

# 逆熱対流を起こす ～ NTEカプセルの開発～

山口義幸

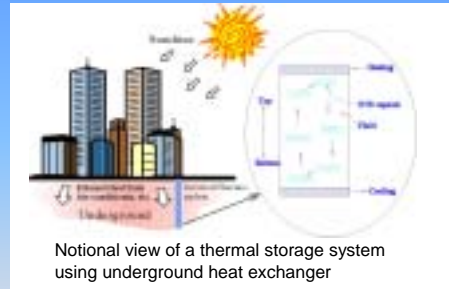
- 負の熱膨張をする装置 (NTEカプセル)
- 形状記憶合金(SMA)を用いたNTEカプセル(2000 - )
- 相変化物質 (PCM)を用いたNTEカプセル(2001 - )
- NTEマイクロカプセル(2002 - )

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## 上部加熱系の伝熱促進



Notional view of a thermal storage system using underground heat exchanger

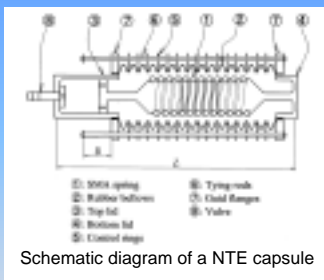
- Underground heat storage is effective to reduce of energy consumption . (Genchi et al. , 1999)
- Is any system able to enhance heat transfer using its own temperature difference?

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## 負の熱膨張をする装置



Schematic diagram of a NTE capsule

Negative Thermal Expansion Capsular Object

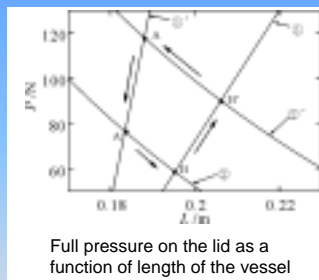
- Shape Memory alloy was employed.
- Control rings and tying rods prevent buckling and inflation of the rubber bellows.

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## NTEカプセルの動作原理



Full pressure on the lid as a function of length of the vessel

$$k_h = 3k_c$$

$$H = 1m, k_c = 3kN$$

- Tension of the SMA spring (Hot)
- Tension of the SMA spring (Cold)
- Full pressure (net) on the lid (on the surface and hot)
- Full pressure (net) on the lid (at the bottom and cold)

- The point A must exist at the left side of the point B.

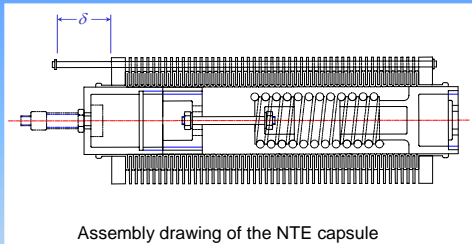
- Does it become impossible to complete the cycle when depth of water becomes too large?

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## NTEカプセルの構成



Assembly drawing of the NTE capsule

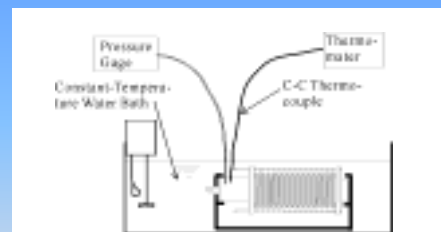
- Dimension of the NTE capsule; 64mm outer diameter and 200mm axial length.
- Ti-Ni SMA spring; 4mm diameter of the wire , 24mm diameter of the coil and 6 turns of an active coil .
- Recover transformation temperature of the SMA; 20 ~ 50 C .

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## 定置実験



Experimental setup for pressure measurements of the vessel of the NTE capsule

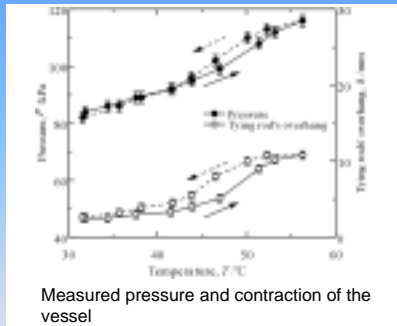
- Fixed in a thermostatic water bath, equilibrium status was measured .

