the cladding average temperatures from ANSYS. The discrepancies in the cladding temperature, although not large, are somewhat puzzling and are being studied further.

Fig. 4.2 Coolant Outlet and Clad Surface (0.1, 0.3, 0.5, and 0.7 m elevation) Temperatures Calculated Using RELAP5 for Fast Transient

Fig. 4.3 Coolant Outlet and Clad Surface (0.1, 0.3, 0.5, and 0.7 m elevation) Temperatures Calculated Using STAR for Fast Transient

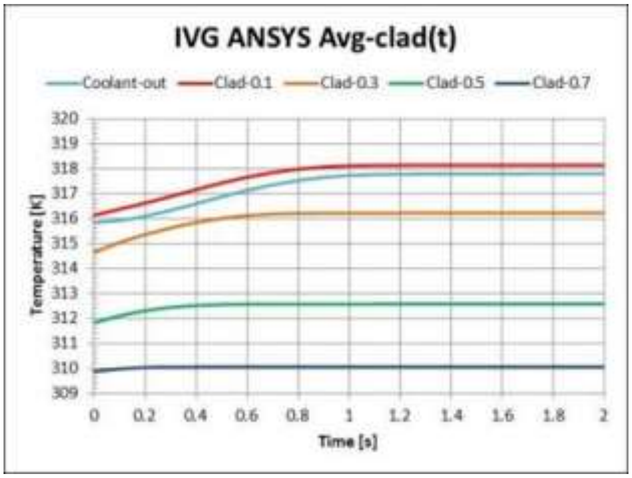

Fig. 4.4 Coolant Outlet and Clad Average (0.1, 0.3, 0.5, and 0.7 m elevation) Temperatures Calculated Using ANSYS for Fast Transient

5. Conclusions

Slow and fast power-increase transients have been modeled using several computer codes for the IVG.1M fuel geometry. The coolant outlet temperature is in good agreement among all three codes. The peak cladding surface temperature from the less-complex RELAP5 analysis is in good agreement with that from a more complex CFD code such as STAR. Comparing solid temperatures at specific axial locations shows some variation among RELAP5, STAR, and ANSYS which deserves further investigation.

References

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[4] Adam R. Kraus, Elia Merzari, and Paul F. Fischer, “Turbulent Flow-Field Comparisons or RANS and LES for a Twisted Pin Lattice Geometry at Low Reynolds Number”, *Proceedings of the ASME 2014 4-th Joint US-European Fluids Engineering Division Summer Meeting and 11th International Conference on Nanochannels, Microchannels, and Minichannels* (FEDSM2014-22166, Chicago, USA, August 3-7, 2014).

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[6] R.A. Irkimbekov, A.A. Murzagalieva, G.A. Vityuk, A.D. Vurim, L.K. Zhagiparova, P.L. Garner, N.A. Hanan, “IVG.1M Reactor Kinetics”, presented at *35-th International Meeting on Reduced Enrichment for Research and Test Reactors* (Vienna, Austria, October 12-16, 2014).

Acknowledgment

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