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PARAMETRIC STUDY ON THERMAL HYDRAULICS CHARACTERISTICS OF A PARTICLE BED REACTOR FOR NUCLEAR THERMAL PROPULSION

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Nuclear Thermal Propulsion (NTP) is regarded as a promising technology and selected as the leading candidate for the human exploration to Mars, as suggested in Design Reference Architecture 5.0 (DRA 5.0). For a long time, many novel NTP systems have been proposed, designed and tested, among which Nuclear Engine for Rocket Vehicle Application (NERVA) is the most famous one. In the NERVA program, enormous technologies were developed and some records were accomplished. Based on these achievements, a more excellent, compact and lightweight design, i.e., particle bed reactor (PBR) was proposed in the 1980s. In this paper, the thermal hydraulics characteristics of a proposed PBR are investigated. By assuming the characteristics are indifferent along circumference, a two-dimensional steady-state analysis concerning the turbulent flows in PBR is performed using Computational Fluid Dynamics (CFD) tool. In addition, some further work investigates the effect of various aspects including flow direction, mass flow rate and the height of nuclear reactor core on the internal flow and heat transfer processes within the reactor core. These findings may provide technical support for the subsequent design of PBR.

I. INTRODUCTION

Interplanetary explorations have attracted increasing attention over the past decades, and will continue in the next many years. However, for a crewed exploration, long term stay in space will damage astronauts' health due to harsh environment full of excessive cosmic rays and micro-gravity. Nuclear Thermal Propulsion (NTP) can be a solution for such related problems. It is a technology of relatively high thrust and high specific impulse, and can reduce the duration time for space travel [1,2]. In addition, NTP is achievable and robust in terms of its mission ability[3].

NTP was firstly proposed in 1950s, and was rapidly developed in 1960s. The principal research activities were performed in two countries, i.e., the United States of America and the Former Soviet Union or Russia[4]. The most representative effort is the Rover and Nuclear Engine for Rocket Engine Application (NERVA) program. During the program, more than 20 reactors were built and tested, and many technologies were developed and some records were accomplished. However, the NERVA program was canceled in 1972 due to some non-technique reasons. Afterwards, a more efficient, compact and lightweight design, i.e., Particle Bed Reactor (PBR) was put forward in 1980s based on the derived knowledge from NERVA. In recent years, the National Aeronautics and Space Administration (NASA) has re-sponsored the NTP research and selected it as the primary option for cargo and crew transfer in outer space. Although the NERVA cluster is considered sufficient for manned mars mission in the Mars Design Reference Architecture 5.0 (DRA 5.0)[5], the exploration ability could be enhanced further if the PBR is fulfilled. Figure 1 shows a schematic view of a PBR system.

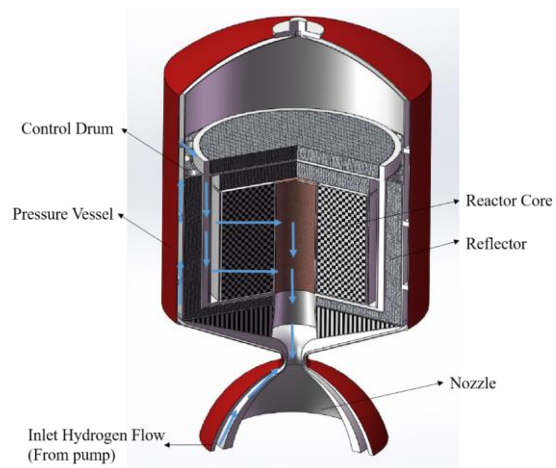

Fig. 1. Schematic view of a PBR system

The thermal hydraulics design is one of the most concerned and challengeable problems in the NTP systems due to the extremely high power density of the reactor core, especially in PBR. Recently, computational fluid dynamics approach has been used increasingly in the nuclear field to solve many complicated problems with regard to the thermal hydraulics in the reactor[6,7]. Thus this paper aims to investigate the thermal hydraulics characteristics of a proposed PBR concept through a two-dimensional steady state analysis based on the computational fluid dynamics tool. Further, the effects of various aspects including flow direction, mass flow rate and height of the reactor core on internal flow and heat transfer processes within the core are discussed as well, which hopes to provide some support for the subsequent design of PBR.

