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Porosity Effect in the Core Thermal Hydraulics for an Ultra High Temperature Gas-cooled Nuclear Reactor

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This study presents an experimental method of porosity evaluation and a predictive thermal-hydraulic analysis with packed spheres in a nuclear reactor core. The porosity experiments were carried out in both a fully shaken state with the closest possible packing and in a state of non-vibration. The predictive analysis considering the fixed porosity value was applied as a design condition for an Ultra High Temperature Reactor Experiment (UHTREX). The thermal-hydraulic computer code was developed and identified as PEBTEMP. The highest outlet coolant temperature of 1316°C was achieved in the case of an UHTREX at Los Alamos Scientific Laboratory, which was a small scale UHTR. In the present study, the fuel was changed to a pebble type, a porous media. In order to compare the present pebble bed reactor and UHTREX, a calculation based on HTGR-GT300 was carried out in similar conditions with UHTREX; in other words, with an inlet coolant temperature of 871°C, system pressure of 3.45 MPa and power density of 1.3 W/cm^3. As a result, the fuel temperature in the present pebble bed reactor showed an extremely lower value compared to that of UHTREX.

Key words: Thermal Hydraulics, Ultra High Temperature Nuclear Reactor (UHTR), Porosity and Pebble Type Fuel.

Nomenclature

A_f: fuel element surface area; (m^2)
C_p: coolant heat capacity; (J/kgK)
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 the fuel element, i.e., the maximum fuel temperature; (°C)
T_{gin}: gas inlet temperature; (°C)
W_{eff}: effective coolant flow rate, dimensionless value due to 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)
$\Delta T_{sf}(z)$: temperature difference between fuel matrix surface and fuel element surface; (°C)

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1. Introduction

Nowadays, the very high temperature gas-cooled reactor project, or so called GIF (Generation IV International Forum), is energetically developing design studies to establish 1,000°C as a coolant outlet temperature and to realize hydrogen production.[1)–2)] Over an extended period, a fundamental design studies have been carried out in the field of high temperature gas-cooled reactors, or HTGR's,[3–8)] which show that the coolant outlet temperature was around 900°C. Interest in HTGR's is increasing in many countries as a promising future energy 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, the high temperature heat supply can provide for hydrogen production, which is regarded as an alternative energy source for oil. Also, outstanding thermal efficiency can be achieved at approximately 900°C with a Brayton-cycle gas turbine plant.

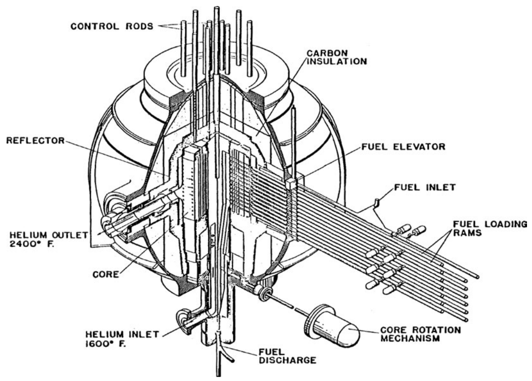

Fig. 1. Reactor structure of UHTREX, quoted from reference[3].

However, the highest outlet coolant temperature of 1316°C was achieved by UHTREX (Figure 1), in Los Alamos Scientific Laboratory in the late 1960's.[3)–4)] A small scale Ultra High Temperature Nuclear Reactor (UHTR) was used to achieve these results. The coolant outlet temperature would have been higher than 1000°C in the UHTR. UHTREX adopted hollow rod type fuel and the highest fuel temperature was 1,582°C, which indicates a value over the current design limit. Based on rough calculations, it was derived that pebble type fuel is superior to hollow rod type fuel with regard to the field of fuel surface heat transfer conditions.[9)]

