FUEL PARTICLE DESIGN FOR A FLUIDIZED BED REACTOR

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INTRODUCTION

This article describes the dimensioning of fuel particles and the fundamental reactor physics mechanisms of a fluidized bed reactor [1]. The reactor consists of a graphite cylinder with outer diameter of about 3 meters and height of 8 meters. Inside the cylinder, a core cavity with cross section of 1 m^2 and height of 6 meters is partly filled with small spherical particles, so-called TRISO particles [2], containing a fuel kernel surrounded by graphite and SiC layers. The outer diameter of these particles was varied. Low enriched UO_2 is used as fuel. Helium is used as coolant, which flows through the core cavity in upward direction, thereby suspending the particles.

The design of the reactor ensures inherently safe operation. In collapsed state, the core is strongly subcritical. Upon increasing the helium flow, the particle bed becomes fluidized and the effective moderator-to-fuel ratio increases, giving rise to an increase of k_{eff}. For helium flows too large, the reactor is overmoderated and k_{eff} decreases again. As a consequence, with a proper choice of system parameters, the reactor is critical only for a very limited range of coolant flows.

Besides the inherently safe character of the reactor, other advantages are the high specific power (power per unit mass of fuel inventory) and the on-line fueling capability. Like pyrolytic carbon layers, the silicon carbide layers of the coated particles prevent the escape of fission products from the fuel particle. Furthermore, the design of the core and reactor is very simple, which together with the modular concept paves the way to cheap and safe nuclear power.

CALCULATION PROCEDURES

First, the k_∞ of the fuel particles was calculated for different diameters of the fuel kernels and for different moderator-to-fuel atomic ratios. The fuel enrichment of the UO_2 fuel kernel was 17%. Because the neutrons mean free path is much larger than the thickness of the TRISO layers, these were homogenised. The resultant atomic densities are $6.94{\cdot}10^{22}$, $8.11{\cdot}10^{21}$, $2.0{\cdot}10^{16}$ and $8.05{\cdot}10^{16}$ atoms per cm^3 for C, Si, ^{10}B and ^{11}B, respectively. The particles were assumed to be at room temperature. The coolant density is $2.42{\cdot}10^{-3}$ grams per cm^3 which corresponds with He at temperature of 1000 K and pressure of 50 bars.

The calculations were performed by use of the CSAS driver of the SCALE system [3]. This uses the codes BONAMI-S and NITAWL-II to calculate resonance-shielded cross sections by the Bondarenko method in the unresolved region and by the Nordheim method in the resolved region. The discrete-ordinates code XSDRNPM-S was used to calculate the neutron spectrum and the eigenvalue and to produce cell-weighted cross sections for the core calculations described further on. The

DANCOFF-MC program [4] calculated the Dancoff factor, which accounts for the probability that a neutron that escapes from a fuel kernel enters another kernel without any collision in between. For all calculations a data library in the XMAS group structure was used based on the JEF2.2 file.

Secondly, calculations in R-Z geometry were performed to calculate k_{eff} as function of core height. These calculations were performed by the diffusion code Bold-Venture [5] and by the Monte Carlo code MCNP4B [6]. For the first, cell-weighted cross sections from the SCALE calculations collapsed to 49 energy groups were used, while for the second point-energy data based on JEF2.2 were used. The latter calculations are probably more accurate because of the point-wise data used and the more exact solution method. For example, it is not straightforward to calculate diffusion coefficients valid for the vacuum between the active core region and the top reflector, while this is not a difficulty for the Monte Carlo method. On the other hand, CPU times for the Monte Carlo calculations are about 10 times larger than for the corresponding diffusion calculations.

RESULTS AND ANALYSIS

Figure 1 shows k_∞ as function of the moderator-to-fuel ratio with the radius of the fuel kernel as parameter. Calculations were done for radii of 0.10, 0.13, 0.15, 0.20 and 0.25 mm. The outer dimension of the particle was changed to vary the moderator-to-fuel ratio. For all calculations the Dancoff factor was equal to 0.752 although in reality this parameter varies with fuel kernel size and moderator-to-fuel ratio. All lines in **Figure 1** show the same trends. At a moderator-to-fuel ratio of about 600, k_∞ has a maximum. For smaller values the reactor is undermoderated, for larger values it is overmoderated. Right of the maximum, k_∞ decreases due to increasing absorption of neutrons by moderator nuclides, while at the left of the maximum k_∞ decreases due to increasing resonance absorption. At a moderator-to-fuel ratio of about 40 and for fuel kernels big enough, k_∞ increases if we reduce the moderator-to-fuel ratio further. In this region, the reactor operates like a fast reactor. Of course, this effect is only seen if the fuel enrichment is large enough.