II. METHODOLOGY

II.A. Reactor Core Description

The investigating PBR here is similar as the previous concept of the critical reactor proposed by Institute of Space Nuclear Power Studies in University of New Mexico[8]. The reactor is a hydrogen cooled fast reactor. The fuel particles are packed randomly in an annular region between hot frit and cold frit. The diameter of a fuel particle is almost 6 mm, and each particle is composed of hundreds of TRISO particles. In the present numerical investigation, the fuel region, cold frit and hot frit are all considered as porous media, and the porosity is 0.38, 0.1 and 0.2, respectively. Besides, the other geometry information is listed in Table I.

Table I. Basic geometry information of PBR

Parameters	Value
Diameter of core, mm	1,014
Height of core, mm	1,200
Diameter of hot gas channel, mm	200
Thickness of hot frit, mm	3
Thickness of pebble bed, mm	281
Thickness of cold frit, mm	2
Thickness of inlet plenum, mm	10
Thickness of radial reflector, mm	111

The computational domain consists of inlet annular plenum, cold frit, fuel region, hot frit and hot gas channel. By assuming the thermal hydraulic characteristics in the reactor core are indifferent along circumference, the computational model is simplified to be a two-dimensional axis-symmetric model, shown in Figure 2. The fission power is assumed to be a uniform profile in the core, and the rated thermal power is 1000 MW. The inlet temperature of hydrogen is almost 200 K, while the mass flow rate is 21 kg/s to ensure a high temperature of exhausted gas. The pressure in the thrust chamber (i.e., outlet of computation model) is 8.0 MPa.

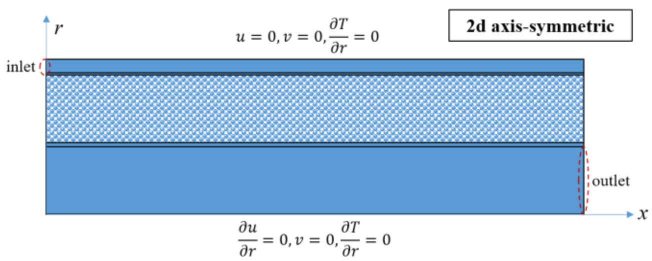

Fig. 2. Simplified two dimensional axis-symmetric computation model of PBR

II.B. Numerical Details

In this paper, the process that the coolant flowing through the particle bed are treated as porous media flow, while the convection heat transfer between the solid matrix and the coolant is evaluated by the non-thermal equilibrium model. For the former one, an additional source term is added into the momentum equation to represent the drag force due to the particle packing, and this term is determined by the model in KTA; for the latter one, the heat transfer rate is related to the heat transfer coefficient and interfacial surface, and the heat transfer coefficient is determined by KTA correlations as well[9,10]. In addition, the process of coolant flowing across the cold frit and hot frit are treated as isothermal porous media flow, and the pressure drop within which are determined by the Ergun equation. Finally, the turbulent flow and the convection heat transfer in the inlet plenum and hot gas channel are investigated by solving the incompressible steady Navier-Stokes equation, and the realizable k-ε model is adopted to model the turbulence, while Reynold analogy is used in the estimation of turbulent heat transfer. In an NTP system, the propellant, i.e., hydrogen enters at approximately 20 K and leaves at near 3000 K. The great temperature difference affects the properties of hydrogen and the thermal hydraulics characteristics within the reactor. In this paper, the real gas Peng-Robinson equation is adopted to determine the density of the hydrogen. Besides, combining the thermodynamics differential relationships and properties of ideal hydrogen, the specific heat capacity of real gas hydrogen can be calculated as well. The molecular viscosity and thermal conductivity can be both determined by semi-empirical correlations which include the dilute gas contribution and excess contribution due to the effect of two-body interaction and many-body collisions of molecules[11].