In the present study, the fuel has been changed to pebble type, a so-called porous media. In order to compare the present pebble bed reactor and UHTREX, a calculation based on HTGR-GT300 was carried out under similar conditions with UHTREX. In other words, the inlet coolant temperature was 871°C, the system pressure 3.45 MPa and the power density 1.3 W/cm^3. The main advantage of a pebble bed reactor (PBR) is that a high outlet coolant temperature can be achieved due to its large cooling surface and high heat transfer coefficient, thus making it possible to achieve high thermal efficiency. Furthermore, fuel loading and discharging procedures are simplified. The PBR system allows for frequent load and discharge, the processes being easier than for other reactor systems loaded with block type fuel, which require reactor shutdown. This report presents the thermal-hydraulic calculated results for a concept design PBR system of 300 MWth for the modular HTGR-GT300 model with a

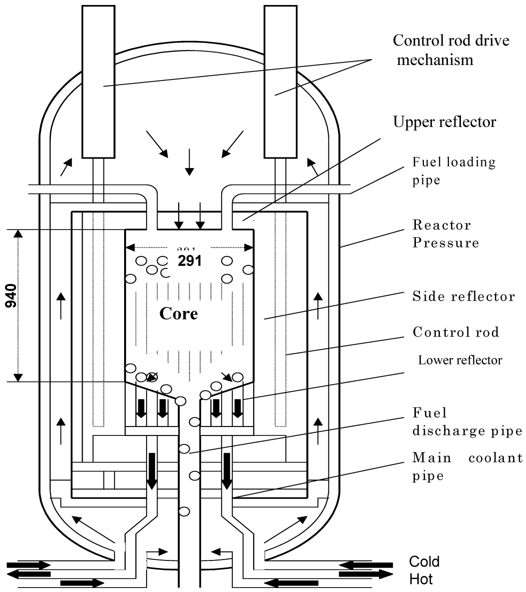

Fig. 2. Concept for the pebble bed reactor for HTGR-GT300.

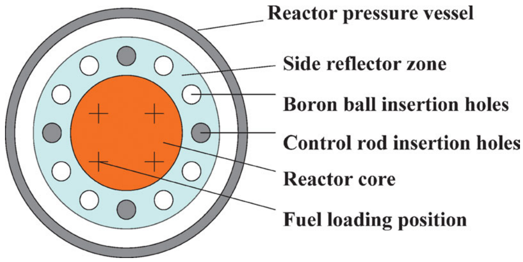

Fig. 3. Core arrangement plane view.

pebble type fuel element, as shown in Figures 2 and 3. Calculation for comparison with UHTREX have also been carried out, and presented.

2. Porosity Experiment

It is very important to measure the porosity of fuel in the reactor core. The porosity experiments were carried out in both conditions of fully shaken down with the closest possible packing and non-vibration states because the reactor is normally operated under conditions of non-vibration. The porosity measurement tools are shown in Figure 4. The porosity was measured by means of packed iron balls in a graduated cylinder.

Fig. 4. Porosity measurement tools.

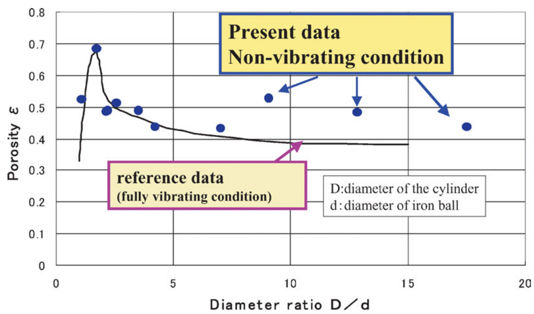

Fig. 5. Relation of porosity and diameter ratio (Solid line quoted from reference[6]).

The number of iron balls were counted with an accurate electronic balance, PM-6100 produced by Mettler Inst. Corp. The resultant ratio between porosity and diameter is shown in Figure 5. Porosity ε changes from 0.4 to 0.7 in the present experiment. Porosity ε will vary from 0.4 to 0.55 in the case of a large diameter ratio beyond 8. In the figure, it is clear that the value of porosity for non-vibration is larger than that under fully vibrating conditions.[6] The difference is very important for analyzing the fuel temperature and for making thermal-hydraulic calculation.

