An analysis of fluid flow characteristics of silicon melt by numerical simulation and model experiments

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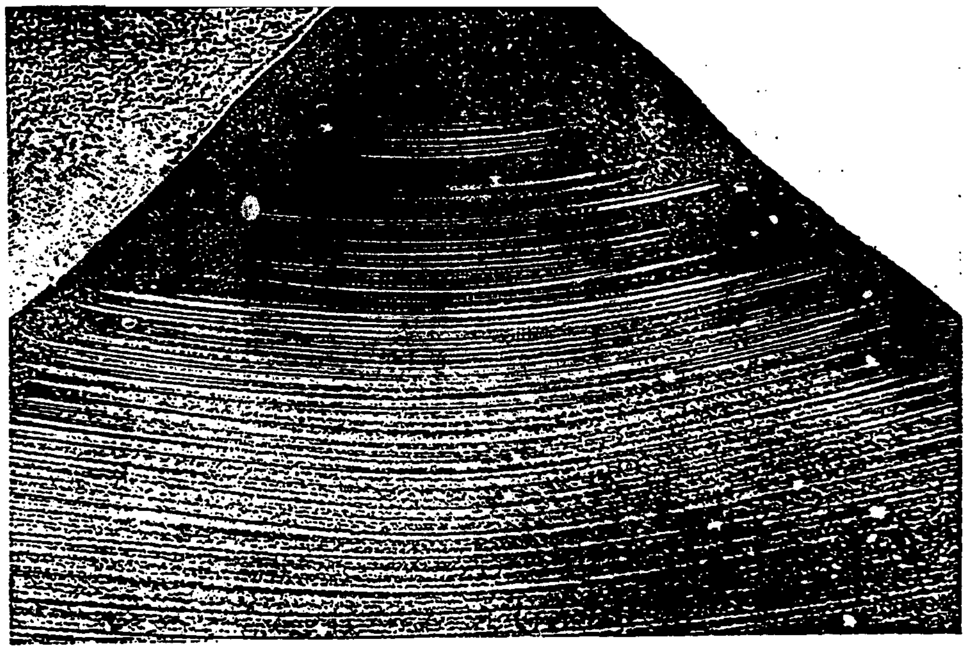
1. Effects of melt flow on the grown crystal

striation pattern

→ oxygen fluctuation in the crystal

→ synchronized with fluctuation of temperature or oxygen concentration in the melt

→ caused by melt flow instabilities

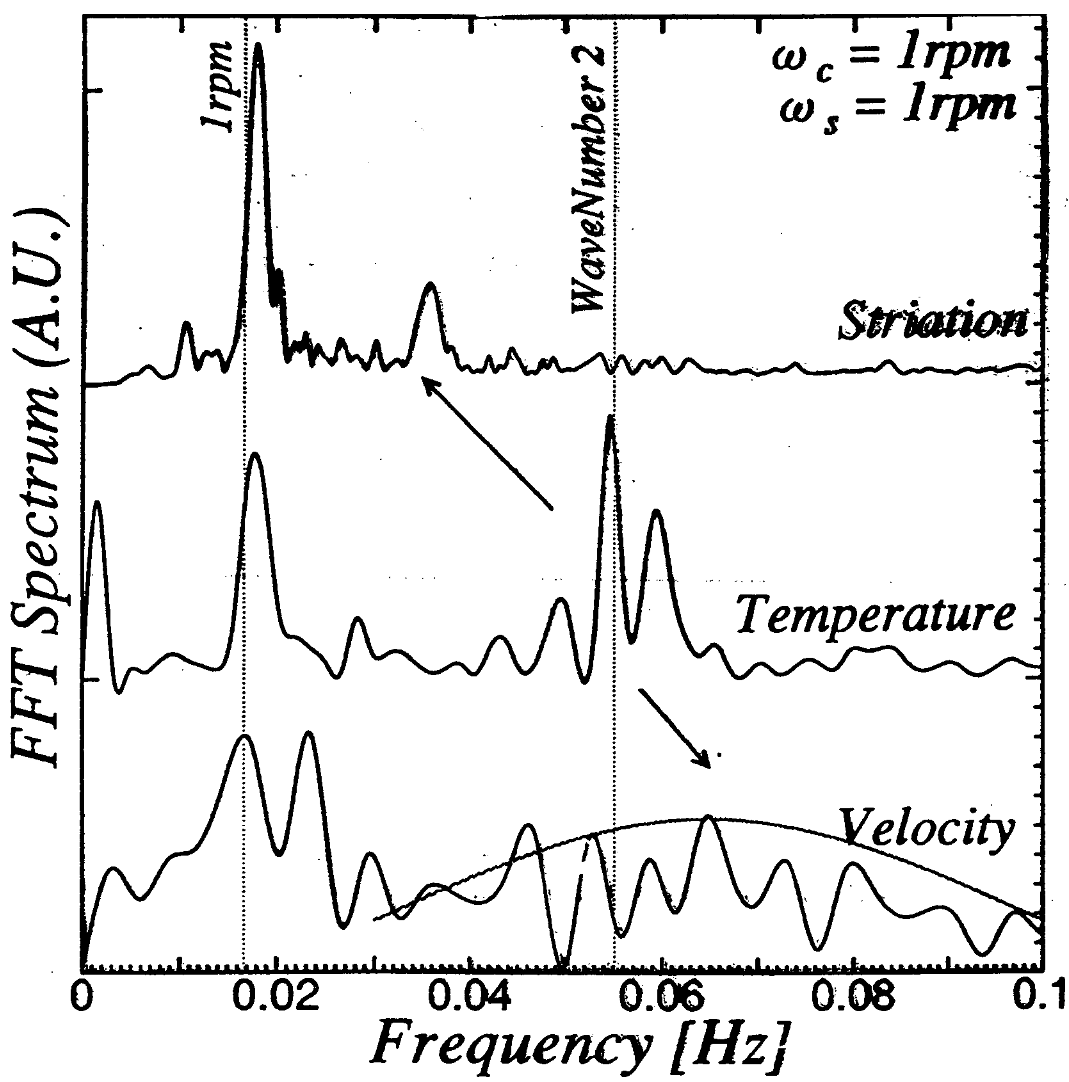


10mm

W. Zulehner et al.

A. Mühlbauer

Relations among striation width (oxygen) in the crystal, temperature and velocity in the melt



