ICANS-XV
15th Meeting of the International Collaboration on Advanced Neutron Sources
November 6-9, 2000
Tsukuba, Japan

18.16
Thermal-Hydraulic Experiments and Analyses on Cold Moderator

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Abstract

A cold moderator using supercritical hydrogen is one of the key components in a MW-scale spallation target system, which directly affects the neutronic performance both in intensity and resolution. Since a hydrogen temperature rise in the moderator vessel affects the neutronic performance, it is necessary to suppress the local temperature rise within 3K. In order to develop the conceptual design of the moderator structure in progress, the flow patterns were measured using a PIV system under water flow conditions using a flat model that simulated a moderator vessel. From these results, the flow patterns (such as recirculation flows, stagnant flows etc.) were clarified. The hydraulic analytical results obtained using the STAR-CD code agreed well with experimental results. Thermal-hydraulic analyses in the moderator vessel were carried out using the STAR-CD code. Based on these results, we clarified the possibility of suppressing the local temperature rise to within 3K under 2MW operating conditions. In order to achieve the cost decreasing of the hydrogen loop, it is necessary to operate it reducing the hydrogen flow rate and the whole hydrogen mass. Then improved moderator concept using blowholes and a twisted tape was proposed, and we have tried to examine the effect of the blowing flow from the inlet pipe. From the experimental and analytical results, the blowing flow could be feasible for the suppression of the stagnant region.

1. Introduction

The Japan Atomic Energy Research Institute (JAERI) and High Energy Accelerator Research Organization (KEK) have been progressing in the design and R&D of a high-intensity proton accelerator under the High-Intensity Accelerator Project[1]. In this project, a neutron scattering facility will be constructed in which high intensity neutrons are generated toward a target by a spallation reaction between the target material and a proton beam of MW-scale power. Then, high intensity neutrons are divided into three energy levels - cold, thermal and epithermal - by moderators which are placed close to the target. In order to select cold and thermal neutrons, supercritical hydrogen will be used as a moderator material (with its excellent pulsed neutronic performance both in sharpness and in high intensity). However, the supercritical hydrogen moderator (cold moderator) has not yet been applied to a MW-scale spallation target. To secure the neutronic performance induced by neutronic analyses, it is necessary to solve technical issues on both the structural strength and the thermal hydraulics. The structural strength of the moderator vessel under supercritical hydrogen conditions of 1.5MPa and 20K also needs to be maintained. With thermal hydraulics, it is necessary to reduce the recirculation and stagnant flows in order to maintain the uniform temperature rise within 3K[2].

The representative structure of the cold moderator is that operated at the ISIS[3] using liquid hydrogen. Figure 1 shows a present model of the cold moderator based on the ISIS moderator. Supercritical hydrogen flows into the vessel through the inner pipe inserted in the vessel. Then, it flows out through the outlet channel between the inner and the outer pipes. To prove the feasibility of this concept, structural and hydraulic analyses as well as flow pattern experiments using a water loop were carried out. This paper introduces the hydraulic analytical and experimental results, and a feasibility of the moderator concept improved based on these results.

2. Flow Pattern Measurements and Hydraulic Analyses of the Present Model

2.1 Experimental Apparatus and Conditions, Analytical Conditions

Flow visualization experiments were carried out under water conditions to clarify the flow patterns and to verify the analysis code. Figure 2 shows the flow diagram of the experimental apparatus for the flow pattern measurement. The water loop was composed of a tank, a pump and a flow meter, supplying water to the test section. The test section that was a flat model simulated a moderator vessel, consisted of acrylic resin for visualization. The height of the inlet pipe was varied at 10, 30 and 50mm, and the inlet water velocity was from 0.5m/s to 3m/s (flow rate: 0.25 – 1.47L/s, Re: 1.4×10^4 – 8.4×10^4) under room temperature. The flow patterns of the impinging jet flow and the jet induced flow were measured with a PIV system. The PIV system was a particle image velocimeter using a laser pulse sheet. In this measurement, small amounts of fluorescence micro particles (10μm) were mixed with water as the tracer. Figure 3 shows an example of a particle image obtained by the PIV system. By processing a series of 100 pictures taken at around 1s intervals using the PIV system, the velocity distribution in the vessel was effectively visualized.

