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Optimization method for the design of hexagonal fuel assemblies

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ABSTRACT

The duct wall and inter-assembly gap make up ~5–15% of the volume of a typical fast reactor core and these components have a profound impact on the system neutron economy. In this paper, a methodology for the design of optimum hexagonal fuel assembly geometries was developed. For each nuclear reactor core made up of ducted assemblies there exists a unique optimum solution of duct wall thickness and inter-assembly gap, where these components have the minimum impact on the core neutron balance while adhering to applicable structural constraints. The assembly duct wall must maintain its structural integrity and intended function while being exposed to a harsh environment of pressure, temperature and neutron fluence causing elastic and inelastic deflections and swelling. Analytical expressions, applicable to any internally pressurized hexagonal structure, were defined for the peak stress and elastic wall deflection. Detailed analysis of fuel assembly duct designs requires finite element code analysis, radial bowing analysis codes and the full temperature, flux and stress distribution over the lifetime of the assembly in the core to accurately estimate creep deformation. The simple analytical methodology presented in this paper can provide a good initial guess for an optimal geometry to be iteratively improved and refined using more advanced codes and methods.

1. Introduction

In most conventional fast reactor designs, fuel rods are arranged in regular lattices inside metal cans called *ducts* (or wrappers). These ducts, together with the fuel rods and associated hardware are referred to as assemblies (or subassemblies). One of three shapes for the structure of these assemblies is generally used:

- Hexagonal.
- Circular.
- Square.

While there is a very large body of published work on the design, analysis and optimization of fuel rods and internal coolant channel geometries, there is comparatively little material available to guide the design and optimization of the fuel assemblies themselves. Useful information and more detailed duct analysis methods than those presented in this study can be found in Ohmae et al. (1972a,b), Chan and Jackson (1979), McWethy (1969), Flowers (1966) and Kim et al. (2001). This paper presents the methodology developed for the ADOPT fast reactor design code to optimize the duct wall thickness and inter-assembly gaps of hexagonal fuel assemblies (Qvist and Greenspan, 2014). The analysis is primarily focused on liquid–metal cooled fast reactors, but is at least partially applicable to hexagonal structures in nuclear reactors regardless of spectra or coolant.

There are a number of reasons why ducted assemblies are used to make up the structure of a nuclear reactor core; the most important can be summarized as:

- Directs coolant flow through the high-resistance path through the fuel rod bundle.
- Enables tailoring of the core flow distribution by orificing inside of the assemblies, directing high flow rate to the core regions where the power is high and vice versa.
- Provides structural support for the fuel rods.
- The ducts, along with the radial core constraint systems, enable the core designer to tailor the core radial expansion reactivity feedback characteristics (which is of great importance to fast reactor safety).
- Provides a barrier to the potential propagation to the rest of the core of a possible accident initiated by for example the rupture of fuel rods in an assembly.
- Helps to arrange desired axial heterogeneity, e.g. an empty space between the top of the fuel bundle and upper reflector (sodium plenum).

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Implementing a ducted assembly design for the core structure also means the addition of a significant fraction of materials that do not contribute to either the fission process or to the active cooling of the core. The duct walls and the spacing between fuel assemblies typically make up a combined 5–15% of the total volume inside a fast reactor core. The impact on the core neutron balance can be profound, especially if the design of the fuel assembly structure is far from optimal, which stresses the importance of a consistent optimization methodology for these components.

Section 2 defines the general constraints applied in the design of fuel assemblies. Section 3 details the geometric relations used throughout the paper for hexagonal steel structures. In Section 4, the methodology to calculate the peak stress induced by the coolant on the fuel assembly duct wall is defined. The wall deflection due differential pressure in the fuel assemblies is given in Section 5. Section 6 presents the time-dependent and inelastic geometry changes to the assembly steel as it is exposed to a reactor environment. All of the preceding results are brought together in Section 7, where an optimization definition is given and an example optimization calculation is performed for HT9 steel. Conclusions and the applicability of the work presented in this paper are summarized in Section 8. Appendix A summarized relevant material properties and correlations used in this study.