2. Experimental and numerical technique

- Small size experiment – silicon melt

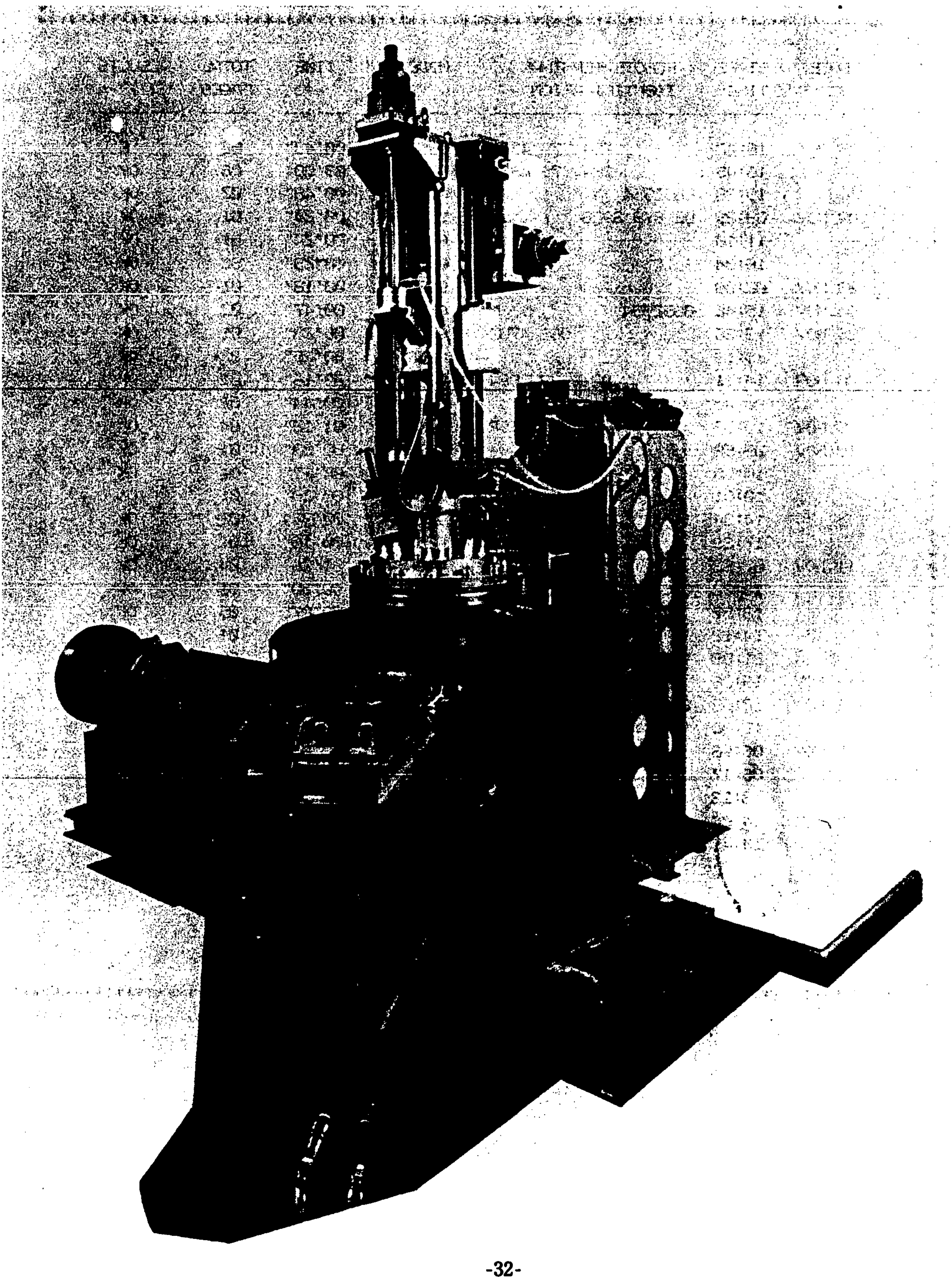
  r=3.5cm, h=3cm

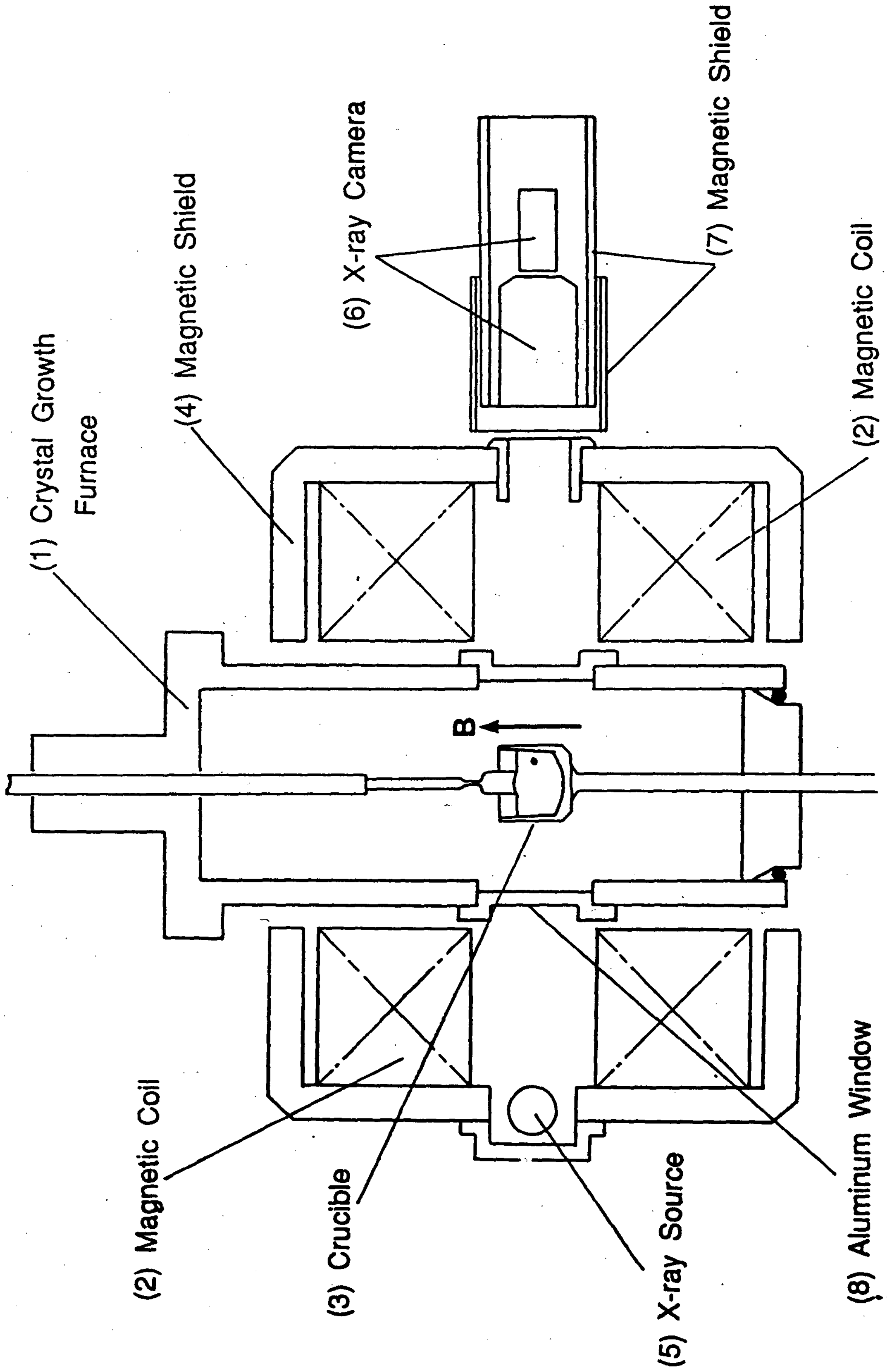
- Medium size experiment – woods metal melt