The hydraulic analysis was carried out with the computational fluid dynamics code, STAR-CD, for use with the steady, incompressible fluid flow under water flow conditions. The turbulence model used the standard k-ε model equations, and the boundary condition was the standard law-of-the-wall boundary condition, and a steady state solution algorithm was used the SIMPLE. Figure 4 shows the analytical model. The model used was the same as the experimental model of a simulated moderator vessel and the flow conditions were also the same as the experimental conditions.

2.2 Experimental and Analytical Results

Figure 5 shows examples of the experimental and analytical results at 10mm height of the inlet pipe and 1.23L/s flow rate. In the experimental result, water flowed into the vessel through the inner pipe, jetted and impinged on the bottom of vessel. Then it flowed parallel with the vessel wall, and a recirculation flow induced by the impinging jet was generated near the corner of vessel. While the flow parallel with the vessel wall increased in velocity gradually, a stagnant region of occurred in the center of the vessel around the inlet pipe. In the analytical results, the recirculation flow and stagnant flow were the same as the experimental ones. Some experiments and analyses that were carried out varying the flow rate and the height of the inlet pipe were also the same as the flow patterns. Thus, flow patterns, such as the recirculation and stagnant flows, were clarified. The hydraulic analytical results obtained using the STAR-CD code agreed well with experimental results.

2.3 Preliminary Thermal-Hydraulic Analyses

Preliminary thermal-hydraulic analyses were carried out for the moderator vessel estimated now using the STAR-CD. The analytical conditions are as follows; liquid hydrogen flowing at 20K, inlet flow rate was changed from 0.49L/s to 2.45L/s, the inlet velocity = 1.0 - 5.0m/s, Re = $1.36\times10^5 - 6.82\times10^5$. The analytical model used was similar to the model in Fig.4, with an added aluminum alloy vessel wall and inlet pipe. The heat deposition values that were obtained from the neutronic calculation in the hydrogen and the aluminum alloy under the 2MW proton beam operation shown in Figure 6[4] were entered the following function including 25% safety margin.

$$[\text{Heat deposition of the hydrogen } (\mathrm{W/cm^3})] = -0.00084381\,x^3 + 0.034134\,x^2 - 0.5187\,x + 3.6121$$

$$[\text{Heat deposition of the aluminum alloy } (\mathrm{W/cm^3})] = -0.0018644\,x^3 + 0.067421\,x^2 - 0.90428\,x + 6.2958$$

Here, x is the distance from a bottom surface of the moderator vessel (cm).

The distribution of the heat deposition in the horizontal direction was not considered for the sake of safety. From the analytical results of velocity distributions, the flow patterns of liquid hydrogen were almost the same as that of water shown in Sect.2.2.

Figure 7 shows an example of the analytical results of temperature distributions, when the inlet flow rate was 1.47L/s (inlet velocity = 3.0m/s). The temperature of vessel wall was higher than one of liquid hydrogen because the heat deposition of the aluminum alloy was larger than one of liquid hydrogen. So the maximum temperature was 23.8K at corner of the vessel wall. As regards to the temperature of liquid hydrogen, a hot spot of 21.7K generated in the stagnant flow rather than in the recirculation flow. Therefore, it is necessary to maintain the temperature rise of the stagnant flow region within 3K in order to keep the neutronic performance.

Figure 8 shows relationships between the flow rate and hydrogen temperature in the stagnant region, outlet temperature of a first moderator and stagnant temperature of a second moderator if connected behind the first moderator. From this result, if a moderator vessel is used for a liquid hydrogen loop, our goal to maintain the temperature rise within 3K can be attained easily in more than 0.8L/s flow rate. However, connecting the second vessel behind the first one is planned in order to reduce the flow rate, the hydrogen inventory, and cost of the moderator system. The stagnant temperature of a second moderator is the sum of the hydrogen temperature in the stagnant region and the outlet temperature of a first moderator. It is also necessary to suppress this temperature rise within 3K. Accordingly, an improved moderator structure was proposed to satisfy this requirement with around 1.0L/s flow rate operation which reduces the flow rate as low as possible.

3. Flow Pattern Measurements and Hydraulic Analyses of the Improved Model

3.1 The Improved Moderator Structure

Figure 9 shows an improved concept of the cold moderator. As a method of suppressing the local temperature rise, installing small blowholes in the inlet pipe that blow hydrogen to the recirculation and stagnant flow region was proposed. A twisted tape used to generate an intense swirl flow in order to maintain high heat transfer rate on the bottom surface of the vessel was also installed into the inlet pipe. Some experiments and analyses were carried out to confirm the effect of these means.

