Chapter 8

Thermal Hydraulics Prediction Study for an Ultra High Temperature Reactor with Packed Sphere Fuels

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Additional information is available at the end of the chapter

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1. Introduction

Nowadays, very high temperature gas-cooled reactor (VHTR) design studies and utilization studies are investigated energetically in the some international conference, especially in the ICONE20 conference (Allelein, 2012, Iwatsuki, 2012, Sato, 2012). The VHTR project so called GIF is developing the design study to establish 1,000 °C as a coolant outlet temperature and to realize the hydrogen production (GIF-002-00,2002, Shiozawa,2005), where GIF is the Generation IV International Forum. For a long time, a fundamental design study has been carried out in the field of the high temperature gas-cooled reactor i.e. HTGR (Fumizawa, 1989b, Fumizawa, 2007), which showed that a coolant outlet temperature was around 900 °C. The interest of HTGR is increasing in many countries as a promising energy future option. There are currently two research reactors of HTGR type that are being operated in Japan and China. The inherent safety of HTGR is due to the large heat capacity and negative temperature reactivity coefficient. The high temperature heat supply can achieve more effective utilization of nuclear energy. For example, high temperature heat supply can provide for hydrogen production, which is expected as alternative energy source for oil. Also, outstanding thermal efficiency will be achieved at about 900 °C with a Brayton-cycle gas turbine plant.

However, the highest outlet coolant temperature of 1316 °C had been achieved by UHTREX, in Los Alamos Scientific Laboratory at the end of 1960's (El-Wakil, 1982, Hoglund,1966). It was a small scale Ultra High Temperature Nuclear Reactor (UHTR). The coolant outlet temperature would be higher than 1000 °C in the UHTR. The UHTREX adopted the hollow rod type fuel; the highest fuel temperature was 1,582 °C, which indicated that the value was over the current design limit. According to the handy calculation, it was derived that the pebble type fuel was superior to the hollow type in the field of fuel surface heat transfer condition (Fumizawa, 1989a).

In the present study, the fuels have changed to the pebble type so called the porous media. In order to compare the present pebble bed reactor and UHTREX, a calculation based on HTGR-GT300 was carried out in the similar conditions with UHTREX i.e. the inlet coolant temperature of 871°C, system pressure of 3.45 MPa and power density of 1.3 w/cm^3. The main advantage of pebble bed reactor (PBR) is that high outlet coolant temperature can be achieved due to its large cooling surface and high heat transfer coefficient making possible to get high thermal efficiency. Besides, the fuel loading and discharging procedures are simplified; the PBR system makes it possible that the frequent load and discharge are easier than the other reactor system loaded block type fuel without reactor shutdown. This report presents thermal-hydraulic calculated results for a concept design PBR system of 300MWth of the modular HTGR-GT300 with the pebble types of fuel element as shown in Figure 1. A calculation for comparison with UHTREX have been carried out and presented as well.