3. Reactor Description

Concept of modular HTGR-GT300

The concept of a pebble-bed type HTGR is shown in Figures 2 and 3 with the main nuclear and thermal-hydraulic specifications presented in Table 1. The coolant gas enters from the outer shell of the primary coolant coaxial tube to the pressure vessel at temperature of a 550°C and pressure of 6 MPa, follows the peripheral region of the side reflectors to the top, then flows downward through the reactor active core. The outlet

Table 1. Major nuclear and thermal-hydraulic specifications.

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

coolant exits through the inner shell of the primary coolant tube at temperature of a 900°C. The cylindrical core is formed by blocks of graphite reflector with a height of 9.4m and diameter of 2.91 m. Holes exist in the reflector, some for use as control rod channels and others for boron ball insertion in the case of an accident.

Fuel element

The two types of pebble fuel elements, consisting of fuel and a moderator, are shown in Figure 6. One is a solid type where the radius of the inner graphite is $r_{co}=0$, and the other is a shell type fuel element. The fuel compacts are a mixture of coated particles.[9]

4. Thermal Hydraulic Analysis

PEPTEMP code

A one-dimensional thermal-hydraulic computer code was developed that was named PEPTEMP,[5] as shown in Figure 7. The code correctly calculates the temperature of the fuel element, coolant gas and core pressure drop using assumed power, power distribution, inlet and outlet temperature, the system pressure, fuel size

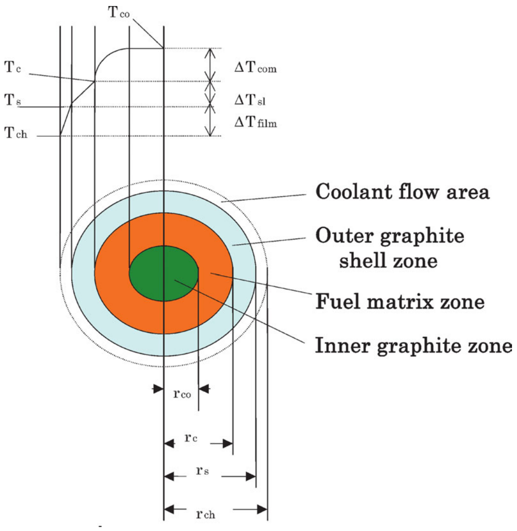

Fig. 6. Relation of a shell type fuel element and temperature difference, where no inner graphite zone is referred to as solid type, i.e., $r_{co}=0$.

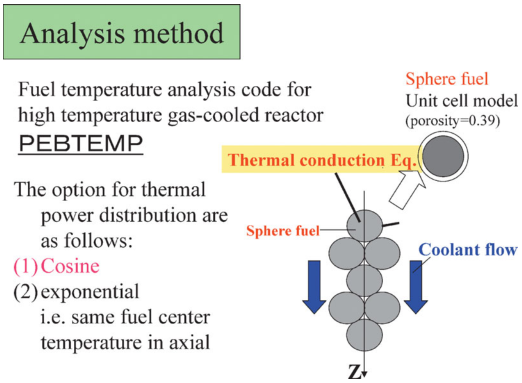

Fig. 7. Analysis method of thermal-hydraulic computer code PEPTEMP.

and fuel type as input data.

The options for fuel type are pebble type, the multi hole block type and hollow rod type. Power distribution for cases of the cosine and exponential are also available. Users can calculate other distributions by preparing the input file.

The maximum fuel temperature is calculated in PEPTEMP as follows:

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

Where $T_f(z)$: fuel temperature at the center of the fuel element (i.e. the maximum fuel temperature); ΔT_{cl}: gas temperature increment from inlet to height z; T_{gin}: gas inlet temperature; $\Delta T_{film}(z)$: temperature difference between the fuel element surface and coolant gas at z; $\Delta T_{sl}(z)$: temperature difference between the fuel matrix surface and fuel element surface; $\Delta T_{com}(z)$: temperature difference between the 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.