  r=10cm, h=10cm

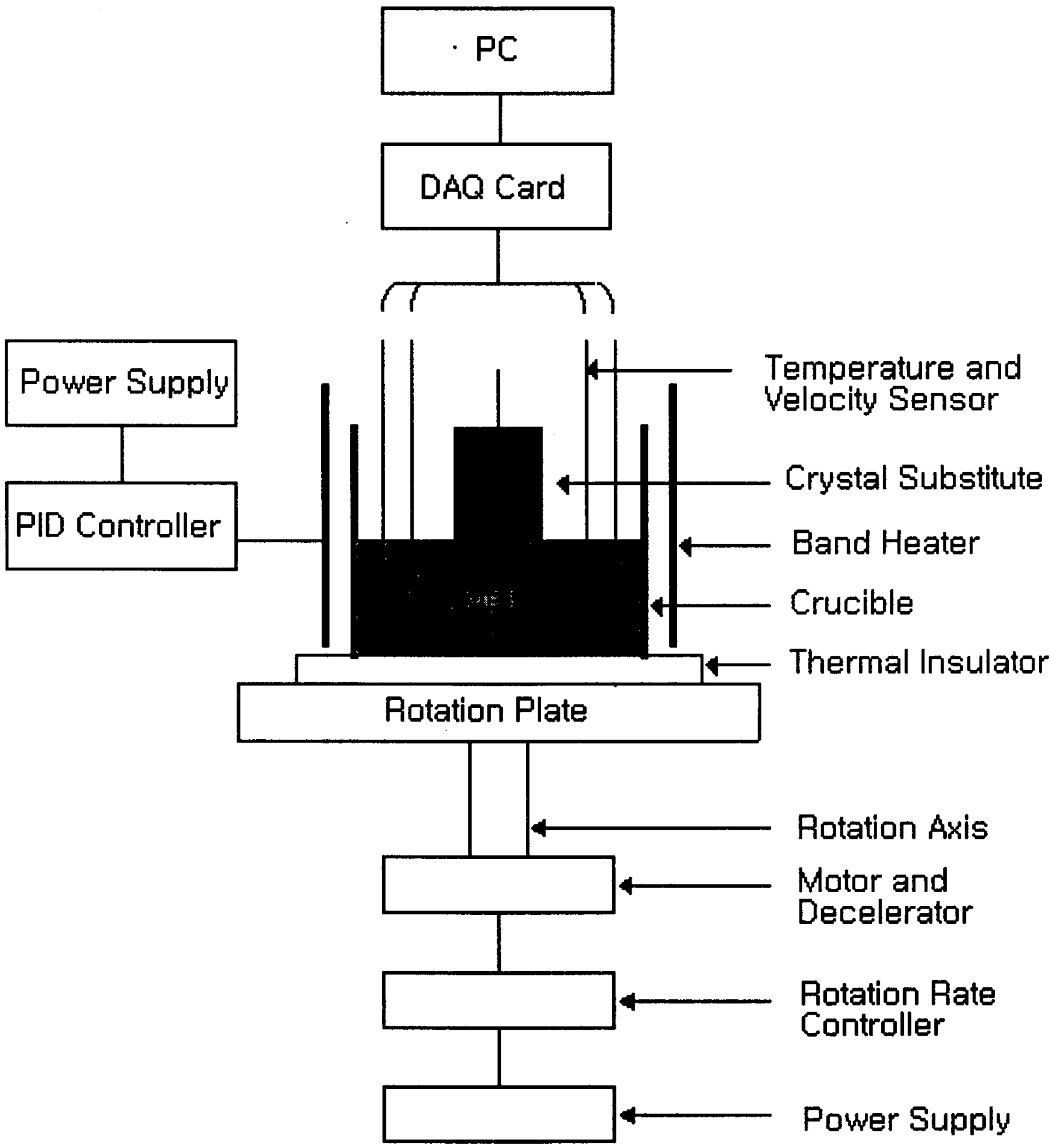
- 3-D numerical simulation

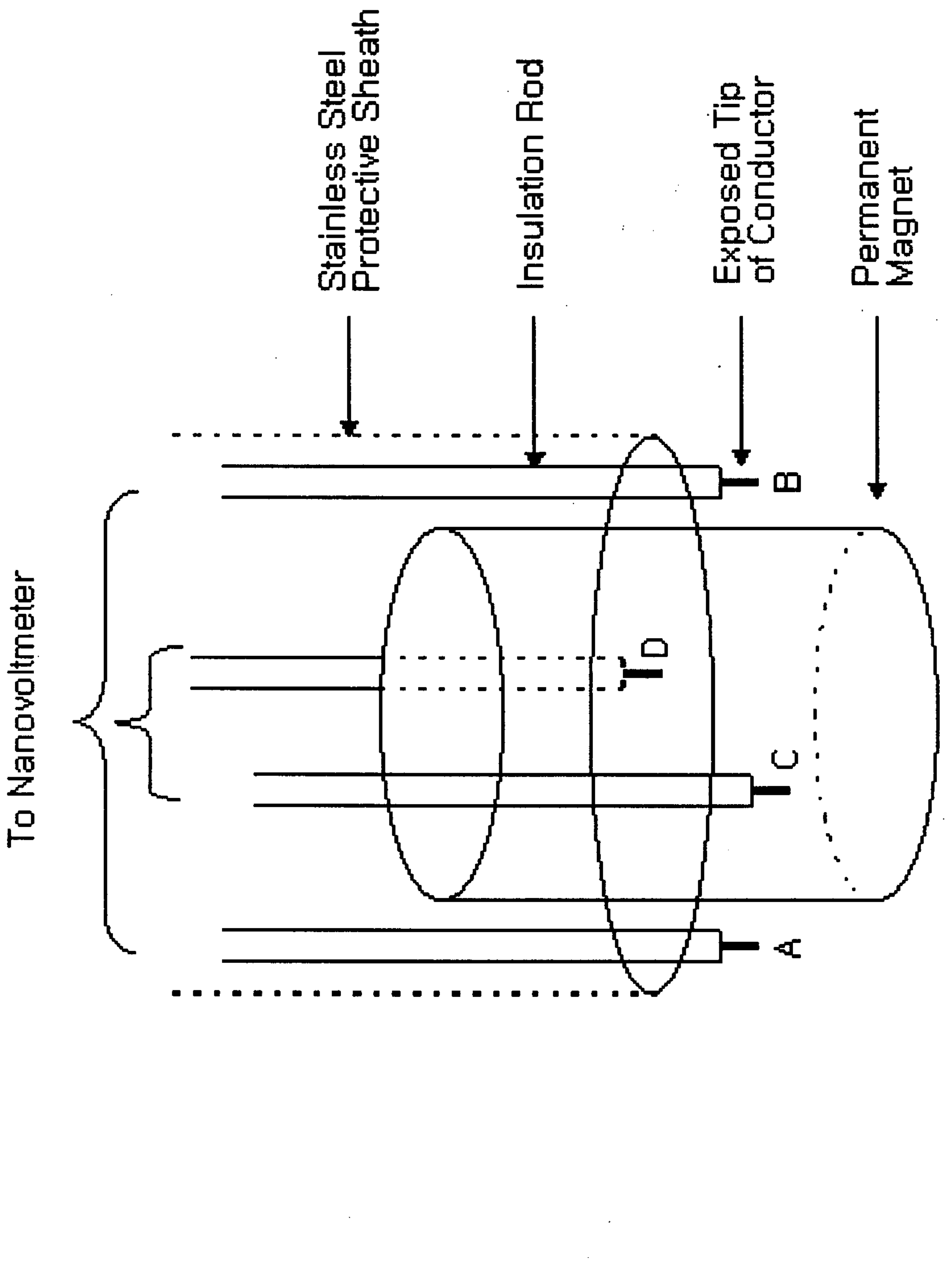
  FDM, $k-\varepsilon$ turbulent model




(1) Crystal Growth Furnace
(2) Magnetic Coil
(2) Magnetic Coil
(3) Crucible
(4) Magnetic Shield
(5) X-ray Source
(6) X-ray Camera
(7) Magnetic Shield
(8) Aluminum Window
B

Schematic diagram of experiment using woods metal





Schematic diagram of velocity probe

3. Flow behavior in oscillatory region

Cause of oscillation : asymmetric profile + rotation

Asymmetric profile : by flow instabilities in the melt

Benard type instability : by temperature difference
(density or surface tension)

Baroclinic instability : by rotation

Magnetic instability

Baroclinic instability

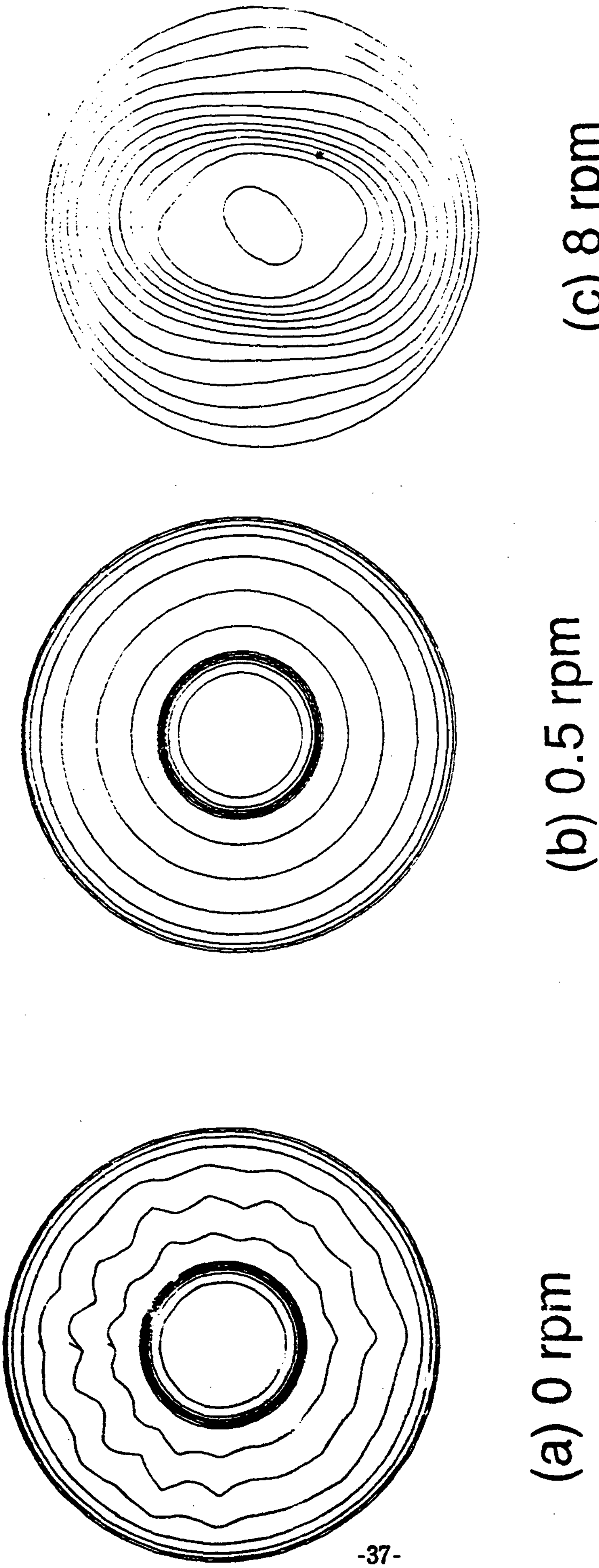
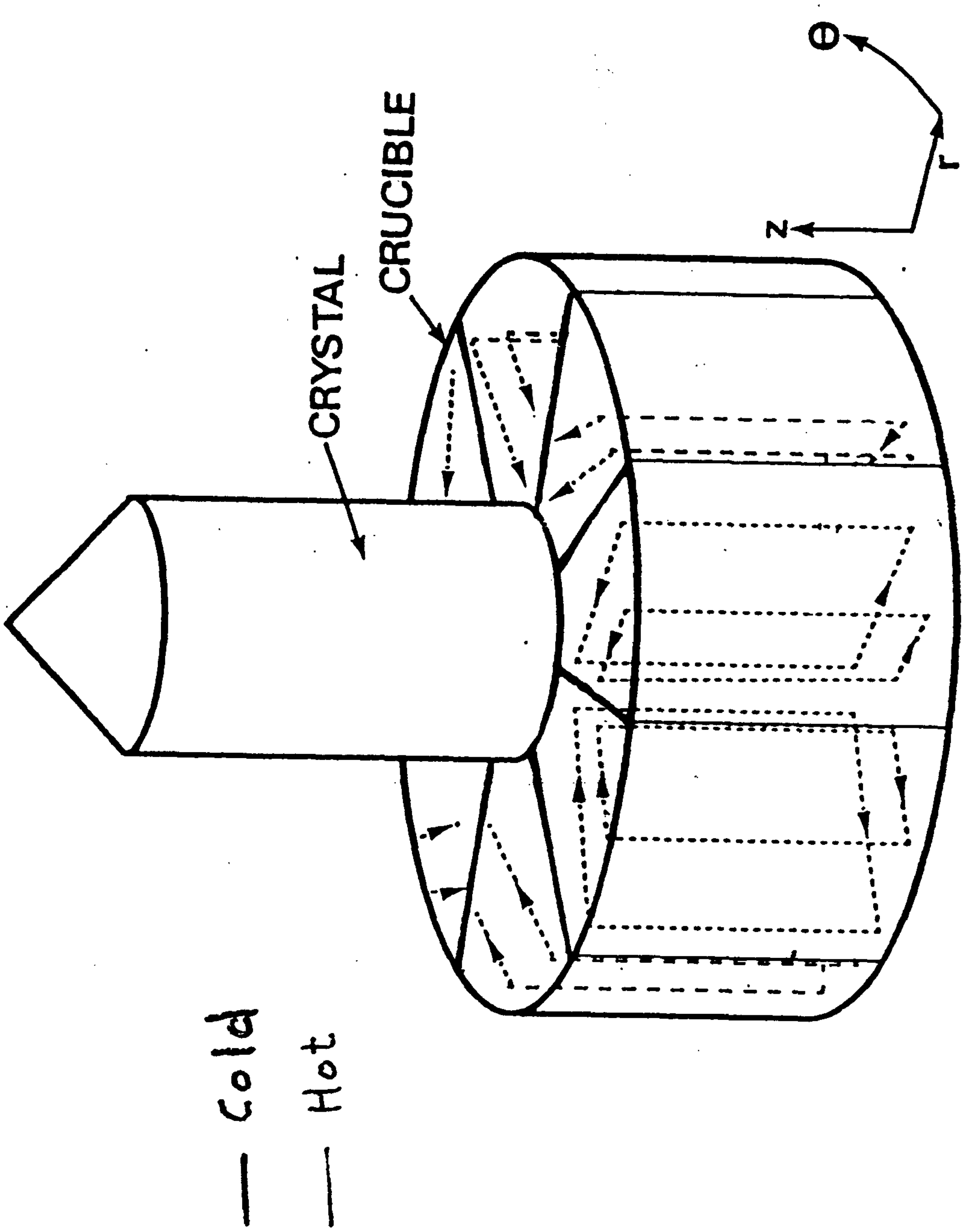
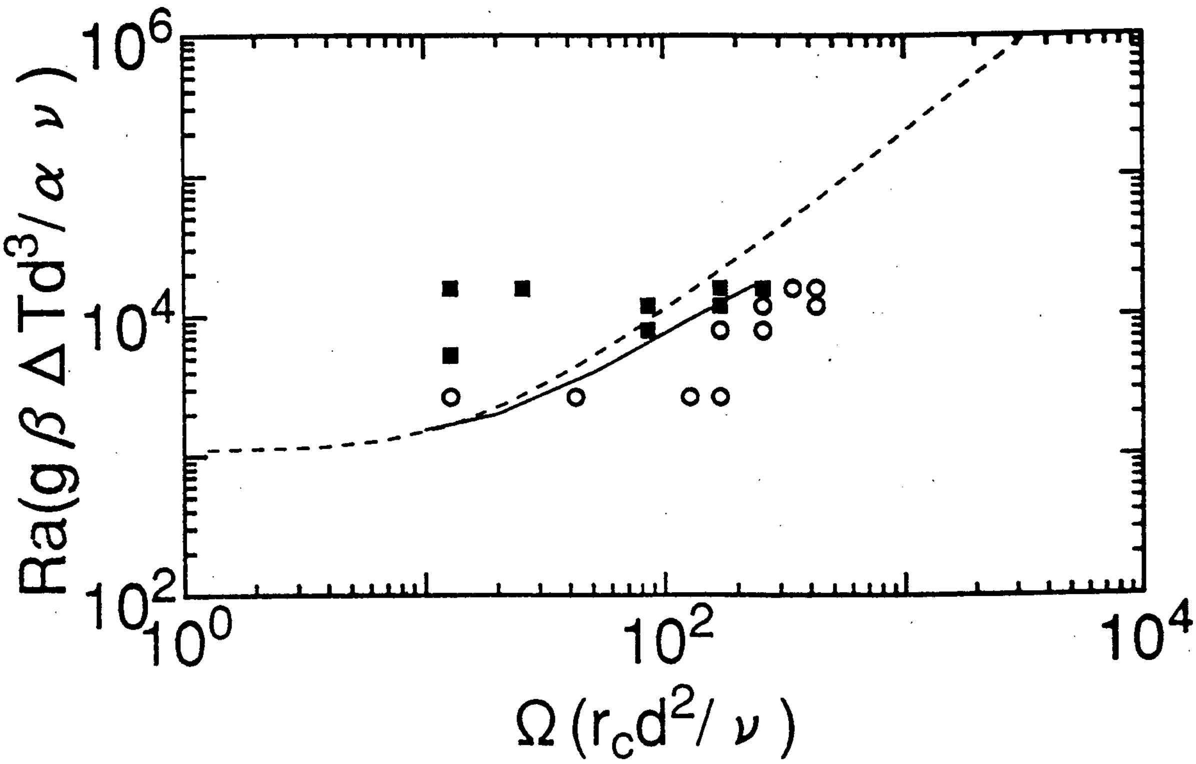


