Investigation of Temperature Transient Response Characteristics of Ceramic Fuel Rod of Open-Cycled Reactor

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Abstract. To investigate the effects of the fuel material property on the temperature safety response characteristics of the new-designed open-cycled reactor with the air as the coolant, the geometric model of the annular fuel rod is built. The parameter model is developed based on the properties of the three types of ceramic material of nuclear fuel including the Uranium dioxide (UO₂), Uranium carbide (UC) and Uranium nitride (UN). The temperature transient response rule of the three kinds of fuel rods at the cases of reactor power step increase is obtained based on the fluid-structure coupling method. The temperature transient response characteristics of three types of ceramic fuel rods open-cycled reactor are analyzed. The numerical results reveal that the peak fuel temperature and the average fuel temperature increase significantly with the step increasing reactor power. The response time of the fuel rod with UC is the longest. The peak fuel temperature and the temperature difference of the fuel rod with UO₂ are the highest. The relative results can lay the theoretical foundation for the fuel material selection, structure design and the safety analysis of the open-cycled reactor.

1. Introduction

The near space vehicle refers to the aircraft or suborbital vehicle or a hypersonic cruise vehicle that flies in the near space for long time. Compared with the aerospace vehicles, it has the advantages of the longer working time, wider coverage, stronger survivability, better mobility, smaller payload, technical difficulty, easier maintenance, etc. It especially has great potential for the development of the communication, information collection, monitoring and other aspects. The nuclear power ramjet (hereinafter referred to as nuclear ramjet) is one of the main power of the high-speed vehicles, especially hypersonic vehicles, which is related to the development and utilization of the space resources and national security strategy. Nuclear power engine is an engine that utilizes the heat energy generated by the nuclear reactor, or directly uses the high-energy particles from the reactor, or uses the energy generated by the explosion of the nuclear bomb as the power of the high-speed aircraft. The nuclear power engine has the outstanding characteristics of the high specific impulse, high energy density, long endurance and large thrust [1]. The nuclear ramjet is based on the conventional power ramjet, which uses a small reactor instead of a combustion chamber as the heat source. Its structure is shown in Figure 1. The working principle of the nuclear ramjet is to use the nuclear reactor to heat the high-pressure air, and then to generate the thrust through the nozzle expansion. Different from the conventional reactor, the reactor in nuclear ramjet is the open-cycled
type, and the cooling medium (coolant) is air. The power, structure, flow and heat transfer characteristics of the nuclear reactor are closely related to the thrust and endurance of the engine.

At present, there are few public reports about nuclear ramjet. Gabrielli et al. [2] studied and introduced the general principle and future requirements of the nuclear thermal propulsion system in the development of space transportation. Venneri et al. [3, 4] studied the feasibility of the application of the low and medium enriched uranium fuel in the nuclear thermal rocket, presented the important reactor parameters, and determined the effectiveness of the technology. Khatry et al. [5] studied the design, operation and data collection possibilities of the nuclear power jet vehicles in Jupiter's atmosphere, and finished the conceptual design of nuclear engines. Walter [6] carried out the engineering design of the Tory II-c type nuclear ramjet reactor, and provided the reactor core design and thermal design parameters. Merkle [7] introduced the system layout and analyzed its performance at different Mach numbers. Rom [8] studied the weight, shielding, heat transfer and structural design of the low temperature nuclear ramjet suitable for the high altitude. In addition, Goldberg [9] conducted a general study on the structure, processing method, physics, shielding and heat exchange design of the Tory II-c. However, there are few domestic researches on the nuclear power engine. Most of them are about the research and summary work of the foreign research studies [1, 10, 11]. Shi and Wei [10] introduced the principle and development of nuclear power engine. Ye and Zhao [11] introduced the research progress of the nuclear ramjet in China and abroad, and predicted the development and application prospect of. In addition, He et al. [1] introduced the principle, development and application prospect of the nuclear rocket. Although the research and development about the nuclear ramjet technology has achieved some success at present, it has not been realized because of the consideration of the radioactive pollution and safety factors.