The numerical simulation is performed by using ANSYS FLUENT[12]. The SIMPLEC algorithm is employed for pressure-velocity coupling. The second upwind scheme is used to discretize the governing equations of continuity, momentum and energy, while first upwind scheme is used for the discretization of the governing equations with regard to turbulence qualities. In addition, the models accounting for the flow in porous media (pebble bed, cold & hot frit) and the properties of hydrogen are embedded in the code though user defined function (UDF).

III. RESULTS AND DISCUSSION

III.A. Baseline Design

A grid system of quadrilateral elements is constructed on the computational domain, in which the cells are all orthogonal. After the grid independence check, the grid of 132480 cells are adopted in the subsequent research.

Moreover, the validation of the approach is performed using the HTR-PM design data.

Following the verification and validation, the characteristics of thermal hydraulics in PBR are investigated. Figure 3 shows the gas velocity in full PBR in a global scale and in the fuel region of the PBR in a local scale. From the figure, it can be noted that the hydrogen flows axially in both inlet plenum and hot gas channel, while flows radially through the entire particle bed, which coincides with the design concept of PBR. However, in a detailed view, the flow is not fully radial in the region adjacent the inlet plenum and hot gas channel, where it is affected greatly by the main flow. In addition, it is observed that the velocity of hydrogen in right side is slightly higher than that in left side, which means a mal-distribution of hydrogen in the fuel region.

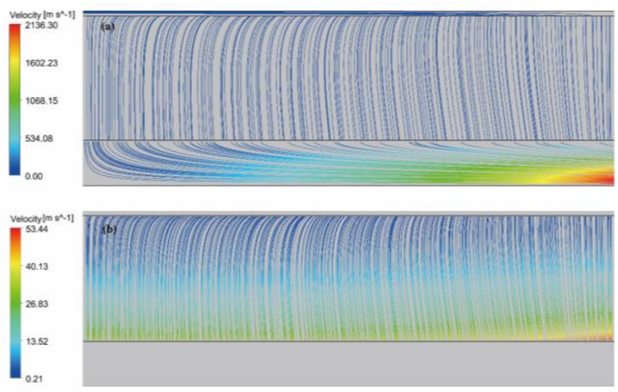

Fig.3. Flow field in reactor, baseline design; (a) in full PBR; (b) in fuel region only, baseline design

Figure 4 shows the local mass flow rate per unit length along axial direction on cold frit and hot frit. As is indicated in the figure, the mass flow rate of hydrogen coolant in right side (flooded region) is exactly greater than that in left side (dry region). Besides, the mal-distribution on hot frit is significant than that on cold frit, which leads to a hot spot in the bottom-left region of pebble bed and a zone of low temperature in the bottom-right region. This is clearly observed in Figure 5. The possible reason explaining the phenomena is attributed to the pressure field. In Figure 6, there is a significant pressure gradient in the hot gas channel along stream-wise direction, where the velocity of hydrogen is extremely high. Therefore, the pressure difference between cold frit and hot frit is non-uniform, and local mass flow rate is non-uniform as well.

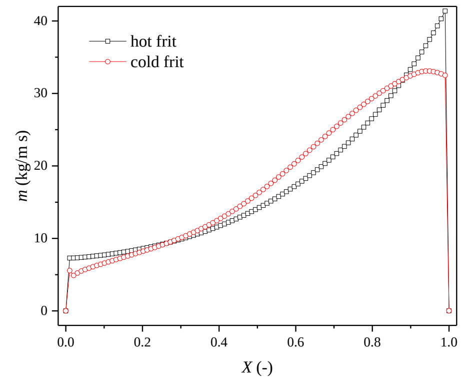

Fig.4. Local mass flow rate per unit length along axial direction on cold and hot frits, baseline design