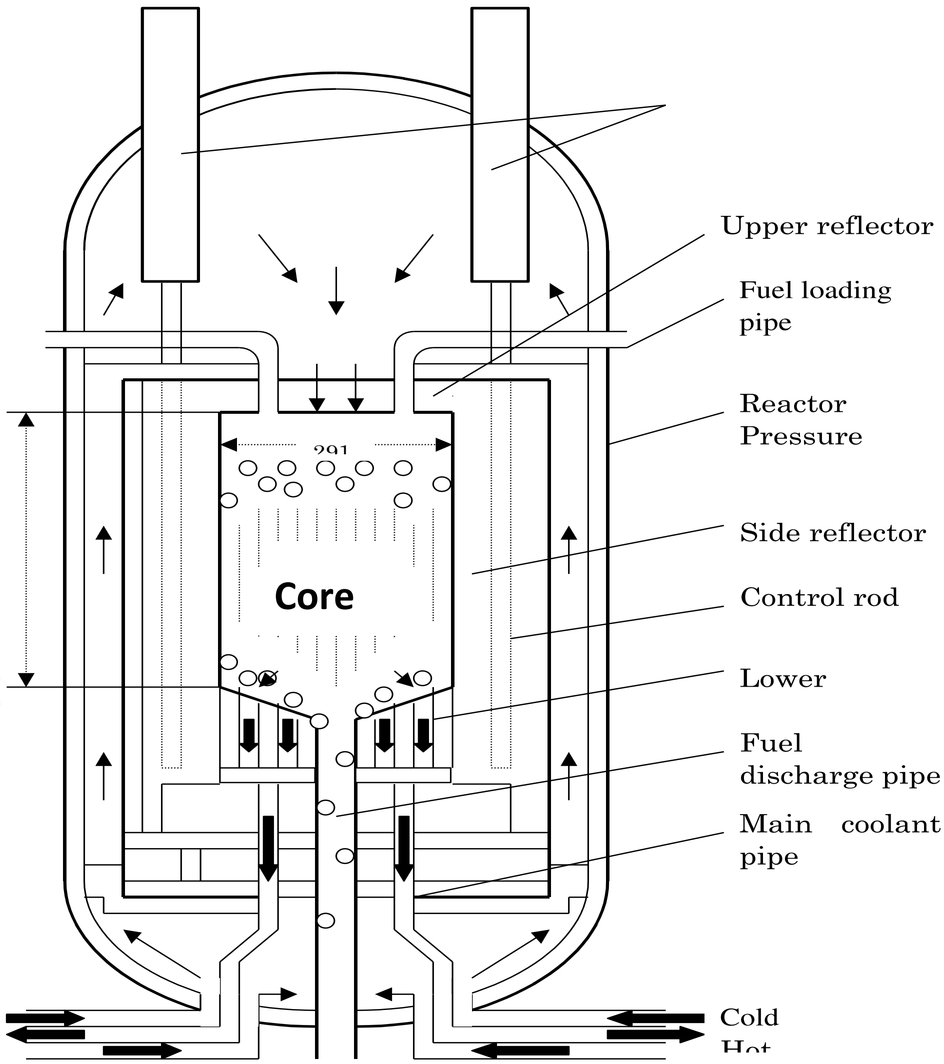

Figure 1. A concept of pebble bed reactor of HTGR –GT300

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2. Porosity experiment

It is very important to measure the porosity of fuel in the reactor core. The porosity experiments carried out in both conditions of fully shaken down to the closest possibly packing and non-vibration, because the reactor is normally operated in the condition of non-vibration. The porosity was measured by packed iron balls in the graduated cylinder and the number of iron balls, which was counted with the accurate electronic balance of PM-6100 produced by Mettler Inst. Corp. As the result, the relation of porosity and diameter ratio was shown in Figure 2. Porosity ε changes from 0.4 to 0.7 in the present experiment. Porosity ε will vary from 0.4 to 0.55 at the large diameter ratio beyond 8. In the figure, it is clear that the value of porosity of non-vibration is larger than the case of fully vibrating condition (El-Wakil, 1982). The difference is very important to analyze the fuel temperature and thermal-hydraulic calculation

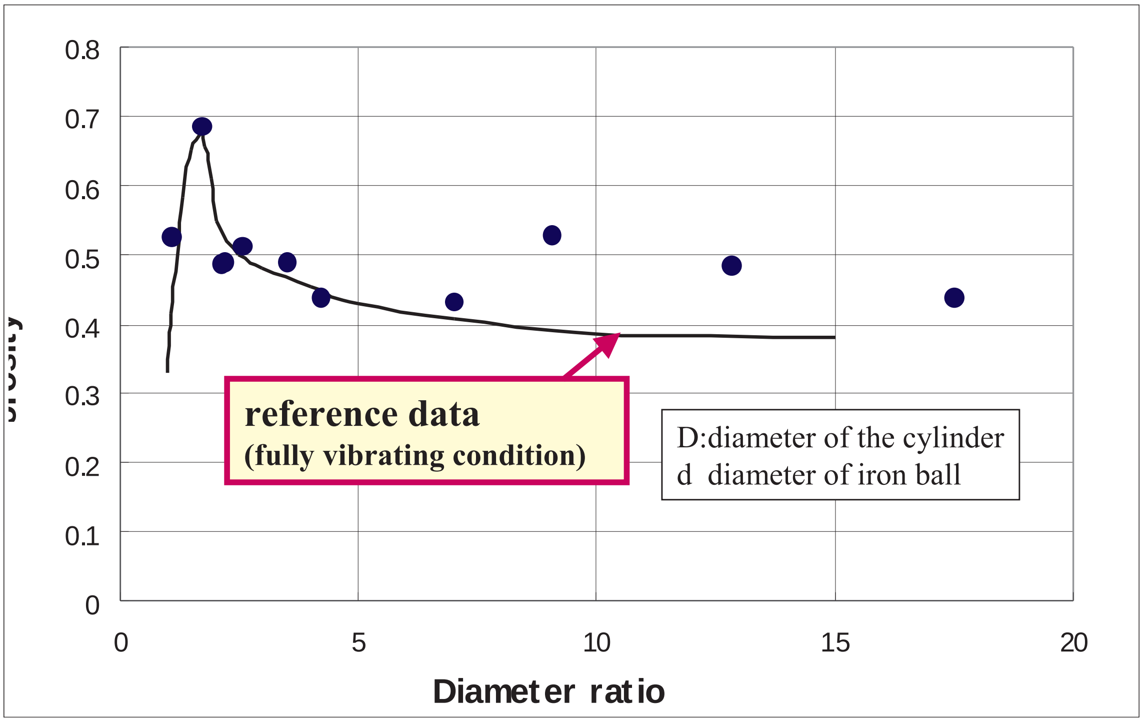

Figure 2. The relation of porosity and diameter ratio. Solid line was quoted from the reference (El-Wakil, 1982).

3. Reactor description

3.1. Concept of modular HTGR-GT300 and GT-600

A concept of pebble-bed type HTGR are shown in Figures 2 and 3 with the main nuclear and thermal-hydraulic specifications presented in Table 1. In the case that the thermal power is 300MW (GT-300), the average power density changes to 4.8 MW/m^3. The coolant gas enters from outer shell of primary coolant coaxial tube to the pressure vessel at temperature of 550°C and pressure of 6 MPa, follows the peripheral region of side reflectors up to the top and goes downward through the reactor active core. The outlet coolant goes out through the inner shell of primary coolant tube at temperature of 900°C. The cylindrical core is formed by the blocks of graphite reflector with the height of 9.4m and the diameter of 2.91m. There exist the holes in the reflector that some of them used for control rod channels and the others used for boron ball insertion in case of accident. In the case that the thermal power is 600MW (GT-600), the average power density changes to 9.6 MW/m^3.

