ANALYSIS OF OPERATIONAL TRANSIENTS IN A FLUIDIZED BED NUCLEAR REACTOR

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ABSTRACT

A theoretical model describing the coupling of neutronics, thermohydraulics and fluidization in a fluidized bed nuclear reactor is presented. Simulations of operational transient conditions are performed, viz. a decrease of coolant flow rate and a change of coolant inlet temperature. These simulations show that the fuel temperature remains below the maximum allowable temperature of TRISO fuel, therefore ensuring a safe operational transient. The maximum reactivity is inherently limited and is rapidly compensated by the passive feedback mechanism.

1. Introduction

FLUBER is a conceptual design of a fluidized bed nuclear reactor that consists of TRISO coated fuel particles contained in a graphite-walled cylinder. The core cavity has a cross sectional area of 1 m^2 and a height of 6 m. The thickness of the axial and radial graphite reflectors is 1 m. Helium is used both as fluidization gas as well as coolant. The outer diameter of the fuel particles is 1 mm and the enrichment of the fuel kernel is fixed at 16.76%. When the helium flow is low enough, the core is packed and subcritical due to a lack of moderation. As the flow is increased, the core expands and reactivity is increased due to the influence of the graphite reflectors. In previous work, a geometric design was used where the reactivity attained a maximum at a certain flow rate and where the reactor became subcritical at high flow rates. The maximum attainable power was rather limited. In the present work, we choose a geometric design where the power attains its maximum at full core expansion. The power that can be reached in this way is somewhat higher than in the previous design.

A recent paper [1] discussed a startup transient that was simulated for an instantaneous increase of flow rate from 4 to 11 kg/s and showed that although the total power of the reactor may reach high values, the fuel temperature is well below safety limits at all times. The current paper describes several operational transients in FLUBER using the point dynamics model with coupled neutronics, thermal-hydraulics and fluidization interaction, which is intended as an improvement to the model presented by Kloosterman et al. [2] and as a reduced model to the fully coupled multidimensional one [3].

2. Model

The fluidization process is described by using the Richardson and Zaki (RZ) correlation which relates the fluidization velocity, $U_{g,s}$, to the bed porosity, ε,

$$U_{g,s} = U_{\infty}\varepsilon_{\infty}^{n} \tag{1}$$

where U_{∞} is the particle terminal velocity and n is a constant. The void fraction is assumed to relax towards the steady state value as given by RZ with a timescale τ,

$$\frac{d\varepsilon}{dt}=\frac{1}{\tau}\left(\varepsilon_{\infty}-\varepsilon\right) \tag{2}$$

The timescale is proportional to the bed height and inverse proportional to the gas velocity which corresponds to the time of propagation of a disturbance through the bed.

The energy equation for the fuel particles is

$$m_p C_{p,p}\frac{dT_p}{dt}=P_t+Q \tag{3}$$

and that for the gaseous coolant is

$$m_g C_{p,g}\frac{dT_g}{dt}=G_{in}C_{p,g}\left(T_{in}-T_{out}\right)-\frac{dm_g}{dt}\left(T_{out}-T_g\right)-Q \tag{4}$$

where P_t is the total power, G_{in} is the inlet mass flow rate of the helium, T_{in} and T_{out} are the inlet and outlet temperature of the helium, the subscripts p and g denote particle and gas respectively. Within the current point model an axially linear gas temperature distribution is employed [2], describing the relation of T_{out} to T_{in} and T_g. The interfacial heat transfer, Q, is based on the Nusselt relation for a single particle. Observe that the mass of particle in the above equations is constant, whereas the mass of coolant includes only that part in the active core region, which varies during a transient.

The basic equations for the point kinetics model is

$$\frac{dP_p}{dt}=\left[\frac{\rho-\beta}{\Lambda}\right]P_p+\sum_{i=1}^{N_p}\lambda_i C_i+\frac{S}{\Lambda} \tag{5}$$

the precursor concentrations further satisfy

$$\frac{dC_i}{dt}=\frac{\beta_i}{\Lambda}P_p-\lambda_i C_i,\quad i=1,\ldots,N_p \tag{6}$$

and the decay heat is formulated as

$$\frac{dP_{d,n}}{dt}=\frac{\gamma_n}{Q_f}P_p-\lambda_n P_{d,n},\quad n=1,\ldots,N_d \tag{7}$$

where P_p is the prompt fission thermal power, P_d is the delayed component, ρ is the reactivity, β denotes the delayed neutron fraction, Λ is the neutron generation time, C_i is the precursor concentration of class i, λ is its corresponding decay-constant, S is the independent neutron source, expressed in power units and Q_f is the prompt recoverable energy per fission. In the present work 6 precursor groups and 15 decay heat groups are employed. There are two components of reactivity feedback existing in the fluidized bed fission reactor: (a) feedback due to variation of the bed height, ρ_{ref}, and (b) feedback from temperature effects, ρ_T :

$$\rho(\varepsilon,T_p)=\rho_{ref}(\varepsilon)+\rho_T(\varepsilon,T_p) \tag{8}$$