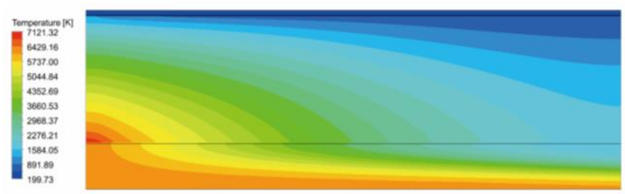

Fig.5. Temperature field in PBR, baseline design

Fig.6. Pressure field in PBR, baseline design

III.B. Parametric study

III.B.1 Effects of flow direction

There are two design of different flow pattern in PBR reactor, viz., “Z” flow pattern and “U” flow pattern. “Z” flow pattern means the inlet and outlet boundary are in different side, and the coolant flows cocurrently in the inlet plenum and hot gas channel. “U” flow pattern is exactly a design that the inlet and outlet boundary are set in the same side, and the hydrogen flows countercurrently in the inlet plenum and hot gas channel. Figure 7 shows the local mass flow rate per unit length along axial direction on cold frit and hot frit for a “U” flow pattern PBR. From which, it is found that the mal-distribution of hydrogen on cold frit and hot frit has been weaken compared to the “Z” flow pattern design, which leads to a significant reduction of maximum temperature within the entire reactor, as shown in Figure 8.

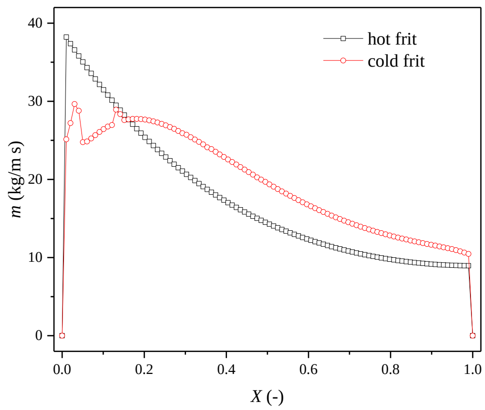

Fig.7. Local mass flow rate per unit length along axial direction on cold and hot frits, “U” flow pattern

Table II lists the general parameters including pressure drop through entire reactor Δp, outlet temperature of exhaust T_{out}, and maximum temperature within the reactor T_{max} of these two flow patterns, which indicates that the change from “Z” flow pattern to “U” flow pattern helps optimize the thermal hydraulic design of PBR. The possible reason accounting for the phenomenon is the pressure difference between hot frit and cold frit along axial direction has been reduced.

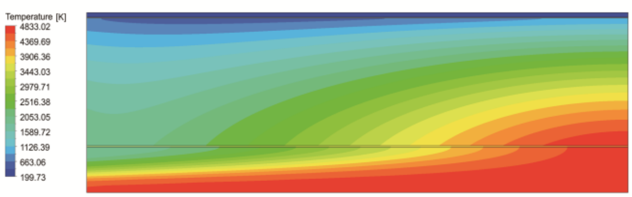

Fig.8. Temperature field in PBR, “U” flow pattern

TABLE II. General parameters of two differnet flow patterns design

Flow pattern	Δp (kPa)	T_{out} (K)	T_{max} (K)
“Z” pattern	872.37	2772.2	7121.3
“U” pattern	867.41	2775.6	4833.0

III.B.2 Effects of mass flow rate

In the design process of PBR for NTP, mass flow rate is an important factor should be considered for thermal hydraulics investigation. In the present work, the effects of mass flow rate are investigated by varying the mass flow rate but keeping the ratio of thermal power to the mass flow rate, i.e., P/m as a constant. Hence the temperature of exhaust and the specific impulse of nuclear thermal rocket can hardly change. Based on the “U” flow pattern design above, three different mass flow rates are selected here, i.e., 17.6 kg/s, 21.0 kg/s and 25.0 kg/s. Table III lists the main thermal and hydraulics performance under the conditions of different mass flow rates. From the table it is clearly found that the pressure drop increases greatly as mass flow rate increases. As for the maximum temperature in the core, only slight reduction is observed when mass flow rate decreases from 25.0 kg/s to 17.6 kg/s.

TABLE III. General performance of the design under different mass flow rate

m (kg/s)	P (MW)	Δp (kPa)	T_{out} (K)	T_{max} (K)
17.6	838.1	620.56	2785.4	4831.4
21.0	1000.0	867.41	2775.6	4833.0
25.0	1190.5	1213.3	2761.0	4884.6

Decreasing the flow rate means a lower pressure gradient in the hot gas channel, which reduces non-uniform profile of pressure difference along the axial direction and thus leads to a more uniform flow redistribution within the reactor core.

