PRACTICAL APPLICATION OF DETAILED THERMOMECHANICAL FEM MODEL OF FUEL ROD

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ABSTRACT*: Commonly used fuel performance codes are usually limited to "1.5" D approximation. This approach is not sufficient to describe the local effects or the impact of the inhomogenities in the boundary conditions, therefore 2D and 3D FEM models are being developed.*
Use of standard industrial FEM codes for fuel rod thermomechanical behaviour has some undeniable benefits (for example rigorous QA, well developed models of contact or fast, non-linear mechanical response) but is not straightforward because there is no access to source code. Some years ago Abaqus code was enhanced in INL by R. Williamson to perform a full simulation of fuel rod behaviour. In our approach to the application of the Abaqus code we incorporate important thermo-mechanical effects via user subroutines, but some models are substituted by loose coupling with the Transuranus code. This approach is a follower of previous effort using more sophisticated FEM SW Abaqus instead of CosmosM and Transuranus code instead of Femaxi-6. The inner gas pressure calculated by Transuranus with the same power history, that is intended for detailed FEM calculation, is fed into the FEM model. There is axial and radial distribution of linear heat rate in Abaqus which changes along with burnup (which is calculated as a user defined variable) on which the material properties depend.
Developed approach can be used for different tasks that stem from new research ideas or from industry issues or just to re-visit the old experiments and try to explain observed behaviour which was could not be modelled with common "1.5D" codes.
We show the basic approach including several applications examples in the poster. As an example of current use, the impact of pellet periodic motion in the cladding, which is suggested by the analysis of the fuel assembly vibrations, on the fuel temperature is shown. 2D r-theta model was prepared assuming various fuel-cladding gap sizes within the manufacturing tolerances. Pellet motion at 1Hz to 100 Hz is analysed (100 Hz value is expected from the fuel assembly vibrational analysis) for both solid and hollow pellets of standard LWR fuel and the reduction of the fuel temperature relative to standard axisymmetric model is quantified. The same approach is also applied to fuel with SiC cladding assuming burnup state where the released fission gases impede the heat transfer, but the gap closure is slow due to creep resistance of SiC. The comparison of this model with the measurements of an older Halden experiment where pellet centre temperatures were measured for helium and xenon in the gap and with concentric and eccentric pellet position is also shown.

KEYWORDS*: fuel rod, thermomechanical modelling, FEM*

I. INTRODUCTION

Thermomechanical behavior of nuclear fuel rod is modeled by fuel performance codes which are usually limited to "1.5" D approximation. This approach is not sufficient to describe the local effects or the impact of the inhomogenities in the boundary conditions, therefore 2D and 3D FEM models are being developed.

Use of standard industrial FEM codes for fuel rod thermo-mechanical behavior has some undeniable benefits (for example rigorous QA, well developed models of contact or fast, non-linear mechanical response) but is not straightforward because there is no access to source code. Some years ago Abaqus code was enhanced in INL by R. Williamson[1] to perform a full simulation of fuel rod behavior. In our approach to the application of the Abaqus code[2] we incorporate important thermo-mechanical effects via user subroutines, but some models are substituted by loose coupling with the Transuranus code[3]. This approach is a follower of previous effort[4,5] using more sophisticated FEM SW Abaqus instead of CosmosM and Transuranus code instead of Femaxi-6. The inner gas pressure calculated by Transuranus with the same power history, that is intended for detailed FEM calculation, is fed into the FEM model. There is axial and radial distribution of linear heat rate in Abaqus which changes along with burnup (which is calculated as a user defined variable) on which the material properties depend.