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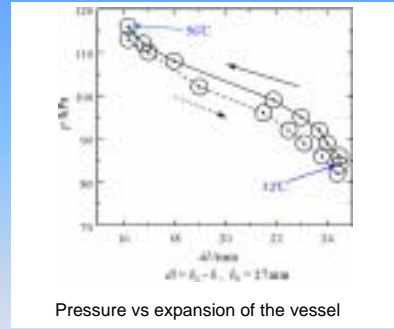
## 定置実験の結果



Measured pressure and contraction of the vessel

•Hysteresis of overhang,  $\delta$ , is seen, but that of pressure,  $p$ , isn't clearly seen.

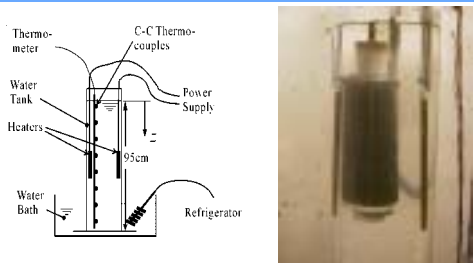
## NTEカプセルの温度応答



Pressure vs expansion of the vessel

•Is the hysteresis in this figure large or small for behavior of the NTE capsule?

## 動作実験の概要



Experimental setup and the NTE capsule

- Diameter of the water tank; 90mm or 150mm.
- Number of tying rods; 6 or 3.

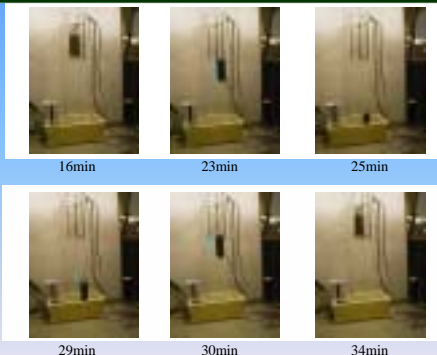
## 動作実験の概要



Photos of the experiment for the NTE capsule into a water layer of top heat mode

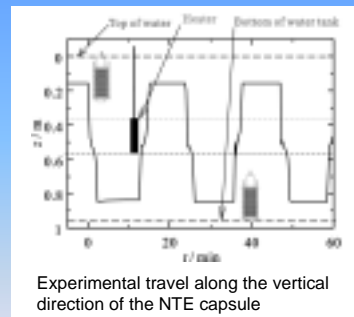
- 6 tying rods of the NTE capsule.
- 90mm diameter of the water tank, 65C. of the top and 28C. of the bottom.

## 動作実験の結果



•The experiment starts at 0min. ( $T_h = 65C.$ ,  $T_c = 28C.$ )

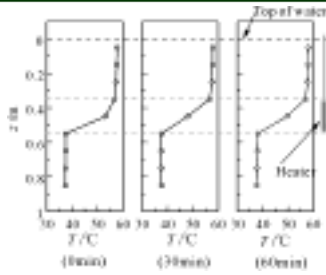
## 動作実験の結果



Experimental travel along the vertical direction of the NTE capsule

- The lower end of the heater;  $z = 0.55m$ .
- $T_h = 58C.$ ,  $T_c = 37C.$

## 水槽内温度分布



Temperature profiles along the vertical direction in the water tank

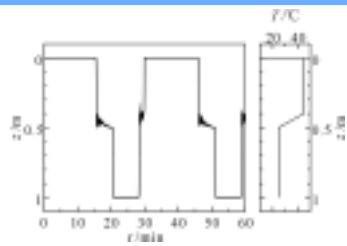
- First, the water tank was kept away for 2 hours.
- The temperature at  $z = 0.45\text{m}$  changed, but others didn't change so much.