3.2. Fuel element

The two types of pebble fuel elements, consisting of fuel and moderator, are shown in Figure 3. One is solid type where radius of inner graphite rco=0, and the other is shell type fuel element. The fuel compacts are a mixture of coated particles (Fumizawa, 1989a).

Thermal power (MW)	300 / 600
Coolant	Helium
Inlet coolant temperature (℃)	550
Outlet coolant temperature (℃)	900
Coolant Pressure (MPa)	6
Total coolant flow rate (kg/s)	172.1 / 344.2
Effective core coolant flow rate *Weff* (kg/s)	141.2 / 282.4
Core diameter (m)	2.91
Core height (m)	9.4
Uranium enrichment (wt %)	10
Average power density(MW/m^3)	4.8 / 9.6
Fuel type (for standard case)	6cm diameter pebble

Table 1. Major nuclear and thermal-hydraulic specification of GT-300 and GT-600

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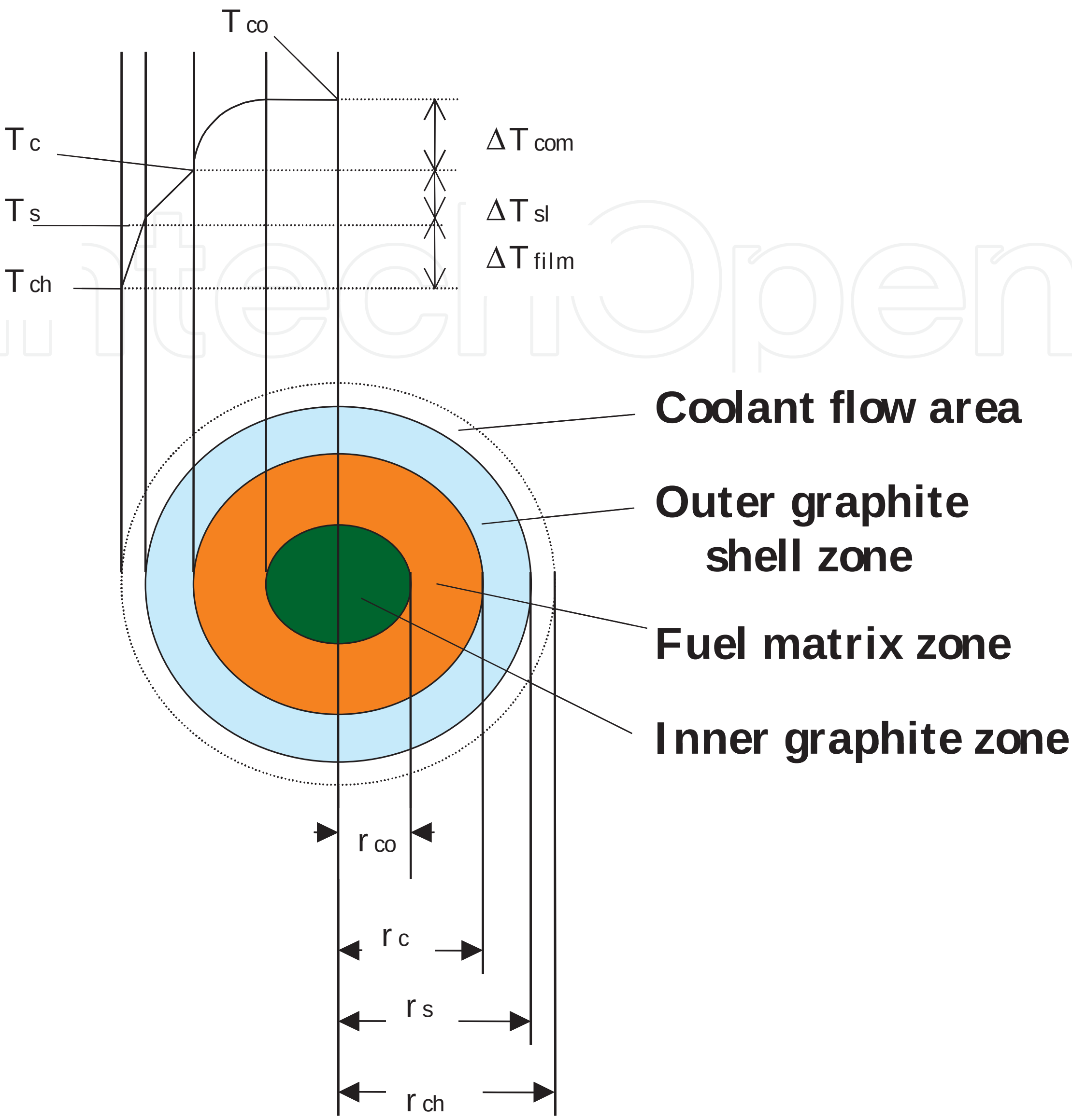

Figure 3. Relation of shell type fuel element and temperature difference, in the case that no inner graphite zone is called the solid type, i.e., rco=0

4. Thermlhydraulic analysis

4.1. PEBTEMP code

A one-dimensional thermal-hydraulic computer code was developed that was named PEBTEMP (Fumizawa, 2007) as shown in Figure 4. The code solves for the temperature of fuel element, coolant gas and core pressure drop using assumed power, power distribution, inlet and outlet temperature, the system pressure, fuel size and fuel type as input data.

The options for fuel type are of the pebble type; the multi holes blockk type and the pin-in-block type. The power distribution for cases of cosine and exponential is available. The users can calculate for the other distributions by preparing the input file.

