Influence of Bubbles on Reactivity and Power in a Fluidized Bed Nuclear Reactor

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FLUBER (Fluidized Bed Thermal Fission Nuclear Reactor) is a conceptual design of a modular reactor utilizing the concept of fuel pellet suspension. It consists of TRISO coated fuel particles contained in a graphite-walled cylinder. Helium is used as a coolant and as fluidizing medium.

It has been observed experimentally that particles in a gas-solid fluidized bed move chaotically and the flow structure is characterized by the occurrence of void regions (or bubbles). The bubble formation and accompanying fuel particle movement present an inhomogeneous state of fuel particle distribution in the core, affecting the reactivity of the core.

To investigate the influence of bubble formation on reactivity of the new design, some static calculations were performed using KENO-V.a code. The reactivity of the inhomogeneous core is compared with that of the corresponding homogeneous core. Further, a theoretical model describing the coupling of neutronics, thermohydraulics and fluidization in a fluidized bed nuclear reactor is applied. Stochastic movements of the fuel particles are accounted for as an additional noise term supplementing the reactivity. Simulations related to the steady state conditions were performed and the magnitude of power fluctuations resulting from particle movements was determined. The result of these simulations is presented in this paper.

KEYWORDS: Fluidized bed nuclear reactor, reactor design, point dynamics modeling, numerical simulation.

I. Introduction
A concept of pellet suspension for nuclear reactor applications has been proposed by several authors. Sefidvash\(^3\) proposed a fluidized bed using uranium dioxide as fuel clad in by zircaloy or stainless steel and using supercritical steam as coolant. A new type of BWR plant design that combines the fluidized bed concept with density-lock mechanism of PIUS has been proposed by Mizuno et al.\(^2\) while Taube et al.\(^3\) proposed also a similar concept using uranium carbide fuel spheres floating in a molten lead coolant. A concept called Pellet Suspension Reactor (PSR) was also proposed\(^4\) with micro fuel pellets are suspended in a helium flow.

All those designs have different types of fuel, coolant and arrangement, however they represent the same feature, i.e. increasing the reactivity by fluidizing or suspending the fuel particles and stopping the operation of the reactor by cutting down the flow of the coolant (hence improving the inherently safety criterion). The concept of fluidized bed has several interesting features to be implemented in nuclear reactors, such as good heat transfer, uniform temperature distribution throughout the core due to good particle mixing thus reducing hot-spot factor, uniform burn-up and simple design.

II. Description of FLUBER
FLUBER (Fluidized Bed Thermal Fission Nuclear Reactor) is a conceptual design utilizing the concept of fuel pellet suspension and it is intended for a modular reactor. It consists of TRISO coated fuel particles contained in a graphite-walled cylinder. An embedded absorber ring containing natural boron to enlarge the shutdown margin is situated at the bottom of the core. Helium is used as a coolant and as fluidizing medium.

Figure 1 shows the schematic view of the reactor. General specifications of the current FLUBER design and its fuel particles are listed in Table 1 and Table 2.

When there is no flow of helium or when the flow is low enough, fuel particles are packed at the bottom of the core and the reactor is subcritical as a result of a lack of moderation. As the flow increases, the particles are fluidized, the core expands and reactivity increases due to increasing moderation by the graphite reflectors.

Development process of FLUBER dated back from 1996 and continuously performed for better performance.\(^5,6,7\) Recent attempts have been done to get a higher output power and a correspondingly higher gas outlet-temperature. The main objective in this case is to increase the excess reactivity of the core when the bed is fully expanded while keeping a reasonable level of shutdown margin. These attempts include redesign of the fuel kernel of the particles, increase of uranium inventory and several changes to the geometry of the reactor.

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Fluidization occurs when the upward drag force exerted by the gas on the particles is big enough to overcome the weight of the particles in the bed. At this point the particles are lifted by the gas, the separation of the particles increases and the particles become fluidized.

The behavior of a fluidized bed can be categorized from properties of the particle and the fluid flow. Geldart introduced a classification of particles based on the average particle diameter and the difference between particle and gas densities.

