Experimental and CFD studies of the flow characteristics of MOX Irradiation Container Assembly

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Abstract. According to the analysis of similarity principle, the operating parameters of the flow distribution experiments of MOX irradiation container assemblies were determined. The distribution experiment of CN-1515Ti irradiation container assembly (one of MOX irradiation container assemblies) was accomplished on the hydraulic test loop of MOX fuel assembly. It was confirmed that the margin distance of irradiation container throttling piece is 17.2mm. Meanwhile the empirical relationship between throttle opening area (S) and the resistance coefficient (ξ) was obtained, which could be used for further similar experiments.

CFD simulation of pin part of the irradiation container assembly had also been executed, which had given the three-dimensional flow field of the pin. By comparing CFD simulation and experimental results, the design and result of experiment was verified.

Key Words: MOX irradiation container assemblies; flow distribution experiments; CFD simulation; throttling sheet

1. Introduction

The core of China Experimental Fast Reactor (CEFR) uses uranium dioxide as its first fuel and then transforms to mixed uranium plutonium oxide (MOX). In the MOX fuel, the plutonium element was added and the enrichment of the uranium element was changed. The each energy produced by fissions of the MOX fuel was not only different from that of the UO2 fuel, but the thermal characteristics were also changed greatly. In order to adapt to these changes, the hydrodynamic characteristics of MOX assemblies need to be re-examined.

In this paper, we only focus on the flow distribution experiment of CN-1515Ti irradiation container assembly simulator (one of MOX irradiation container assemblies). In the experiment, the size of the slotted throttling structure of the simulant pin of the CN-1515Ti Assembly was determined to meet the rated pressure drop demands at the rated sodium flow rate of the module and confirm whether additional throttling devices is required. At the same time, the hydraulic characteristics of CN-1515Ti irradiation container assembly simulator were studied in the corresponding Re number range.

2. Experimental object and experimental loop

The design requirements of CN-1515Ti Irradiation Container Assembly are as follows:

Pressure drop: 0.25MPa (assembly total pressure drop)

Mass flow: 0.125kg / s (operating conditions: 100% rated power)

The experimental object is the CN-1515Ti Irradiation Container Assembly simulator, which is same to the real component in size, shape and processing technology. CN-1515Ti Irradiation Container Assembly simulator is shown in Figure 1, which mainly consists of the operating head, the transition section, hexagonal tube, the transition section and the pin connector.

Figure 1 CN-1515Ti Irradiation Container Assembly simulator

The pin connector is the end of the assembly where water or sodium flow into. In the experiment, the pressure drop of the whole component under the rated flow could be changed by adjusting the margin size of the throttle piece on the pin connector of assembly to meet requirement. The pin connector of assembly shows in Figure 2 and the throttle pieces on pin connector shows in Figure 3. The pin connector was connected to other parts with threads.

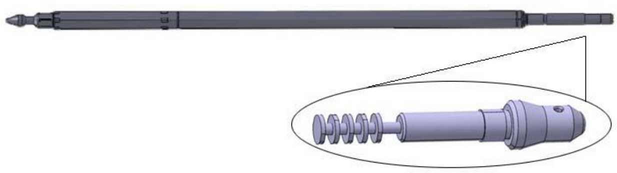

Figure 2 Pin Connector of Assembly

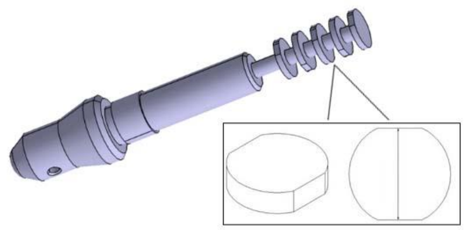

Fig.3 Axial and front view of throttle pieces on Pin Connector

The experiment was carried out on the hydraulic experiment loop of MOX fuel assembly. Figure 4 shows the experimental section, which mainly consists of the components to support assembly and seals to ensure that the flow into the assembly was measured by flow meters. Near the import and export of assembly two pressure port were set up to fetch the pressure difference.

