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STRUCTURAL STUDY OF THE COLD MODERATOR

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The Japan Atomic Energy Research Institute is developing a 5MW-spallation target system under the Neutron Science Project. A cold source moderator using supercritical hydrogen is one of the key components in the 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 ensure the smooth flow of hydrogen while at the same time suppressing the recirculation and stagnant flows which cause hot spots. On the structural strength side, it is necessary to maintain the strength of the moderator vessel under supercritical conditions of 1.5MPa and 20K. The flow patterns of the impinging jet flow and the jet induced flow were measured using a PIV system under water flow conditions with the simplified moderator model. The hydraulic analytical results obtained using the STAR-CD code agreed well with this experimental result. Preliminary structural analysis was carried out to clarify any technical problems regarding the concept of a thin-walled structure for the cold moderator vessel. Structural analytical results showed that the maximum stress of 112MPa occurred on the moderator surface, which exceeded the allowable design stresses of ordinary aluminum alloys. The above-mentioned results are assumed to be a base of the structural design for a moderator vessel of the future.

Keywords: Spallation Target System, Neutron Science Project, Cold Moderator,
Supercritical Hydrogen, Temperature Rise, Flow Pattern, Jet Flow,
Recirculation and Stagnant Flow, Structural Analysis, Aluminum Alloy

冷減速材の構造設計に関する研究

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原研で開発を進めている5MW規模の核破砕ターゲットシステムにおいて、超臨界水素を用いる冷減速材は中性子強度やパルス性能などの中性子性能に直接影響する重要な機器である。特に冷減速材容器内における水素温度の上昇が中性子収率に影響するため、冷減速材容器の設計では再循環流や停滞流の発生などホットスポットの発生要因を抑制して円滑な流動を実現する必要がある。一方、構造強度の点においては、1.5MPa、20K の超臨界水素条件の下で減速材容器の構造強度を維持する必要がある。そこで、冷減速材容器の簡易モデル試験体を用いて、入口噴流管による衝突噴流とその随伴流の流動パターンを水流動条件下で測定した。その結果、STAR-CD コードによる流動解析結果の流動パターンとよく一致した。また、冷減速材容器の薄肉構造における技術的な課題を明らかにするため、予備的な構造強度解析を行った。その結果、容器には 112MPa の最大応力が生じ、通常のアルミ合金の許容応力を超えた結果となった。以上の結果を今後の構造設計の基礎にする。

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1. Introduction

The Japan Atomic Energy Research Institute (JAERI) is progressing in the design and R&D of a high-intensity proton accelerator under the Neutron Science Research 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 5MW of 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 the 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 regarding both the structural strength and the thermal hydraulics. The structural strength of the moderator vessel under a supercritical hydrogen condition 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.

The representative structure of the cold moderator is that operated at the ISIS(2) using liquid hydrogen. **Figure 1** shows a concept 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 analytical and experimental results.

2. Hydraulic Study

2.1 Flow Pattern Measurement and Hydraulic Analysis

The cold moderator using supercritical hydrogen is one of key components in the 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 ensure the smooth flow of hydrogen while suppressing the recirculation and stagnant flows which cause hot spots. Flow visualization experiments were also carried out under water conditions to clarify the flow patterns and to verify the analysis code.

Figure 2 shows the flow diagram and the outer view 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. In the test section, which a simplified moderator model consisting of acrylic pipes was used. The jet flows out of an inner pipe of 25mm into an outer pipe of 60mm. The flow patterns of the impinging jet flow and the jet induced flow were measured with a PIV system. The PIV system is 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. By processing a series of 100 pictures taken at around 1ms 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 3** shows the analytical model. The model used was the same as the experimental model of a simplified two-dimensional type with dimensions of 25mm of the inner pipe diameter, and 60mm of the outer pipe diameter. The nozzle height was changed from 2mm to 30mm, and the inlet water velocity was from 0.5m/s to 3m/s under room temperature. **Figure 4** is an enlargement of the analytical results. This shows that a recirculation flow caused by the jet blowing out from the inlet pipe nozzle is generated around the inner pipe. A recirculation flow length, shown in **Fig.4**, is a height from bottom of the outer pipe to top of recirculation flow region where is a boundary of upward flow and downward flow.

Figure 5 shows the relationship between the inlet velocity and the recirculation flow length. The height of the nozzle from the bottom was fixed at 10mm (the same distance as the concept shown in **Fig.1**) and the inlet water velocity was changed from 0.5m/s(Re=14,000) to 3.0m/s(Re=84,000). The experimental results agree very well with the analytical results, and were about 50mm without dependence on the inlet velocity. **Figure 6** shows the relationship between the height of the nozzle and the recirculation flow length. The inlet velocity was fixed at 3.0m/s, and the nozzle height was changed from 2mm to 30mm. The experimental results confirm the analytical results when the nozzle height is more than 10mm, and the recirculation flow length is about 50mm. However, below a 10mm height, the measured lengths become lower than the analytical results produced. This variation is caused by the vibration of the inner pipe, which was observed in the experiments. From these results, flow induced vibration could be effective in suppressing the occurrence of the recirculation flow, which may be due to flow perturbation caused by the pipe vibration. **Figure 7** shows some of the experimental and analytical results. The measured flow patterns reveal the recirculation flow clearly and agree very well with the analytical results.

2.2 Preliminary Thermal Hydraulic Analyses in the Cold Moderator Vessel

Preliminary thermal hydraulic analyses were carried out for the moderator vessel estimated now using the STAR-CD. Two analytical models shown **Fig.8**, which were drawn based on **Fig.1**, were prepared for the analyses. A transfer tube connecting the components of the moderator system has two vacuum layers at both the inside and outside of the return supercritical hydrogen in order to insulate the heat from the outside and to maintain the cryogenic condition. In model A, the innermost vacuum layer is installed to a section where is connected with the flat moderator vessel. Alternately, the vacuum layer is installed to upstream of about 50mm from the section connected with the vessel in model B. In both models the moderator vessel is the same size, while the diameter of the transfer tube of model B is larger than the one of model A in order to get the hydrogen flow rate to increase.

The analytical conditions are as follows; liquid hydrogen flowing at 20K, inlet velocity was changed from 1.0m/s to 9.0m/s, Re = 1.53×10^{6} - 1.37×10^{7}(model A), 1.91×10^{6} - 1.72×10^{7}(model B). The heat deposition that was obtained from the neutronic calculation in the hydrogen shown **Fig.9**(3) was entered as following a fitting function;

$$\text{Heat deposition (W/cm}^3\text{)} = -0.00223x^3+0.083787x^2-1.1606x+8.3729$$

x : The distance from a bottom surface of the moderator vessel (cm)

The distribution of the heat deposition of the horizontal direction and the thermal conduction of the inner pipe were not considered estimating to the safety side. The heat generation of an aluminum alloy that is the vessel material was not also considered to simplify the analyses.

Figure 10 shows a example of the analytical results of velocity and temperature distributions, when the inlet velocity was 3.0m/s in model A. Similarly, **Fig.11** shows model B. Both results of the velocity distributions reveal the recirculation flows clearly. From the temperature distributions, hot spots where the hydrogen temperature rises were generated in the center of the recirculation flow. The temperature rise was 4.7K in model A and 3.9K in model B when set at 3.0m/s inlet velocity. This is because the flow rate of model B is more than model A's due to a difference of the pipe diameter. **Figure 12** shows the relationship between the inlet flow velocity and the temperature rise. From this figure, it is necessary to secure the velocity for 4.7m/s or more in order to suppress the temperature rise within 3K for model A. In the case of model B, the velocity only has to be 4m/s or more. From these results, we clarified the hydrogen flow condition to suppress the uniform temperature rise.

Another method of suppressing this temperature rise is made possible by installing small holes in the inlet pipe that blow hydrogen to the recirculation flow region, which causes the temperature rise. A twisted tape used to generate an intense swirl flow in order to maintain high transfer rate on the bottom surface of the vessel is also installed into the inlet pipe. Some experiments and analyses to confirm the effect of these means are being prepared at present.