As mentioned above, nowadays, there are few researches on the nuclear power engine. And most of the researches on the high-temperature and high-speed air flow and heat transfer characteristics are about the gas heat exchanger [12-14]. There is almost no research on the safety analysis and the flow and heat transfer characteristics of the reactor core under the conditions of the nuclear ramjet operation. However, during the actual operation process of the nuclear power ramjet, the flowing of the high temperature and high speed air through the channel in the reactor will produce the flow instability, can cause the flow induced vibration, cause the local overheating, damage the reactor core and affect the safety and operation performance of the nuclear power ramjet. Its transient safety characteristics are more important than the existing PWR. In addition, the surrounding environment parameters and the motility of the nuclear ramjet vary greatly, which can lead to the transient change of the fuel temperature of the reactor core. The transient temperature response is closely related to the safety of the reactor. Therefore, it is necessary to study the core physical design and transient safety analysis. In the present paper, the selection of the nuclear fuel and the transient safety characteristics of the nuclear ramjet reactor are studied.

2. Simulation method

2.1. Geometric model

The structure cross section schematic of the nuclear ramjet is shown in Figure 1. Its working principle is that the high-speed air enters the annular cavity through the inlet, decelerates and is pressurized at the inlet of the reactor, and then enters the nuclear reactor to remove the heat generated the reactor. At the same time, the high-pressure air is heated, and then expands and accelerates. Finally, it flows out of the reactor the pressure reduces and the speed increases in the nozzle to generate the thrust. The power, fuel type and structure of nuclear reactor are related to the performance of the engine.
Figure 1. Structure schematic of the nuclear ramjet [7].

As shown in Figure 2, the typical open-cycled reactor fuel element can be hollow hexagonal or annular fuel rod [6]. There is no fuel assembly in the open-cycled reactor, and the center of the fuel element is the flow path of the air coolant. As shown in Figure 3, the inner diameter of one kinds of the annular fuel element is 5.8 mm, the outer diameter is 7.2 mm and the length is 100 mm. The calculation model selected in this study is the annular fuel element.

Figure 2. The schematic of the open-cycled reactor core.

Figure 3. Structure of annular fuel element (a) Three-dimensional structure, (b) Cross-section.

2.2. Numerical method

In the operation process of the open-cycled reactor, as there is no fuel assembly, and the annular fuel element is not covered by the shell, which directly contacts with the surrounding air coolant, once the reactor is in operation, it is difficult to shut down. Thus, its safety characteristics are particularly important and it is necessary to conduct the detailed analysis of its transient behavior during the possible accident process. In this paper, the transient temperature response characteristics of the fuel element in an open-cycled reactor under the condition of instantaneous power rise (power step rise) are studied, three kinds of ceramic nuclear fuel, including UO$_2$, UC and UN, were selected to analyze
the transient temperature response characteristics of the fuel under the condition of reactor power step-up. The analysis of the transient safety characteristics can provide basis for the selection of open-cycled reactor fuels.

According to the Figure 3, the geometric model of the annular fuel element is axisymmetric. In the actual calculation and analysis process, the axisymmetric model can be used to simplify the simulation. In this study, the software of Fluent is used to analyze the instantaneous temperature response of the annular fuel element under the condition of the power step-up, and the software of ICEM (The Integrated Computer Engineering and Manufacturing code) is used to draw the geometric model (Figure 4). In the simulation, the dotted line at the center is set as the symmetry axis; the outermost side of the solid domain is set as the symmetry boundary; the coolant is set as the ideal compressed air; and the solid domain is set as the symmetry boundary. The calculation condition and parameters of the power instantaneous step process are as follows: the power load steps from 100% full power to 110%, 118%, 130% and 150%, respectively. The reference pressure is set as 0.1 MPa. The inlet boundary condition is the pressure inlet boundary and the gauge pressure is 10000 Pa. The outlet boundary condition is the pressure outlet boundary and the gauge pressure is 0 Pa. The total temperature of the inlet air is 450 K, and the internal heat source (1×10^8 W/m^3 under the rated 100% working condition; the total reactor thermal power is about 50MW) is set in the fuel solid domain. The realizable k-epsilon model is used for the solution. The Simple algorithm is used for the pressure velocity coupling. The transient calculation is used, and the calculation time step is 0.01 s after the independent verification of time step.