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II. THERMOMECHANICAL FEM MODELS

II.A. Modeling approach description

Most of the thermo-mechanical phenomena modeled by fuel performance code (such as Transuranus) are taken into account in the detailed FEM models. Most of them are directly modeled via user subroutines such as cladding and fuel creep, fuel swelling, cladding axial growth, ...
In 2D r-z the pellet cracks are simulated by lowering the elastic constants (similar approach as in Transuranus code), in 2D r-theta and 3D models pellet cracks are modeled explicitly (by radial and axial cracks).
No explicit fuel relocation model is used but to some extent the relocation is taken into account by explicit modeling of the pellet fragments. No analysis of their relative forced movements have been performed so far, but this paper gives an example of the analysis of similar phenomena – forced movement of whole pellet inside the cladding.

So far the only missing important model is the fission gas release which is simulated by the rod inner pressure changes according to Transuranus calculation of the same power history.

Friction coefficient in the contact solution between pellet and cladding was tested from slip condition (frictionless) to stick condition (rough) in different cases (2D and 3D), default value is set to 0.1 (in some structural calculations 0.25-0.3) which gives best results compared to measurement of cladding diameter and elongation (the same value is as default used in our Transuranus calculations). Pellet-pellet cladding contact is usually modeled with friction coefficient 0.05 or 0.1 to achieve stability of the solution.

Heat transfer via heat transfer coefficient and the coolant temperature or prescribed cladding outer temperature are defined as boundary condition.

Several detailed FEM models were developed as 2D r-z (different number of pellets is assumed), 2D r-theta or 3D. The geometry is prepared according to solved problem where e.g. influence of pellet shape can be assessed in the 2D r-z models, The geometry is prepared in the Abaqus/CAE or is transferred in as CAD model.

Standard finite element (FE) type is coupled temperature-displacement quadratic with reduced integration, in pure thermal or structural calculations heat transfer or structural FEs are used. The size of FEs is chosen according to solved problem based on validation calculations and our experience to reach reasonable computational time with sufficient accuracy.

II.B. Examples of application

The range of use of developed approach has two main application areas:
- structural calculations of fuel rod, individual parts of fuel rod and assembly,
- detailed simulation of fuel rod thermo-mechanical behavior.

Necessary part of models development is validation which is done not only as code-to-code comparison of the same power history, initial and boundary conditions and with similar nodalization but also using experimental data for both application areas (as our Transuranus base).

I.B.1. Examples of structural calculations

For the first part we have used Abaqus to calculated friction forces of the control rods in the deformed guide tubes[6], force needed to remove the fuel rod from the lower plate (VVER fuel rods in Temelin TVSA-T fuel assembly have fuel rods mounted in the lower plate by the collet type lower plug), simulation of mandrel tests that was done in the frame of OECD SCIP-II project[7], rod bow simulation, material mechanical tests simulation, force between cladding and spacer grid dimples, etc.

I.B.2. Examples of thermo-mechanical simulations

For the second point the local models of pellet-cladding interaction were developed during last few years. The influence of number of cracks on the cladding hoop stress was assessed[8], MPS simulation during power ramp (Fig. 1 shows the example of calculated temperature and hoop stress distributions in 3D and 2D model), inter-pellet gap simulation, LOCA ballooning behavior, RIA calculations, detailed PCMI calculations[9], pellet crack evolution[10], etc.