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## 数値計算結果



Calculated travel along the vertical direction of the NTE capsule

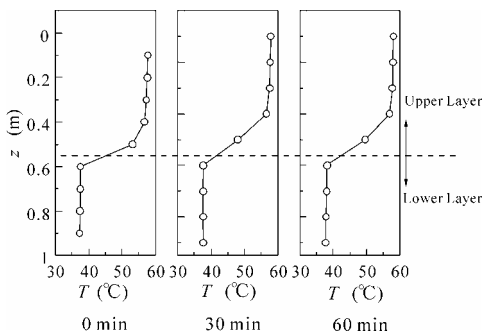
- Density of water according to temperature is considered.
- Temperature profile of the water layer is fixed.

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## 熱輸送の評価

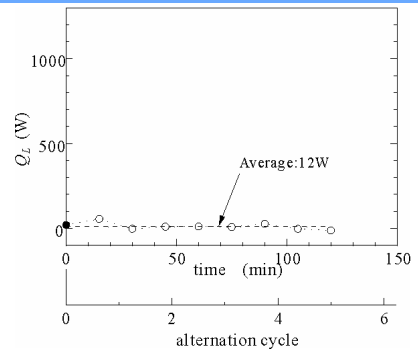


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## NTEカプセルの熱輸送効果

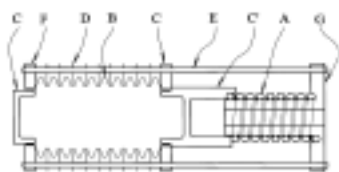


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## 改良型NTEカプセル



- A: SMA spring
- B: Rubber bellows
- C: Lid(a)
- C': Lid(b)
- D: Control rings
- E: Tying rods
- F: Bottom flange
- G: Guide flanges

Schematic diagram of a NTE capsule  
(Present Type: SMA spring is set outside of bellows)

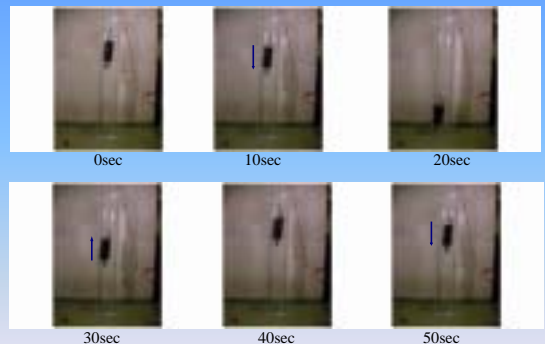
- 形状記憶合金ばねをベローズの外側に配置.

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## 動作実験の結果



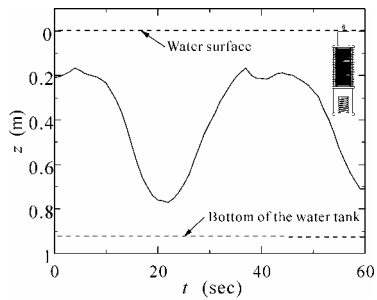
$T_h = 60$ ,  $T_c = 20$

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## 動作実験の結果

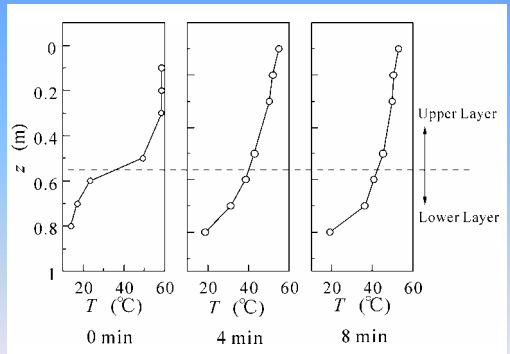


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## 水槽内温度分布

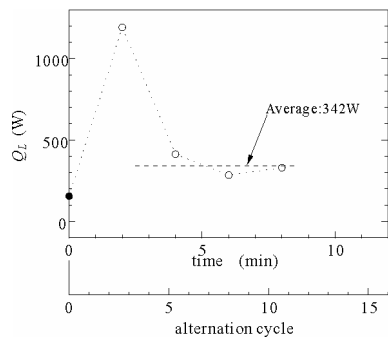


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## NTEカプセルの熱輸送効果



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## 計算モデル基礎式

ペローズ-ばねの力 力のつり合い

$$\begin{cases} F_l = (P_l - P_w - P_a)A_l \\ F_s = k(L - L_f) \end{cases} \quad F_l = F_s$$