**Figure 4.** Two-dimensional geometric model of annular fuel element.

In the calculation, it is necessary to define the physical parameters of three kinds of ceramic fuels. Due to the reasons of the processing and manufacturing and in order to prevent the fuel densification, the density of ceramic fuels is usually 90%-98% of the theoretical one. The density of three kinds of ceramic fuels selected in the calculation is 95% of the theoretical density. The specific density values are shown in Table 1.

| Ceramic fuel type | Fuel density ρ/ kg/m^3 |
|------------------|------------------------|
| UO2              | 10.43×10^3             |
| UC               | 12.95×10^3             |
| UN               | 13.61×10^3             |

The key physical parameters of ceramic fuel include fuel density, thermal conductivity and specific heat capacity at constant pressure. Generally, when the temperature is below 1600 °C, the thermal conductivity of uranium dioxide will decrease with the increasing temperature. When the temperature is over 1600 °C, the thermal conductivity of uranium dioxide will increase with the increasing temperature.

For the cold pressed sintered uranium dioxide with a density of 95% of the theoretical value, the calculation formula of thermal conductivity [15] is as follows:

\[ \kappa_{95} = \frac{3824}{T + 402.55} + 4.788 \times 10^{-11} (T + 273.15)^3 \]  

(1)

Where, \( \kappa_{95} \) is the thermal conductivity of uranium dioxide with the density equivalent to 95% of the theoretical value, W/(m·K); \( T \) is the temperature, °C. The range of application of the formula: \( T \in [0, \)
2450] °C, fuel consumption 0~10 MW·d/t(U). The thermal conductivity of the sintered uranium dioxide at other densities can be calculated by Maxwell-Eucken equation as follows:

\[ \kappa_p = \frac{1 - \varepsilon}{1 + \beta \varepsilon} \kappa_{100} \]

(2)

Where, \( \kappa_p \) and \( \kappa_{100} \) is the thermal conductivity of uranium dioxide with pores and with theoretical density, respectively; \( \varepsilon \) is the porosity of fuel; \( \beta \) is the constant depending on the material, which is determined by experiments about the material process [15]. For uranium dioxide with not less than 90% of theoretical density (\( \varepsilon \leq 0.1 \)), \( \beta \) is 0.5; otherwise, \( \beta \) is 0.7.

The specific heat \( c_p \) of uranium dioxide at constant pressure can be expressed as a function of temperature, and the corresponding formula [15] is as follows:

\[ c_p = \begin{cases} 
304.38 + 2.51 \times 10^{-2} T - 6 \times 10^6 / (T + 273.15)^2, & T \in [25, 1226] \, ^\circ\text{C} \\
-712.25 + 2.789 T - 2.71 \times 10^{-3} T^2 + 1.12 \times 10^{-6} T^3 - 1.59 \times 10^{-10} T^4, & T \in (1226, 2800] \, ^\circ\text{C} 
\end{cases} \]

(3)

Where, \( c_p \) is the specific heat capacity at constant pressure, J/(kg·°C); \( T \) is the temperature, °C.

The calculation method of thermal conductivity and specific heat capacity at constant pressure of uranium carbide and uranium nitride fuel is similar to that of uranium dioxide [16-18]. For uranium carbide ceramic fuel, the calculation formula of thermal conductivity [16] is:

\[ \kappa = 20.4 + 2.836 \times 10^{-6} (T - 570)^2 \]

(4)

Where, \( \kappa \) is the thermal conductivity of uranium carbide, W/(m·K); \( T \) is the temperature, °C. The range of application of the formula: \( T \in [570, 2000] \, ^\circ\text{C} \).

The specific heat \( c_p \) of uranium carbide at constant pressure can be expressed as a function of temperature, and the corresponding formula is [16]:

\[ c_p = 77.07 + 0.4883 \times 10^{-2} T - 4.907 \times 10^{-4} T^2 + 2.153 \times 10^{-7} T^3 - 3.22 \times 10^{-11} T^4 \]

(5)

For uranium nitride ceramic fuel, the calculation formula of thermal conductivity [17] is:

\[ \kappa = 1.37 T^4 \frac{1 - \varepsilon}{1 + \varepsilon} \]

(6)

Where, the range of application of the formula: \( T \in [50, 2000] \, \text{K} \).