3.2 Experimental and Analytical Results

Some experiments and analyses for the improved concept were carried out under the same conditions of Sec.2.2 with blowholes and a twisted tape installed in the inlet pipe.

Figure 10 shows examples of the experimental and analytical results at 10mm height of the inlet pipe and 1.23L/s of the flow rate. In the experimental and analytical results, blowing water into the vessel through the blowholes was verified. The recirculation flow region was reduced by the effect of this blowing flow. The stagnant region was also reduced slightly. However, the flow rate from the bottom of the inlet pipe significantly decreased (about 30%) compared with the previous model. The temperature rise of the bottom of the moderator vessel was expected because of the reduction of heat removal with a drop of the flow velocity.

3.3 Preliminary Thermal-Hydraulic Analyses

Thermal-hydraulic analyses were carried out for the improved concept by similar methods. Figure 11 shows an example of the analytical results of temperature distributions, when the inlet flow rate was 1.47L/s (inlet velocity = 3.0m/s). The maximum temperature was 26.0K at the bottom of vessel wall. The reason for this increased temperature is the decreased flow rate from the bottom of the pipe discussed above. In the temperature of liquid hydrogen, which affects the neutronic performance, the maximum temperature was 21.9K at a stagnant region between the blowholes. There was no significant difference between this result and a previous model's result. If the optimizations of blowholes (such as a number, a size and a position etc.) are carried out, it is possible that the temperature rise of the moderator will be suppressed more effectively.

4. Conclusions

To prove the feasibility of suppression of the local temperature rise within 3K, which is one of the difficulties in the design of cold moderator using hydrogen, the visualized experiments and hydraulic analyses were carried out under water flow conditions. From these results, the flow patterns were clarified and the hydraulic analytical results agree well with the experimental results. In the thermal-hydraulic analyses under liquid hydrogen flow conditions, it was verified that the hot spot is generated in the stagnant flow region rather than in the recirculation flow region. In the case of using one moderator vessel for a liquid hydrogen loop, the loop operating condition, which can satisfy the thermal requirement easily, was estimated.

An improved moderator concept using blowholes and a twisted tape was proposed to decrease the cost of the moderator system. The experiments and analyses were carried out to confirm the effect of these adaptations. From these results, we verified that the blowing flow could be feasible for the suppression of the recirculation and stagnant flow regions.

References

[1] The Joint Project Team of JAERI and KEK, JAERI-Tech 2000-003(2000) (in Japanese).

[2] T. Aso et al, “Structural and Hydraulic Study on Cold Moderator”, ICANS-XIV, Volume 2, p.904-812(1998).

[3] T. A. Broom, “Prospects for Target and Methane Moderators at ISIS”, ICANS-XIII, pp.632-643(1995).

[4] M.Teshigawara (JAERI), private communication.