3. Structural Study

Maintaining the structural strength of the moderator vessel while under a supercritical condition of hydrogen at 1.5MPa and 20K continues to be one of the major technical issues in the design of the cold moderator. It is necessary for the wall thickness of the vessel to be as thin as possible in order to maintain high neutron transmission rates in relation to a high neutron yield. Forged aluminum alloys are generally used for the vessel materials, both for the cold moderator as well as the thermal or epithermal moderator, because they both absorb neutrons at a lower rate. To obtain a clearer idea of the allowable thickness in forging aluminum alloys, stress analyses were carried out for the thin-walled structure shown in **Fig.1** under the following conditions :

Vessel size: 120mm wide, 120mm high, 50mm long and 3mm thickness
180mm in curvature radius of vessel surface
Temperature: 20K
Internal pressure: 1.5MPa
Vessel material: Forged aluminum

The structural analysis code ABAQUS was used to analyze the distribution of stress. Then, a structural model was divided into 4800 elements using the 3-D quadrilateral shell element.

Figure 13 shows one of the analytical results of the distribution of stress on the inner and the outer vessel surface. As a result, the maximum Mises stress is the sum of the membrane and bending stresses generated on the ridgeline. The maximum value was 99MPa on the outer surface and 112MPa on the inner surface, respectively. **Table 1** shows the design stresses of candidate materials for the vessel. A6061 (Al-Mg-Si-Cu-Cr) and A5083 (Al-Mg-Mn-Cr) are used widely for cryogenic vessels. A2014 (Al-Cu-Mg-Mn-Si) is used as a structural material for liquid hydrogen/oxygen fuel tanks used for rockets. The design stress of each material is 63MPa of A6061, 68MPa of A5083 and 110MPa of A2014(4), which is lower than the maximum Mises stress of 112MPa. To keep the structural strength, the vessel wall needs to be thickened as per this table. However, the wall needs to be as thin as possible when factoring in the neutronic viewpoint. **Figure 14** shows the neutron transmission ratio to the required thickness against the allowable stress. As seen in this figure, A2014 reveals a good performance for the vessel material, so we plan to use A2014. In addition, as the design stress of A2014 is lower than 112MPa, a new vessel structure is being proposed here. This is a structure in which the thickness of a face that is produced the neutron beam leaves 3mm, the ridgeline which generated the maximum Mises stress is thickened around 5mm. We are preparing the structural analysis for this vessel structure, and planning an experiment for strength under high pressure using water.

On the basis of stress analysis and flow visualization results, the moderator vessel was modified as shown in **Fig.15**. The vessel materials used are the aluminum alloys such as A2014. Dimensions of the vessel are 120mm wide, 120mm high, and 50mm long and 3-4mm thick. A twisted tape is installed inside the inner pipe in order to keep high heat transfer rates on the bottom surface of the vessel by the swirl flow caused by the twisted tape. Following this, most of the supercritical hydrogen flows through the inlet pipe towards the bottom of the vessel, but small amounts of flow bypass through small holes located at the bottom half of the inlet pipe to suppress the recirculation flow.

4. Conclusions

The cold moderator using supercritical hydrogen, works as a filter of the high intensity neutrons generated at the spallation target under a 5MW proton beam. Flow patterns of the impinging jet flow and the jet induced flow were measured under water flow conditions. The hydraulic analytical results agree very well with the experimental results. Both results clearly indicated the recirculation flow. From the results of preliminary thermal hydraulic analysis for the moderator vessel, it was verified that the recirculation flows were generated in the vessel and the hot spots were generated in the recirculation flow region. We clarified the hydrogen flow condition in order to suppress the uniform temperature rise. Since the cold moderator has not yet been applied to a MW-scale target, preliminary structural analyses were carried out to clarify potential technical problems regarding the concept of a thin-walled structure for the cold source moderator. Structural analytical results showed that the maximum Mises stress of 112MPa occurred on the moderator surface, which exceeds the allowable design stresses of ordinary forged aluminum alloys under the supercritical condition of 1.5MPa and 20K. The moderator vessel should be redesigned in its basic structure while at the same time maintaining the compact, thin-walled and flat surface structure. Based on the analytical and experimental results, a new moderator concept using the thin-walled structure has been proposed to maintain its strength and to suppress the recirculation flow. We will keep improving a new concept in order to successfully construct a high neutronic performance with good mechanical and thermal hydraulic performances so as to complete the MW target system.

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(3) Watanabe, N., et al., "Towards a High-Efficiency Pulsed Cold Neutron", Proceedings of the 14th Meeting of the ICANS, pp743-750 (1998)

(4) Institution for Safety of High-Pressure Gas Engineering: regulation laws collection (1993), (in Japanese).

Table 1. Design stresses of candidate aluminum alloys

Material	Design stress	Endurable thickness for the stress of 112MPa
A6061	63MPa	5.3mm
A5083	68MPa	4.9mm
A2014	110MPa	3.1mm

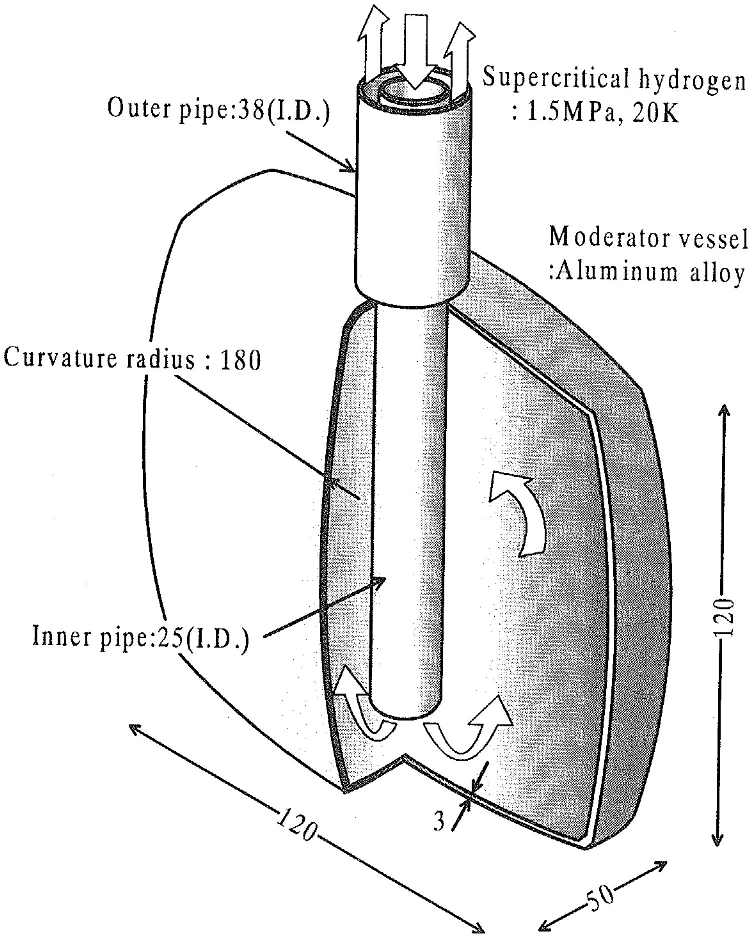
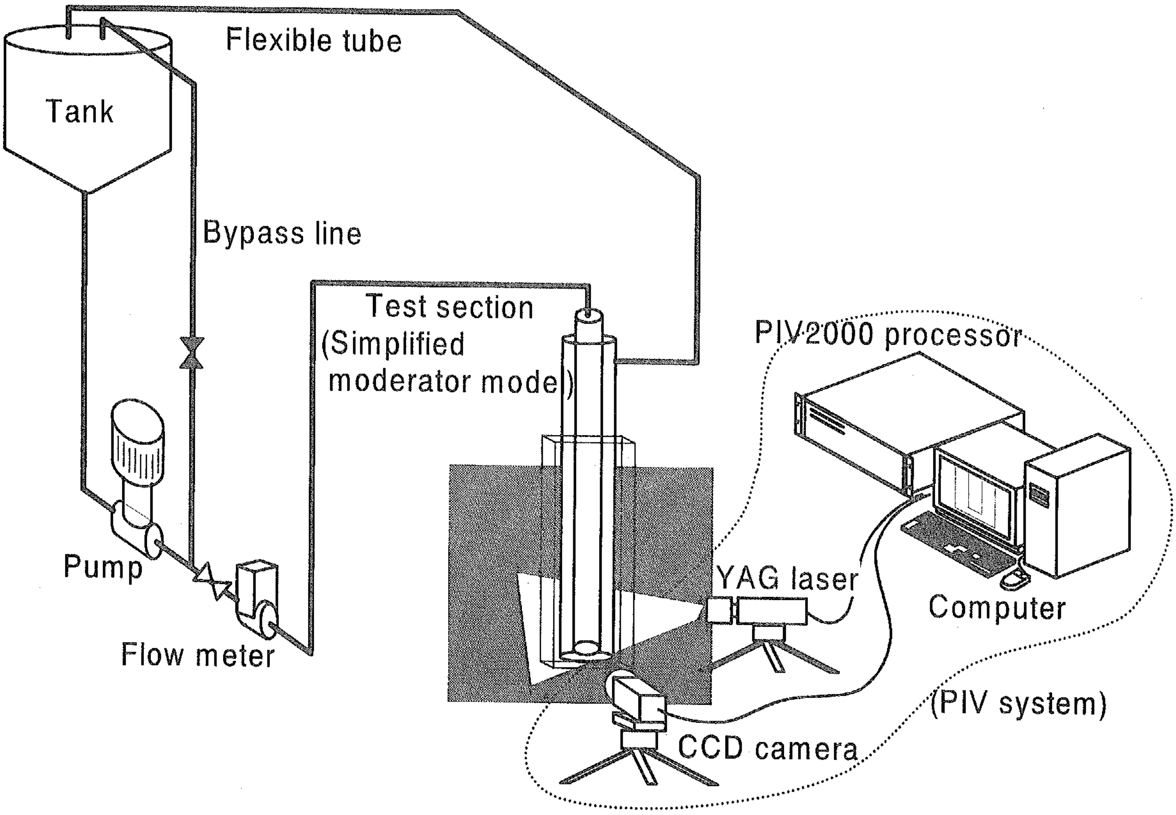
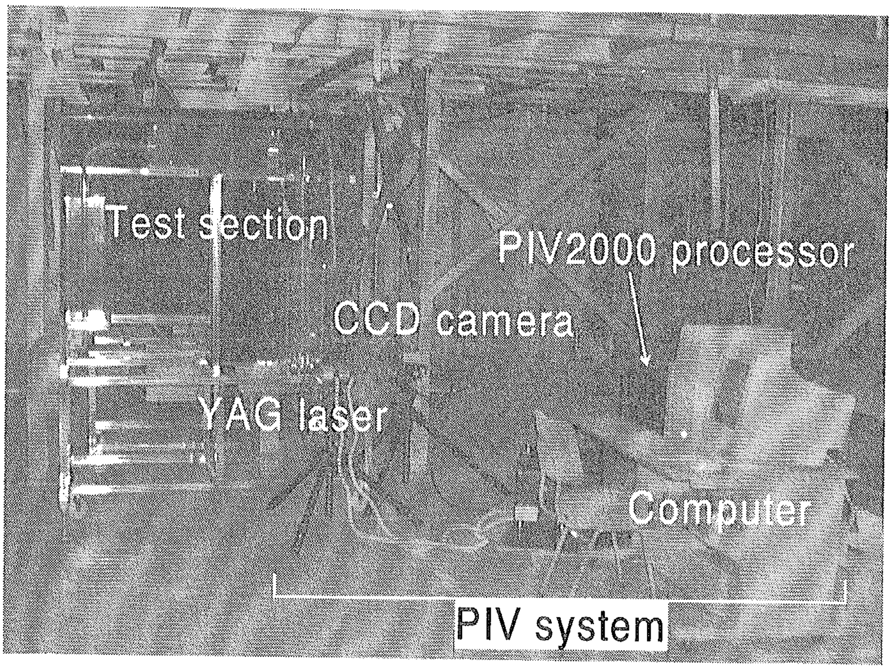