ペローズ-ばねの熱収支

$$\begin{cases} KS_l(T_w - T_l) = (m_a c_a + M_l c_l) \frac{dT_l}{dt} \\ KS_s(T_w - T_s) = M_s c_s \frac{dT_s}{dt} \end{cases}$$

状態方程式(ペローズ内)  $P_l \bar{A}_l L_l = m_a R_a T_l$

運動方程式  $\frac{1}{2} C_D \rho_w |v| A_{\max} - V(\rho - \rho_w)g = -M\alpha$

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## NTEカプセル諸元

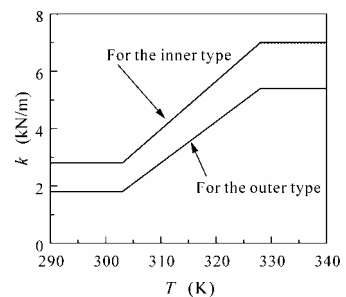
Variable	Symbol	Unit	Value	
			Inner type	Outer type
Atmospheric pressure	$p_a$	kPa	101.3	
Viscosity of fluid	$\mu$	$\mu\text{Pa}\cdot\text{s}$	800	
Standard fluid density	$\rho_{std}$	$\text{kg}/\text{m}^3$	995	
Largest cross section of the vessel	$A$	$\text{cm}^2$	18.10	18.10
Effective sectional area of the vessel	$A_{10}$	$\text{cm}^2$	13.90	13.90
Heat capacity of the vessel	$C_v$	J/K	800	800
Heat capacity of the spring	$C_s$	J/K	65.0	40.0
Diameter of the equipment	$d_{eq}$	mm	64.0	64.0
Initial length of the vessel	$L_0$	mm	180.0	180.0
Free length of the vessel	$L_f$	mm	166.0	166.0
Mass of the equipment	$M$	g	433	433
Surface area of the vessel	$S_b$	$\text{m}^2$	0.500	0.500
Surface area of the spring	$S_s$	$\text{m}^2$	0.100	0.100
Initial pressure in the vessel	$p_0$	kPa	170.0	130.0
Solid body product of the equipment	$V_0$	$\text{cm}^3$	200	220
Water-vessel overall heat transfer coefficient	$K_b$	$\text{W}/\text{m}^2\cdot\text{K}$	4.00	4.00
Air-spring overall heat transfer coefficient	$K_s$	$\text{W}/\text{m}^2\cdot\text{K}$	2.00	—
Water-spring overall heat transfer coefficient	$K_c$	$\text{W}/\text{m}^2\cdot\text{K}$	—	8.00

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## 形状記憶合金のばね定数

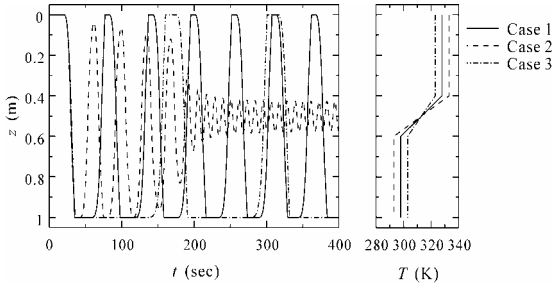


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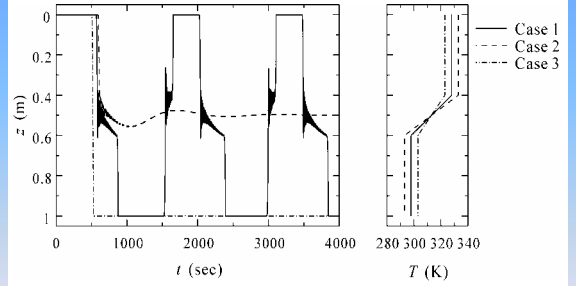
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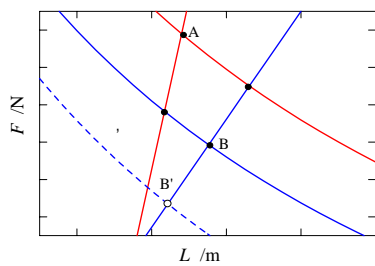
### 計算結果（ばね外側タイプ）