The maximum fuel temperature will be calculated in PEBTEMP as follows:

$$T_f(z) = T_{in} + \Delta T_{cl}(z) + \Delta T_{film}(z) + \Delta T_{sl}(z) + \Delta T_{com} \quad (1)$$

Where $T_f(z)$: fuel temperature at the center of fuel element i.e. the maximum fuel temperature; ΔT_{cl}: gas temperature increment from inlet to height *z*; T_{in}: gas inlet temperature; $\Delta T_{film}(z)$: temperature difference between fuel element surface and coolant gas at *z*; $\Delta T_{sl}(z)$: temperature difference between fuel matrix surface and fuel element surface; $\Delta T_{com}(z)$: temperature difference between maximum fuel temperature and outer surface fuel temperature; q''' : power density; A_f: fuel element surface area; *z*: axial distance from the top of the core; *g*: coolant mass flow rate; C_p: coolant heat capacity.

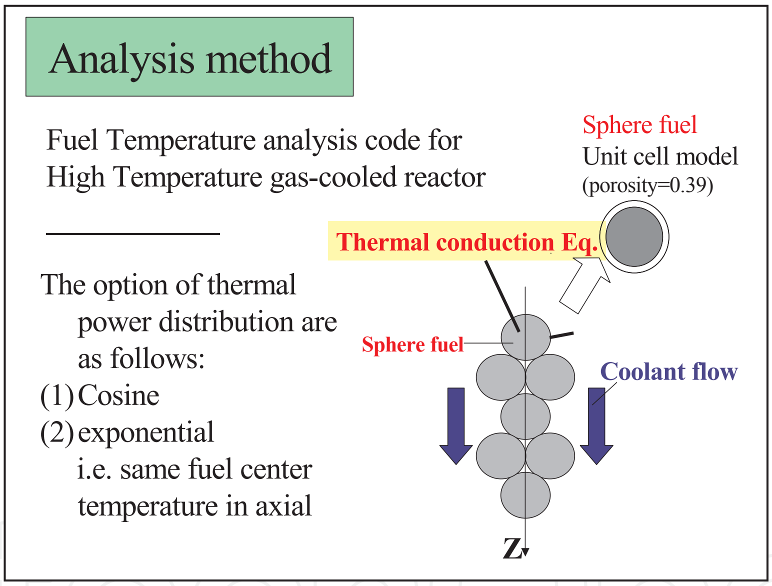

Figure 4. Analysis method of thermal-hydraulic computer code PEBTEMP

4.1.1. Temperature difference in the spherical fuel element

Figure 3 shows fuel configuration of the solid type and the shell type fuel element. In the solid type, ΔT_{com} is given as follows;

$$\Delta T_{com}(z) = T_{co} - T_c = \frac{q'''(z) r_c^2}{6\lambda_c} \quad (2)$$

In case of shell type fuel element, ΔT_{com} can be calculated by following expression;

$$\begin{aligned}\Delta T_{com}(z) &= T_{co} - T_c \\ &= \frac{q'''(z)}{6\lambda_c}\left(r_c^2 - 3r_{co}^2 + \frac{2r_{co}^3}{r_c}\right)\end{aligned} \tag{3}$$

4.1.2. Film temperature difference

The film temperature differences are calculated as follows;

$$\begin{aligned}\Delta T_{film} &= T_s - T_{ch} \\ &= \frac{q'''(z)r_c^3}{3r_s^2 h}\end{aligned} \tag{4}$$

4.1.3. Heat transfer coefficient

Heat transfer coefficient h in Equation (4) is calculated using following correlation (Heil, 1969):

$$h = 0.68\rho v_s C_p \mathrm{Re}^{-0.3}\,\mathrm{Pr}^{-0.66} \tag{5}$$

$$\mathrm{Re} = \frac{\rho v_s d}{(1-\varepsilon)\mu} \tag{6}$$

Where, ρ: coolant density; v_s: coolant velCity; Re: Reynolds number; Pr: Prandtl number; ε: porosity; d: fuel element diameter and μ: viscosity of fluid.

4.1.4. Pressure drop

Pressure drop through the core expresses by following correlation (Heil, 1969):

$$\Delta P = 6.986\frac{(1-\varepsilon)^{n+1}}{\varepsilon^3}\mathrm{Re}_p^{-n}\,\rho v_s^2\frac{H}{d}K + \Delta P_a \tag{7}$$

$$n = 0.22 \tag{8}$$

$$K = 1 - (1 + n + 3\frac{1-\varepsilon}{\varepsilon})0.26\frac{d}{R} \tag{9}$$

$$\mathrm{Re}_p = \frac{\rho v_s d}{\eta} \tag{10}$$

Where, H: core height; R: core radius and ΔP_a: acceleration pressure drop.

4.2. Effective flow rate calculation

As many blocks of graphite form the reflector, there exist gaps by which the coolant flow may pass through as shown in Figure 5. Actually, only one portion of coolant passes through the reactor core from the top to bottom. This portion is called effective flow rate and can be calculated iteratively in the code. It is well known that the pressure drop in the PBR core is higher than that of the hollow type or the multi-hole type fuel core. Considering the pressure drop, the empirical equation used in this code is as follows (Fumizawa, 1989a):

$$W_{eff} = 0.98 - 0.012\Delta P \tag{11}$$

Where, W_{eff}: effective coolant flow rate that has dimensionless value due to the normalization by the total coolant flow rate (kg/s).