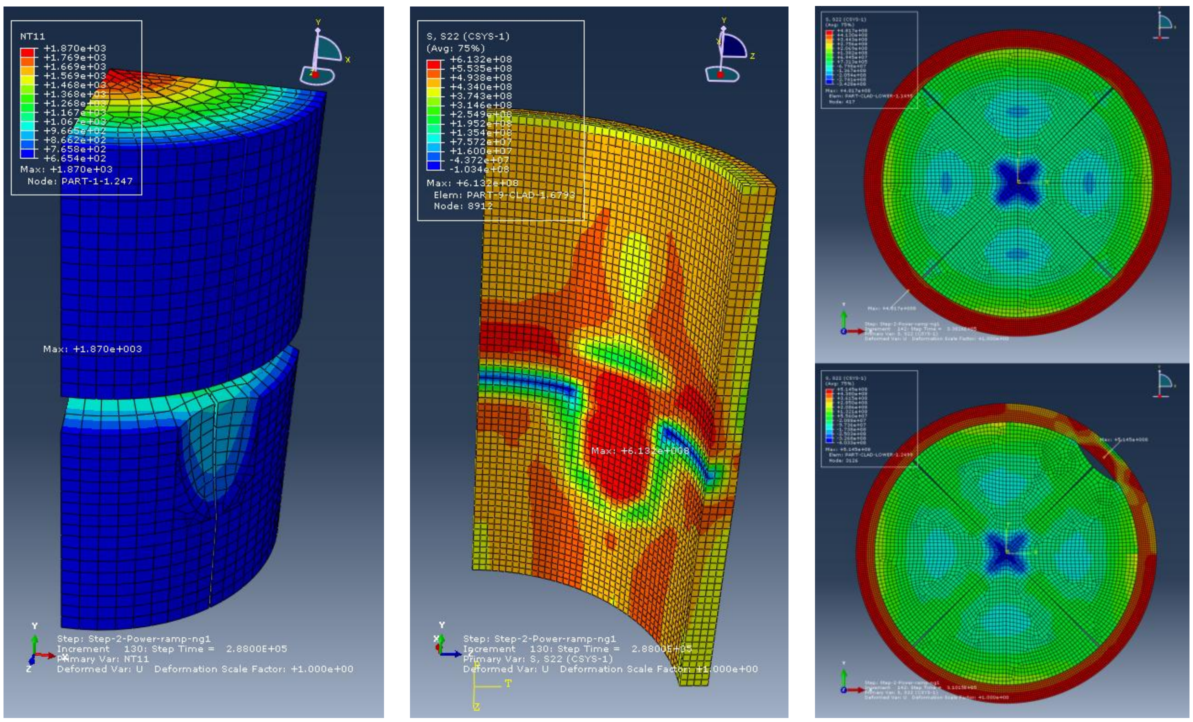

Fig. 1 Example of missing pellet chip model: left - calculated temperature distribution (3D model), middle - calculated hoop stress in cladding (3D model), right - calculated hoop stress no chip vs. chip (2D model).

III. EXAMPLE OF APPLICATION - VIBRATIONAL BEHAVIOR

III.A. Fresh UO_2 fuel with Zircaloy cladding

As a part of the modeling support to the Temelin NPP an analytical model of the fuel rod vibrational modes under given boundary conditions is being developed at the University of West Bohemia. The primary goal of the model is to help to understand the influence of the fuel assembly design and driving forces (coolant flow, pressure pulses, core barrel motion, …) on the grid-to-rod fretting, but a movement of the pellets in the rod has also been analyzed. As the fuel performance codes assume that the pellet is static, we have decided to model the impact of the periodic pellet motion within the cladding on the fuel temperature. Symmetrical 2D r-theta model was prepared assuming various fuel-cladding gap sizes within the manufacturing tolerances so that minima and maxima of gap width are chosen. The fresh fuel dimensions and properties are used due to largest gap. Pellet motion at 1Hz to 100 Hz is analysed (100 Hz value is expected from the fuel assembly vibrational analysis) for both solid and hollow pellets of standard LWR fuel.

The calculation starts with power increase followed by stabilization of temperature, after that the cladding is moved to just touch the cladding at the point on the symmetry axis (i.e. hot gap is closed on one side and doubled on the other) with required periodicity - 1, 10, 50 and 100 Hz are chosen. Stationary calculations with pellet in central position and off center position were also performed as a reference case.

The assumed linear power generated in the pellet is 300 W/cm, uniformly distributed. Cladding outer temperature is prescribed to 280 °C, inner and outer pressures are typical PWR values. Gap conductance is given as a dependence on the gap width based on the Transuranus calculation assuming 100 % He. Symmetrical boundary conditions are applied on the bottom axis (see Fig. 2). Quadratic coupled temperature-displacement finite elements with reduced integration are used, the nominal FE size is 200 microns in the fuel and 150 microns in the cladding. No pellet cracking and relocation of fragments is assumed.