Fig. Isothermal lines on the top plane


CRYSTAL
CRUCIBLE
z
r
θ
Cold
Hot



■ Rayleigh-Benard (calculated)

○ not " (")

--- Ra_c (chandrasekhar)

— Ra_c (Goldstein) → cylindrical

* Ra & Ω for unstable layer

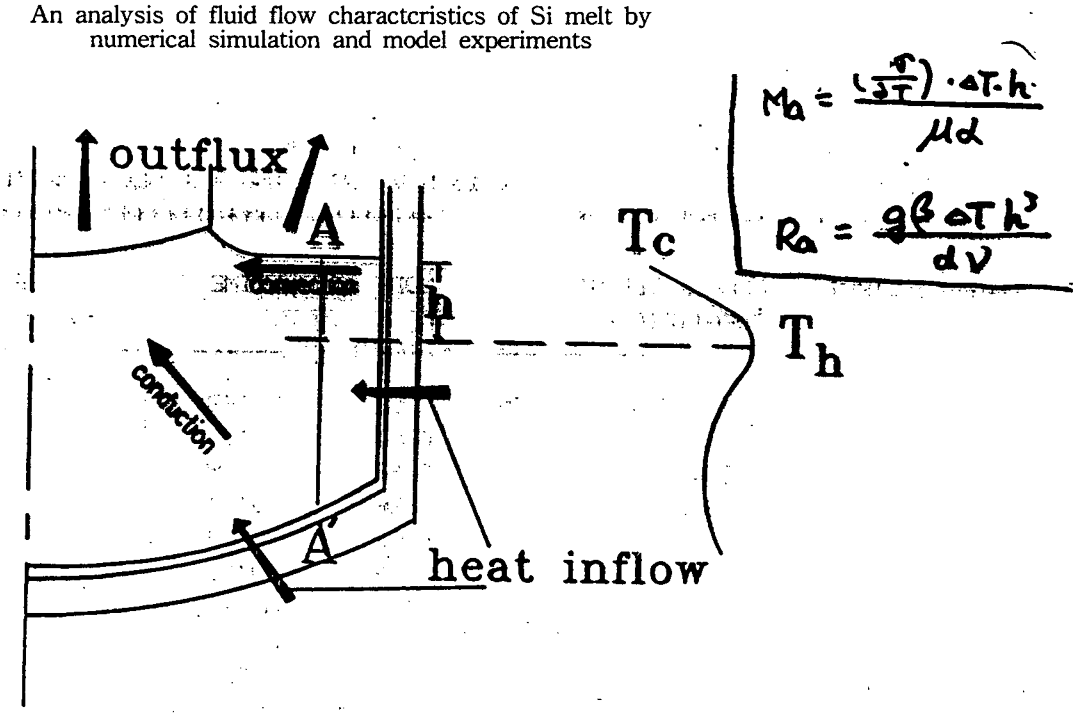
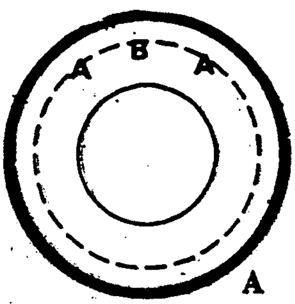


Fig. 10. (a) The schematic diagram of heat transfer in the melt.

(b) Vertical temperature profile along line A-A′ of (a).



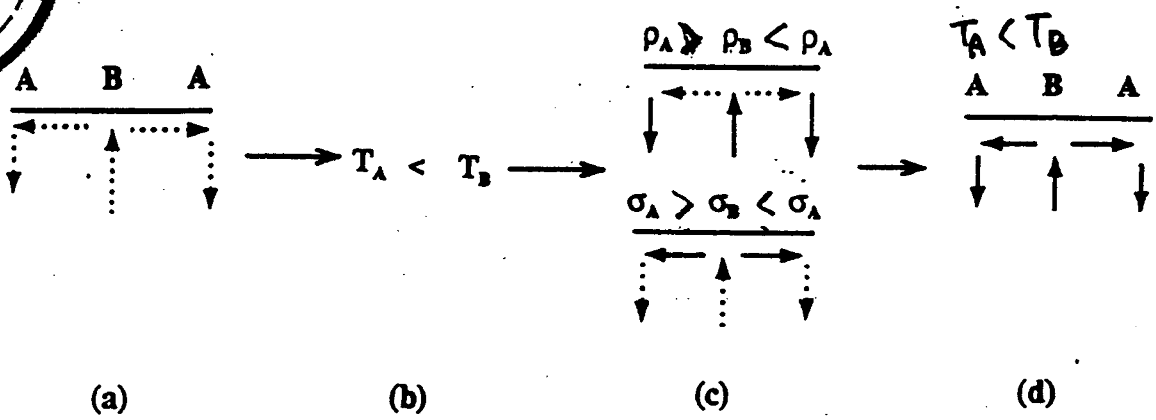


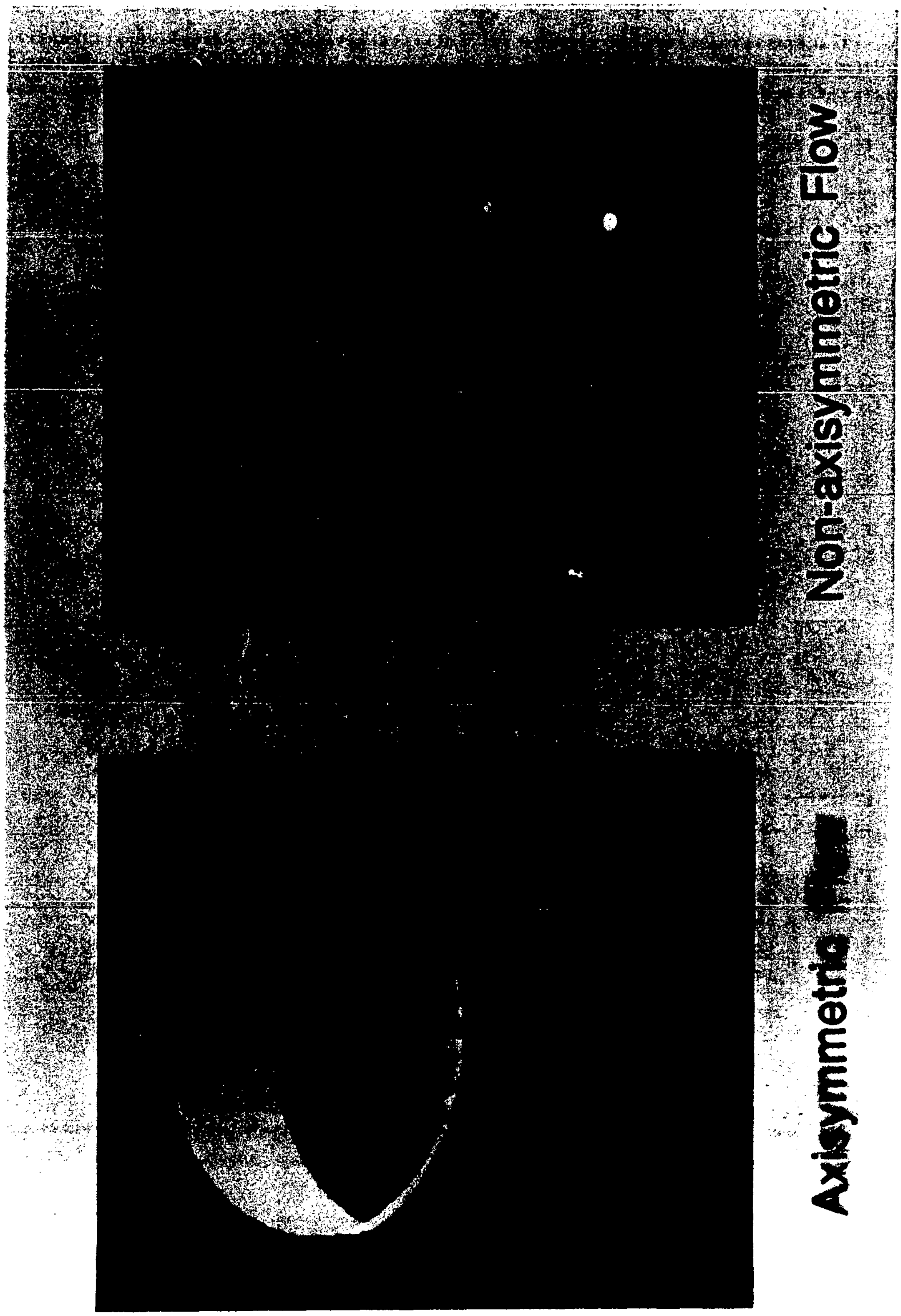
Fig. 11. Procedure of stabilizing roll structure