ΔP: pressure drop through the core (kPa)

Figure 6 shows the flowchart of iterative calculation with effective coolant flow rate. The pressure drop effect for effective coolant flow rate in the PBR core is presented in the author's former paper (Fumizawa, 2007).

5. Calculation results

5.1. Calculation results for HTGR-GT300

Figure 7 shows the coolant pressure as a function of fuel diameter with different effective coolant flow rate from 0.5 – 1.0. This figure shows that the coolant pressure strongly depends on the effective coolant flow rate as well as fuel element diameter especially in case of the diameter smaller than 4cm. The pressure drop is inversely proportional with fuel element diameter.

Figure 8 shows the dependence of maximum fuel temperature on fuel diameter and leakage flow. The maximum fuel temperature of solid type and shell type fuel elements was calculated for different fuel diameter from 3.5 cm to 10 cm and the coolant flow leakage was taken into account. According to Eq. (9), the core adopted small diameter fuel element means high leakage coolant flows. In the viewpoint of the thermal-hydraulics, the diameter of solid type fuel around 5 cm has the lowest fuel temperature. The fuel temperature in case of shell type fuel is lower than that of solid type, and the thinner layer of fuel matrix the lower fuel temperature can be achieved.

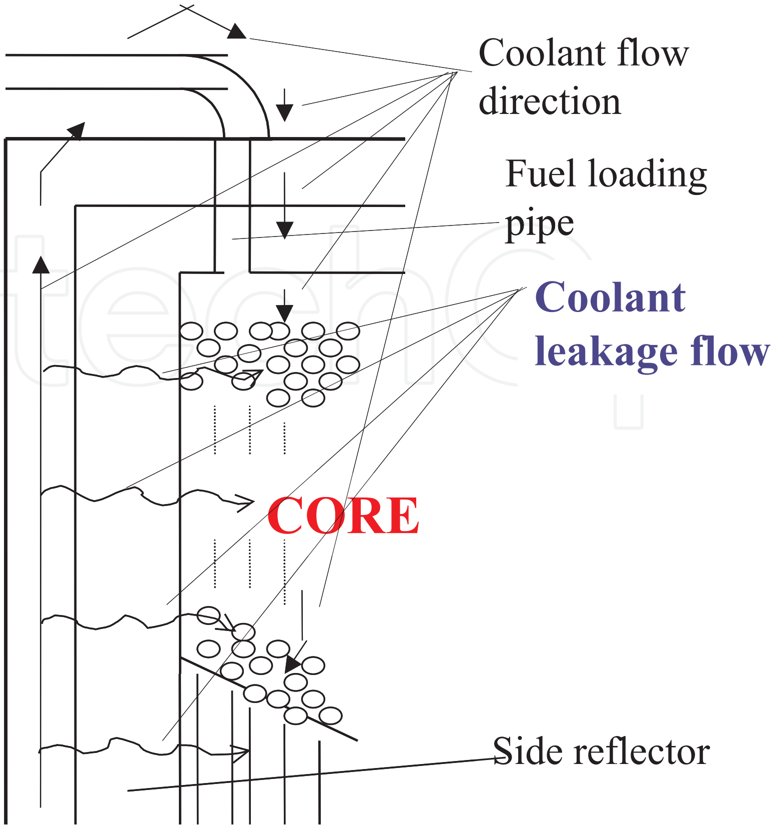

Figure 5. Coolant leakage flow concept

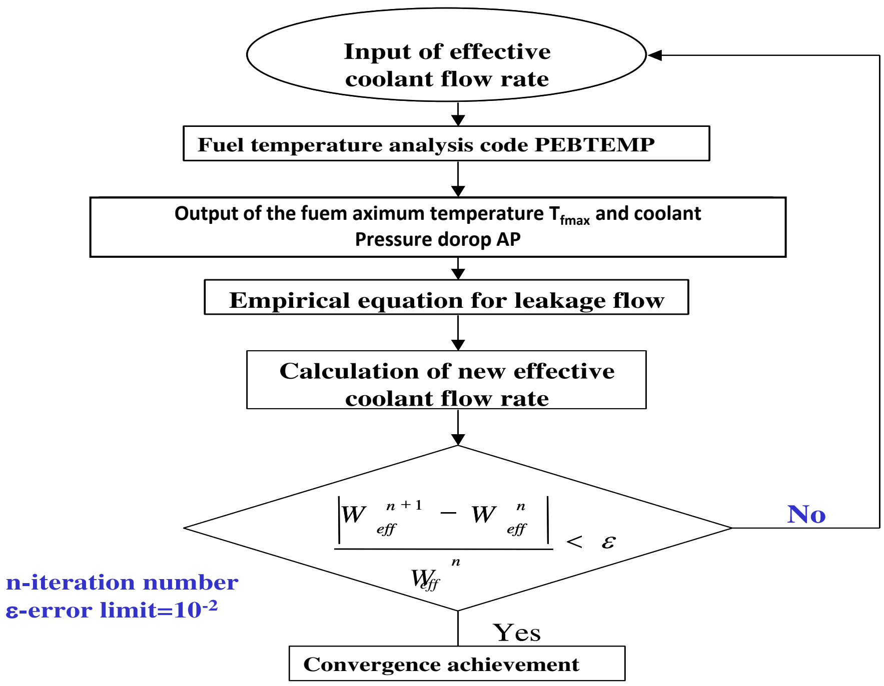

Figure 6. Flowchart of iterative calculation

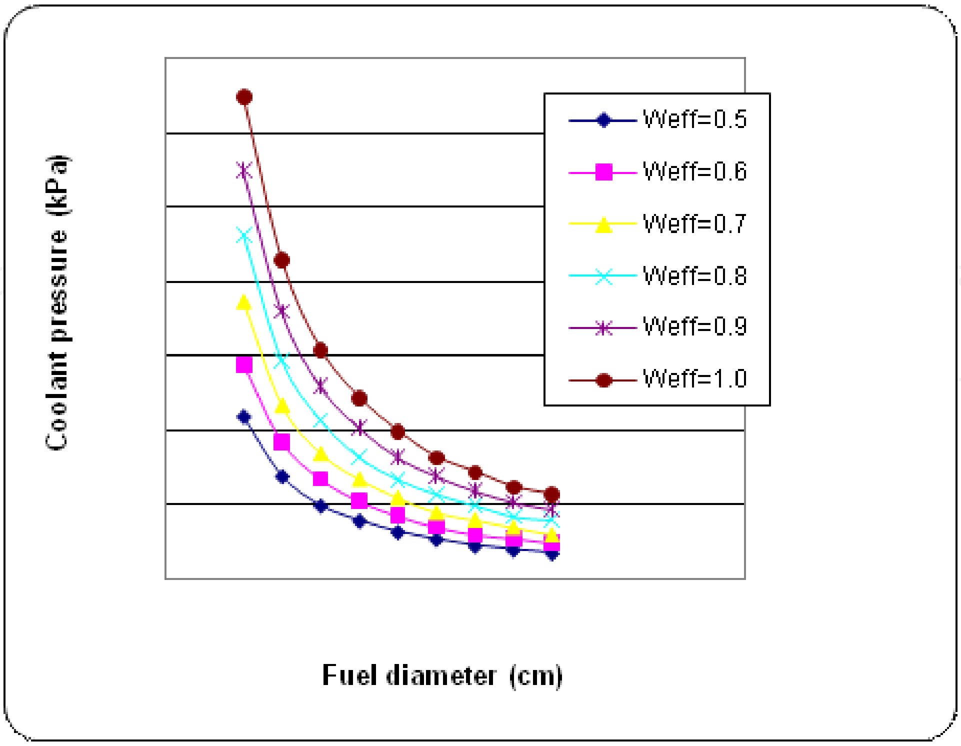

Figure 7. Coolant pressure as a function of fuel diameter for different effective coolant flow rate

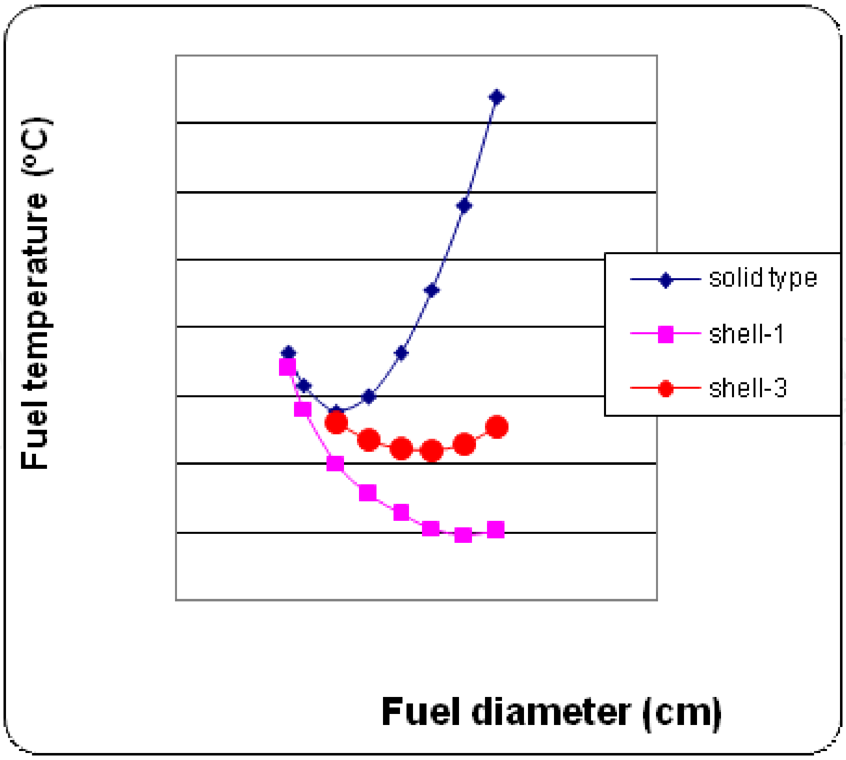

Figure 8. Maximum fuel temperature dependence on fuel diameter and leakage flow

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5.2. Comparison between the fuel temperatures of both cores

The high power density effects are shown in Figures 9 and 10, which indicate the dependence of maximum fuel temperature on outlet coolant temperature for GT-300 and GT-600 with different porosity and W_{eff}=1. The maximum fuel temperature for GT-600 is 168 °C higher than that for GT-300 where the outlet coolant temperature is 900 °C and the porosity is 0.39. The maximum fuel temperature for GT-600 is 163 °C higher than that for GT-300 where the outlet coolant temperature is 1150 °C and the porosity is 0.39.