Fig.1 Concept of the cold moderator.



(a) Flow diagram



(b) Outer view

Fig.2 Experimental apparatus for flow pattern measurement.

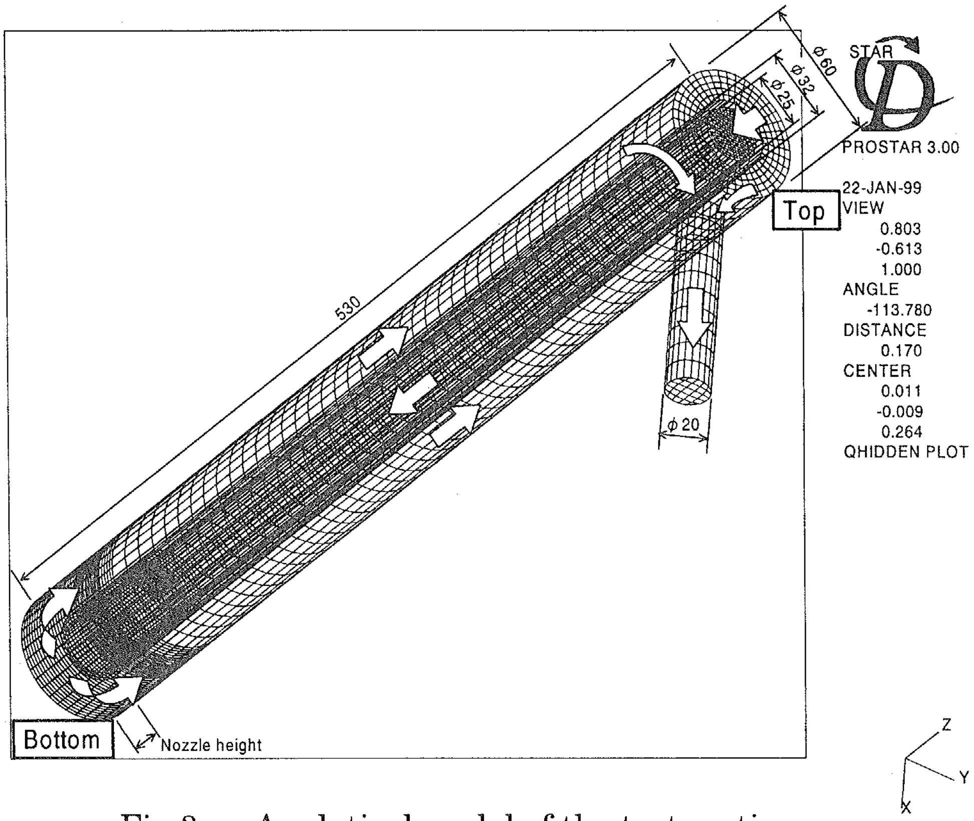


Fig.3 Analytical model of the test section.

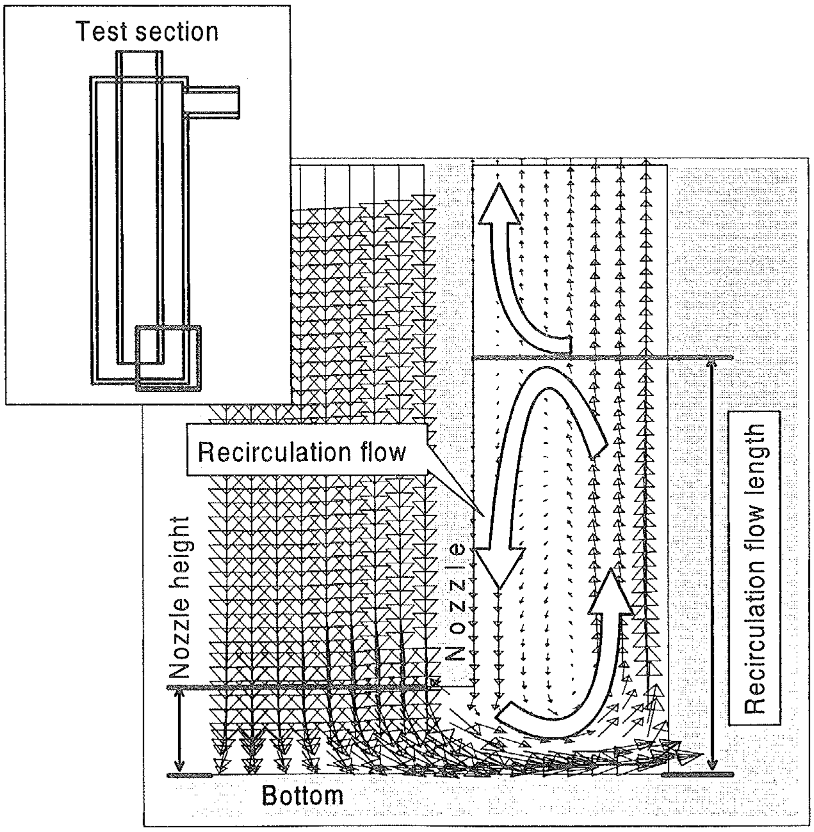


Fig.4 Recirculation flow and recirculation flow length.