Calculated shift of temperature maximum to the side with larger gap are for stationary calculations depicted in Fig. 2 for solid and in Fig. 3 for hollow pellet design. Time evolution of pellet maximum temperature for different vibration frequencies is shown in Fig. 4 for hollow pellet with maximum pellet-cladding gap. Results are summarized in Table I. and several conclusions can be drawn:

- hollow pellet stationary off centre position leads to increase of maximum pellet temperature (due to presence of He filled central hole - the left part of fuel in Fig. 3 is thus isolated by wider gap and central hole)
- solid pellet stationary off centre position gives lower maximum pellet temperature
- imposed vibrations of frequency 100 Hz lower the maximum pellet temperature of about 30 to 70 °C for both solid and hollow pellet (movements are shorter than the time constants)
- the pellet maximum temperature decrease grows with increasing frequency - there seem to be some saturated value
- the position of temperature maximum moves in stationary calculation from centre for the solid pellet, hollow pellet still has the maximum in the inner diameter
- the temperature maximum remains in the pellet centre (both solid and hollow) for vibrational calculations

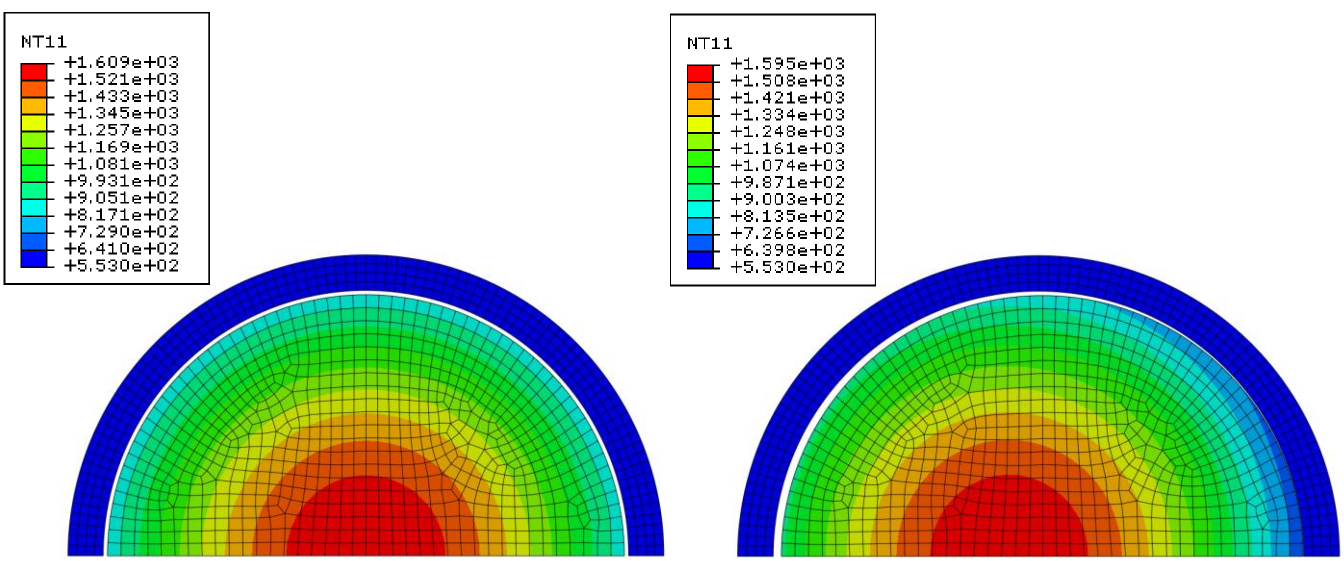

Fig. 2 Calculated temperature for central (left) and off-center (right) solid pellet stationary position in the cladding (temperature scale in Kelvins).