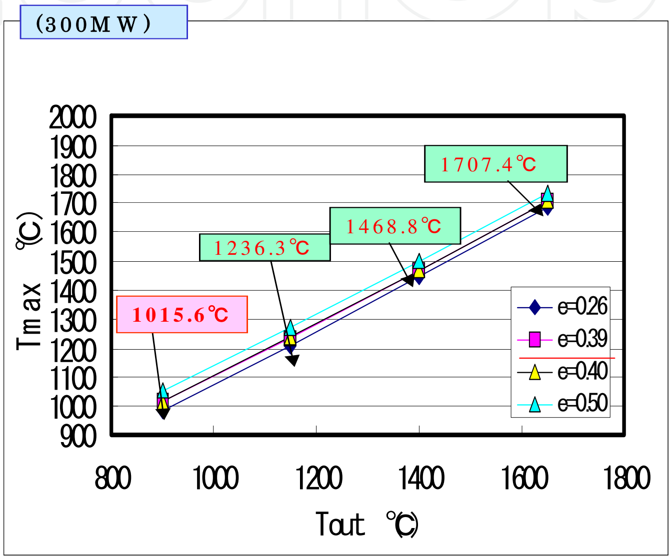

Figure 9. Dependence of maximum fuel temperature on outlet coolant temperature for GT-300 with different porosity and W_{eff}=1.

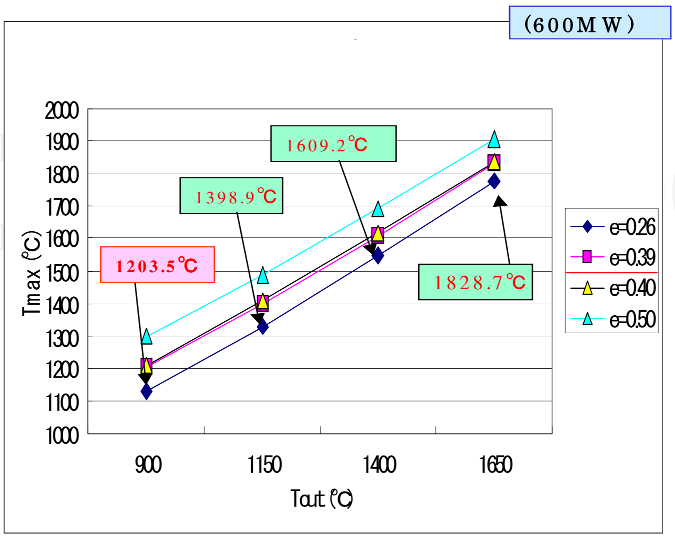

Figure 10. Dependence of maximum fuel temperature on outlet coolant temperature for GT-600 with different porosity and W_{eff}=1.

5.3. Calculation for a New Ultra High Temperature Reactor Experiment (NUHTREX)

The highest outlet coolant temperature has been achieved in case of UHTREX,i.e.,Ultra High Temperature Reactor Experiment (Fumizawa, 1989b) at Los Alamos Scientific Laboratory. UHTREX is the 3 MWth gas cooled reactor loaded hollow cylinder fuel element type in the hollow cylinder graphite bl Ck. The coolant (Helium) flows horizontally outward from inner hollow through fuel channel. The maximum outlet coolant temperature of 1316°C was recorded on June 24, 1969 (Fumizawa, 2000).

In order to compare the present PBR case with the UHTREX case, a calculation for a HTGR-GT300 was carried out using conditions similar to the UHTREX case, i.e. an inlet coolant temperature of 871°C, system pressure of 3.45 MPa and power density of 1.3 W/cm^3. The hot channel factor of 1.0, 1.1, 1.2, and 1.3 are chosen for the present calculation. The calculated results are presented in Figure 11. The results indicate that the fuel temperature of the present PBR case is much lower value compared to that of the UHTREX case, i.e. 1582 °C. Therefore, the present PBR system design will be named as NUHTREX i.e. New UHTREX, which will be one of the UHTR. Figure 12 shows the maximum fuel temperature in various core porosity and fuel diameter. High fuel temperature obtained from the high porosity and large fuel diameter, where W_{eff}=1.0, solid type fuel, standard case.