Temperature difference in the spherical fuel element

Figure 6 shows the fuel configurations of the solid type and shell type fuel elements. 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 the case of a shell type fuel element, ΔT_{com} can be calculated by following expression:

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

Film temperature difference

The film temperature differences are calculated as follows:

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

Heat transfer coefficient

Heat transfer coefficient h in Equation (4) is calculated using the following correlation:[10)]

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

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

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

Pressure drop

Pressure drop through the core is expressed by following correlation:[6)]

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

$$\text{and } n = 0.22, \quad (8)$$

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

$$\mathrm{Re}_p = \frac{\rho v_s d}{\eta} \quad (10)$$

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

Effective flow rate calculation

As many blocks of graphite form the reflector, there exist gaps by which the coolant flow may pass through[11)], so called leakage flow as shown in Figure 8. Actually, only one portion of the coolant passes through the reactor core from the top to bottom. This portion is called the effective flow rate and can be calculated iteratively in the code. The empirical equation used in this code is as follows:[11)]

$$W_{eff} = 0.98 - 0.012\, \Delta P \quad (11)$$

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

Figure 9 shows the flowchart of the iterative calculation with the effective coolant flow rate.

5. Calculation Results

Calculation results for HTGR-GT300

Figure 10 expresses the axial distribution of the solid type fuel center with a different effective coolant flow rate. In this calculation, the fuel element was kept unchanged and equal to 6 cm while the effective coolant flow rate changes in the range of 0.5–1.0. Figure 11 shows the coolant pressure as a function of fuel diameter with varying effective coolant flow rates 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 cases where the diameter is smaller than 4 cm. The pressure drop is inversely proportional with the fuel element diameter. According to Eq. (7) and Eq. (11) in Fig. 9, the realistic effective coolant flow rate and coolant pressure are cal-

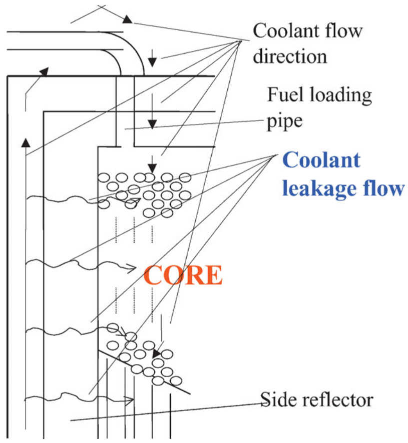

Fig. 8. Coolant leakage flow concept.

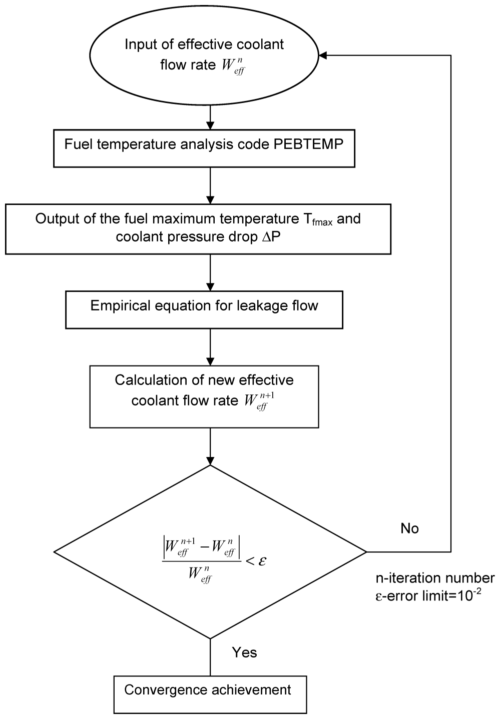

Fig. 9. Flowchart of iterative calculation.