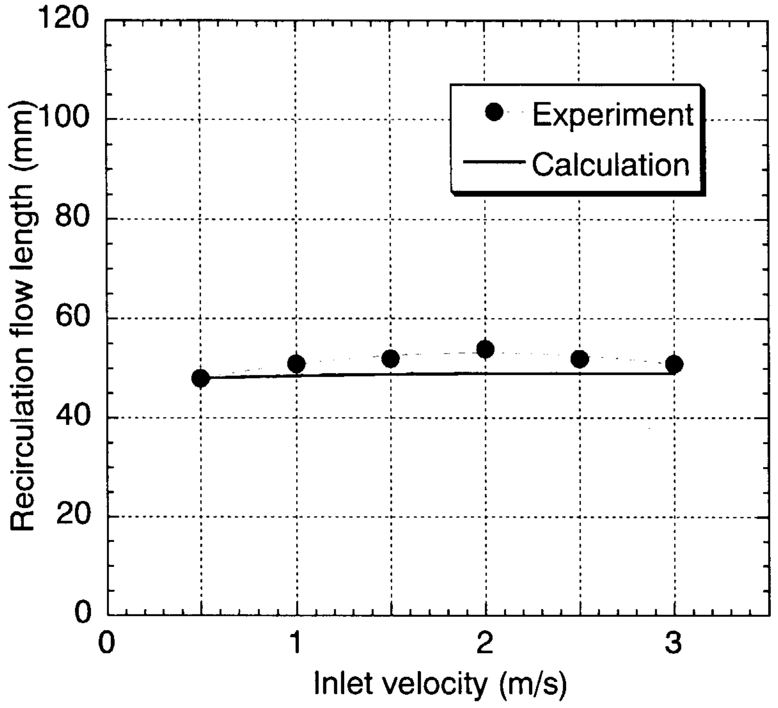


Fig.5 Relationship between the inlet velocity and the recirculation flow length.

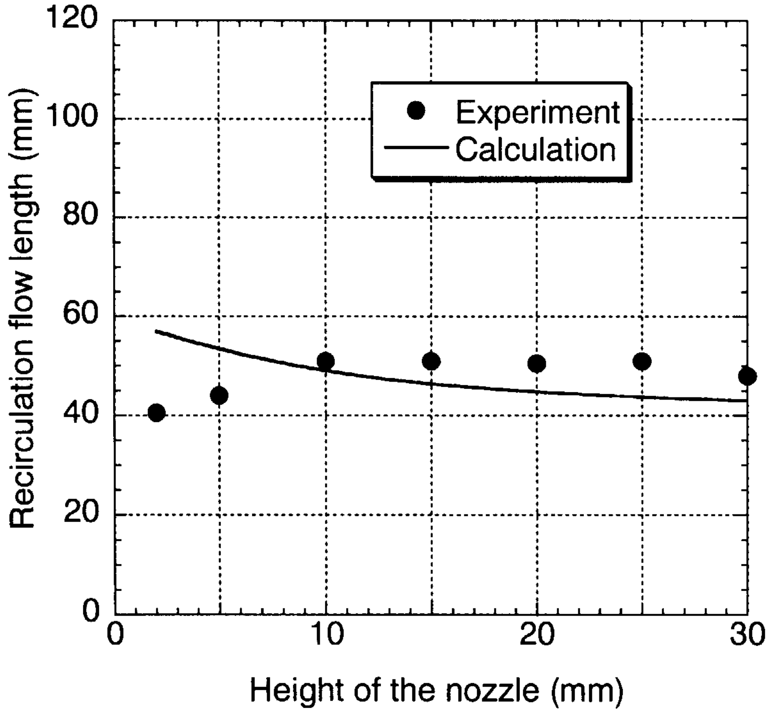
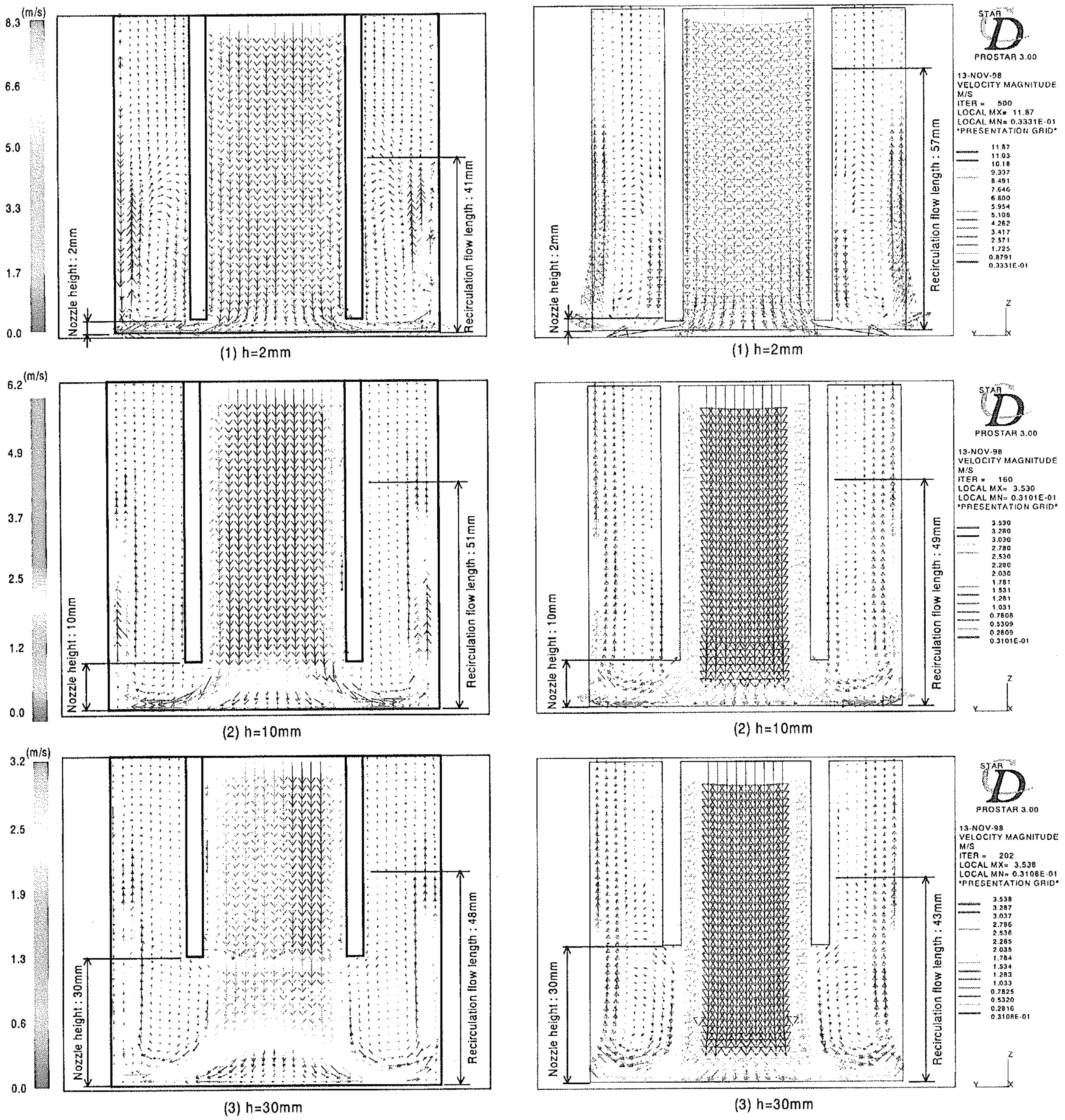
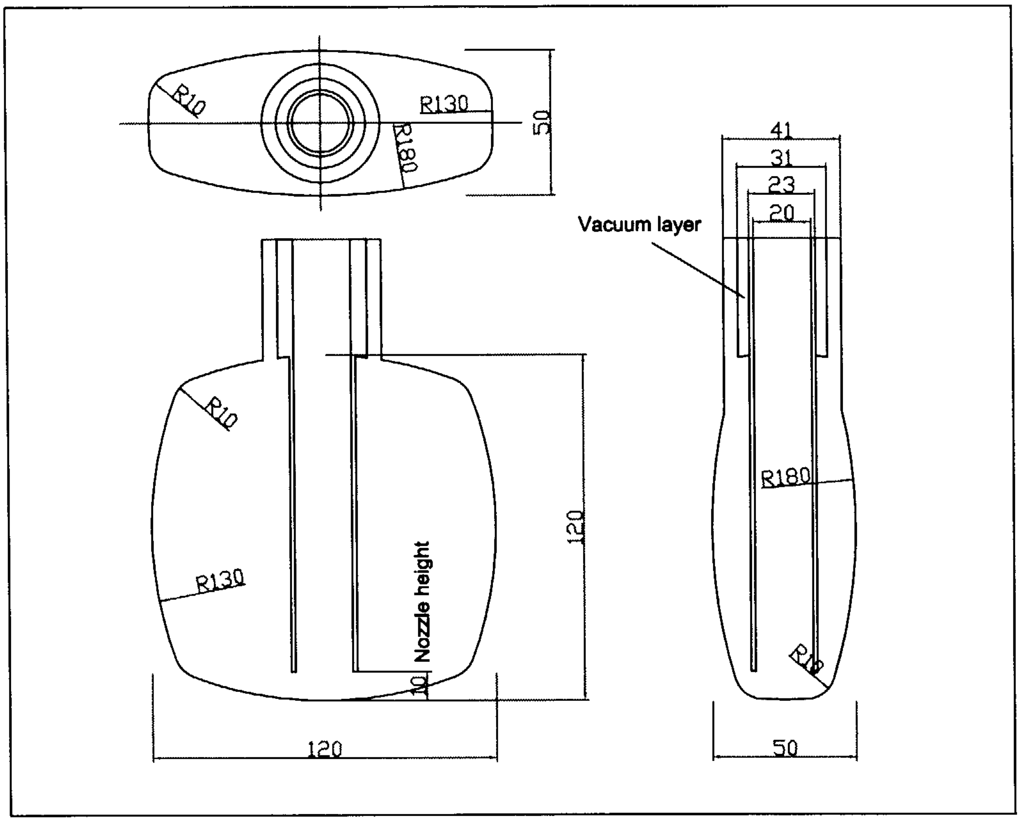