The specific heat \( c_p \) of uranium nitride at constant pressure can be expressed as a function of temperature, and the corresponding formula is [18]:

\[ c_p = [51.14(\theta / T)^2 \exp(\theta / T) + 0.009491 T + \frac{2.6415 \times 10^{11}}{T^2} \exp(-18081 / T)] / 0.249 \]

(7)

According to the above formula, the thermal conductivity and specific heat capacity of three ceramic fuels at different temperatures are shown in Figure 5 and Figure 6, respectively.

Figure 5. Thermal conductivity of three types of the ceramic fuels at different temperatures.
Figure 6. Comparison of specific heat of three types of ceramic fuels at different temperatures.

3. Result analysis and discussion

3.1. Steady state operation with full power

Under the full power operation conditions, the temperature contours and velocity contours of the air fluid domain, the fuel solid domain and the fluid domain of three different ceramic fuel elements are presented in Figure 7 and Figure 8 respectively. Figure 7 reveals that the temperature distribution of three different types of fuels elements is basically the same. The temperature of uranium dioxide fuel is slightly higher than that of uranium carbide and uranium nitride, but the overall difference is slight. It is mainly because the thermal conductivity of uranium dioxide is lower than that of uranium carbide and uranium nitride, and the temperature gradient in the fuel elements is larger. The air temperature inside the fuel element of uranium dioxide is slightly lower than that of the other two fuels. This is mainly because the specific heat capacity of the constant pressure of uranium dioxide is larger than that of the other two fuels, and the fuel itself will absorb a certain amount of heat. Figure 8 reveals that the air velocity distribution of three different ceramic fuel elements is basically the same, and the velocity difference is small, which is consistent with the result at the same heat flow density. To a certain extent, it reveals the accuracy of the calculation results. It should be noted that since there is no analysis result of transient response of fuel element in nuclear ramjet, the model is verified by comparing with the experimental results of air flow and heat transfer characteristics in the existing heating tube [19]. Through the validation, the discrepancies between the numerical results and the experimental one is between ±10%.

It should be noted that the reactor safety characteristics are vitally important. Therefore, in order to fully compare the performance of the three kinds of fuel, almost each parameter such as the average fuel temperature, the peak fuel temperature, the response time of the fuel element and their safety characteristics are analyzed in the present paper.
Figure 7. Temperature contours of three types of ceramic fuel elements under 100% power load (a) UO₂ (b) UC (c) UN.

Figure 8. Velocity contours of three types of ceramic fuel elements under 100% power load (a) UO₂ (b) UC (c) UN.
3.2. Transient response characteristics of fuel element temperature under power step conditions
The calculated average fuel temperature and peak fuel temperature (maximum fuel temperature) of uranium dioxide fuel element under the reactor power step-up condition (Table 1) over time are shown in Figure 9 and Figure 10, respectively. Figure 9 and Figure 10 reveal that when the reactor power step increases, the peak temperature and average temperature of the fuel element increase rapidly and reach a new stable value after 30–50 s. That is because when the reactor power step increases, the reactor power increases instantaneously and the fuel temperature increases at the same time. With the increase of the step power, the time for the fuel element temperature to reach a stable value increases gradually. And the corresponding peak temperature and average temperature of the fuel increase correspondingly, with an increase range of 20–250 K. That is because the increasing step power will result in larger amount of power and it takes longer time to heat the fuel. For the reactor safety, the fuel temperature is usually limited to a certain value, i.e. highest fuel temperature. As the fuel temperature increases, the difference between the fuel temperature and the limited highest fuel temperature decreases. Thus, the temperature safety margin of fuel element will reduce, which may threaten the integrity of fuel (cause fuel melting). In the actual operation process of open-cycled reactor, the corresponding safety measures should be taken into account.

In addition, it can be seen from the Figure 9 and Figure 10 that the peak temperature of fuel is about 70-120 K higher than the average one. That is because the heat generated by the fuel is transfer from the center of the fuel to the outside and the temperature in the fuel is nonuniform. Therefore, the peak temperature of fuel during the actual reactor design process should be paid more attention. However, the variation tendency is almost the same. According to the transient response results of fuel element temperature, the temperature response time of fuel element is very short (only tens of seconds). Therefore, in the open-cycled reactor design process, the fast action control and protection system should be used to prevent the fuel element temperature from exceeding the limit value and lead to the fuel meltdown.