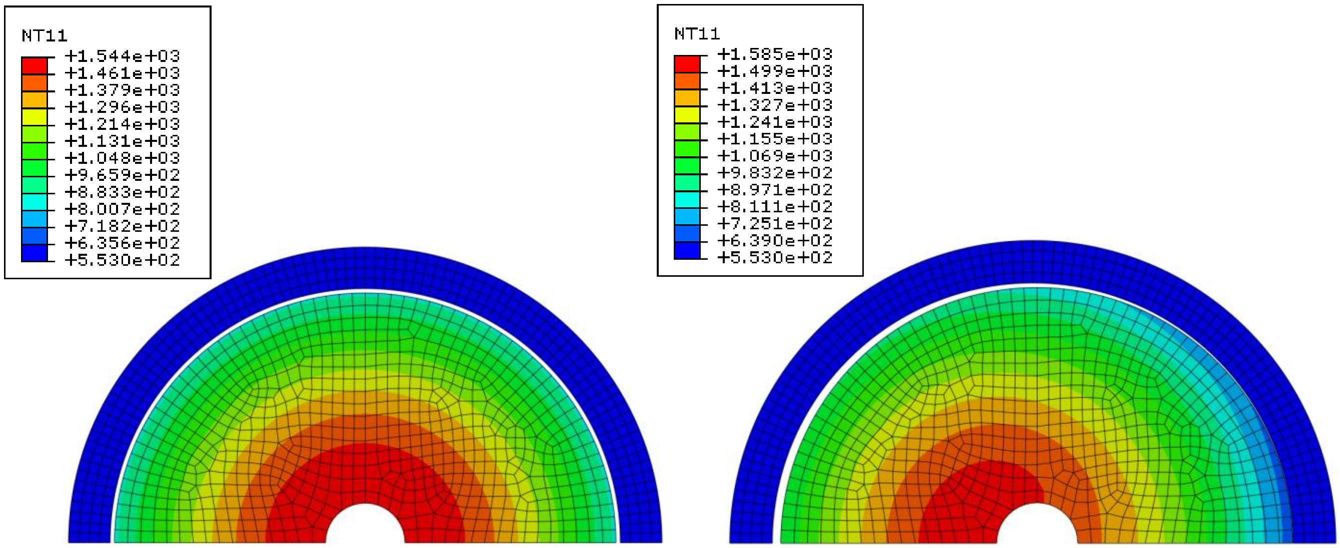

Fig. 3 Calculated temperature for central (left) and off-center (right) hollow pellet stationary position in the cladding (temperature scale in Kelvins).