Fig.6 Relationship between the height of the nozzle from the bottom and the recirculation flow length.

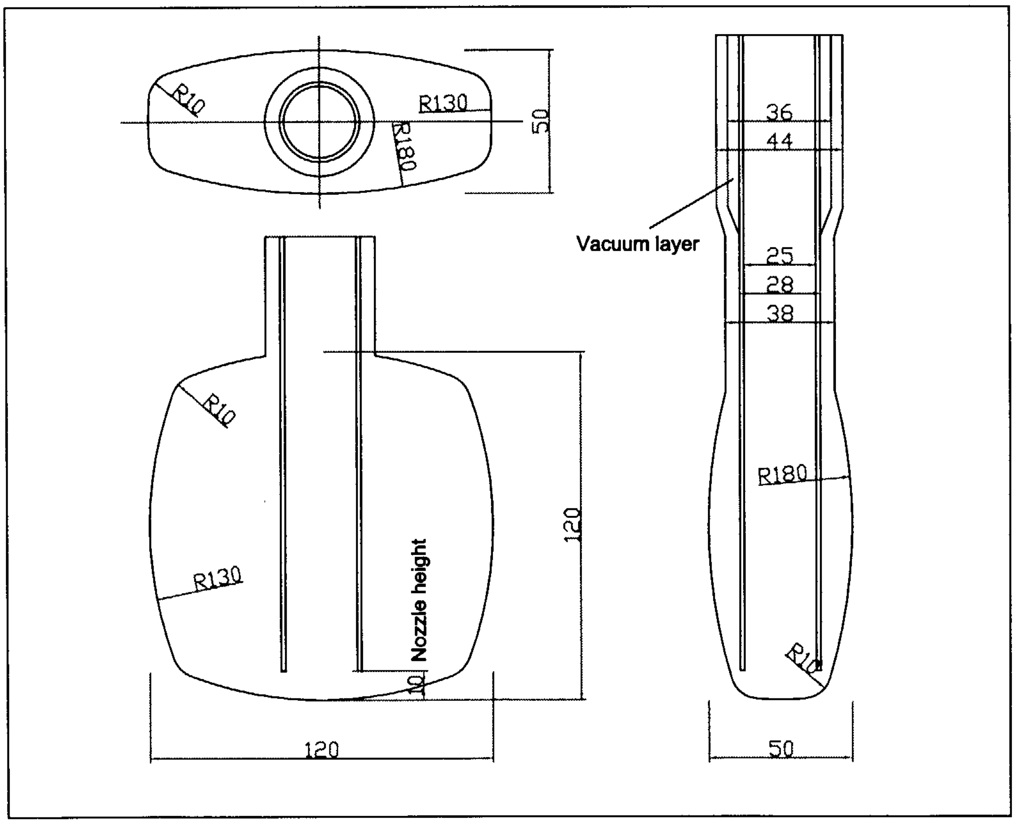


(a) Experimental results (b) Analytical results

Fig.7 Velocity distributions obtained by the experiments and the analyses when the height of the nozzle from the bottom was (1)2mm, (2)10mm and (3)30mm.



(a) Model A



(b) Model B

Fig.8 Structural drawing of the model A and B

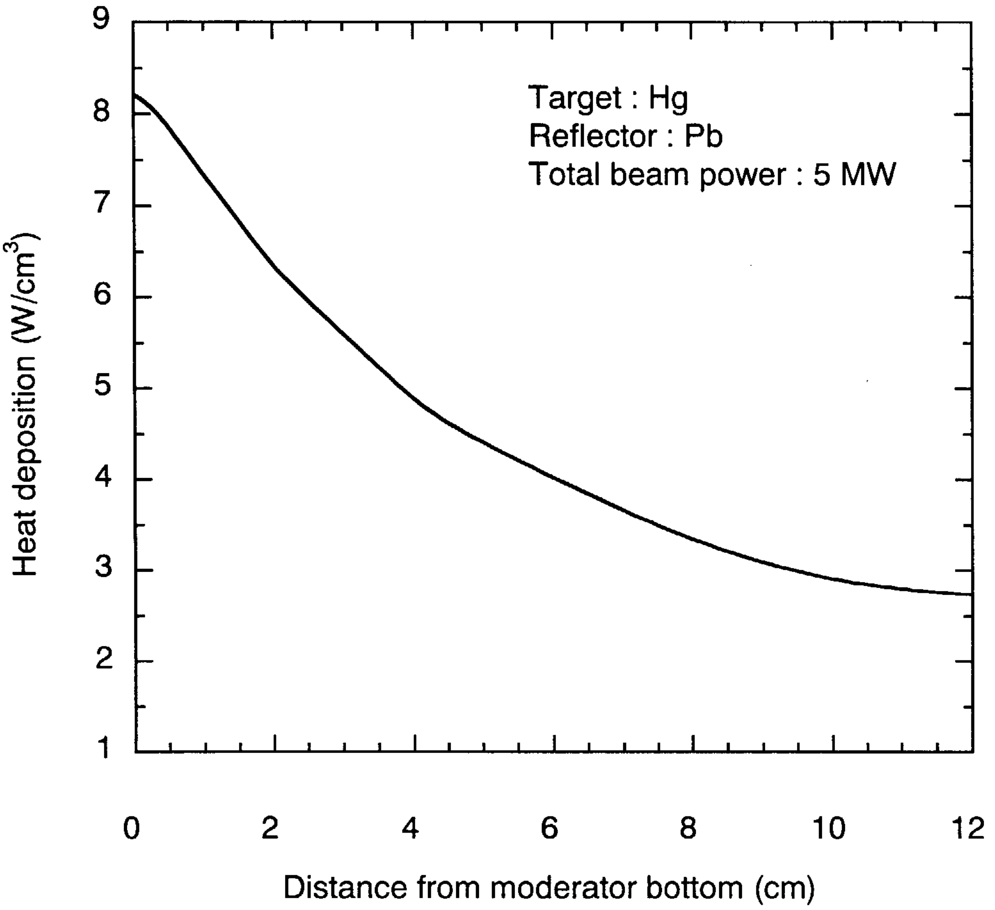
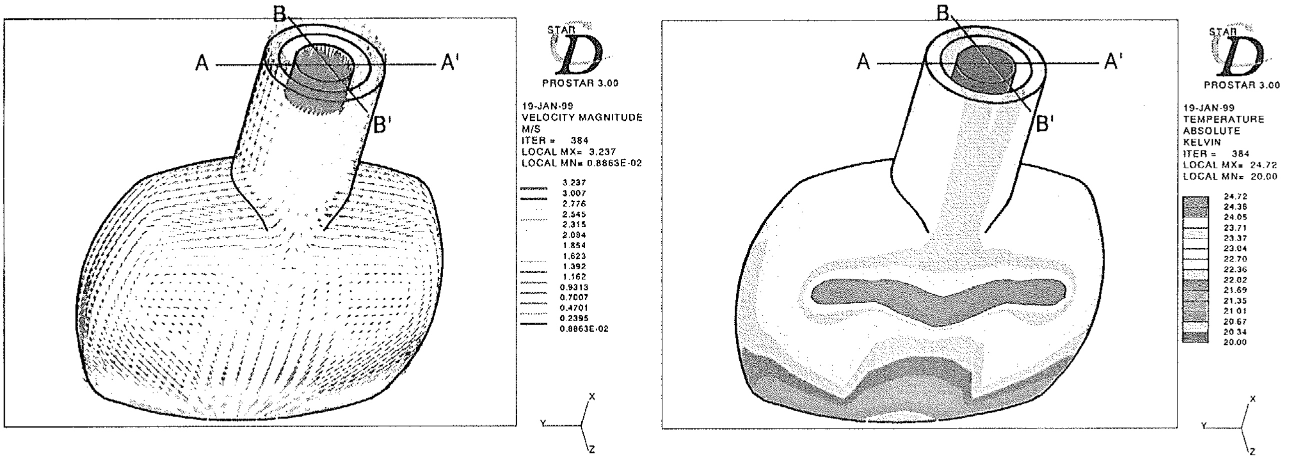
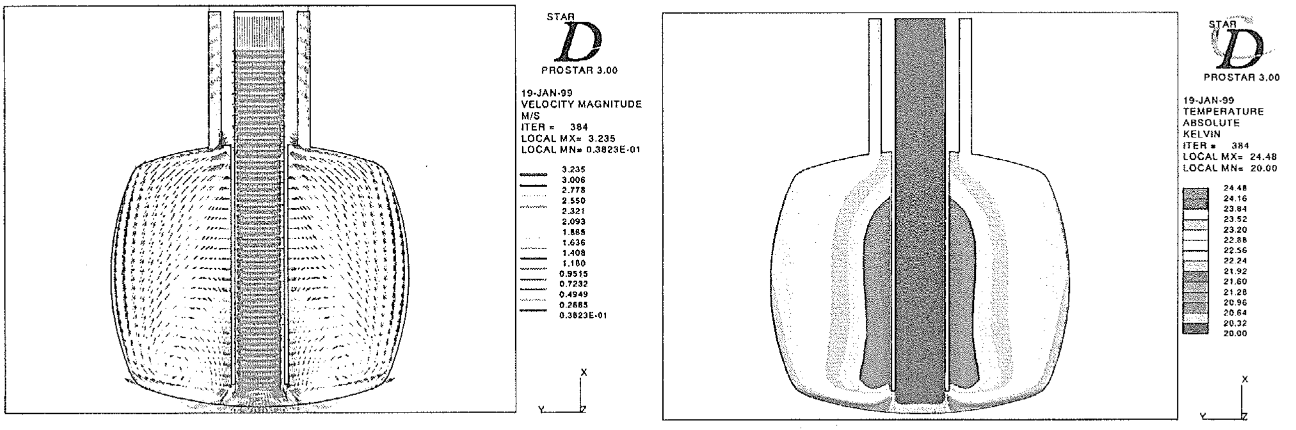


