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Transient analysis of temperature distributions in the hot channel of a VVER-1200 reactor using COMSOL Multiphysics

C.J. Odii
Scientific Supervisor: Prof., Dr. A.G. Korotkikh
Tomsk Polytechnic University, Russia, Tomsk, Lenin str., 30, 634050
E-mail: monoexiton@yahoo.com

Abstract. *The axial and radial temperature distributions in the hottest channel of a VVER-1200 reactor core were analyzed using Multiphysics coupling heat transfer in solids and fluids and k-epsilon turbulent flow in COMSOL. The thermal and geometric properties of the fuel rod were modeled to closely resemble those of a VVER-1200 reactor fuel rod, incorporating the internal cavity, fuel meat, gas gap, cladding, and coolant layers. The volumetric heat generation rate (VHGR) was calculated from the linear heat generation rate and then multiplied by the peaking factors and non-uniformity coefficients. A heat flux was applied to the coolant wall, along with a VHGR heat source of approximately* $9.2 \cdot 10^8$ *W/m³ on the fuel meat. The maximum centerline temperature in the hottest channel was found to be approximately 1804 °C.*

Key words*: heat generation rate, fuel rod, temperature distribution, reactor core.*

Introduction

Evaluating key thermal hydraulics parameters, such as linear heat generation rate, centerline temperature, critical heat flux, and others, is essential for the safe operation of nuclear reactors [1, 2]. The parameters of the fuel rod used in this analysis closely mimic those of the VVER-1200 fuel rod, taking into account aspects like rod length, diameters, and the thermal properties of various layers, including the cavity, fuel meat, gas gap, cladding, and coolant. The calculated volumetric heat generation rate (VHGR) was applied as a heat source to the fuel meat, while heat flux was implemented on the coolant wall. Additionally, parameters such as the inlet velocity, inlet temperature, and outlet pressure of the turbulent coolant flow were also considered.

Research methods

We conducted numerical simulations using COMSOL Multiphysics for this work. Initially, we created a model that included various layers representing the cavity, fuel meat, gas gap, cladding, and coolant, as shown in Fig. 1 a. The thermal properties of the fuel meat, gas gap, and cladding were obtained from the literature as seen in Table 1, while the thermal properties of the coolant were calculated using the IAPWS-IF97 Excel steam table.

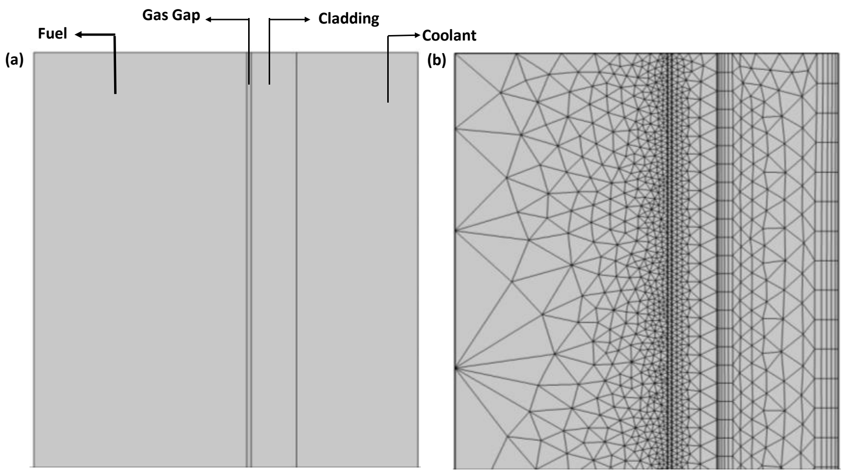

Fig. 1. Geometrical model of the fuel rod (a) showing each layer (b) meshed layers

Table 1

Modeling parameters of fuel rod and coolant [1–3]

Parameter	Value	Parameter	Value
VHGR	$9.2 \cdot 10^8$ W/m^3	Coolant inlet temperature	571 K
Heat transfer coefficient	58000 W/m^{2}K	Coolant inlet velocity	5 m/s
Fuel pellet domain radius	0.0032 m	Coolant pressure outlet	$1.62 \cdot 10^7$ Pa
Fuel cavity thickness	0.0006 m	Clad density	6550 kg/m^3
Gas gap thickness	0.000065 m	Clad specific heat capacity, cp	285.8J /kgK
Cladding domain thickness	0.000685 m	Clad thermal conductivity	19.2 W/mK
Coolant domain thickness	0.001825 m	Fuel density	10445 kg/m^3
Rod length	3.76 m	Fuel specific heat capacity	236 J/kgK
Fuel thermal conductivity	3.048 W/mK	Helium specific heat capacity	5000 J/kgK
Helium density	125 kg/m^3	Helium thermal conductivity	0.276 W/mK

In the COMSOL environment, we selected water as the material for the coolant using the built-in material options. For the fuel meat, gas gap, and cladding, we created custom materials and manually input their thermal properties in the basic properties section. After configuring the necessary physics and multiphysics settings, we meshed the geometry using both the physics control mesh and the normal mesh option as seen in Fig. 1 b.

We employed a steady-state solver to calculate the temperature distribution, followed by a time-dependent solver modeled over a duration of 0 to 30 seconds COMSOL was capable of evaluating temperature, heat flux, and other distributions for all layers, as well as coolant velocity, pressure, and various turbulence parameters along the rod. However, in this study, we focused our analysis on the axial temperature distribution for all layers of the rod and the radial temperature distribution at the center of the rod.

Results

For the hottest fuel rod, the temperature contour in 1, 10 and 30 seconds are shown in Fig. 2 a–c.