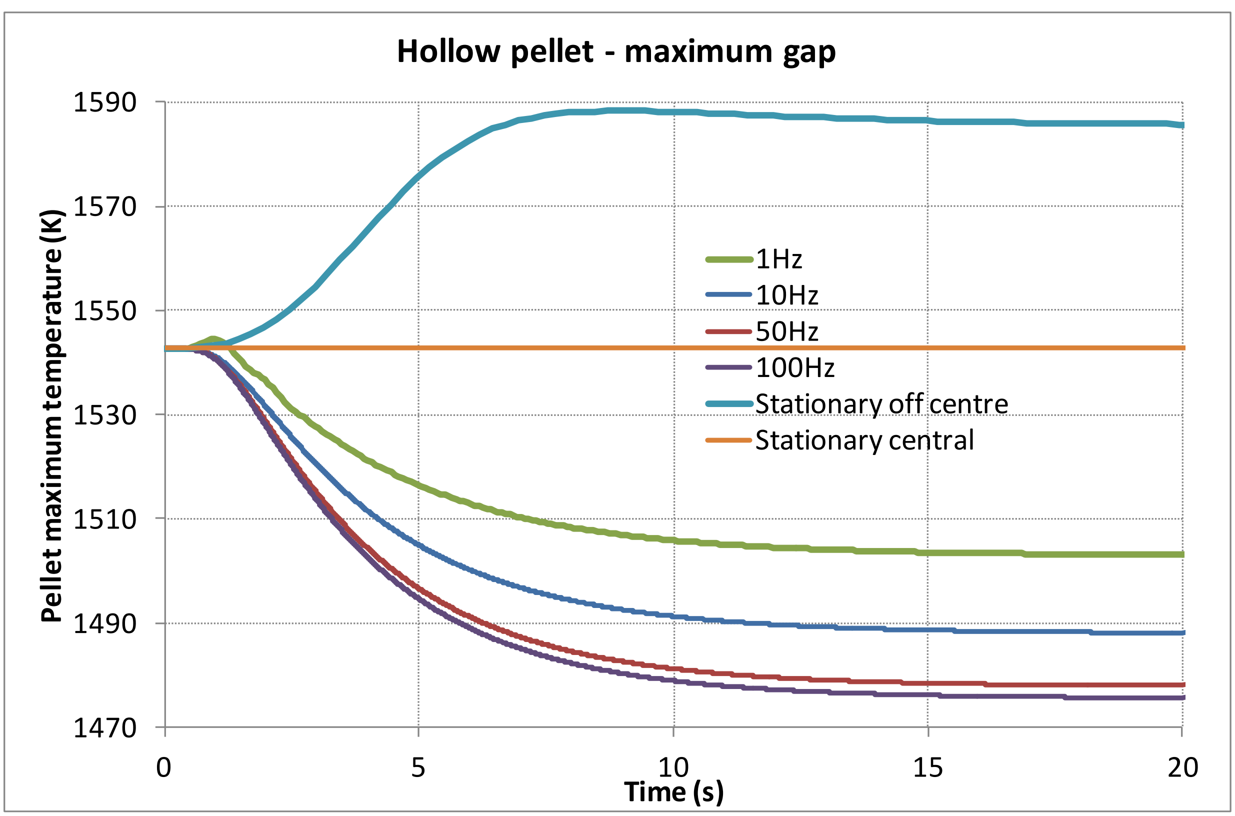

Fig. 4 Time evolution of maximum temperature (hollow pellet with maximum pellet-cladding gap) for different vibration frequencies.

TABLE I. Summary of calculated maximum pellet temperatures.

		Hollow pellet				Solid pellet			
		Minimum gap		Maximum gap		Minimum gap		Maximum gap	
		Temperature		Temperature		Temperature		Temperature	
Calculation	Position	maximum	delta	maximum	delta	maximum	delta	maximum	delta
Stationary	Centred	**1359**	**0**	**1543**	**0**	**1422**	**0**	**1609**	**0**
	Off centre	**1386**	**27**	**1585**	**43**	**1410**	**-12**	**1595**	**-14**
Vibration	**1 Hz**	1343	**-16**	1503	**-40**	1405	**-18**	1568	**-42**
	10 Hz	1335	**-23**	1488	**-54**	1397	**-25**	1553	**-56**
	50 Hz	1329	**-30**	1478	**-65**	1390	**-32**	1543	**-67**
	100 Hz	1327	**-32**	1476	**-67**	1388	**-34**	1540	**-69**

III.B. Irradiated UO_2 fuel with SiC cladding

The same approach was applied to fuel with SiC cladding. This case is interesting as the SiC-SiC cladding has been considered as an Accident Tolerant material, but its thermo-mechanical properties are quite different. Mainly, due to slow expected creep the fuel-pellet gap closure will be slower and the gap impact on the fuel temperature more pronounced. Following assumptions were therefore used in the modeling:
burnup 40 MWd/kgU, radial gap (hot) 40 microns, fission gas release (FGR) 10 %, outer diameter and cladding thickness same as in previous case with solid pellet with maximum gap as well as LHR and boundary conditions. Material properties were prepared according to recent publications[11,12].
Fuel thermal conductivity is lowered according to chosen burnup value, FGR impede heat transfer through the gap which is still open due to creep resistance of SiC. Calculated maximum temperature (pellet centre) for central position of pellet is 2018.5 K. The calculations showed that maximum pellet temperature decrease is less than 10 K for low frequencies and ~10 K for 100 Hz which is much smaller than for fresh state considered in the previous chapter - see Fig. 5 and time constants are longer. The main reason is the smaller gap size which effect is in this case larger than burnup effect.