### 計算結果（ばね内側タイプ）



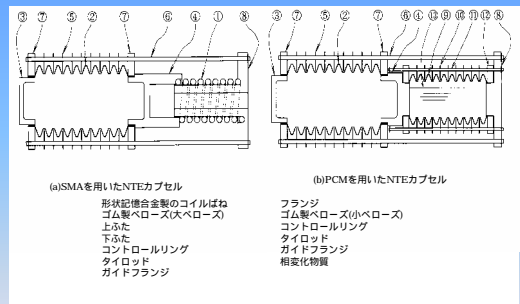
### SMAを用いたNTEカプセルの動作限界



SMAを用いたNTEカプセルの力の関係

水深が深くなると、つりあい点がBからB'へ移動。

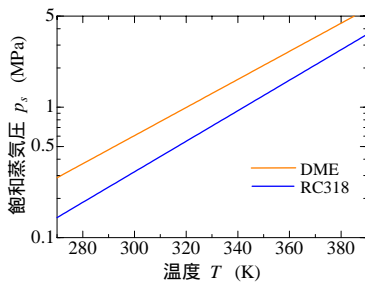
### 相変化物質を用いたNTEカプセル



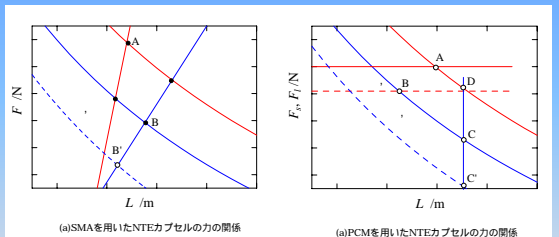
(a)SMAを用いたNTEカプセル

(b)PCMを用いたNTEカプセル

### PCMの飽和蒸気圧



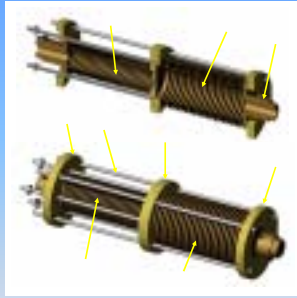
### NTEカプセルの動作原理



(a)SMAを用いたNTEカプセルの力の関係

(a)PCMを用いたNTEカプセルの力の関係

## PCMを用いたNTEカプセルの製作



Pressurized Air  
PCM  
Valve  
Top Flange  
Middle Flange  
Bottom Flange  
Large Bellows  
Small Bellows  
Guide Shaft

Figure  
Schematic diagram of new-model NTE capsule

## 計算モデル基礎式

各ベローズの力 力のつり合い

$$\begin{cases} F_l = (P_l - P_w - P_a)A_l \\ F_s = (P_s - P_w - P_a)A_s \end{cases} \quad F_l = F_s$$

各ベローズの熱収支

$$\begin{cases} KS_s(T_w - T_s) = (m_G c_G + m_L c_L + M_s c_s) \frac{dT_s}{dt} + \Delta h_v \frac{dm_G}{dt} \\ KS_l(T_w - T_l) = (m_a c_a + M_l c_l) \frac{dT_l}{dt} \end{cases}$$

小ベローズ内の気相と液相の割合

$$A_s L_s = \frac{m_G}{\rho_G} + \frac{m_L}{\rho_L}$$

運動方程式

$$\frac{1}{2} C_D \rho_w |v| A_{\max} - V(\rho - \rho_w)g = -M\alpha$$

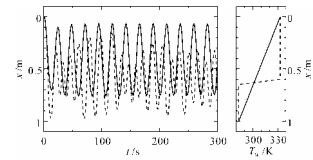
## NTEカプセル諸元

	Large NTE capsule	Small NTE capsule
Diameter [mm]	64	31
Total length [mm]	420	170