It has been observed experimentally that if the flow velocity of the fluid is increased, particles in a gas-solid fluidized bed move chaotically and the flow structure is characterized by the occurrence of void regions (or bubbles). The bubble formation and accompanying fuel particle movement present an inhomogeneous state of fuel particle distribution in the core. Several flow regimes may occur in a fluidized bed and in general it can be based on bubble behavior, such as particulate, bubbling, slugging, turbulent and fast turbulent fluidization.\(^9\)

The TRISO particles used in FLUBER are of type D according to Geldart’s classification. For this type of particles, a fluidized bed tends to have a slugging and turbulent regime. In the slugging regime, the size of bubbles or slugs, which are formed by the coalescence of bubbles, is comparable to the bed diameter. In the turbulent fluidization, bubbles and particle clusters may become indistinguishable and the tendency for bubble breakup is enhanced as the gas velocity increases, resulting in reduced presence of large bubbles.

This paper will discuss the influence of bubbles on the reactivity and to investigate the extent of such reactivity change to the power.

### III. Statics

#### 1. Calculational Procedure

All calculations have been carried out using the INAS code system (IRI-NJOY-AMPX-SCALE) with nuclear data libraries based on the JEF2.2 data file.

The major part of the calculations is done with the three-dimensional KENO-V.a Monte Carlo program\(^{10}\) with a cell-weighted 172 group library created by the CSAS module\(^{11}\).

Within the current model, the particles are assumed to have a uniform distribution in a rhombohedral array. This arrangement makes the value of particle packing factor at packed conditions equal to \((\pi/3 \sqrt{2} = 0.7405)\) or the void fraction equals to 0.2595. However, experimental data\(^{12}\) shows that the statistical distribution of a random packing of particles gives a minimum void fraction of 0.391 ± 0.0016 and thus the value of 0.4 (corresponding to a bed height of 122.36 cm) is chosen as the minimum void fraction for subsequent calculations.

#### 2. Static Behavior of a Homogeneous Bed

Figure 2 shows the reactivity of the core as a function of the bed height at different fuel temperatures. At room temperature (293 K), the moderator-to-fuel ratio ensures that the reactivity of the packed bed remains below the intended shutdown margin, thus assuring a safe shutdown state in the absence of coolant flow. As the bed expands, the core reactivity increases up to the maximum value (the excess reactivity).

The figure also shows the influence of temperature on the reactivity. The reflector temperature is set in an equilibrium value between fuel temperature and room temperature. The

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**Table 1** FLUBER specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of the core cavity [cm]</td>
<td>79.8</td>
</tr>
<tr>
<td>Height of the core cavity [cm]</td>
<td>600</td>
</tr>
<tr>
<td>Height of the whole reactor [cm]</td>
<td>800</td>
</tr>
<tr>
<td>Thickness of the radial reflector [cm]</td>
<td>100</td>
</tr>
<tr>
<td>Thickness of the axial reflector [cm]</td>
<td>100</td>
</tr>
<tr>
<td>Thickness of radial absorber [cm]</td>
<td>50</td>
</tr>
<tr>
<td>Height of radial absorber [cm]</td>
<td>50</td>
</tr>
<tr>
<td>Concentration of radial absorber [ppm]</td>
<td>50</td>
</tr>
<tr>
<td>Collapsed-bed height (at 40% of porosity) [cm]</td>
<td>122.36</td>
</tr>
<tr>
<td>Uranium inventory [kg]</td>
<td>220</td>
</tr>
<tr>
<td>Enrichment [% weight]</td>
<td>16.76</td>
</tr>
<tr>
<td>Helium pressure [bar]</td>
<td>60</td>
</tr>
</tbody>
</table>

**Table 2** Fuel specifications

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, ([\text{g/cm}^3])</th>
<th>Outer diameter, ([\text{mm}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>UO(_2) kernel</td>
<td>10.88</td>
<td>0.25</td>
</tr>
<tr>
<td>Porous carbon buffer layer</td>
<td>1.1</td>
<td>0.77</td>
</tr>
<tr>
<td>I-PyC coating</td>
<td>1.9</td>
<td>0.85</td>
</tr>
<tr>
<td>SiC coating</td>
<td>3.2</td>
<td>0.92</td>
</tr>
<tr>
<td>O-PyC coating</td>
<td>1.9</td>
<td>1.00</td>
</tr>
</tbody>
</table>

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![A Schematic View of FLUBER](image_url)
reactivity decreases as the fuel temperature increases, thus giving a negative temperature coefficient. The contribution due to the reflector temperature is positive because of the decrease in absorption rate of the reflector and increase in the number of reflected neutrons as the reflector temperature increases. However, the total temperature coefficient is negative, giving a safe and stable operation of the reactor.