Fig.9 Heat deposition in the cold moderator using liquid hydrogen.





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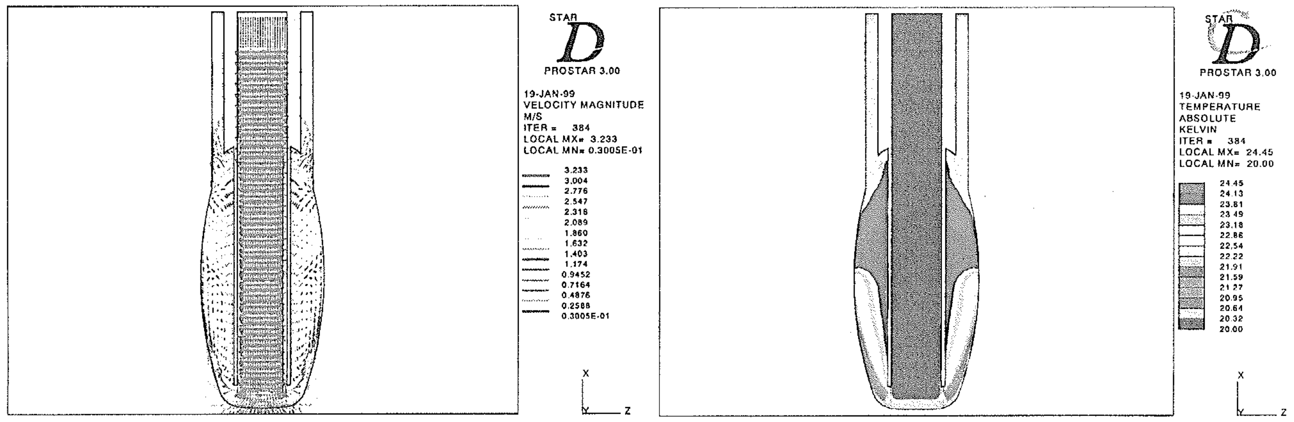

(Section B-B') (Section B-B')

(a) Velocity distributions (b) Temperature distributions

Fig.10 Analytical results of velocity and temperature distributions for the model A. (the inlet velocity : 3m/s)

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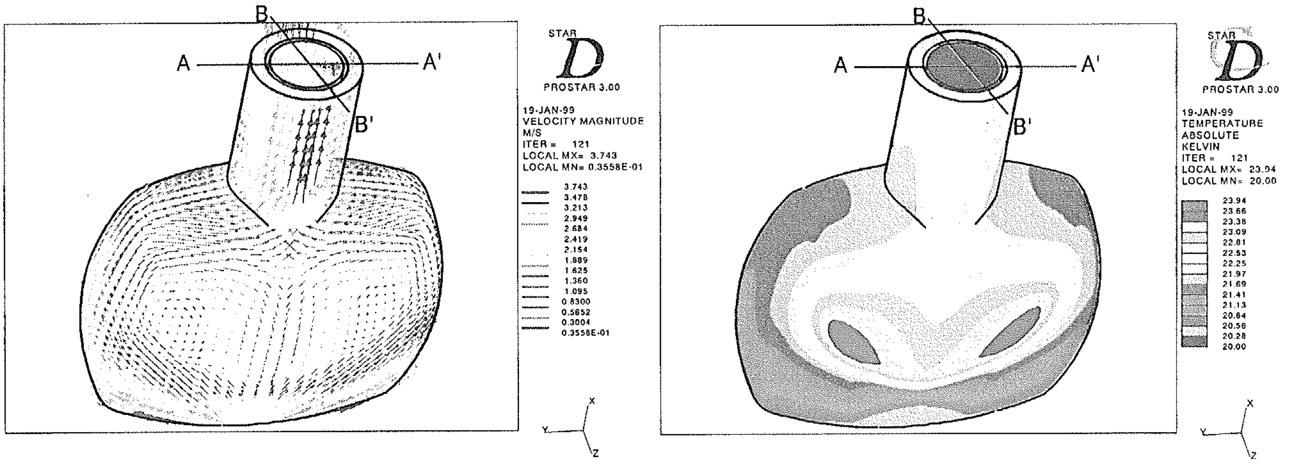
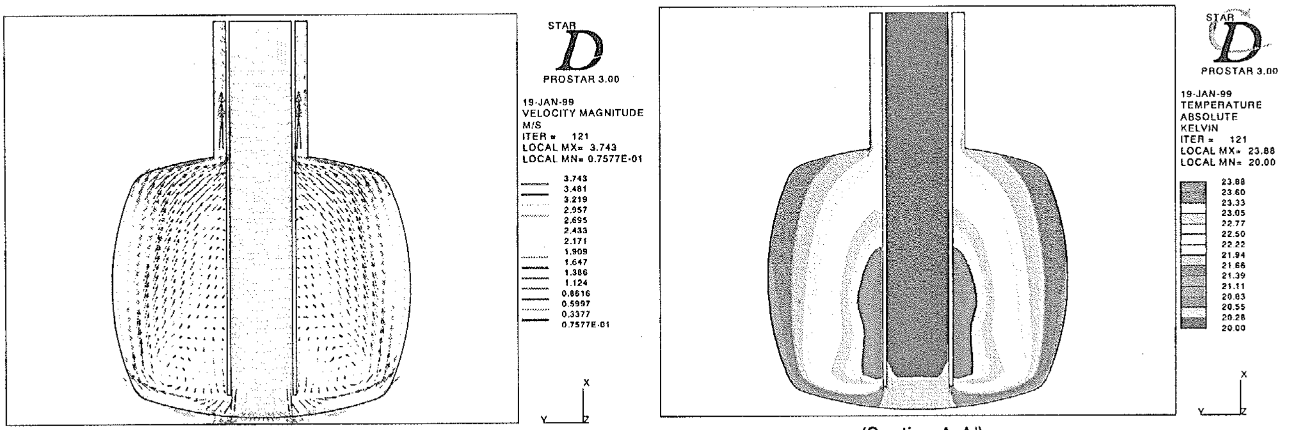
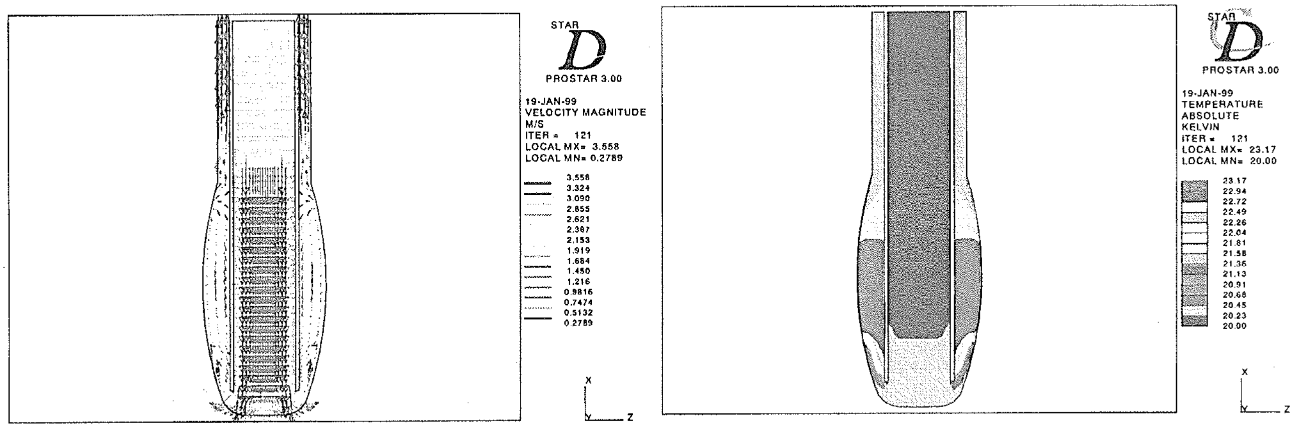