III.B.3 Effects of core height

Four reactors of different height are selected to investigate the effects of core height on thermal hydraulics. Except the core height, the parameters including mass flow rate (m=21 kg/s), total thermal power (P=1000 MW), porosity on hot frit (α=0.15), thickness of particle bed (δ=23.7 cm) and diameter of hot gas channel (d=24 cm) are all same. Table IV has listed the calculated results with regard to the thermal hydraulics of these four PBRs. From the table, it is obvious that the outlet temperature almost keeps unchanged for these four designs. Maximum temperature increases, while pressure drop decreases as height of core increases. The reduction of pressure drop is due to the decreases of the velocity of hot gas through pebble bed and across hot frit. Figure 9 shows the temperature field of these four PBRs, from which it is found that the temperature is distributed more uniformly when height reduces from 140 cm to 80 cm.

TABLE IV. General parameters of four designs of different height

Height h (cm)	Δp (kPa)	T_{out} (K)	T_{max} (K)
80	1033.9	2798.5	3093.8
100	767.6	2798.0	3250.2
120	618.2	2797.8	3467.1
140	523.4	2797.6	3747.1

The reduction of maximum temperature is due to that the pressure difference between the cold frit and hot frit along axial direction vary less than before. Specifically speaking, velocity in the core becomes higher, which increases the pressure drop across the hot frit and through the fuel bed, and pressure difference in the hot gas channel has been decreased due to a reduced flow path of hot hydrogen.

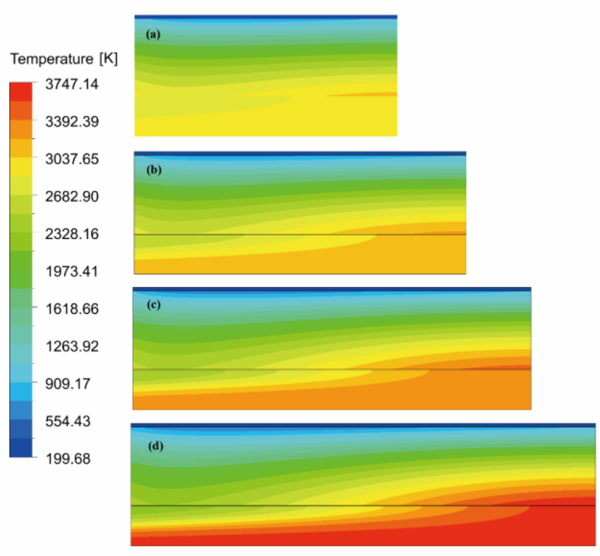

Fig.9. Temperature field in rectors of different height; (a) *h*=80 cm; (b) *h*=100 cm; (c) *h*=120 cm; (d) *h*=140 cm

. IV. CONCLUSIONS

Nuclear thermal propulsion is regarded as a promising technique for manned space activities or interplanetary exploration in the next few decades, and PBR is the most efficient, compact and lightweight design among all proposed concepts. However, the thermal hydraulic design is one of the most challengeable problems for PBR. In the present work, the characteristics of thermal hydraulics are studied through numerical simulation. Besides, the effects of flow direction, mass flow rate and core height on the thermal hydraulics are investigated briefly. The main conclusions are as follows:

(1) The hot spot is caused by the mal-distribution of hydrogen in the fuel region, which is attributed to the pressure profile on the cold and hot frit.

(2) Flow pattern is an extremely significant factor to PBR. “U” flow pattern is superior to “Z” flow pattern in preventing hot spot from emerging.

(3) Raising the mass flow rate can increase the pressure drop through bed, across hot frit and within hot gas channel, the joint effects of these three terms affect little on the thermal field in the core, but contributes a lot to the pressure field in the core.

(4) Decreasing the core height lowers the peak temperature in the core. However, the pressure drop in the entire PBR increases greatly.

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