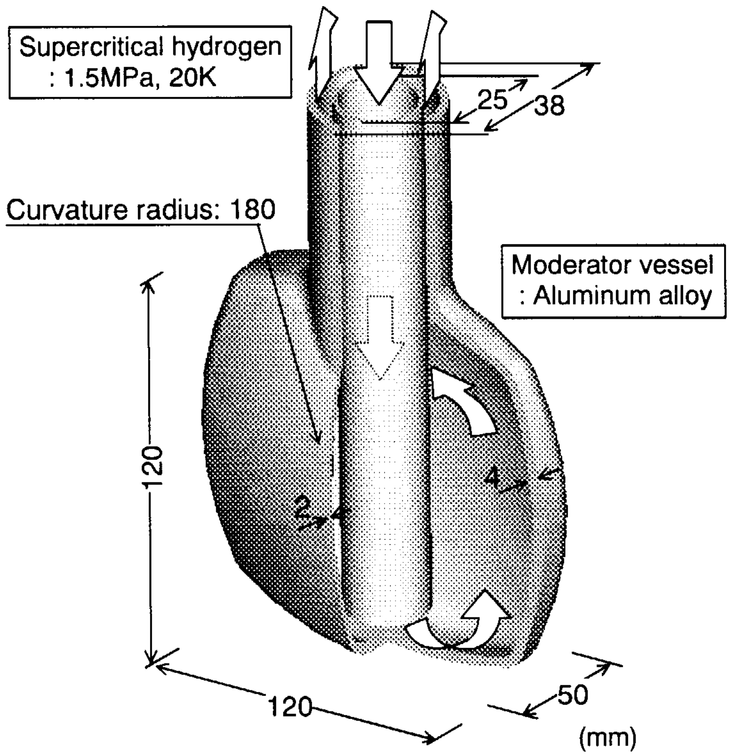

Fig.1 Concept of the Cold Moderator

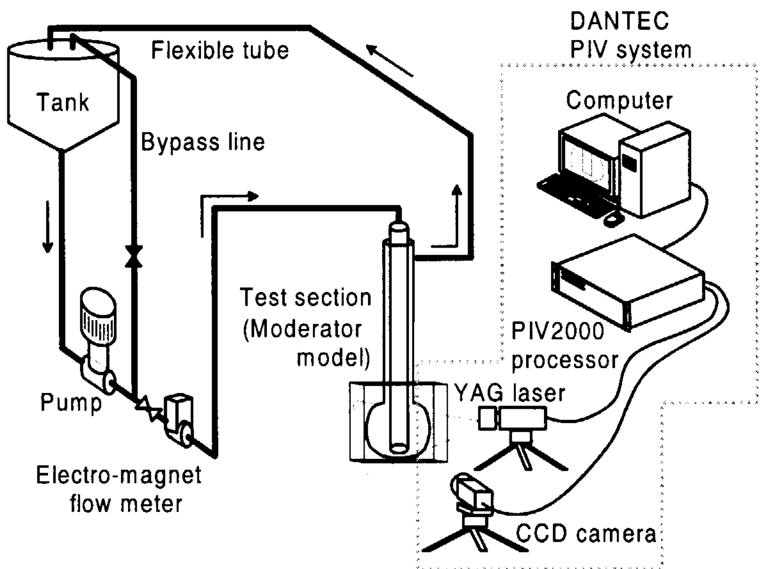

Fig.2 Experimental Apparatus for Flow Pattern Measurement

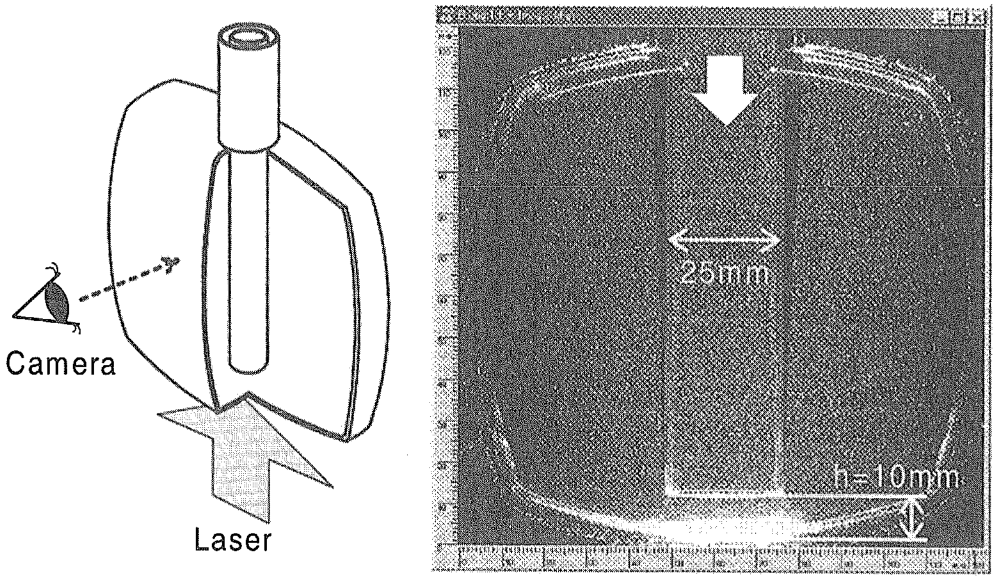

Fig.3 Particle Image obtained by PIV