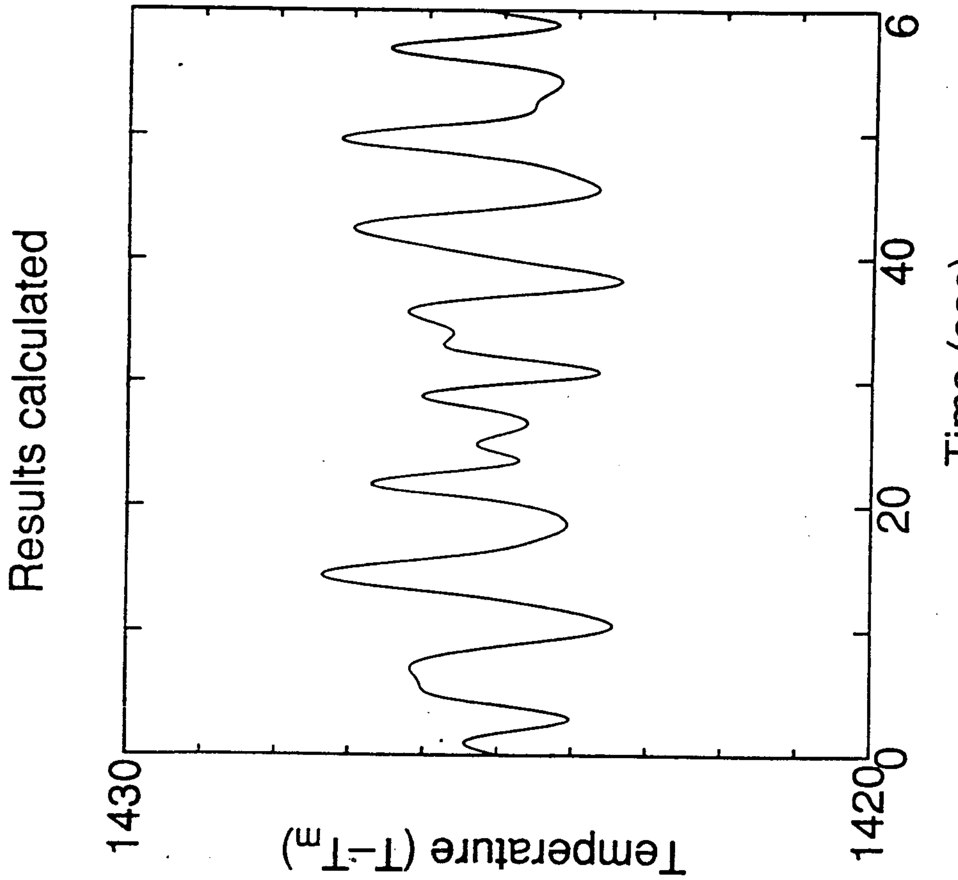
(a) Fluctuations occur from instabilities of flow.

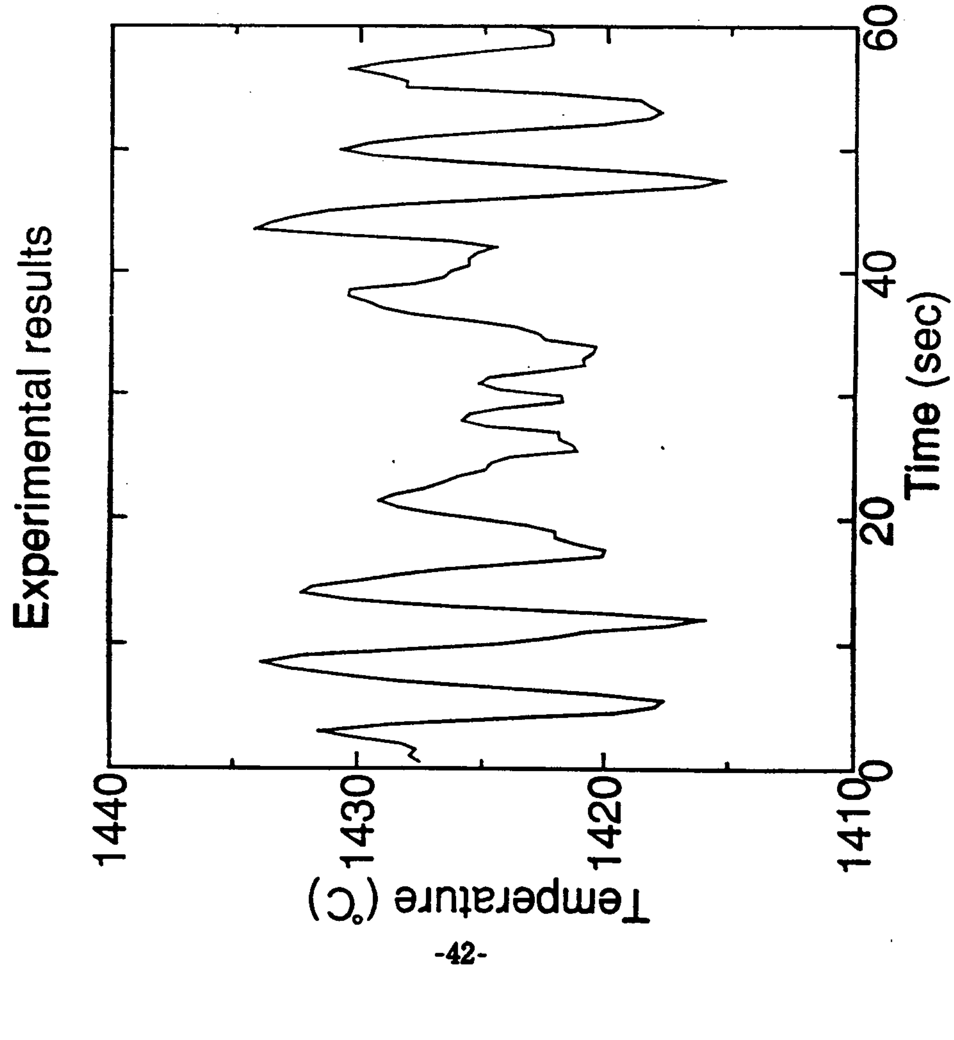
(b) Temperature of B increases.