Two different formulations are used for the temperature feedback (i) a steady state formulation where the reflector temperature is assumed to be in between that of the core and room temperature, and (ii) a transient formulation where the reflector is assumed to stay at its initial temperature. This leads to the following statements

$$\rho_{T,ss}=\alpha_{d,t}\left(\varepsilon\right)\left(T_p-T_{ref}\right) \tag{9}$$

$$\rho_{T,tr}=\alpha_{d,t}\left(\varepsilon\right)\left(T_i-T_{ref}\right)+\alpha_{d,c}\left(\varepsilon\right)(T_p-T_i) \tag{10}$$

where $\alpha_{d,t}$ and $\alpha_{d,c}$ are the total and core temperature coefficients respectively. T_{ref} is the temperature at which the standard reactivity curve is known, and T_i is the fuel temperature at the inception of the transient. The present design of the reactor uses 170 kg of uranium and the reflector has an embedded absorber ring containing 20 ppm of natural boron located at the bottom of the core. Figure 1 shows the static reactivity and Doppler coefficients as a function of the bed porosity, together with fitted curves that have been used in the subsequent simulations. These static calculations have been performed with the criticality code KENO-Va.

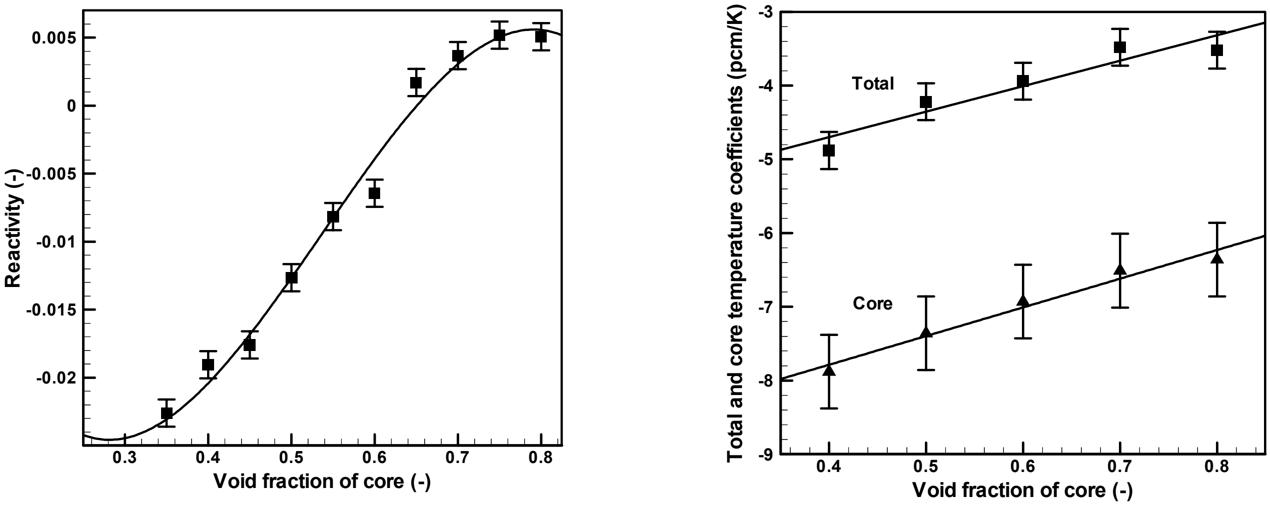

Figure 1. Reactivity (left) and temperature coefficients (right) as a function of the bed porosity. Reference temperature of the fuel is 693 K and the total mass of uranium in the bed equals 170 kg.