![Figure 9](image_url)

**Figure 9.** Average fuel temperature over time at cases of the step increase of reactor power

Note: 110% refers to the step increase of power from 100% to 110%.
3.3. Comparison of temperature transient response characteristics of fuel elements with different materials

In order to quantitatively analyze the temperature response time, the average fuel temperature, peak fuel temperature and the transient response characteristics of the three types of fuel elements under conditions of the open-cycled reactor power step-up are compared. Through the data processing, the response time, peak fuel temperature and peak fuel temperature of fuel elements of three different types of fuel elements over time are presented in Figure 11-13. It reveals that the response time of three types of fuel elements increases almost linearly with the increasing step power load. Generally, the response time of uranium carbide fuel is the longest in the calculation range of this paper. The response time of uranium dioxide and uranium nitride fuel is almost the same. But the difference is not significant. From the perspective of transient response time, it is better to choose the uranium carbide fuel, due to the longer response time of the fuel element temperature is. Thus, the fuel temperature rises slowly during the process of the power step increase, which can be controlled and protected for a longer time. And it is relatively safer.

![Figure 10](image-url) Fuel peak temperature over time at cases of the step increase of reactor power.

![Figure 11](image-url) Response time of fuel element at cases of different step levels of reactor power load.

Figure 12 and Figure 13 reveal that the peak temperature and temperature rise of the fuel element with uranium dioxide are higher than that of uranium carbide and uranium nitride when the reactor power step increases. In addition, with the increase of the power load, the difference between the peak
temperature of uranium dioxide fuel and the other two becomes larger and larger. This is mainly due to
the fact that the thermal conductivity of uranium dioxide decreases gradually with the increasing
temperature (Figure 5), which is much smaller than that of the other two fuels. The results indicate that
the temperature of fuel element with uranium dioxide is higher and increases faster during the process
of power step increase. It is more likely to threaten the safety of the reactor system. Therefore, from
the perspective of the transient safety characteristics, the safety performance of fuel elements with
uranium carbide and uranium nitride is better than that of uranium dioxide.

![Figure 12. Fuel peak temperature changes with the step level of reactor power load.](image1)

![Figure 13. Temperature rise of fuel peak temperature over the step level of reactor power load.](image2)

In conclusion, from the perspective of the transient response characteristics of the reactor fuel
elements, the performance of the uranium carbide fuel is the best, followed by the uranium nitride
fuel, and the safety performance of the uranium dioxide fuel is the worst. Therefore, both the uranium
carbide and uranium nitride can be adopted as the nuclear fuel with better transient safety
characteristics during the fuel selection of open-cycled reactor.

4. Conclusions
In this paper, three kinds of ceramic nuclear fuels including uranium dioxide, uranium carbide and
uranium nitride, which may be used in the new open-cycled reactor with air as coolant, are selected
and analyzed from the point of the temperature transient response. The transient temperature response
characteristics of three types of fuel elements in the process of the instantaneous step-up power of the reactor are emphatically analyzed. The peak temperature, average temperature and response time of different fuel elements are obtained and are analyzed for the safety performance. From the perspective of the transient response, suggestions for the selection of new type of open-cycled reactor fuel elements are made. The main conclusions are as follows:

(1) In the range of the design conditions, when the reactor power step increases, the temperature of fuel element increases rapidly, reaching a stable value in about 30-50 s; the increase range of fuel temperature is between 20-250 K; the peak temperature of fuel is 70-120 K higher than the average temperature of fuel, so corresponding protective measures should be taken to reduce the fuel temperature.

(2) Among the three kinds of fuel elements, uranium carbide has the longest transient response time and longer protection time. From the perspective of the transient safety characteristics, uranium carbide and uranium nitride can be used as the nuclear fuel of open-cycled reactor.

(3) The results of the numerical calculation and transient safety analysis can provide the technical support for further research on the reactor fuel selection and accident safety analysis, and guide the reactor design. However, in the final selection of the nuclear fuel, the radiation performance and thermal expansion performance of the fuel should be considered at cases with high temperature.

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