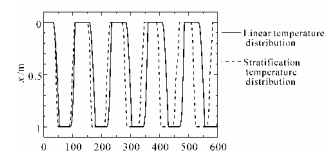
	Larger NTE capsule		Smaller NTE capsule	
	Large Bellows	Small Bellows	Large Bellows	Small Bellows
Material	Rubber	Teflon	phosphor bronze	phosphor bronze
Outside Diameter	48 mm	31 mm	26 mm	17 mm
Inside Diameter	35 mm	25 mm	17.8 mm	10.3 mm
Thickness	0.8 mm	0.5 mm	0.4 mm	0.4 mm
Number of Threads	49	40	20	27
Length	100 mm *	40 mm *	50 mm	50 mm

\* The NTE capsule had most shrunk at this condition

## 計算結果 (水深1m)

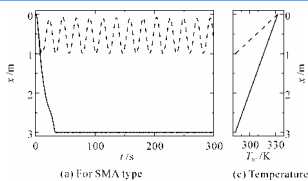


(a) For SMA type (c) Temperature

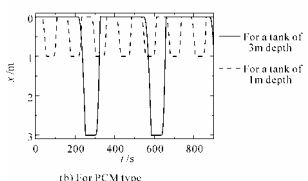


(b) For PCM type

## 計算結果 (水深3m)



(a) For SMA type (c) Temperature



(b) For PCM type

## 上部加熱系の伝熱促進



## 動作実験結果 ( $Q=47\text{ W}$ , $T_c=5$ )

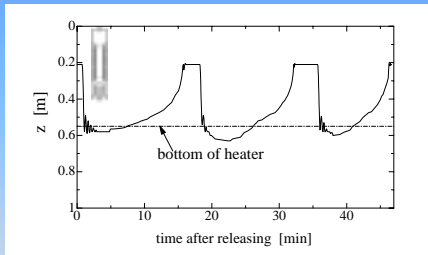


Figure  
Travel of NTE capsule

## 動作実験結果 ( $Q=33\text{ W}$ , $T_c=13$ )

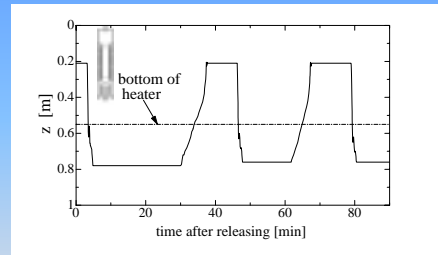
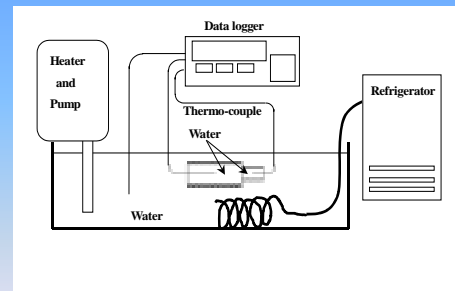