In addition, the curves are linear for bed height larger than 300 cm, and a bit concave for bed height smaller than 300 cm. The reason for this behavior is the presence of the embedded side absorber. When the bed height is smaller than 300 cm, influence of the side absorber is large, but when the bed expands more, the influence becomes less and simultaneously more neutrons reenter to the upper part of the core, scattered from the reflector.

![Fig. 2](image)

**Fig. 2** Static reactivity of the present design for different fuel temperature. Reflector temperature is set in a value between fuel temperature and room temperature. ρ_{sm} and ρ_{ex} are the shutdown margin of reactivity and excess reactivity, respectively. The standard deviation of k_{eff} gives 0.0005, but it is not shown in the graphs for clarity reason.

### 3. Bed with Bubbles

To simulate the occurrence of bubbles in the reactor, some void regions were implemented into the KENO model. These void regions are regarded as bubbles. Two types of bubble models were used, i.e. a model with one large bubble and a model with many intermediate size bubbles.

Within the first model, the bubble has a diameter of 100 cm and it is intended to represent the condition of slugging regime where large bubbles present in the bed. This model is justified because the ratio of bubble diameter to bed diameter is larger than 0.6. \(^9\)

The second model represents a condition of turbulent fluidization where the distribution of particles and bubbles tend to be homogeneous. Bubbles in this model have a diameter of 5 cm. In both models, particles that were previously contained in the bubbles volume were distributed evenly to the rest of the core volume, keeping the bed height constant. The bed height is fixed at a constant value of 600 cm.

In the one-bubble model, the center of the bubble coincides with the axis of the core. The axial position of the bubble center is varied for 11 different positions, with 50 cm of increment. **Figure 3** is an example of the arrangement of the bubble in the core. The results of such calculation are given in **Fig. 4**.

![Fig. 3](image)

**Fig. 3** Front view (left) and upper view (right) of the one-bubble model, showing an example of one position of bubble.

![Fig. 4](image)

**Fig. 4** The effective multiplication factor as a function of axial position of bubble within the one-bubble model.

When the bubble height is low enough (for example when the bubble height is 50 cm as shown in **Fig. 3**), fuel particles with low importance are distributed to the rest of the core. It means that the particles now become more important and introduce a high increase of reactivity. On the other hand, a large decrease of reactivity will occur whenever particles
move from a more important region into a less important one. Previous calculations\(^{13}\)) indicated the presence of thermal neutron peak around height of about 350 cm. A bubble present in this region will inevitably perturb the neutron distribution and at the same time more fuel particles are moved to the side absorber region (a low important region) as well. Hence, the reactivity in this case will be largely decreased. When the bubble moves upward to this height, the reactivity obviously decreases.

The same situation also applies to the region close to the upper axial reflector where a thermal neutron peak occurs. This situation can be seen in Fig. 4 when the bubble height reaches 550 cm.

It can be inferred that a slugging fluidization gives a high reactivity deviation from the homogeneous state within the magnitude of 278 pcm. Therefore, operation at this regime is strongly not recommended.

The second model incorporates many bubbles (in this case 212 bubbles arranged in triangular arrays) contained in a layer. Layers of bubbles are further stacked on top of the other layer, starting from the bottom of the core, with a displaced position of the bubbles, giving a rhombohedral arrangement of bubbles. The bed height is kept constant, while the number of layers is increasing. (See Fig. 5). The distance between two midplanes of the layers is 10 cm.

The reactivity deviation from the homogeneous bed in this model is smaller compared to the one-bubble model (in the order of about 150 pcm vs. 278 pcm). In operation, this model would be more likely for the operational range of FLUBER.

IV. Dynamics
1. Model

The fluidization process is assumed to be described by the Richardson and Zaki (RZ) correlation, relating the fluidization velocity, \(U_{f,s}\), to the bed porosity, \(\varepsilon\)

\[
U_{f,s} = U_{e} \varepsilon^n
\]

and the terminal velocity, \(U_{\infty}\), is given by the following

![Fig. 5. An example of bubble arrangements in the many-bubble model. The front-view (left) shows twenty-four layers of bubbles extending from the bottom of the core. The upper-view (right) shows the displaced triangular array creates a rhombohedral arrangement.](Image)

Fig 6. The effective multiplication factor as a function of number of bubble layers.