3. Results

Figure 2 shows the steady state conditions for the fuel temperature and the total power based on an inlet helium temperature of 543 K. The reactor starts to produce power at a flow rate of about 4.6 kg/s and rises towards its maximum at 14 kg/s. The curve for the fuel temperature follows that of the reactivity and reaches its maximum earlier. Around 14 kg/s, the porosity of the bed reaches its maximum value (height of the bed equals the height of the cylinder) and beyond that the model becomes invalid. The temperature of the coolant (not shown) is almost equal to that of the fuel particles due to the excellent heat transfer.

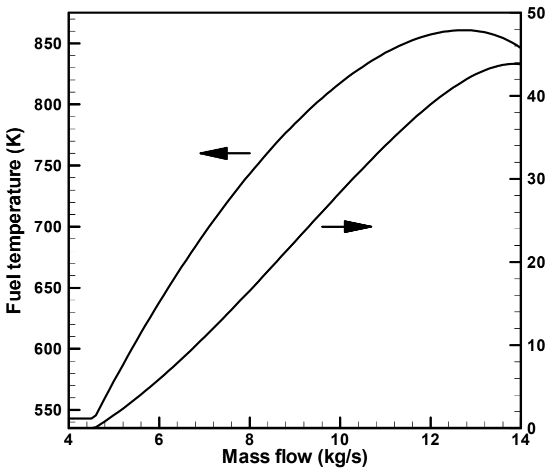

Figure 2. Fuel temperature and total power as a function of the coolant mass flow rate in steady state conditions.

Two kinds of operational transients were simulated to investigate the effect to the fluidized bed nuclear reactor, i.e. a decrease in the flow rate and a change in the helium inlet temperature. These transients are considered to represent a broad range of possible operational transients.

In the first case, the flow rate is instantaneously decreased at time 0 from 11 kg/s to 8 kg/s after the reactor reaches the steady state condition at 11 kg/s. This transient, for example, can occur as a result of a pump disturbance or as an intended decrease of power output. Results of this transient are shown in Figure 3.

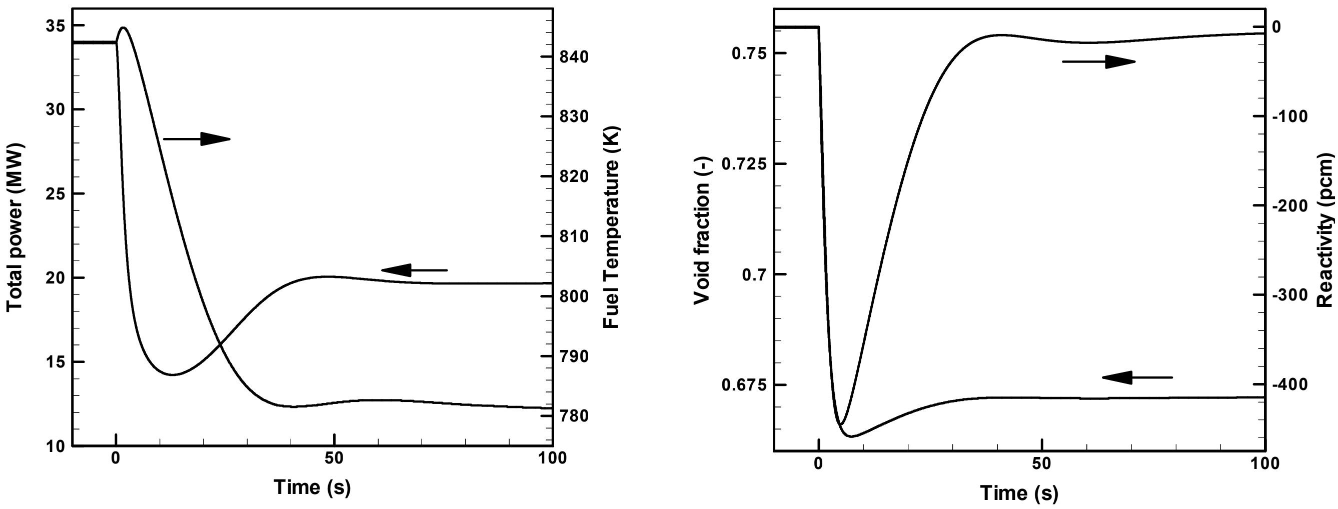

Figure 3. Total power and fuel temperature (left) and porosity and reactivity of the core (right) versus time during a decrease of flow rate from 11 kg/s to 8 kg/s.