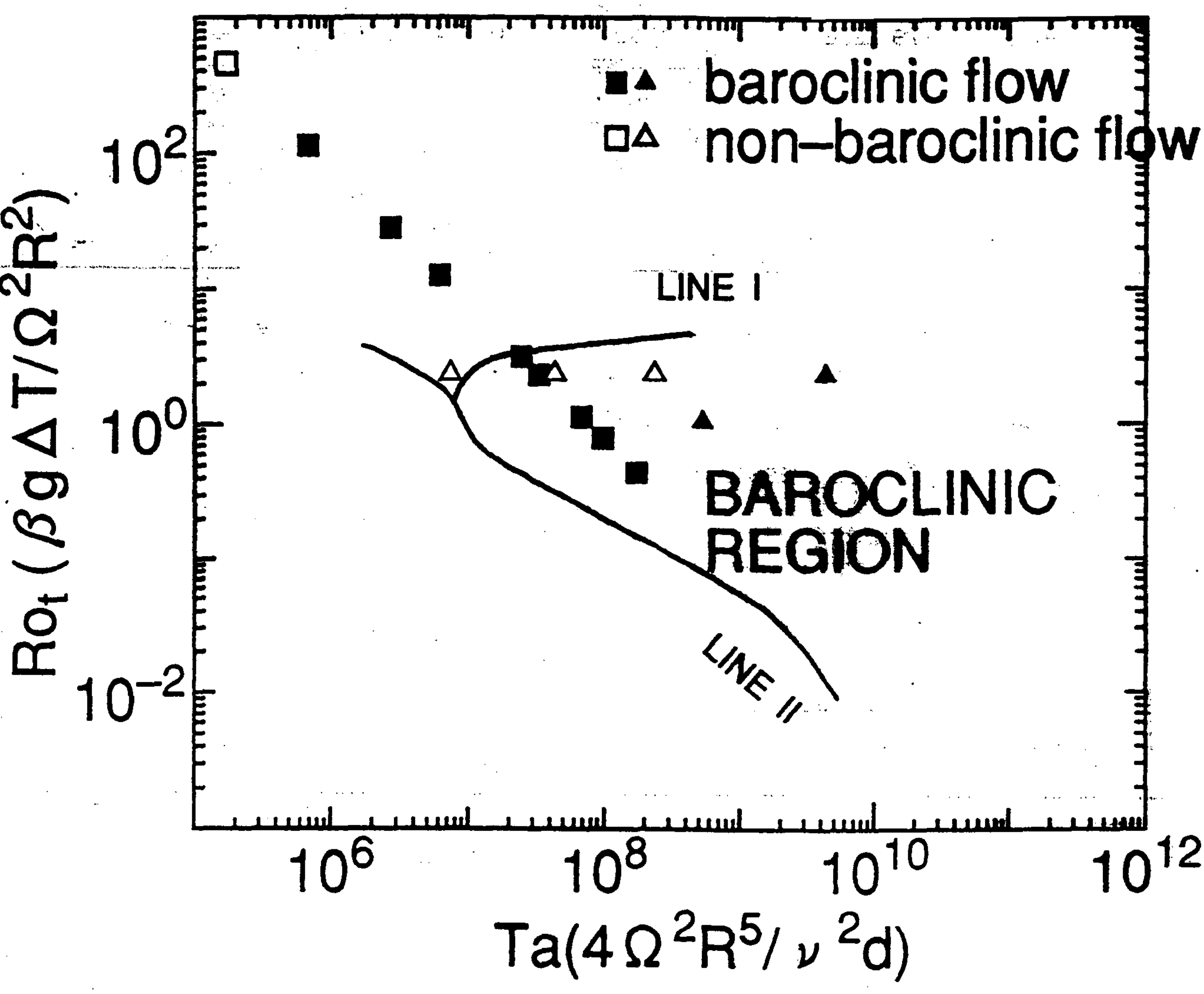
(c) Because of the temperature difference, the value of surface tension or density become different. These differences promote the fluid flow which has same direction of the initial fluctuation.

(d) Fluctuations change to the stable roll type flow pattern.


Non-axisymmetric Flow
Axisymmetric

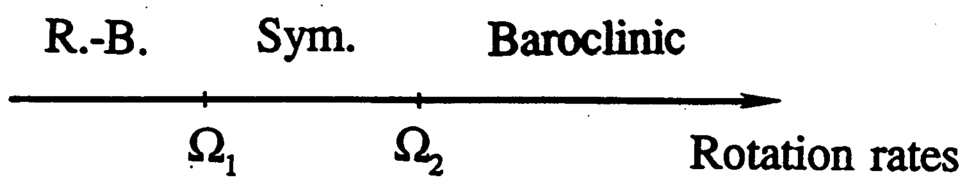

Results calculated
Time (sec)
Temperature ($T-T_m$)
1430
1420
0
20
40
6


Experimental results
Time (sec)
Temperature (°C)
1440
1430
1420
1410
0
20
40
60



△▲ adiabatic calculation

Instabilities exist at rotations of crucible

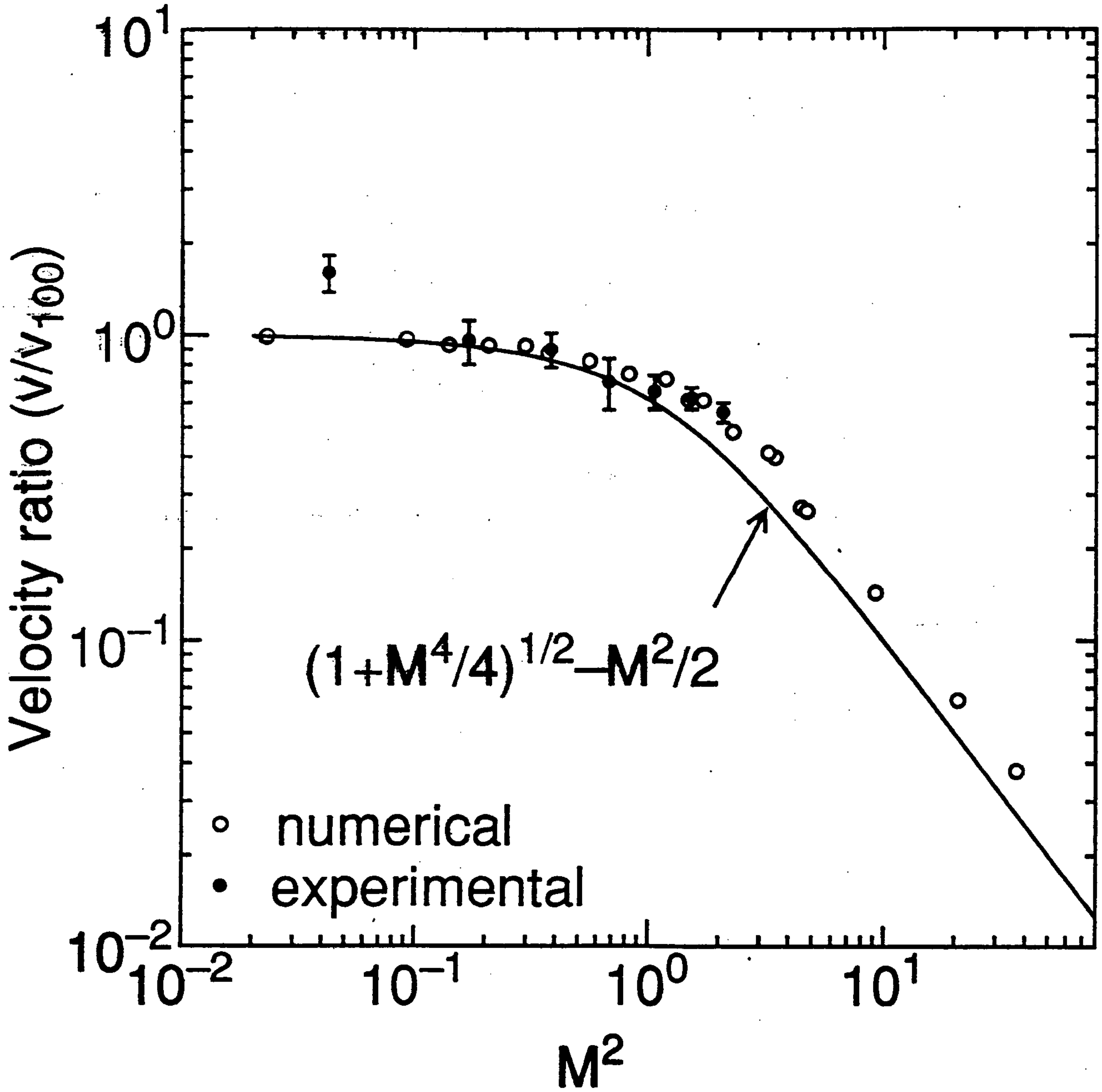


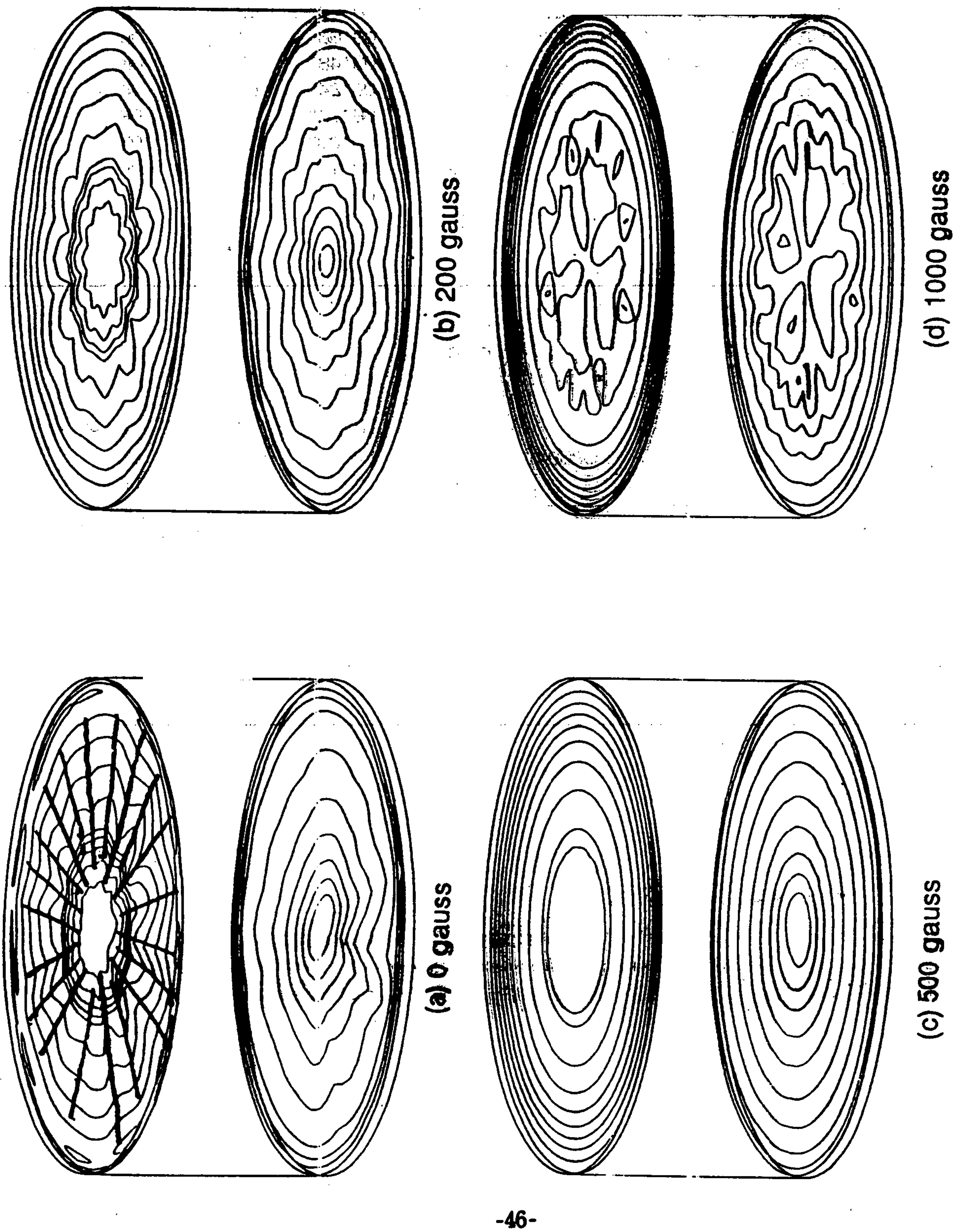
Rayleigh-Benard instability remains to Ω_1.