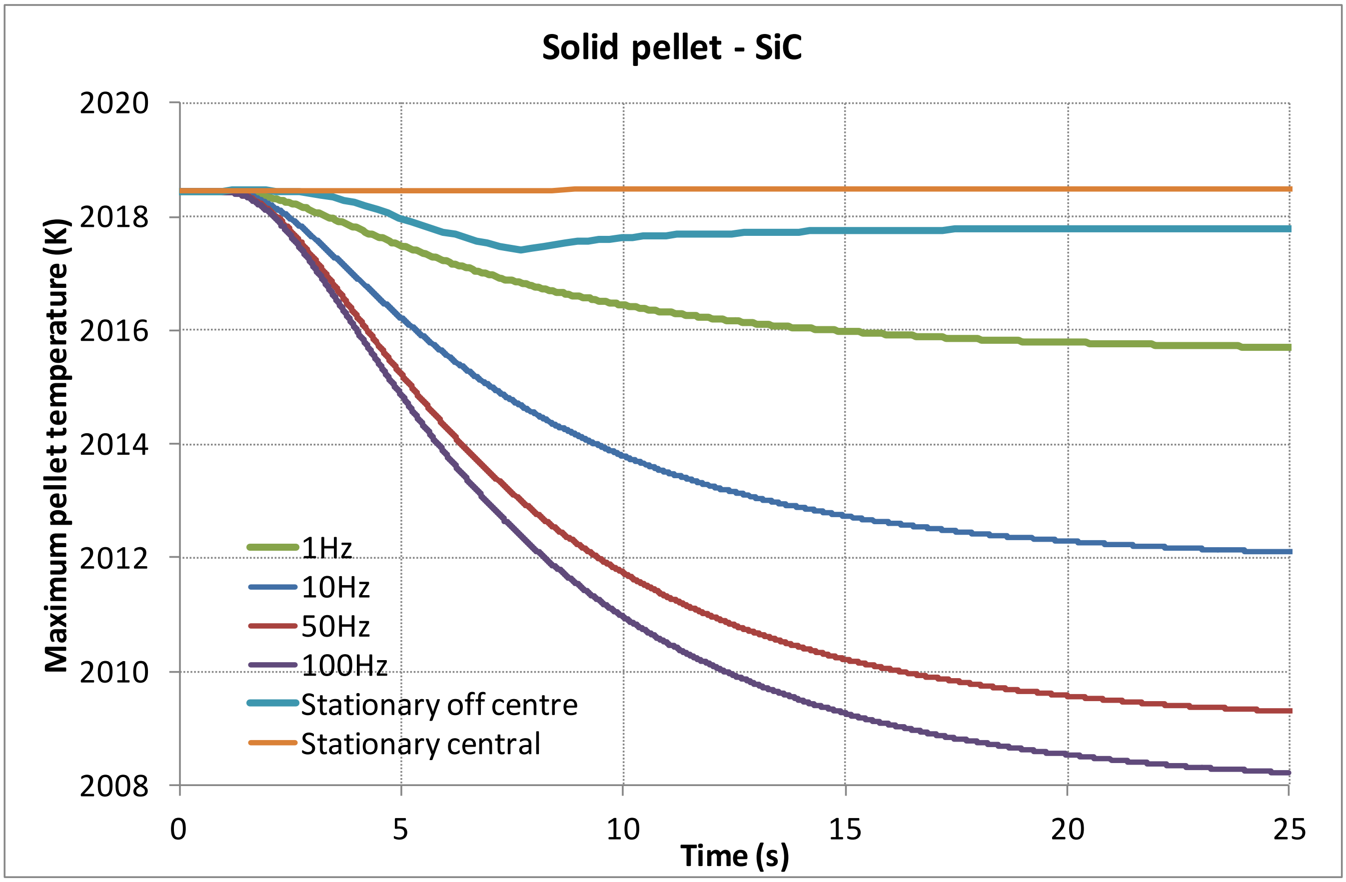

Fig. 5 Time evolution of maximum temperature (SiC cladding, solid pellet, 40 microns radial pellet-cladding gap) for different vibration frequencies.