As the flow rate decreases, the porosity of the core decreases very rapidly. Concurrently the cooling capacity of the helium decreases and during the first few seconds, the fuel temperature increases. This combined event affects the reactivity that further decreases steeply the total power. As the heat generated in the core decreases, the fuel temperature begins to drop. It is clear that the reactivity (and consequently the total power) will increase through the Doppler feedback to a new equilibrium state. It should be observed that the fuel temperature jump is minor during the first few seconds of the transient.

In the second case, the helium inlet temperature is instantaneously decreased at time 0 by 100 K after the reactor reaches the steady state condition at 11 kg/s. Results of this transient are shown in Figure 4.

As the coolant temperature decreases, the helium density increases but the mass flow rate is kept constant, giving a decrease in the superficial velocity. Consequently the bed starts to contract, resulting in a sudden decrease in reactivity. After this, the decrease of the fuel temperature causes a rise in reactivity due to temperature feedback, creating a rise in power output.

A reverse event similarly occurs when the inlet temperature increases by 100 K (not shown in this paper). The fuel temperature rises up to about 870 K (an increase of about 50 K) within the first 20 seconds before it drops to a new equilibrium point.

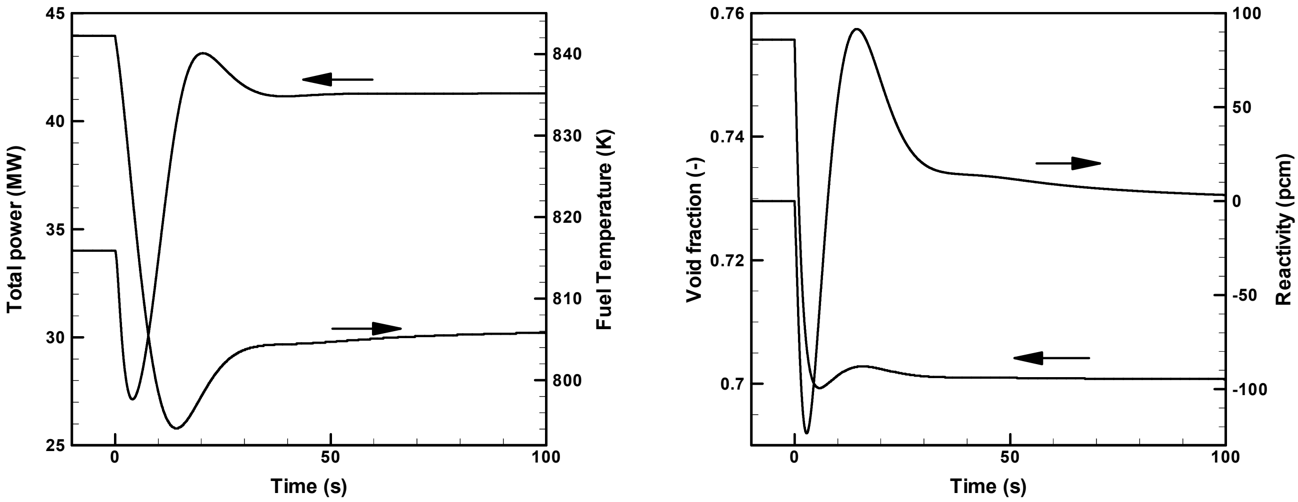

Figure 4. Total power and fuel temperature (left) and porosity and reactivity of the core (right) versus time during a decrease of helium inlet temperature from 543 K to 443 K.

This kind of transient shows the behavior of the fluidized bed nuclear reactor which is very useful for load-following purposes. When the heat extracted from the helium increases in the turbine, the inlet temperature to the core decreases and it leads to an increase in the reactor power to accommodate a larger power demand. Conversely when the load demand decreases, the inlet temperature to the core increases and furthermore the power generated in the core decreases.

Both types of simulations show a rapid response of the reactor to the introduced perturbation and always end up in a new equilibrium state without compromising the safety margin of the fuel.

4. Conclusions

A theoretical model has been presented for describing the coupled thermo-fluid dynamics, and neutronics in a fluidized bed nuclear reactor. The neutronics model is a point kinetics model including decay heat. The thermo-fluid dynamics is based on a relation between fluidization velocity and porosity of the bed, combined with global thermal balance equations.

Numerical studies of operational transients, viz. a step change in coolant mass flow rate and a coolant inlet temperature transient, show that the maximum fuel temperature remains below the safety margin of TRISO fuel. Furthermore, the maximum reactivity that can be introduced in all transients, is inherently limited and is rapidly compensated by the passive feedback mechanism.

5. References

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