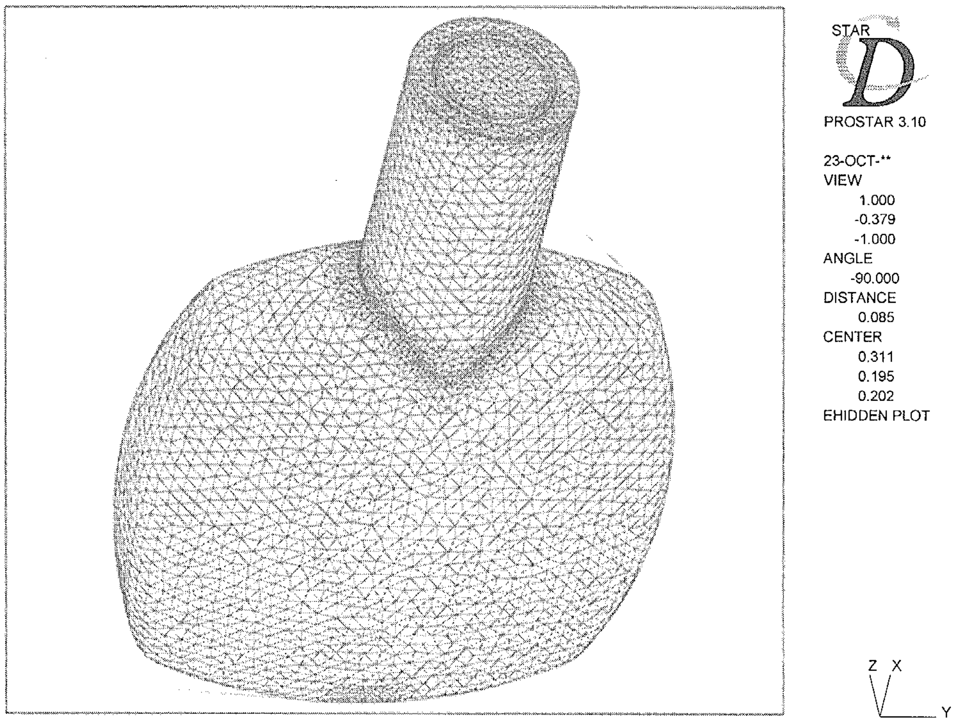

Fig.4 Analytical Model of the Moderator Vessel

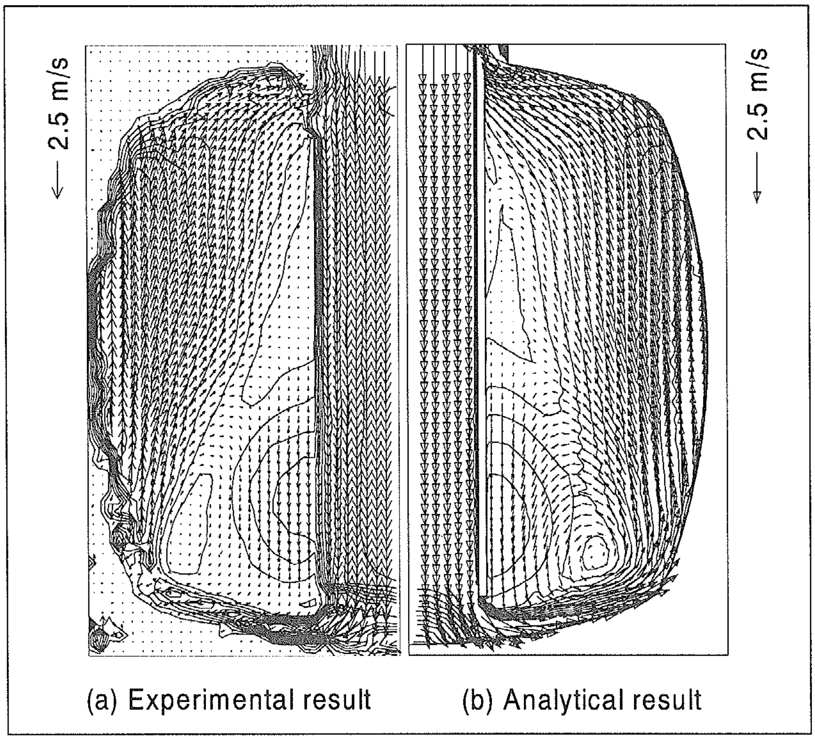

Fig.5 Experimental and Analytical Results of Flow Pattern Measurements at 2.5m/s Inlet Velocity