The result of this simulation is slightly different from that of the first model. In this many-bubble model, the ratio of void volume to the core increases as number of layers increases while in the one-bubble model, the ratio is constant. It can be inferred that as the number of layers increases, fuel particles become more packed, hence reducing the mean free path of neutron at the upper part of the active core. However, when the number of layers increases even more, the situation of the active core becomes more homogeneous, and the effects of particle migration from a less important zone to a more important zone are compensated by the migration from a more important zone to a less important zone.

The reactivity deviation from the homogeneous bed in this model is smaller compared to the one-bubble model (in the order of about 150 pcm vs. 278 pcm). In operation, this model would be more likely for the operational range of FLUBER.
relation

\[ U_c = \sqrt{\frac{4(\rho_p - \rho_s)gd_p}{3C_d\rho_g}} \]  

(2)

An improvement to the model as used by Kloosterman et al.\(^5\), is to assume the void fraction to relax towards the steady state value as given by RZ with a timescale \( \tau \). The time-scale is chosen as the ratio of the bed height and the gas velocity, which corresponds to the time of propagation of a disturbance through the bed.

\[ \frac{d\varepsilon}{dt} = \frac{1}{\tau}(\varepsilon - \varepsilon_{eq}) \]  

(3)

The energy equation for the fuel particles is

\[ m_pC_{p,p}\frac{dT_p}{dt} = P_i + Q \]  

(4)

while that for the gaseous coolant is

\[ m_gC_{p,g}\frac{dT_g}{dt} = G_mC_{p,g}(T_{in} - T_{out}) - \frac{dm_g}{dt}(T_{out} - T_g) - Q \]  

(5)

Within the current point model, a well-mixed gas temperature distribution is employed, thus the second term in the right hand side of Eq. (4) vanishes.

The interfacial heat transfer, \( Q \), is based on a single-particle Nusselt relation.

\[ Nu = 2 + 0.66Re^{\frac{1}{2}}Pr^{\frac{1}{3}} \]  

(6)

The basic equations for the point kinetics model \(^{14}\) are

\[ \frac{dP_p}{dt} = \left[ \frac{\beta - \beta}{\Lambda} \right] P_p + \sum_{i=1}^{N_p} \lambda Ci + \frac{S}{\Lambda} \]  

(7)

\[ \frac{dC_i}{dt} = \frac{\beta_i}{\Lambda} P_p - \lambda_i C_i, \quad i = 1, \ldots, N_p \]  

(8)

and for the decay heat equation is

\[ \frac{dP_{d,n}}{dt} = \frac{\gamma_n}{Q_f} P_p - \lambda_{d,n} P_{d,n}, \quad n = 1, \ldots, N_d \]  

(9)

In the present work, we use 6 precursor groups and 15 decay heat groups.

Three components of reactivity are present in the fluidized bed fission reactor: (a) feedback due to variation of the bed height, \( \rho_{\text{of}} \), (b) feedback from temperature effects, \( \rho_T \) and (c) stochastic redistribution of the fuel particles, modeled as an external reactivity, \( \rho_{\text{ext}} \):

\[ \rho(\varepsilon, T_p, t) = \rho_{\text{of}}(\varepsilon) + \rho_T(\varepsilon, T_p) + \rho_{\text{ext}}(t) \]  

(10)

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

\[ \rho_{T,\text{st}} = \alpha_{d,\text{st}}(\varepsilon)(T_p - T_{\text{ref}}) \]  

(11)

\[ \rho_{T,\text{tr}} = \alpha_{d,\text{tr}}(\varepsilon)(T_p - T_r) + \alpha_{d,\text{t}}(\varepsilon)(T_p - T_t) \]  

(12)

where we have introduced the total and core temperature coefficients, \( \alpha_{d,\text{tr}} \) and \( \alpha_{d,\text{t}} \).

The external reactivity is computed from an AR(1) model, as follows:

\[ \rho_{\text{ext}}(t) = a_0 \rho_{\text{ext}}(t-1) + Z(t) \]  

(13)

Figure 7 and 8 show the static reactivity and temperature coefficients as a function of the bed porosity, together with fitted curves that have been used in the subsequent simulations.
2. Steady State Power

Figure 9 shows the steady state conditions (obtained by long term time integration combined with a Newton-method) 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 20 kg/s and rises towards its maximum at about 37 kg/s. Around 37 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 9](image)

**Fig. 9** Fuel temperature and total power as a function of the coolant mass flow rate in steady state conditions.

The nature of fluidization also implies that the power density and specific power varies along the bed expansion. Figure 10 shows that at maximum bed expansion the power density achieves about 10 MW/m³, which is 10 times smaller than a conventional PWR or BWR reactor (3600 MWe with the average enrichment of 4%). The maximum specific power of FLUBER is larger than that of conventional PWR or BWR. Given in kW/kg of uranium, FLUBER reaches about 14 times larger, while given in kW/kg of U-235, FLUBER reaches about 3.5 times larger.