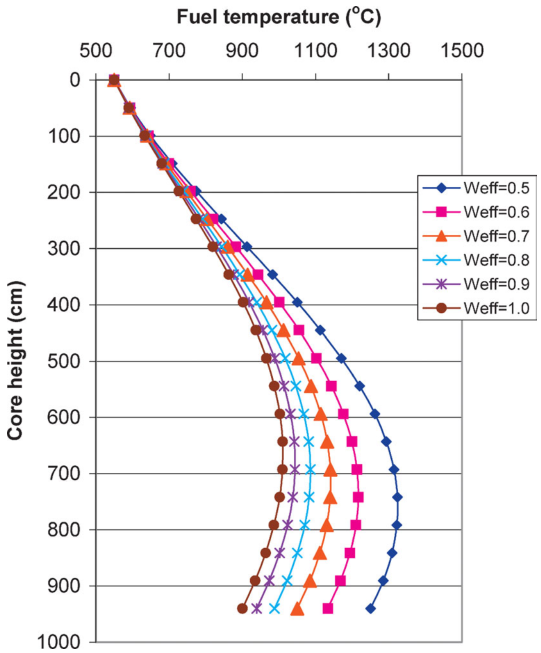

Fig. 10. Axial temperature distributions of solid type fuel center with varying effective coolant flow rates.

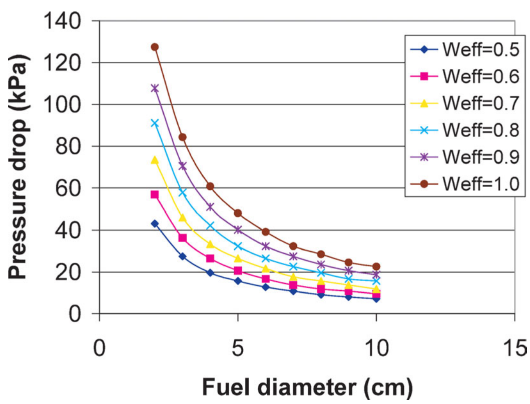

Fig. 11. Coolant pressure drop as a function of fuel diameter for varying effective coolant flows.

culated in the same diameter of the fuel element. Table 2 shows the evaluated effective coolant flow rate and the coolant pressure drop in solid type fuel elements for varying diameters from 3.5 cm to 10 cm. The maximum fuel temperature in the solid type fuel elements is shown in Fig. 12. The maximum fuel temperature has the optimum value, i.e. the lowest value in the fuel di-

Table 2. Effective coolant flow rate and coolant pressure drop in a solid type fuel element.

Fuel diameter d (cm)	Effective coolant flow rate W_{eff}	Coolant pressure drop ΔP (kPa)
3.5	0.565	34.0
4.0	0.602	31.5
5.0	0.645	27.8
6.0	0.685	24.5
7.0	0.713	22.1
8.0	0.736	20.4
9.0	0.756	18.6
10.0	0.773	17.2

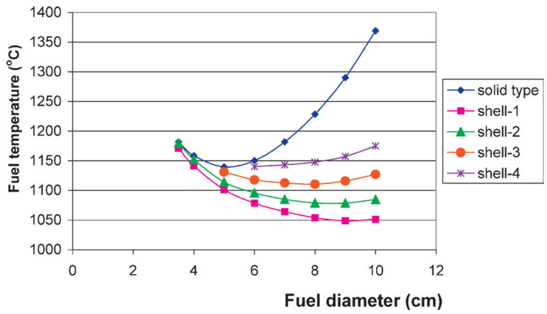

Fig. 12. Maximum fuel temperature dependence on fuel diameter with several types of fuel elements taking into consideration leakage flow.

ameter range from 3.5 cm to 10 cm. In terms of thermal-hydraulics, solid type fuel with a diameter of approximately 5 cm has the lowest fuel temperature. Table 3 shows the geometrical dimension of solid and shell type fuel elements. The fuel temperature of shell type fuel is lower than that of the solid type, and the thinner the layer of the fuel matrix, the lower the fuel temperature that can be achieved.

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

The highest outlet coolant temperature was achieved in an UHTREX (Ultra High Temperature Re-

Table 3. Geometrical dimension of solid and shell type fuel elements.