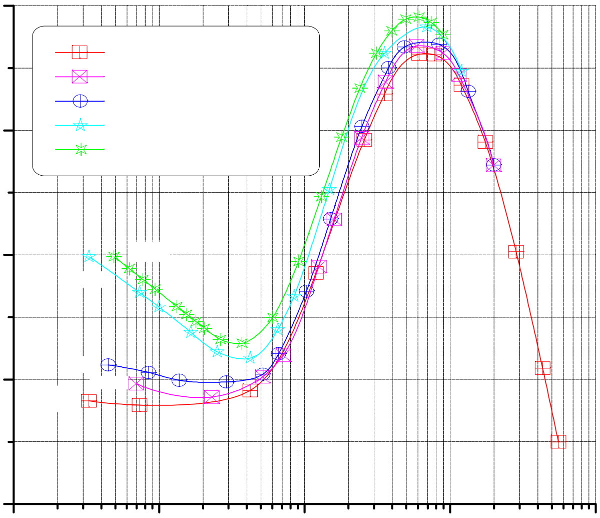

Figure 1. *k_∞ as function of moderator-to-fuel ratio. Left from the maximum, the reactor is undermoderated, at the right it is overmoderated.*

Besides the general behavior of k_∞ described above, there is a trend that for small moderator-to-fuel ratios k_∞ is very sensitive to the diameter of the fuel kernel, while for large ratios, the differences between the k_∞ curves becomes very small. This effect can be explained by the four-factor formula: the fast fission factor ε, the resonance escape probability p, the thermal utilization f and the average number of neutrons per thermal absorption in the fuel η. For small values of the moderator-to-fuel ratio, the neutron spectrum is very hard and k_∞ varies mainly due to ε and p

which are both very sensitive to the diameter of the fuel kernel. The larger this diameter, the more resonance shielding and the higher *p*. For large values of the moderator-to-fuel ratio (>600), almost all neutrons that escape from a fuel kernel scatter by moderator nuclides, which implies that k_∞ is not sensitive to ε and *p* but to the thermal utilization *f*.

Table 1: *The factors of four-factor formula for different moderator-to-fuel ratio in fuel particle for over-moderated region.*

N_m/N_f	ε	p	f	η	k_∞
587	1.12	0.77	0.88	2.03	1.54
894	1.08	0.84	0.83	2.03	1.53
1149	1.06	0.87	0.79	2.04	1.49
1987	1.04	0.92	0.69	2.04	1.34

For a fuel kernel diameter of 0.26 mm, the four factors calculated by the VAREX program [7] are given in Table 1. In the overmoderated region both ε and *p* tend to unity with increasing moderator-to-fuel ratio, while the thermal utilization *f* decreases. The latter indicates that in this region more and more neutrons are absorbed by moderator nuclides. The number of neutrons released per thermal absorption in the fuel η does not depend on the moderator-to-fuel ratio but on the fuel composition.

Figure 2 shows explicitly the dependence of k_∞ as function of the kernel radius with the moderator-to-fuel ratio as parameter. In all cases, the Dancoff factor equals 0.752 like for the previous **Figure 1**. Two trends can be seen. First, for all curves k_∞ increases with increasing kernel radius, but for large moderator-to-fuel ratios this dependence becomes very weak. See for example the curve for a moderator-to-fuel ratio of 1644. This corresponds to the fact that in **Figure 1** all curves coincide in the overmoderated region (moderator-to-fuel ratio > 1000). Secondly, k_∞ for a moderator-to-fuel ratio of 42 is lower than for a ratio of 20, while it is higher for larger ratios. At the other extreme, k_∞ for a moderator-to-fuel ratio of 1644 is lower than for a ratio of 620. Again this corresponds with the behavior shown in **Figure 1**.