Baroclinic instability occurs from Ω_2.

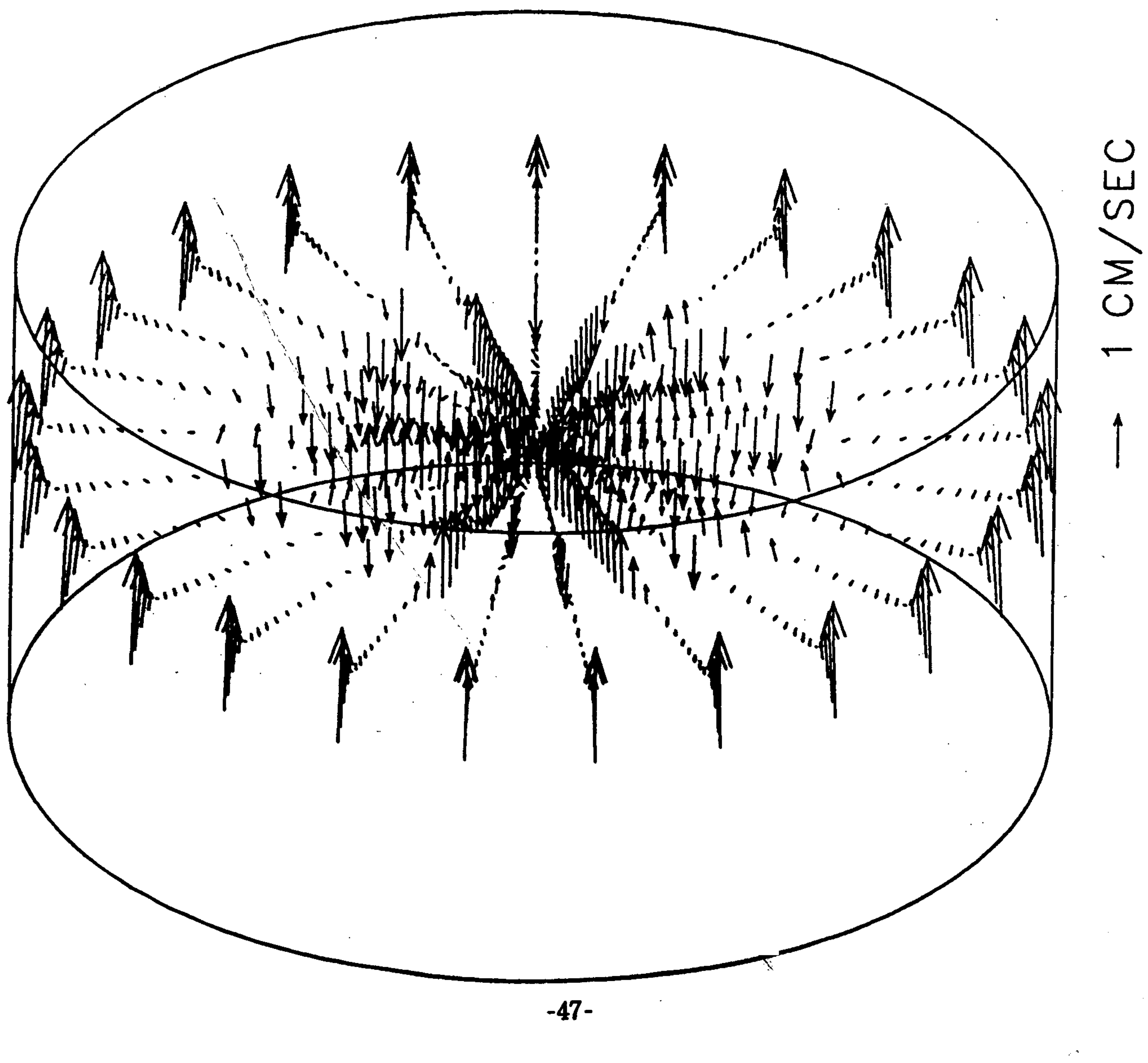
Small crucible (diameter is 7 cm) : $\Omega_1 < \Omega_2$.

Large crucible (diameter is 20 cm or 40 cm) : $\Omega_1 > \Omega_2$.


10^1
10^0
10^{-1}
10^{-2}
Velocity ratio (V/V_{100})
$(1+M^4/4)^{1/2}-M^2/2$
numerical
experimental
10^{-2}
10^{-1}
10^0
10^1
M^2



Isothermal lines (R=20 cm, H=10 cm)


1 CM/SEC

Effects of axial magnetic field

(1) Flow velocity decrease

$$\frac{V}{V_0} = \sqrt{1 + \frac{M^2}{4}} - \frac{M}{2}, \quad M: \frac{h\sigma B_0^2}{\rho V_0}$$

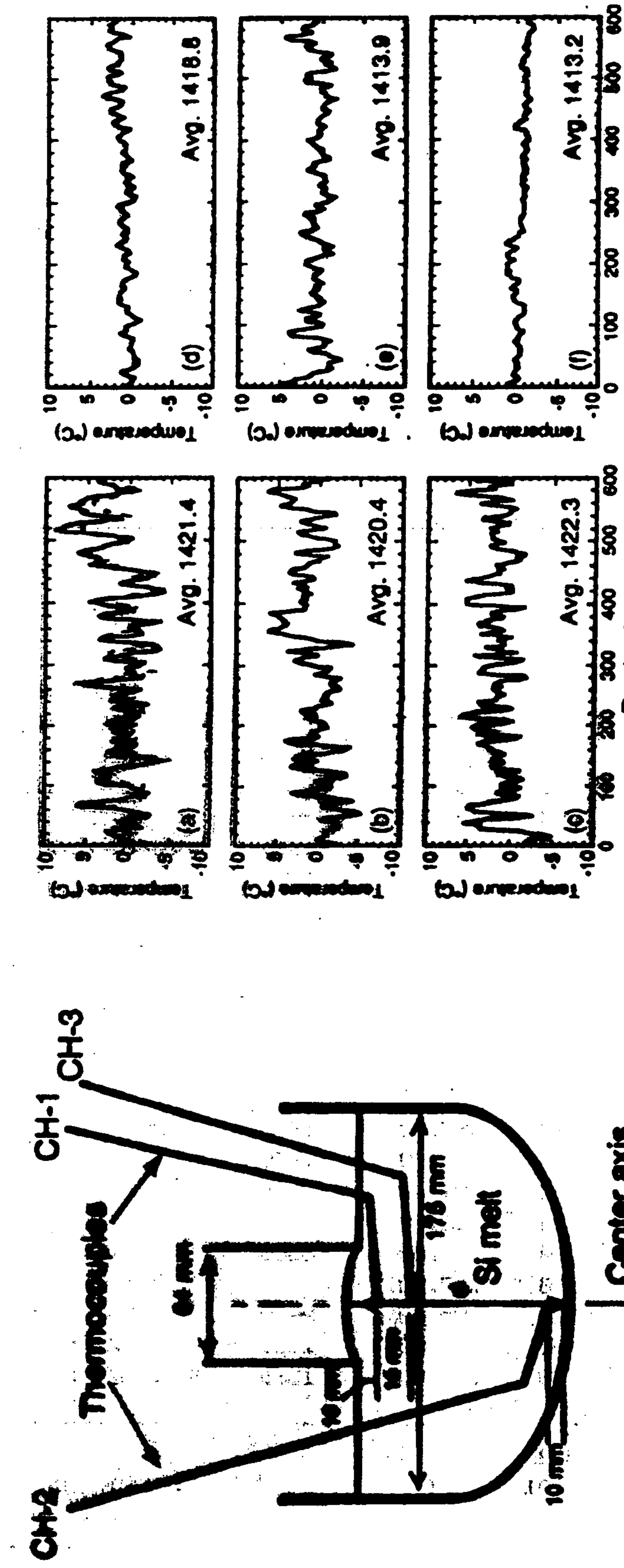
(2) Suppress the Benard-type instabilities.

(3) 3-D cell structure in a high magnetic field.