Fuel diameter (cm)	Matrix outer diameter	Diameter of inner graphite of shell type fuel: $2\gamma_{co}$ (cm)			
		Shell-1 (t=0.5 cm)*	Shell-2 (t=1.0 cm)	Shell-3 (t=1.5 cm)	Shell-4 (t=2.0 cm)
3.5	2.5	1.5	0.5	—	—
4.0	3.0	2.0	1.0	—	—
5.0	4.0	3.0	2.0	1.0	—
6.0	5.0	4.0	3.0	2.0	1.0
7.0	6.0	5.0	4.0	3.0	2.0
8.0	7.0	6.0	5.0	4.0	3.0
9.0	8.0	7.0	6.0	5.0	4.0
10.0	9.0	8.0	7.0	6.0	5.0

* t: fuel matrix thickness$=2(\gamma_c-\gamma_{co})$

actor Experiment)[8] at Los Alamos Scientific Laboratory. UHTREX is a 3 MWth gas cooled reactor loaded with hollow rod fuel elements in the hollow rod graphite block. The coolant (Helium) flows horizontally outward from the hollow inner chamber through the fuel channel. The maximum outlet coolant temperature of 1316°C was recorded on June 24, 1969.[9]

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. They are an inlet coolant temperature of 871°C, system pressure of 3.45 MPa, power density of 1.3 W/cm^3 and effective coolant flow rate W_{eff} of 1.0. Hot channel factors of 1.0, 1.1, 1.2, and 1.3 were chosen for the present calculation. The calculated results are presented in Figure 13. The results indicate that the fuel temperature of the present PBR case has a much lower value compared to that of the UHTREX case (i.e. 1582°C). Therefore, the present PBR system design will be designated as NUHTREX (i.e. New UHTREX) and will be classified as a e UHTR.

Figure 14 shows the maximum fuel temperature at various core porosities and fuel diameters. In a standard case, high fuel temperature is obtained from high porosity and large fuel diameter, where W_{eff}=1.0 and solid type fuel is used.

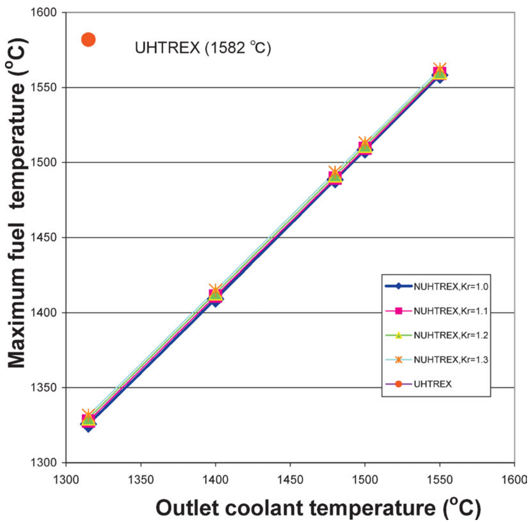

Fig. 13. Dependence of maximum fuel temperature on outlet coolant temperature for NUHTREX with varying hot channel factors (Kr) and the UHTREX case with W_{eff}=1.0.

6. Conclusion

Porosity ε will vary from 0.4 to 0.55 at large diameter ratio beyond 8. It is clear that the value of porosity

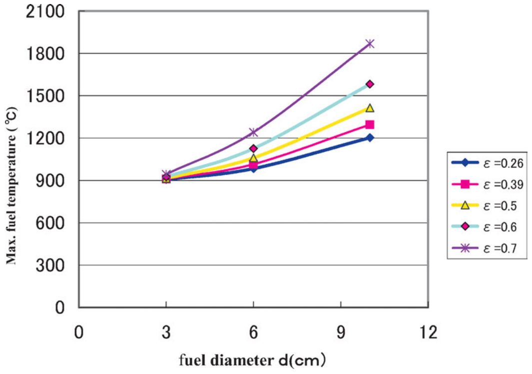

Fig. 14. The maximum fuel temperature at various core porosities and fuel diameters with W_{eff}=1.0.

under non-vibration conditions is larger than under fully vibrating conditions (see Figure 5). High fuel temperature is obtained from high porosity and a large fuel diameter (see Figure 14). In terms of thermal-hydraulics, solid type fuel with a diameter of approximately 5 cm has the lowest fuel temperature. The fuel temperature of shell type fuel is lower than that of solid type fuel, because a lower fuel temperature can be achieved with the thinner layer of the fuel matrix (see Figure 12). With the same maximum fuel temperature, the PBR type nuclear reactor core can achieve a much higher coolant temperature than that of UHTREX (see Figure 13).

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