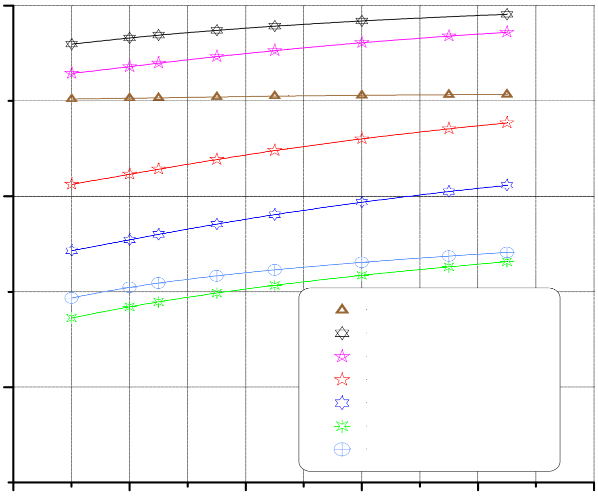

Figure 2: *k_∞ as function of kernel radius. For very large moderator-to-fuel ratio k_∞ becomes independent of the kernel radius.*

Figure 3 shows k_{eff} as function of core height, where the height change due to core expansion caused by large helium flow mode. For these calculations, which were performed by the diffusion code Bold Venture [5] and the Monte Carlo code MCNP4B [6], the whole core surrounded by radial and axial graphite reflectors has been modeled. The particles in the core have an outer diameter of 1 mm and a fuel kernel diameter of 0.26 mm, which corresponds with a moderator-to-fuel ratio of 160. Both curves in **Figure 3** show the same behavior. For a core height of 136 cm and a corresponding void fraction of 48% the core is subcritical (Bold Venture). Upon increasing the helium flow, the core expands and the fast neutrons leak away to the graphite surroundings where they are moderated and reflected. Effectively this increases the moderator-to-fuel ratio and k_{eff} of the system. When the core expands to a height larger than 300 cm, it becomes overmoderated and k_{eff} decreases. This means that too many neutrons leak away to the graphite where they are absorbed. The difference between the two curves is probably due to differences in data treatment (multi-group versus point-energy data) and differences in calculation methods (diffusion theory versus Monte Carlo).

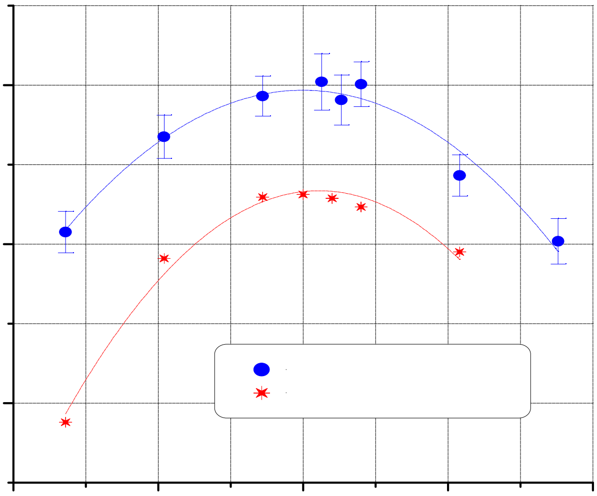

Figure 3. *k_{eff} as function of height of expanded core. With increasing core height, the effective moderator-to-fuel ratio increases. Below 300 cm, the core is undermoderated, above it is overmoderated.*

CONCLUSIONS AND FURTHER WORK

It has been shown that reactor physics mechanisms can limit the eigenvalue of a fluidized bed reactor. This means that the reactor is subcritical when the coolant flow is too small or too large. This is due to the fact that k_∞ of the fuel has a maximum as function of the moderator-to-fuel ratio. For values larger, which corresponds to a too large expansion of the core, the reactor becomes overmoderated, while for values smaller, which corresponds to a too small coolant flow, the reactor becomes undermoderated.

For a fuel enrichment of 17%, the operational moderator-to-fuel ratio is between 100 and 300. This means that for a particle outer diameter of 1 mm, the fuel kernel diameter may range between 0.30 and 0.22 mm.

Further work will concentrate on the influence of fuel enrichment and total core inventory, and on the various reactivity coefficients of temperature.

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