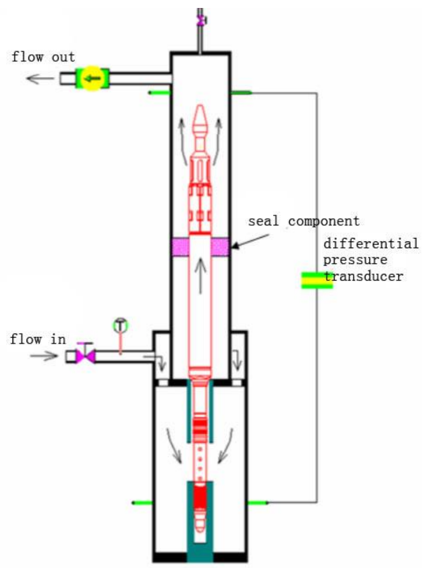

Fig.4 the diagram of the Experimental section

3. Experimental design

In accordance with the requirements of the similar theory and the principles of hydraulic engineering, the following three similar criteria were meted: geometric similarity, boundary conditions similarity and dynamic similarity.

As the experiment assembly was exact same to the actual prototype one, both geometric similarity and boundary conditions similarity criterion were fully met.

According to the similarity principle, it is known that for constant pressure steady flow (steady flow), dynamic similarity is similar to the Reynolds criterion as the Euler number must be the same when the Reynolds number in experimental case is the same as the one in actual prototype.

In the geometric similarity condition, when the Reynolds number in the experimental condition is the same as the Reynolds number in the prototype, the flow resistance coefficient ξ of the two is equal. Thus, water can be used to simulate sodium for experimentation.

As long as the water simulation experiment to ensure that the Reynolds number range can cover the one in the actual operating conditions. The resistance characteristics of the prototype can be calculated according to the experimental ones.

In this experiment, we used water at 96 °C whose kinematic viscosity was equal to ones of sodium at 360 °C. The pressure drop of the simulator in sodium is also equal to ones in water. $\Delta P_{water} = \Delta P_{sodium}$。

Volume flow of water： $q_{water} = \frac{\pi}{4} d^2 u_{water} = \frac{\pi}{4} d^2 u_{Na360} \sqrt{\frac{\rho_{Na360}}{\rho_{water}}} = \frac{G_{Na} \times 3600}{\rho_{Na360}} \sqrt{\frac{\rho_{Na360}}{\rho_{water}}}$

Where, q_{Na} is sodium volumetric flow rate； G_{Na} is sodium mass flow rate。

Set values into the above formula, q_{water} is 3.947 m^3/h and G_{Na} is 0.493 m^3/h. On the other hand, the assembly has the sodium pressure drop of 0.25MPa in the rated flow of 0.125kg / s, so the drag coefficient of the entire assembly can be calculated:

$$\xi_{Na} = \frac{2\Delta P_{Na360}}{\rho_{Na360} \upsilon_{Na360}^2} = \frac{2\Delta P_{Na360}}{\rho_{Na360}\left(\frac{4G_{Na}}{\rho_{Na360} \cdot \pi d_{360}^2}\right)} = \frac{\Delta P_{Na360} \cdot \rho_{Na360} \cdot (\pi d_{360}^2)^2}{8G_{Na}^2}$$

Therefore, the experimental method is as follows: controlling the flow rate through simulator to 0.493m^3/h, and the resistance coefficient of the whole simulator is 2802.10^5 by modifying the size of the throttle piece on the pin connector. At the same time, the pressure drop of the member was 0.25 MPa.

In this experiment, the way to meet the requirements is modifying the margin size of the throttle pieces which is shown in Figure 3.

4. Experimental results and analysis

Finally, after several experiments, we determined that the margin size of the throttle was 17.2mm. The pressure drop and flow rate show in Figure 5. It is illuminated that the pressure drop is about 243kPa at the flow rate of 0.493m^3 / h, which is very close to the required value.