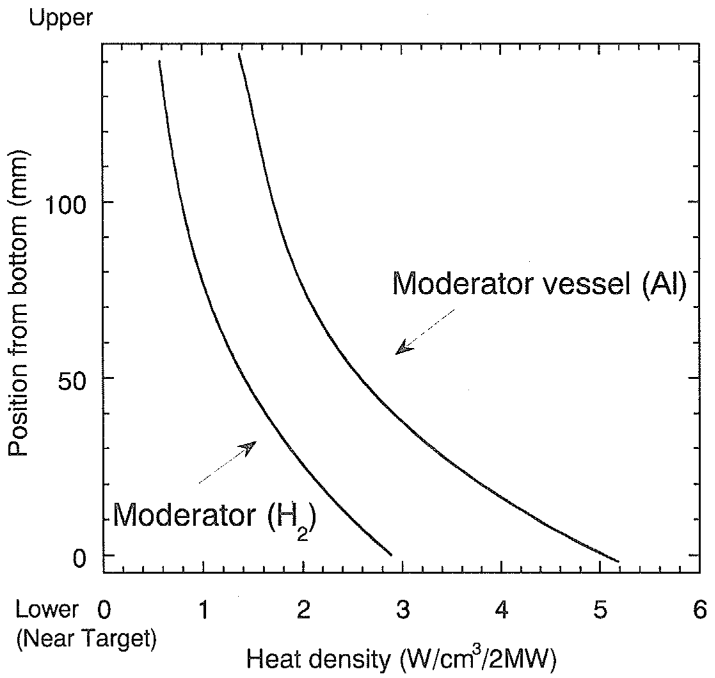

Fig.6 Heat Density Distribution in the Cold Moderator under the 2MW Proton Beam Operation