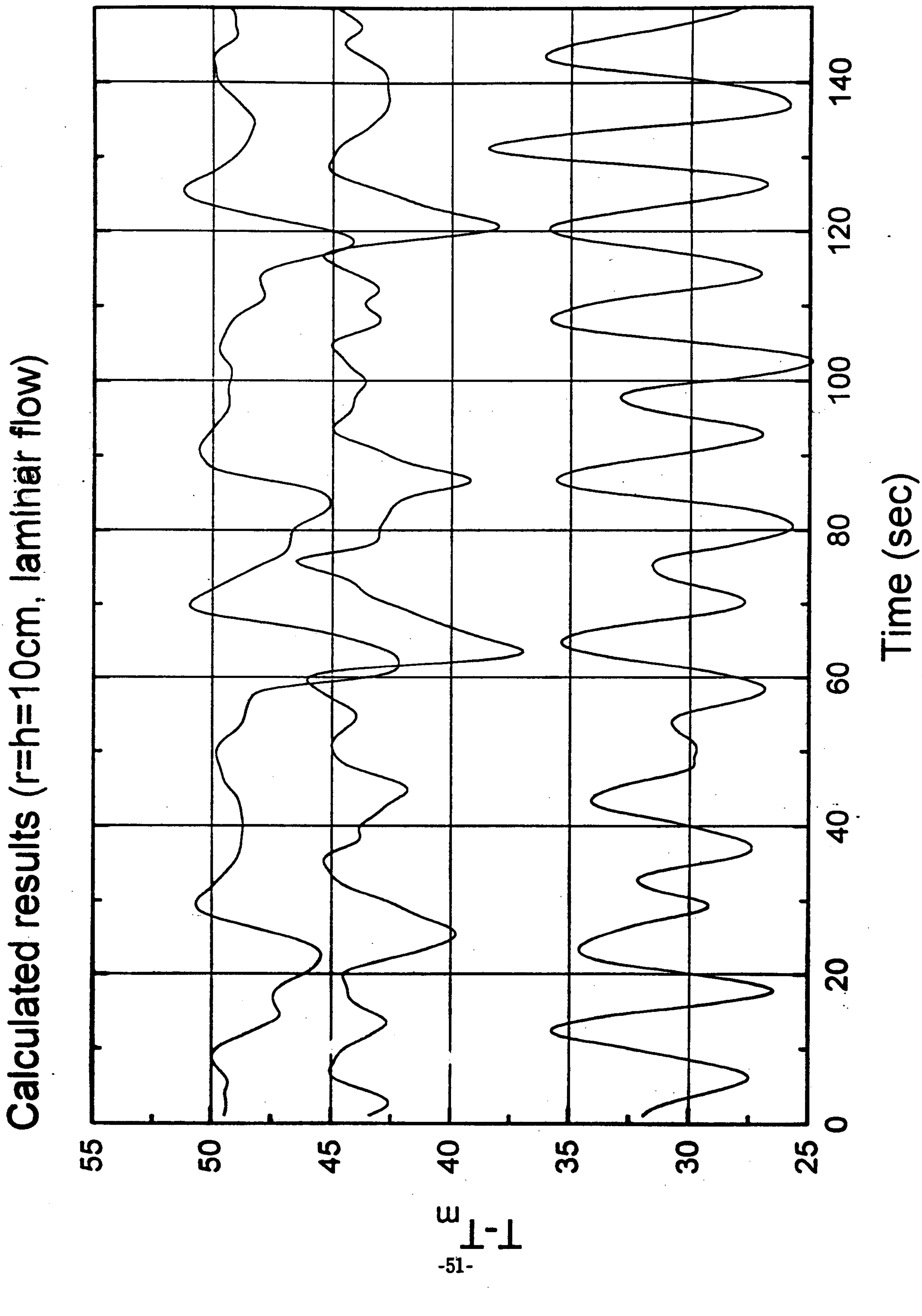
4. Flow behavior in turbulent flow

Micro fluctuation – frequencies show white band

Simulation with turbulent model – average velocity



S. Togawa et al., Journal of crystal growth 160(1996) 41-48


Calculated results (r=h=10cm, laminar flow)
Time (sec)
T-Tm
0
20
40
60
80
100
120
140
25
30
35
40
45
50
55

Average velocities in the melt (cm/sec) at different crucibles

	small	medium	large
laminar	1.97	3.28	4.12
turbulent	1.69	2.84	3.62

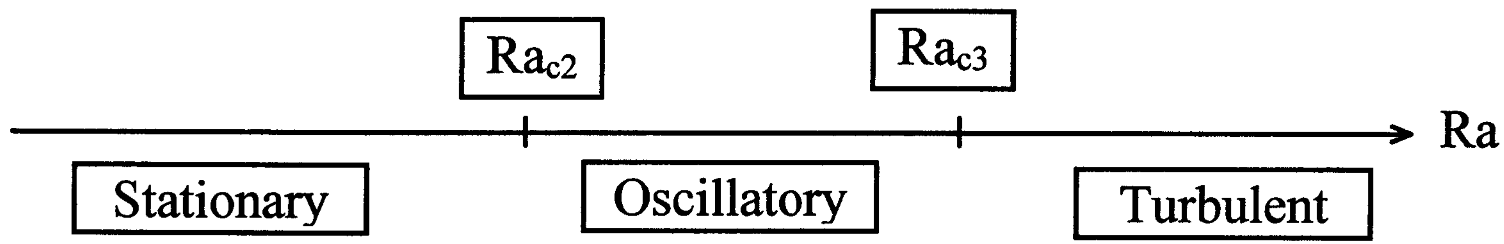
laminar : fluctuate, not axisymmetric profile

turbulent : no fluctuation, axisymmetric profile

verification : fluctuation behavior or azimuthal profile

5. Transitions from laminar to turbulent

Summary of previous experiments

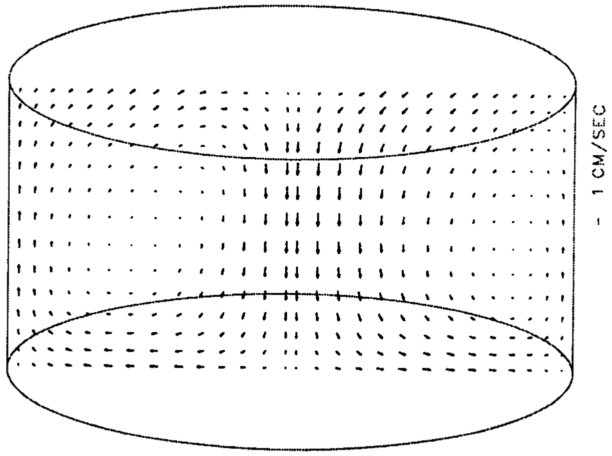


He : Ra_{c2} 9×10^4, Ra_{c3} 5×10^5

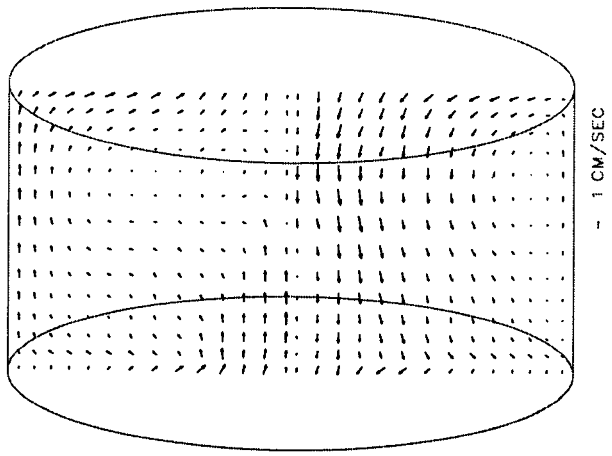
Silicone oil : $4 \times 10^5 \sim 5 \times 10^6$ (oscillatory)

Silicon melt : 5×10^5 (oscillatory), 10^8 (turbulent)

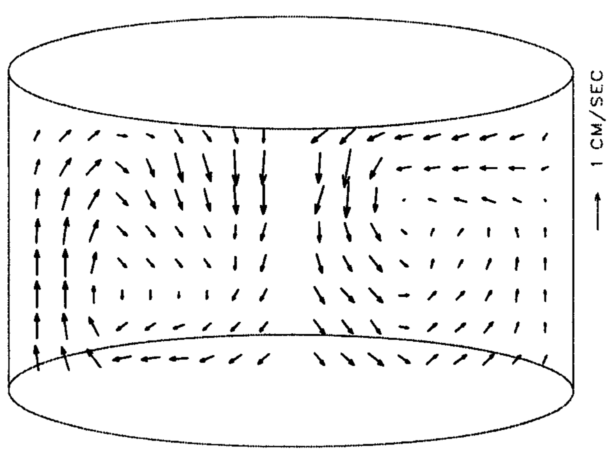
Low Prandtl number $Ra_{c2}=0.16 \sim 8 \times 10^5$ (aspect ratio)



Turbulent model calculation



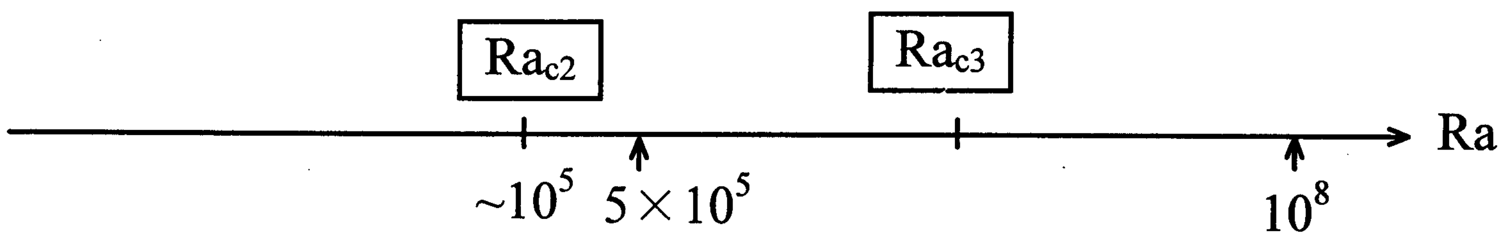
Laminar model calculation



Experimental results

Transition Rayleigh numbers depend on melt property and aspect ratio.

For silicon melt



Experiment and calculation at $Ra = 10^7$

Characteristics of Fluid flow : Turbulent flow.

For numerical simulation :

$k-\varepsilon$ turbulent model can be adopted.

Therefore Ra_{c3} is about 10^6.