Resistance coefficient shows in Figure 6. It is concluded that the resistance coefficient tends to be stable with the assembly flow changing. It can be considered the resistance square area had been entered at this time, while the drag coefficient has nothing to do with the Reynolds number. From the data of flow rate of 0.478m^3 / h, we take 4 values. The average value of the resistance coefficient is 2709.156, which is very close to the required resistance coefficient (2802.105). The error is only 3.32%.

The resistance coefficient of the processed throttle piece has been met, so there is no need for another modification.

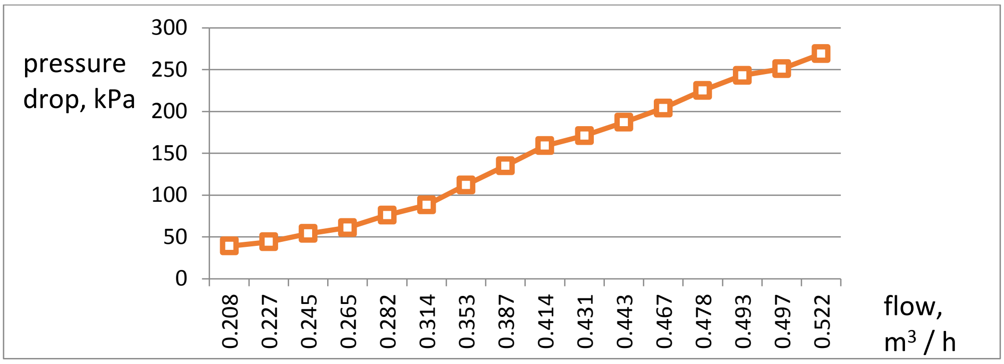

Figure 5 flow rate and pressure drop curve in the final experimental

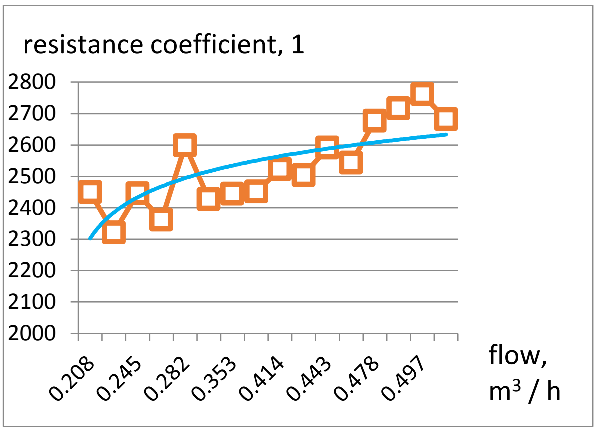

Figure6 resistance coefficient curve in the final experimental

Finally, after several experiment, the opening size (17.2 mm) of the pin was determined.

In the experiment, the pin was the same in the form of openings (both circular whose symmetrical sides were cut off as shown above). So the resistance coefficient depends only on the area while the form of the opening could be exclude, while.

It is assumed that the formula is $S^x \cdot \xi = K$. The experimental data are fitted as shown in the following figure:

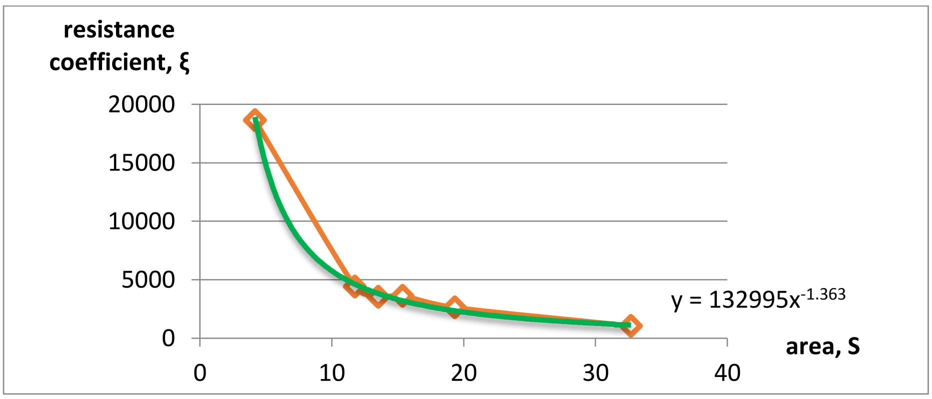

Figure7 the opening area S and the drag coefficient ξ curve

5. CFD Simulation

The CFD simulations target was to investigate 3D field distribution of assembly and verify experimental data. As the meshing of the full assembly is consuming due to the fuels and wire wraps, only the section of simulator pin connector was modelled. However, the experiment both on assembly with pin connector and assembly without pin connector were carried out. The pressure drop data of pin connector can easily concluded by data of assembly with pin connector subtracted by the one of assembly without pin. We also found that most pressure drop were introduced by the pin connector.

In order to obtain real physical results, a grid-independent solution is required. The model of the throttle piece with 17.2mm margin was simulated by two different grid numbers: 500,000 and 1.1 million. The comparison of the two simulation results is as follows: 500,000 grid and 1.1 million grid have a little difference of less than 3% between the simulated results, it can be considered 500,000 grid has reached the grid-independent solution. So 500,000 grid were chosen.

The turbulence was modelled by standard $k-\varepsilon$ model. Mass flow inlet and pressure outlet was set as boundary conditions.

Table 1 the comparison between CFD simulation and experiment data

Volumetric flow, m3/h	**experiment pressure drop, kPa[1]**	**CFD pressure drop, kPa**	**Deviation, %**
0.208	39	44.1	13.1
0.227	44	53.7	22.0
0.245	54	63.2	17.0
0.265	61	73.4	20.3
0.282	76	84.5	11.2
0.314	88	103.7	17.8
0.353	112	134.1	19.7
0.387	135	160.6	19.0
0.414	159	182.9	15.0
0.431	171	199.9	16.9
0.443	187	210.4	12.5
0.467	204	232.4	13.9
0.478	225	243.9	8.4
0.493	243	259.5	6.8
0.496	251	263.4	4.9
0.522	269	292.3	8.7

Note 1: experiment pressure drop =pressure drop of full assembly – press drop of assembly without pin connector

The CFD simulation results and hydraulic experimental data were compared, and the comparison results is shown in Table 1. It is concluded that the largest deviation between CFD simulation and experiment data was 22% at 0.227 m^3/h. However, the deviation decrease along with the flow rate growing. While the flow reached 0.496m^3/h (rated flow), the deviation became nearly small, about 5%. The flow distribution of the pin connector section at this flow is shown in Figure 8. It is concluded that the most pressure drop is introduced in throttle pieces area where flow suddenly changing.

It is obtained that both CFD simulation and experiment data is reasonable and vilified.

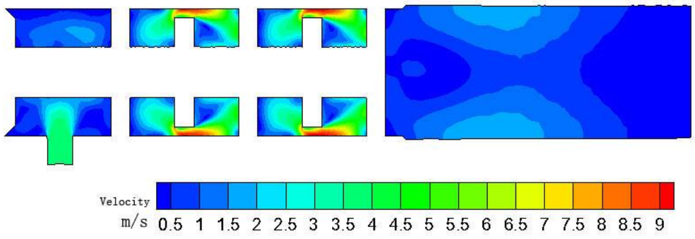

Figure 8 the speed distribution of the pin section

6. Conclusions

Based on the actual parameters of CEFR-MOX assembly, the experimental scheme was designed by analysing and demonstrating the similarity principle. The flow characteristics of CN-1515Ti irradiation containers assembly (one of MOX irradiation container assemblies) was studied by experimental method. The margin size of throttle piece on the pin connector of assembly determined by the experiment results was 17.2mm. Then the empirical formula of S - the area of the opening and ξ-resistance coefficient was concluded as $\xi * S^{1.363}=132995$, which could be used for similar experiments.

The CFD simulation of the pin connector part of the irradiation container assembly was carried out, and the three-dimensional flow field of the pin was obtained through calculation.

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