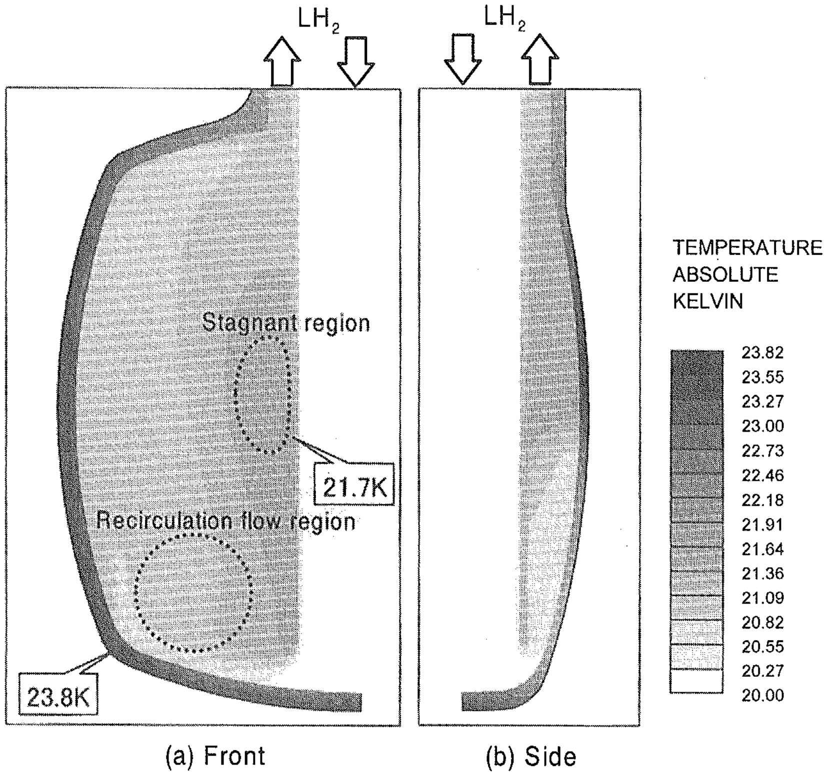

Fig.7 Analytical Result of Temperature Distribution under Liquid Hydrogen Flow

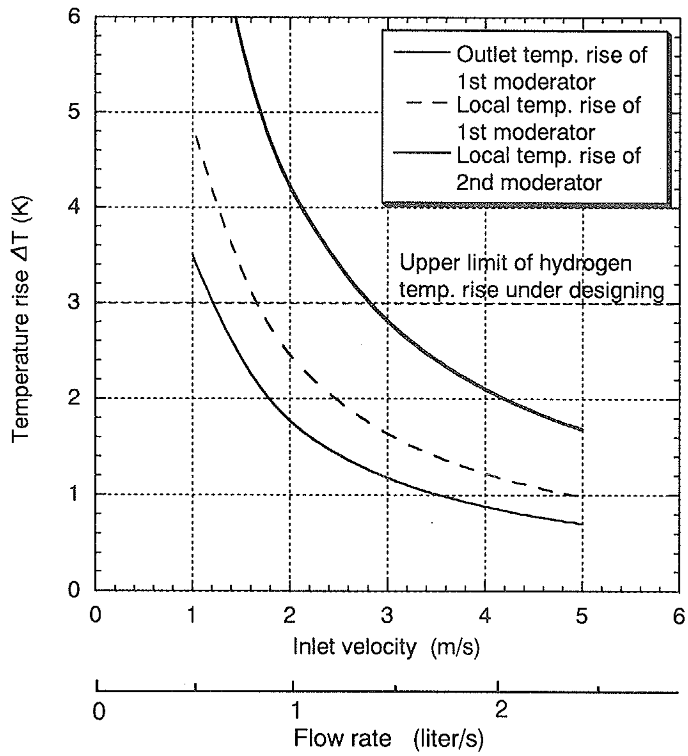

Fig.8 Relationship between Flow Rate and Hydrogen Temperature Rise Obtained by Analytical Results