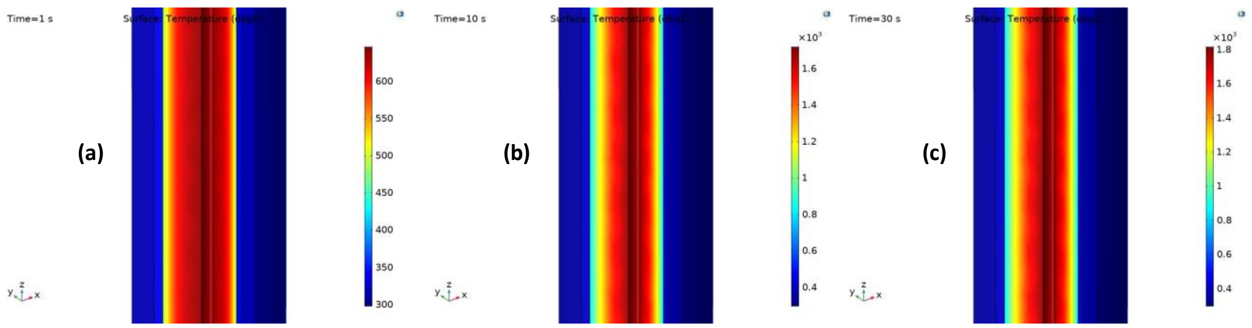

Fig. 2. Temperature contour distributions for (a) 1 s; (b) 10 s; (c) 30 s

The axial and radial peak fuel temperature was calculated to be 1804 °C, as seen in Fig. 3 a, f. The maximum outer fuel surface temperature reached approximately 820 °C, as seen in Fig. 3 b, while the maximum temperature of the inner cladding surface was around 420 °C, as seen in Fig. 3 c. The maximum outer cladding surface temperature was about 353 °C, as seen in Fig. ay take even longer in other systems depending on the computer's processing capacity. A common observation during the computation was that after 20 s, with time steps of 0.1 s, the temperature differences between time steps began to reduce significantly until they became negligible at around 33 (d) and the outlet coolant temperature was approximately 340 °C, as seen in Fig. 3 e. Each of these maximum temperatures occurred around 30 seconds into the solver's allotted time. However, it took COMSOL about 7 hours of computational time for the solution to converge, and it m 0s.

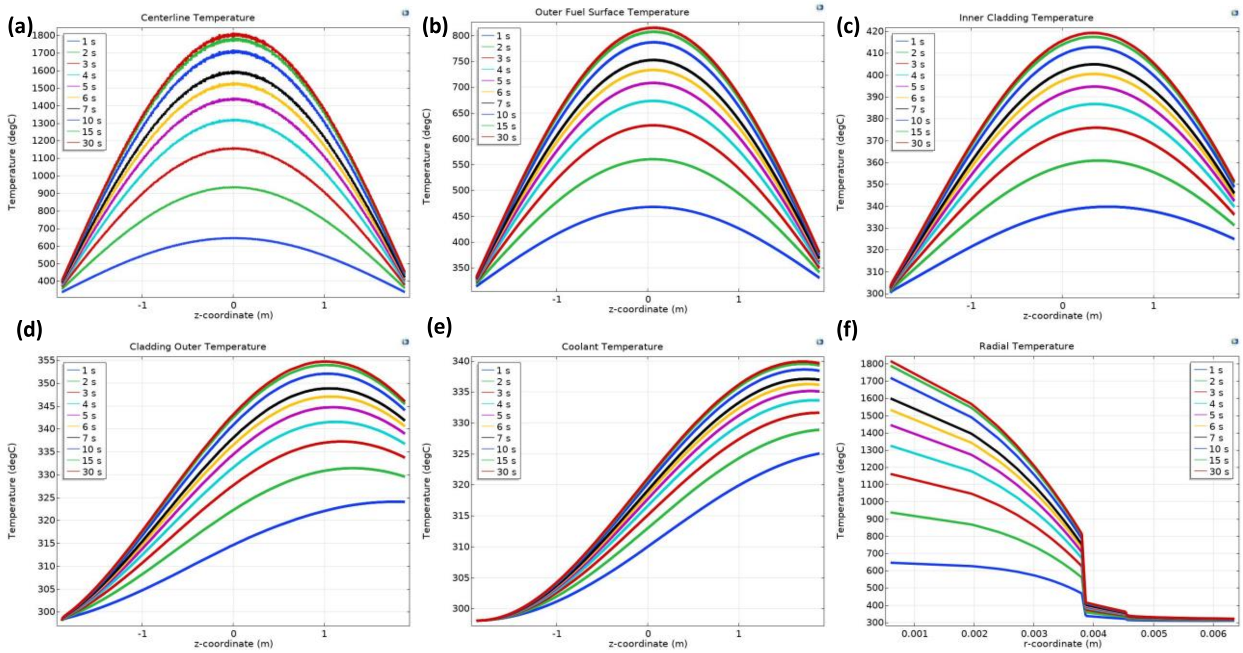

Fig. 3. Temperature distributions for (a) centerline; (b) fuel outer surface; (c) inner cladding surface; (d) outer cladding surface; (e) coolant; (f) radial distribution at rod center

Conclusion

We can conclude that the multiphysics coupling of heat transfer in solids and fluids, along with k-epsilon turbulent flow models in COMSOL, can effectively replicate a thermal-hydraulics analysis of heat transfer and coolant flow within the channel of a nuclear reactor core. This is contingent upon accurately modeling the geometry and thermal-hydraulic parameters of the fuel channel in question in COMSOL.

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