(Section A-A')

(Section A-A')



(Section B-B')

(Section B-B')

(a) Velocity distributions

(b) Temperature distributions

Fig.11 Analytical results of velocity and temperature distributions for the model B. (the inlet velocity : 3m/s)

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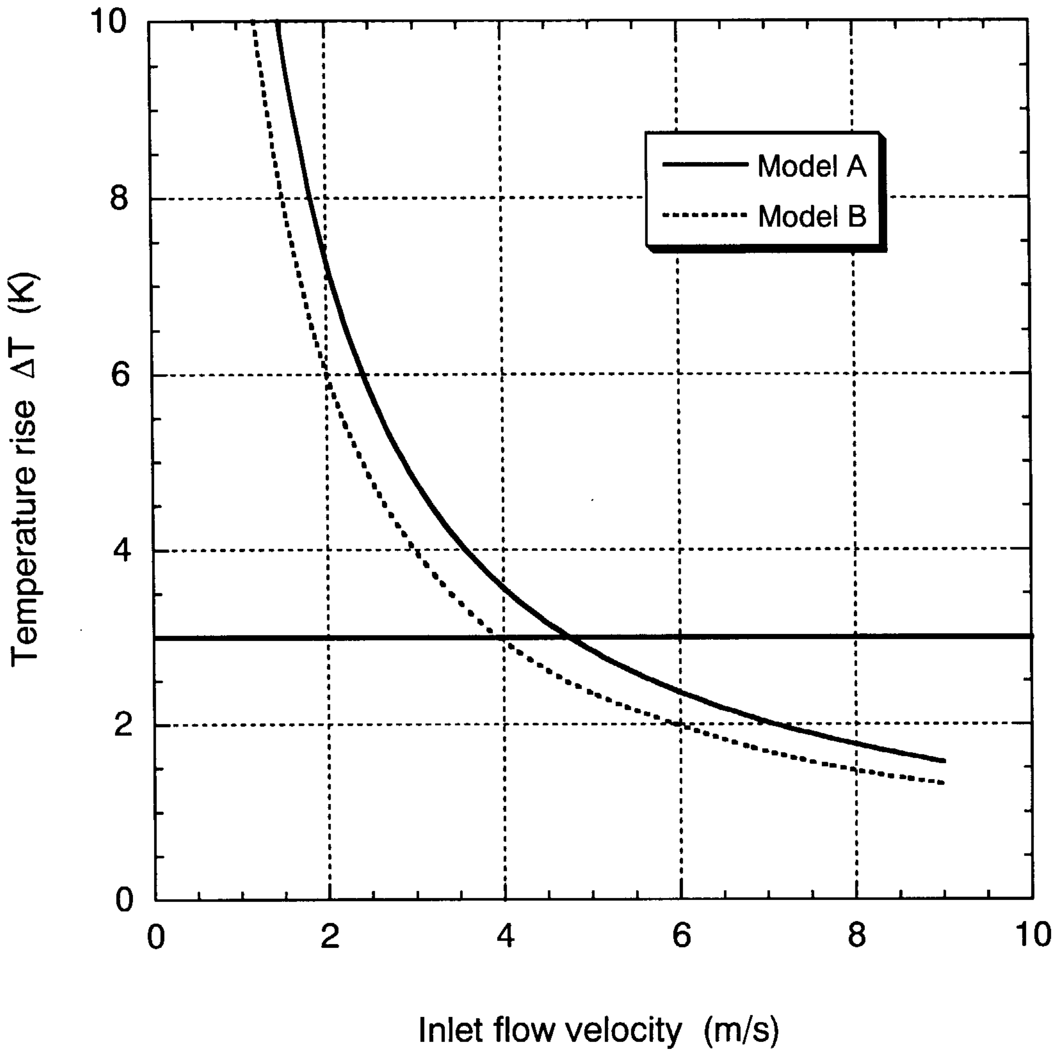
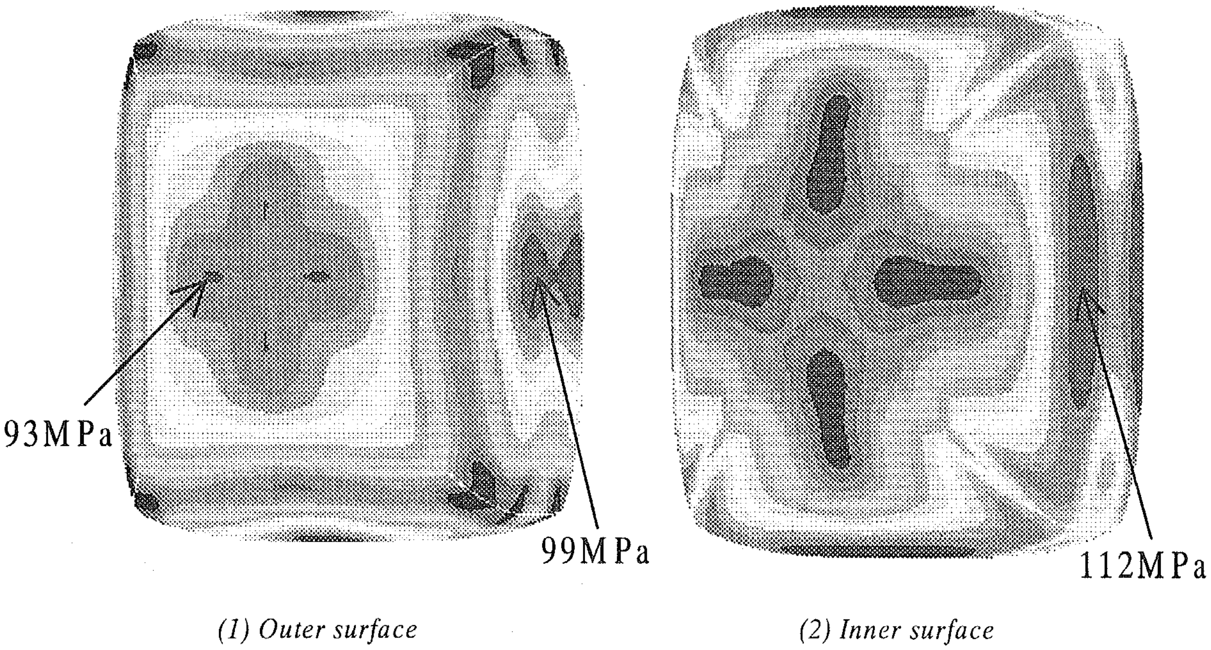


Fig.12 Relationship between the inlet velocity and the temperature rise from the analytical results for model A and B.