3. Fluctuations due to particle movements

A time trace (with a flow rate of 36 kg/s) was simulated with a duration of 30 minutes and the observed power output together with the gas temperature and bed height is shown in Fig. 11. For this calculation, the standard deviation of the AR(1) model is fixed at 150 pcm.

![Figure 10](image)

**Fig. 10** Power density and specific power.
However, in the multidimensional reactor dynamics, the situation is more complicated as the radial redistribution of temperature only varies about 50 K. Fluctuations of the gas temperature is in fact more important from an electricity generation point of view. Figure 11(c) shows that the response of the helium temperature to reactivity change is less sensitive (cf. Fig. 11(a)).

Fluctuations of the bed height give the magnitude of about 30 cm and less sensitive to reactivity change. This behavior can be understood as within the point model, changes in the bed height (or particle void fraction) are influenced by the gas temperature feedback (see Eq. 1 – 3). However, in the multidimensional reactor dynamics, the situation is more complicated as the radial redistribution of particles occurs.

The time traces have a resemblance to that obtained from the calculations of previous design (see ref. 16). Although the current design has a larger variance of external noise (and consequently a larger output power), the maximum fuel temperature remains below the maximum permissible temperature of TRISO particle.

V. Conclusions

Static and dynamic calculations have been performed for FLUBER with inclusion of bubbles in the active core. The static calculations show that the one-bubble model (representing the condition of slugging fluidization) gives large values of reactivity change from its corresponding homogeneous model. Therefore, operation condition with slugging regime is strongly not recommended.

The dynamic calculations show that the power output of the core is very fluctuational. However, the helium temperature has a less sensitive response, thus giving a close to steady operation of turbo-generator. Moreover, the fuel temperature, which is several degrees higher than the helium temperature thanks to excellent heat transfer, is still far below the maximum permissible temperature of TRISO particle (~ 1875 K), thus ensuring a safe operation.

Nomenclature

- $d_p$: Diameter of fuel particle
- $g$: Gravity acceleration
- $G_{in}$: Inlet mass flow rate
- $n$: Richardson-Zaki constant
- $Nu$: Nusselt number
- $P_d$: Delayed power
- $P_p$: Prompt fission thermal power
- $Pr_g$: Prandtl number
- $P_t$: Total power
- $Q$: Interfacial heat transfer
- $Q_r$: Prompt recoverable energy per fission
- $Re_p$: Reynolds number
- $S$: Independent neutron source
- $T_g$: Temperature of helium
- $T_{i}$: fuel temperature at the onset of the transient
- $T_{in}$: Inlet temperature of helium
- $T_{out}$: Outlet temperature of helium
- $T_p$: Temperature of fuel particles
- $T_{ref}$: Temperature at which the standard reactivity curve is known
- $U_{g,s}$: Superficial velocity
- $Z$: Random process with zero mean of reactivity
- $\alpha$: Autoregressive coefficient
- $\alpha_{dc}$: Core temperature coefficient
- $\alpha_{dt}$: Total temperature coefficient
- $\beta$: Delayed neutron fraction
- $\varepsilon$: Porosity
- $\Lambda$: Neutron generation time
- $\lambda$: Decay constant
- $\rho$: Reactivity

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**Fig. 11** Trace of states as a function of time for a steady system subject to external noise on the reactivity (150 pcm standard deviation). Insets show the trace over period of the first 100 seconds.

**Fig. 11(a)** shows the (total) reactivity trace for the first 100 seconds. The power is shown to be highly fluctuating with a maximum output about twice the average while the temperature only varies about 50 K. Fluctuations of the gas temperature is in fact more important from an electricity generation point of view. **Figure 11(c)** shows that the response of the helium temperature to reactivity change is less sensitive (cf. Fig. 11(a)).
\[ \rho_p \] Density of fuel particle
\[ \rho_s \] Density of coolant
\[ \rho_{\text{ext}} \] External reactivity
\[ \rho_{\text{ref}} \] Bed height variation component of reactivity
\[ \rho_{\text{ss}} \] Steady-state reactivity
\[ \rho_T \] Temperature component of reactivity
\[ \tau \] Relaxation time constant

References