2. Constraints for fuel assembly designs

2.1. Fuel assembly size constraints

A number of both structural and neutronic requirements must be imposed on the design of fuel assemblies in order to define the overall size, shape and thickness of components. Most geometric parameters of fuel assemblies are inter-dependent, i.e. changing one parameter implies a change in all other parameters. The overall size and corresponding reactivity worth of an individual fuel assembly should be limited so that the potential reactivity insertion rate and power transient from meltdown and gravity collapse of any one fuel assembly will be terminated by normal operation of the reactor safety systems with no loss of fuel pin integrity in other fuel assemblies in the core. The size of an assembly may also be limited by criticality concerns if flooded with water during ex-vessel shipment.

These requirements apply to all cores made up of assemblies, but some additional requirements apply specifically to cores where individual fuel assemblies are designed to change positions or are to be replaced individually. Hence, "battery"-type cores where the entire core is swapped out at once, where no individual assembly operations are performed are exempt from the following restrictions. For other cores, the allowable assembly weight is limited by the capacity of the shuffling/reloading machine. If assemblies are periodically discharged from the core, the heat removal capability of the refueling machine must match the decay heat from the assembly, which also puts a limit on the assembly size and individual assembly power level. It is difficult to quantify these overall size constraints in any general sense without knowing details about the specific reactor system. In practice, hexagonal fuel assemblies for fast reactors typically have a flat-to-flat duct wall distance of 10–18 cm and rarely exceed 23 cm even in conceptual designs (Waltar et al., 2012).

2.2. Operational constraints on duct wall thickness and inter-assembly gap

The required thickness of the duct and the gap between adjacent assemblies depend on the assembly size, the primary system pressure drop, temperature profile, fast neutron fluence and the properties of the duct steel. The conditions which the assembly is exposed to in the core can profoundly alter its geometry. An obvious design requirement is that the withdrawal force required to lift any assembly out of the core at any time during the cycle is within the capacity of the shuffling or reloading machine. Two adjacent assembly walls must not be in such strong contact as to preclude their withdrawal. An additional design requirement is that shutdown (SCRAM) assembly geometries must remain in a state where their function and operational time-constants are not changed. The fuel assembly duct walls next to a control assembly are thus not allowed to distort the adjacent walls. A conservative requirement is therefore that the assembly should be designed in such a way as to avoid adjacent duct-to-duct wall contact (+ some optional gap margin) except at the locations of duct spacer pads, at any point during the cycle.

Additionally, the peak stress and membrane stress in the duct wall steel should remain below the peak design stress of the specific material. As will be shown in Section 6, this requirement often sets the effective minimum duct wall thickness for any specific design.

3. Geometry definitions

The layout and relevant components of a hexagonal fast reactor fuel assembly with a triangular lattice of 127 fuel rods is shown on the left side of Fig. 1. The geometric parameters used in the analysis of the hexagonal duct structure are given on the right side of Fig. 1. The parameters are defined as follows:

t = The wall-thickness of the duct (mm).
a = The distance between the center of the hexagon and the mid-wall of the duct (mm).
R = the mean corner radius (mm).
L = one half length of the straight section of the duct wall side (mm).

4. Peak stress analysis

4.1. Defining the maximum duct stress due to internal pressure

During reactor operation, the internal assembly coolant exerts a pressure differential on the duct wall. The pressure differential across the duct wall can be estimated from the pressure drop between the inlet and outlet coolant plenum of the core. Commercial sodium-cooled fast reactor designs have total pump nozzle-to-nozzle pressure drops ranging from 100 kPa up to about 1 MPa. ~20–40% of this pressure is lost in the internal structures below the fueled region of the hexagonal rod bundle. Fig. 2 shows the axial components and the fraction of remaining coolant pressure in the fuel assembly by axial position using values taken from CRBRP design report (Safety Analysis Report, 1974).

The thickness of the duct wall in non-fueled sections of the assembly is of low importance to the core neutron balance. In these regions, particularly below the active core where the coolant pressure is the highest, the duct walls can be made thick enough to meet all constraints without adversely impacting core performance. The local yield stress of the duct wall decreases with increasing axial location due to higher temperatures, but for commonly used or proposed fast reactor duct materials (HT9, T91, D9, EP-823 steel) in the typical temperature range (~350 °C in the duct at the lowest part of the fueled region, ~500 °C at the top), the drop in yield stress is significantly smaller than the drop in pressure and applied stress for most configurations. The relative drop in yield stress going from 350 °C to 500 °C is 6%, 11%, 13% and 20% for