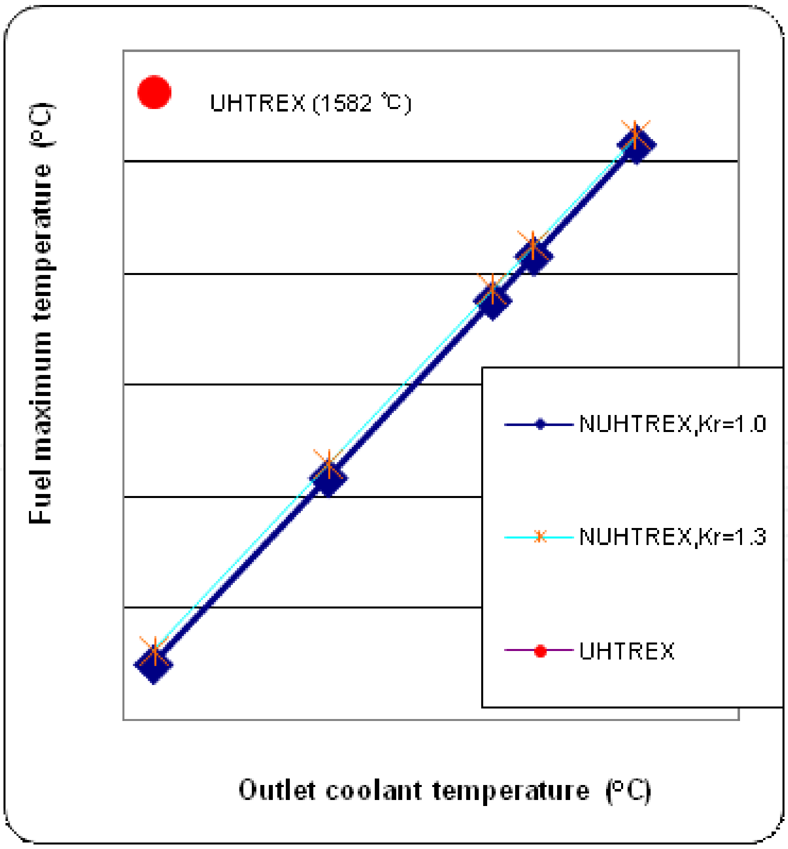

Figure 11. Dependence of maximum fuel temperature on outlet coolant temperature for NUHTREX with different hot channel factor (Kr) and UHTREX case.

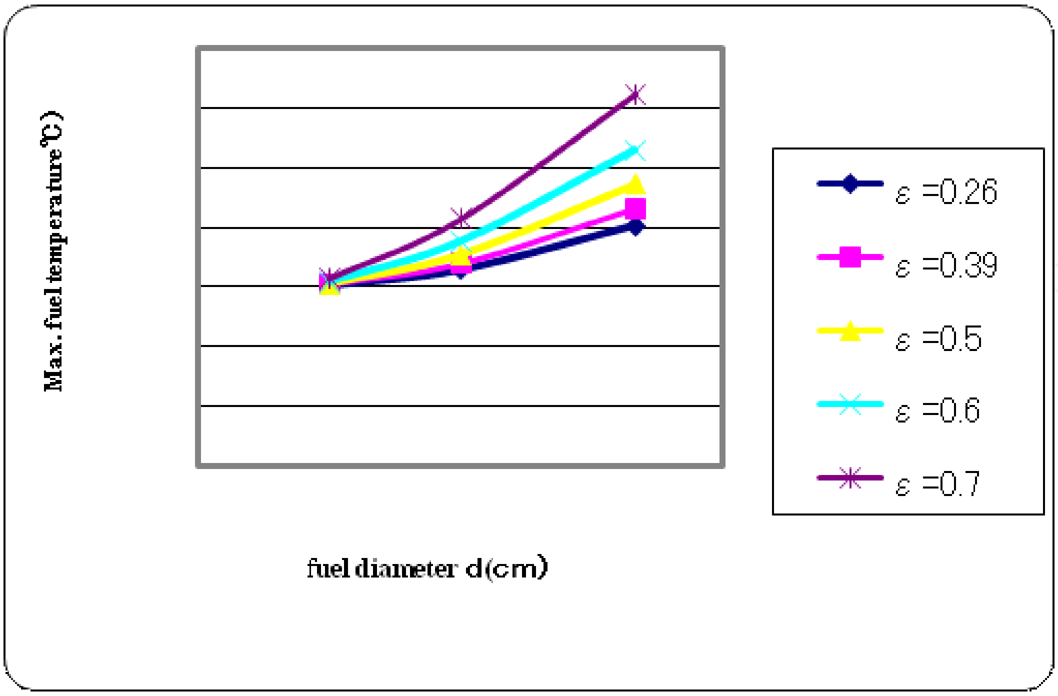

Figure 12. The maximum fuel temperature in various core porosity and fuel diameter

6. Conclusions

From present study, following items are summarized. It is clear that the value of porosity of non-vibration is larger than the case of fully vibrating condition. High fuel temperature obtained from the high porosity and large fuel diameter. In the viewpoint of the thermal-hydraulics, it is clarified that the diameter of solid type fuel around 5 cm has the lowest fuel temperature. The fuel temperature in case of shell type fuel is lower than that of solid type, because the thinner layer of fuel matrix the lower fuel temperature can be achieved. The maximum fuel temperature (Tmax) for GT-600 is higher than that for GT-300, for instance, Tmax for GT-600 is 168 °C higher than that for GT-300 where the outlet coolant temperature is 900 °C and the porosity is 0.39.

Nomenclature

A_f: fuel element surface area; (m^2)

C_p: coolant heat capacity; (J/kgK)

g: coolant mass flow rate; (kg/s)

H: core height; (m)

h : heat transfer coefficient; (W/m^{2}K)

q''': power density; (W/m^3)

R: core radius; (m)

Re: Reynolds number

$T_f(z)$: fuel temperature at the center of fuel element, i.e., the maximum fuel temperature; (°C)

T_{in}: gas inlet temperature; (°C)

T_{out}: gas outlet temperature; (°C)

W_{eff}: effective coolant flow rate, dimensionless value due to the normalization

z: axial distance from the top of the core; (m)

ΔP: pressure drop through the core (kPa)

ΔP_a: acceleration pressure drop; (kPa)

ΔT_{cl}: gas temperature increment from inlet to height z; (°C)

$\Delta T_{com}(z)$: temperature difference between maximum fuel temperature and outer surface fuel temperature; (°C)

$\Delta T_{film}(z)$: temperature difference between fuel element surface and coolant gas at z; (°C)

$\Delta T_{sl}(z)$: temperature difference between fuel matrix surface and fuel element surface; (°C)

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