Figure  
Travel of NTE capsule

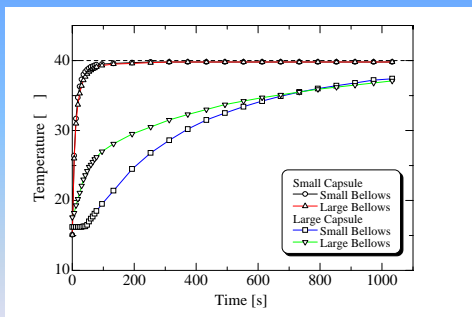
## 小型NTEカプセルの製作



## 温度応答実験



## 温度応答測定結果



## 熱膨張率測定実験

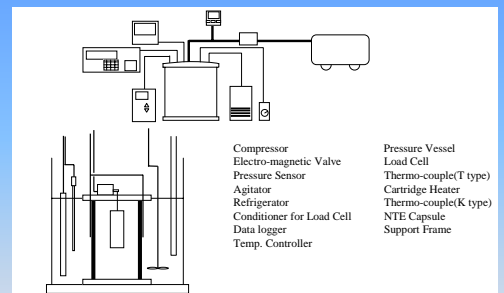
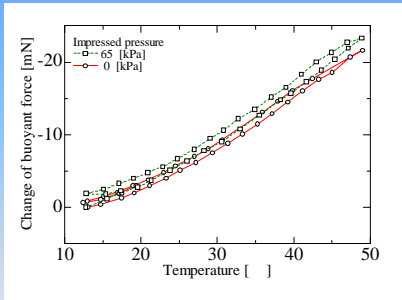


Figure  
Experimental apparatus for measuring  
coefficient of thermal expansion

## 熱膨張率測定結果

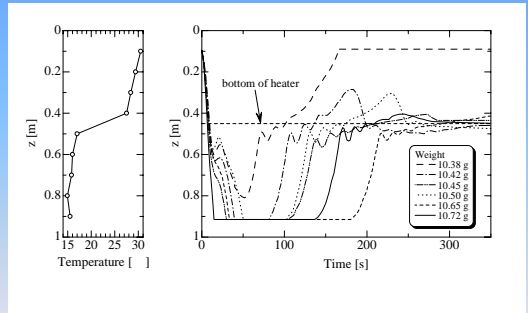


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## 小型 NTE カプセルの動作実験結果



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## 上部加熱系の熱伝促進 (その他の研究)

### NTEマテリアルの開発

- 京大・芹沢ら (機構を考案)
- Rensselaer大・Berglesら (SMA使用)
- 大阪大・片岡ら (SMA使用)\*
- 東工大・中別府ら (NTEマイクロカプセル)\*

### 温度差を利用して熱媒体を駆動

- 早大・勝田ら (熱電変換利用)
- 熊本大・井村ら (上部に蒸発器を設置)\*

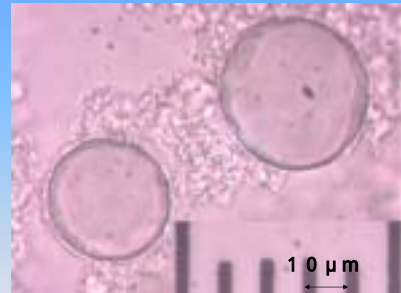
\* 機械学会, 伝熱学会に講演資料あり.

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## 硫酸ナトリウム水溶液のマイクロカプセル化



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## 熱分析結果

	硫酸ナトリウム 水溶液含有 マイクロカプセル	硫酸ナトリウム 水溶液	濃度2.3%食塩水 + 硫酸ナトリウム
凝固点	18.9	21.6	18.6
融点	17.1	28.8	16.6
潜熱	(44.4J/g)	77.3J/g	88.1J/g

### 使用した試薬

- 親水性モノマー:ヘキサメチレンジアミン
- 疎水性モノマー:テフタロイルジクロリド
- 有機溶媒:シクロヘキサノールホルム
- 混合溶媒
- 界面活性剤:ソルビタントリオレート
- pH調整剤:炭酸ナトリウム
- 相間移動触媒:TOMAC
- 過冷却解除剤:四水ウ酸ナトリウム

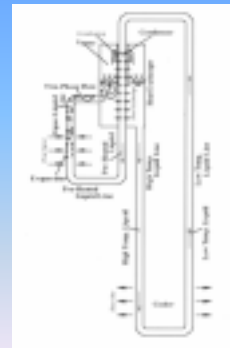
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## トップヒート型ループ熱サイホン

\* 下図:一法師 他, 第38回日本伝熱シンポジウム, (2001), 745-746. より



- 蒸気圧で作動流体を輸送
- 蒸発器を上部に設置
- 顕熱を輸送
- 低温側熱交換器
- 循環流量の確保

•他に, 浸透圧式, スイッチングチャンバー式などがある.

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