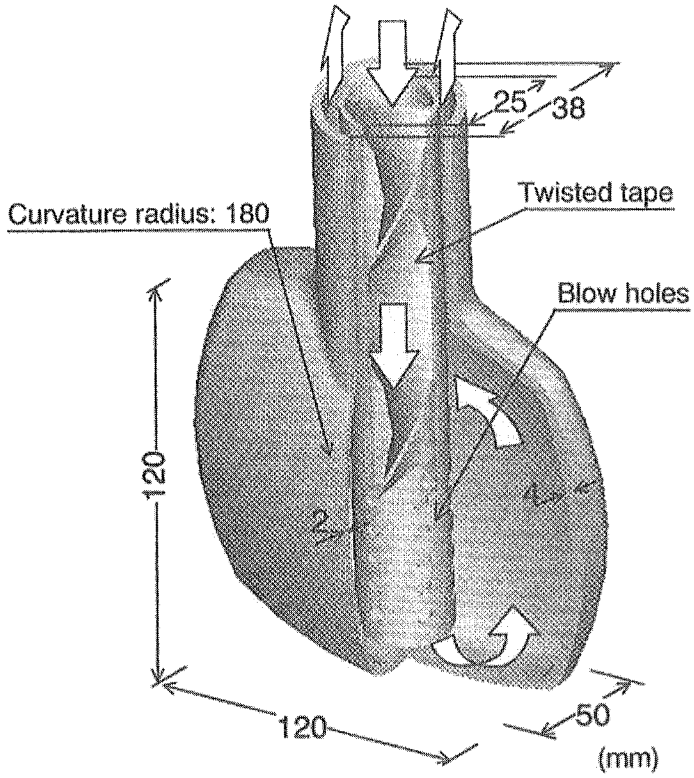

Fig.9 Improved Concept of the Cold Moderator

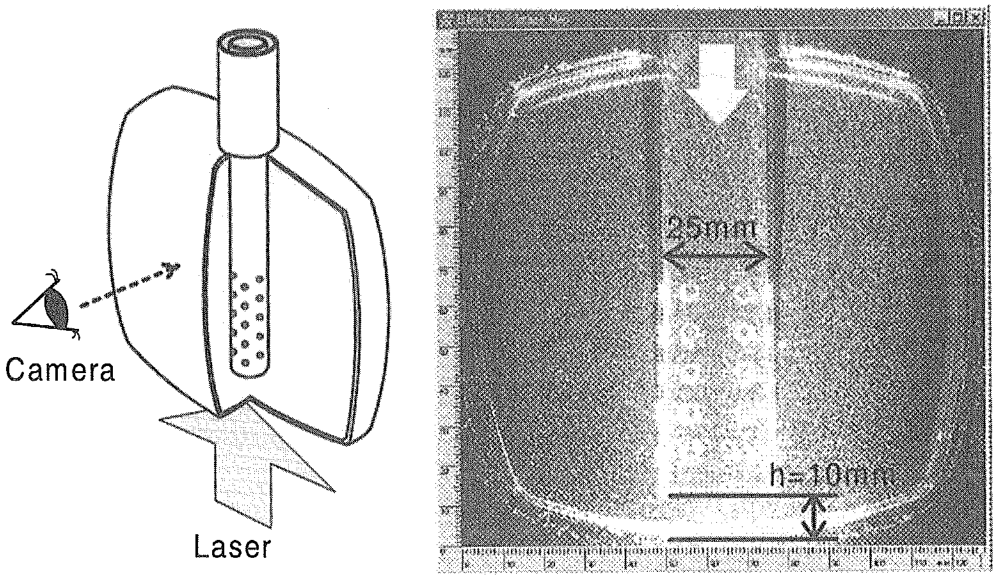

Fig.10 Particle Image obtained by PIV

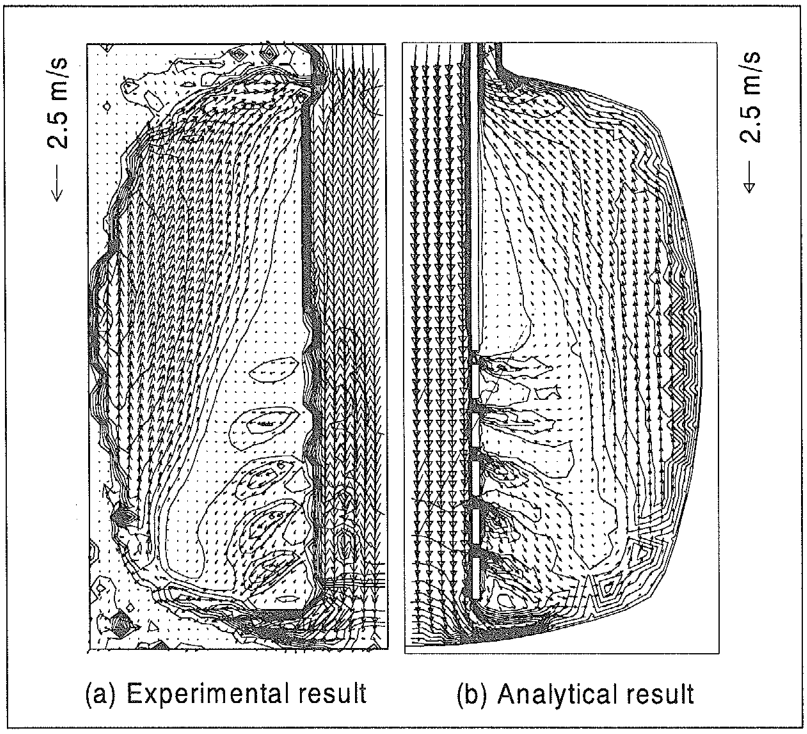

Fig.11 Experimental and Analytical Results of Improved Flow Pattern at 2.5m/s Inlet Velocity

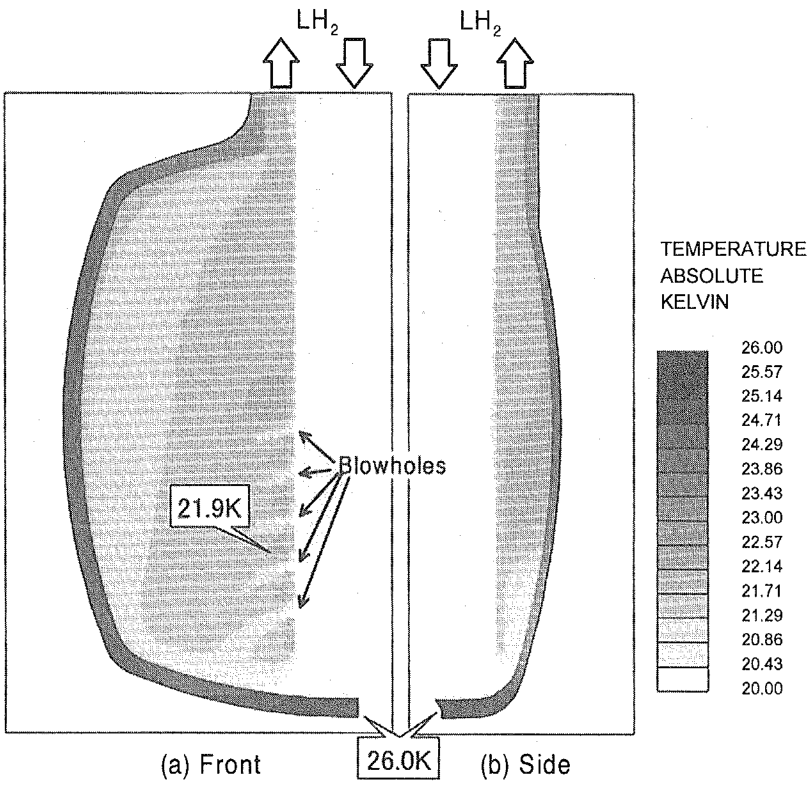

Fig.12 Analytical Result of Temperature Distribution under Liquid Hydrogen Flow Improved