III.B. Approach validation - concentric and eccentric pellet position

Validation of presented approach was started using data from old Halden test IFA 431 where eccentric vs. concentric pellet position in cladding was experimentally tested[13]. This test was already used for validation of 3D model developed in BISON code two years ago[14]. Our 2D calculations results are shown in Fig. 6 where measurements are plotted by black lines while calculations by colored lines. Concentric cases filled with helium (rod 1 and rod 3) are modeled very well. For xenon filled concentric pellet position (rod 4) and eccentric position (rod 4), the calculations yield in temperature overestimation because there is influence of PCI of end pellets in the stack in the experiment resulting in the decrease of pellet cladding gap which is not modeled in 2D so far. One way how to simulate this situation is instantaneous increase of cladding outer pressure to reach real pellet gap size (which is assumed in report[13]) in 2D model. More precise is 3D model which is currently under development. Secondly, the pellet-cladding gap conductance used so far showed to be insufficient because it does not increase with increasing contact pressure. New user subroutine to respect this fact is under development and it is expected that the calculated temperature will be closer to the measurement.

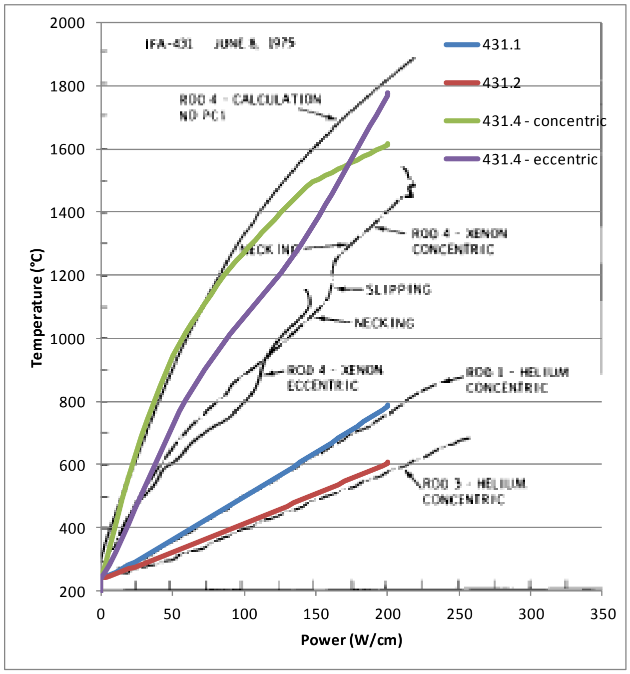

Fig. 6 Measured (black lines) and calculated (colored lines) temperature in the pellet centre as a function of power.

IV. CONCLUSIONS

Detailed thermomechanical FEM models of fuel rod and its parts were described with example of its practical application. Developed approach can be used for different tasks that stem from new research ideas or from industry issues or just to re-visit the old experiments and try to explain observed behavior which was could not be modeled with common ”1.5D” codes.

The presented poster shows several applications of the “non classical” fuel thermal analysis. A validation of the models has been performed using the experiments with eccentric fuel pellets performed in the past in Halden reactor.

As the modeling of the rod vibrational movement may lead to the periodic movement of the fuel pellets in the cladding as long as the fuel cladding gap is open, this case was also modeled and compared to the reference scenario assumed by the most fuel performance codes (i.e. static concentric pellets). The calculations show non-negligible decrease in the predicted peak fuel temperature (approximately to 1450 °C from 1500 °C). This result is interesting because it provides a similar effect as commonly modeled static relocation of fuel pellet fragments.

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