(1) Outer surface *(2) Inner surface*

Fig.13 Stress distributions on inner and outer vessel surfaces. (Vessel thickness : 3mm, Inlet pressure : 1.5MPa, Material : aluminum alloy)

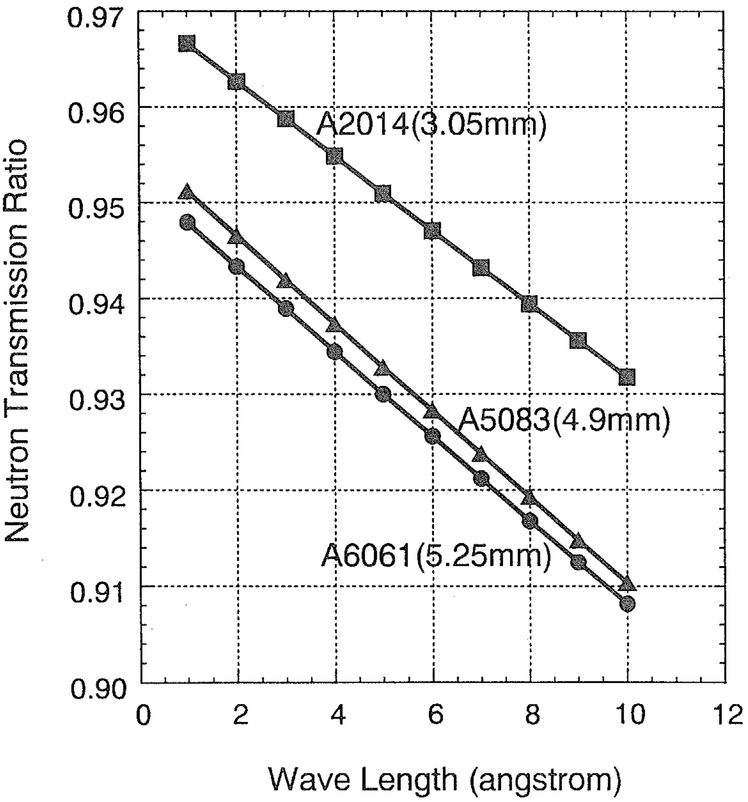


Fig.14 Neutron transmission ratio to the required thickness against the allowable stress.

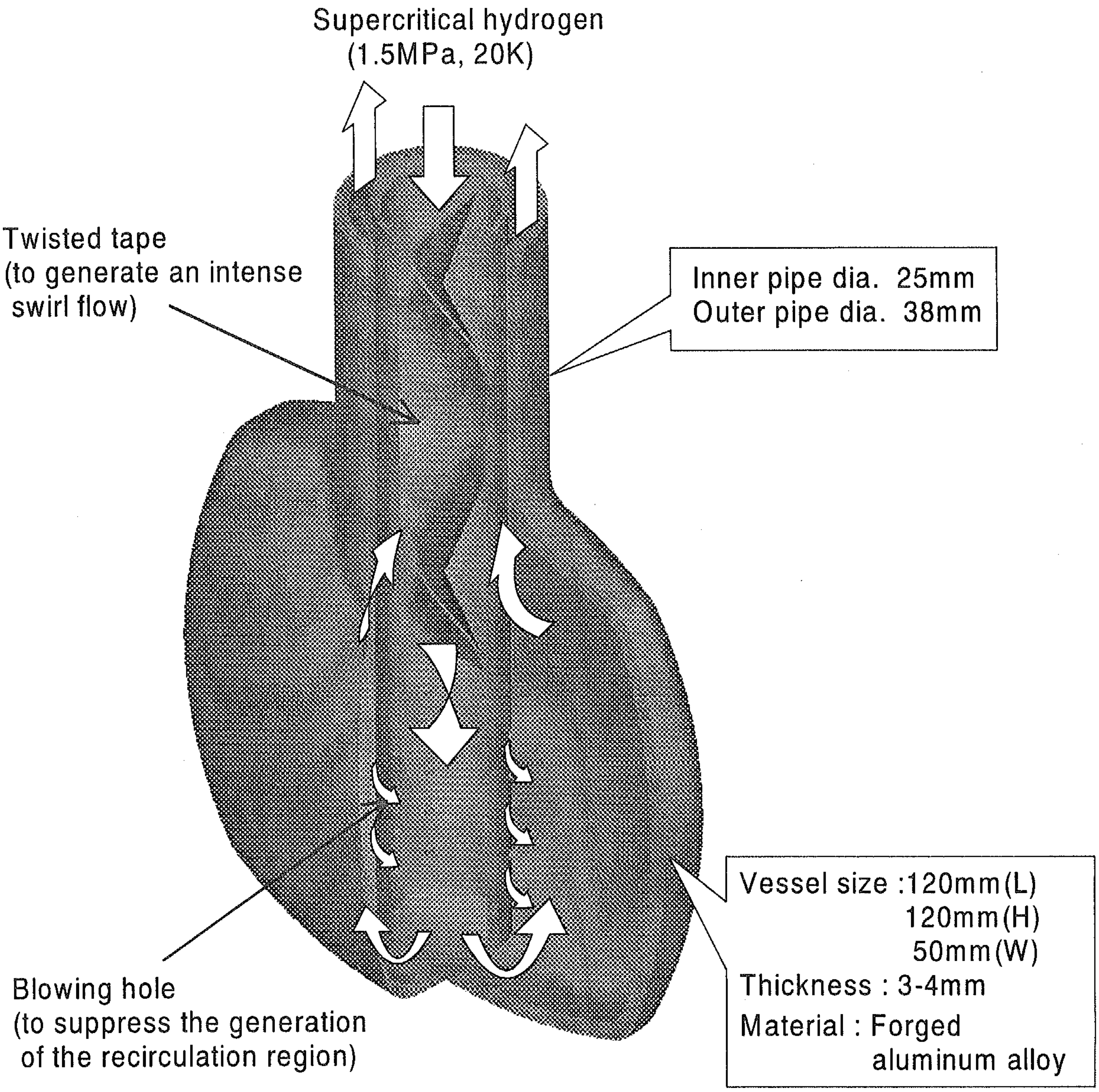


Fig.15 New concept of the cold moderator.

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国際単位系(SI)と換算表

表1 SI基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表2 SIと併用される単位

名称	記号
分，時，日	min，h，d
度，分，秒	°，′，″
リットル	l，L
トン	t
電子ボルト	eV
原子質量単位	u

1 eV = 1.60218×10^{-19} J

1 u = 1.66054×10^{-27} kg

表5 SI接頭語

倍数	接頭語	記号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

表3 固有の名称をもつSI組立単位

量	名称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	m·kg/s^2
圧力，応力	パスカル	Pa	N/m^2
エネルギー，仕事，熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表4 SIと共に暫定的に維持される単位

名称	記号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

1 Å = 0.1 nm = 10^{-10} m

1 b = 100 fm^2 = 10^{-28} m^2

1 bar = 0.1 MPa = 10^5 Pa

1 Gal = 1 cm/s^2 = 10^{-2} m/s^2

1 Ci = 3.7×10^{10} Bq

1 R = 2.58×10^{-4} C/kg

1 rad = 1 cGy = 10^{-2} Gy

1 rem = 1 cSv = 10^{-2} Sv

（注）

1. 表1－5は「国際単位系」第5版，国際度量衡局 1985年刊行による。ただし，1 eVおよび1 uの値はCODATAの1986年推奨値によった。
2. 表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. barは，JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4. EC閣僚理事会指令ではbar，barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換算表

力	N(-10^5dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘度　1 Pa·s(N·s/m^2) = 10 P(ポアズ)(g/(cm·s))

動粘度　1 m^2/s = 10^4St(ストークス)(cm^2/s)

圧	MPa(=10 bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
力	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J(=10^7 erg)	kgf·m	kW・h	cal(計量法)	Btu	ft・lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal = 4.18605 J (計量法)
= 4.184 J (熱化学)
= 4.1855 J (15 °C)
= 4.1868 J (国際蒸気表)

仕事率　1 PS (仏馬力)
= 75 kgf·m/s
= 735.499 W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

(86年12月26日現在)

STRUCTURAL STUDY OF THE COLD MODERATOR