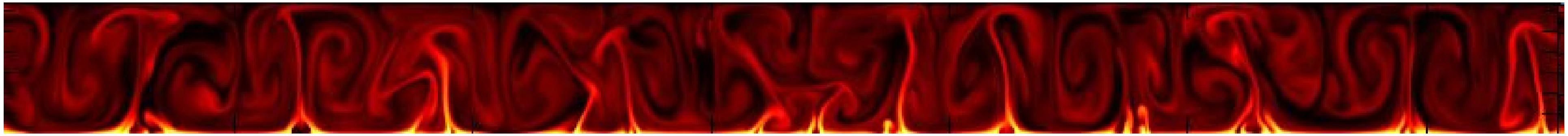

Natural convection heat transfer characteristics on supercritical helium

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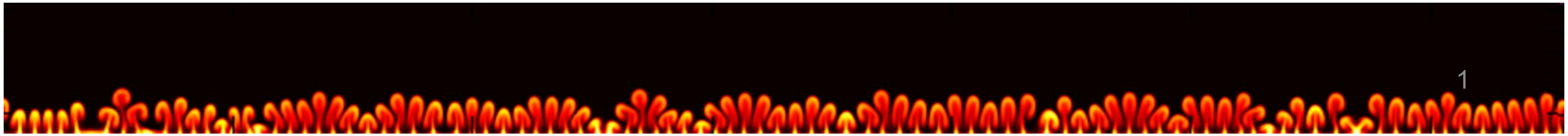
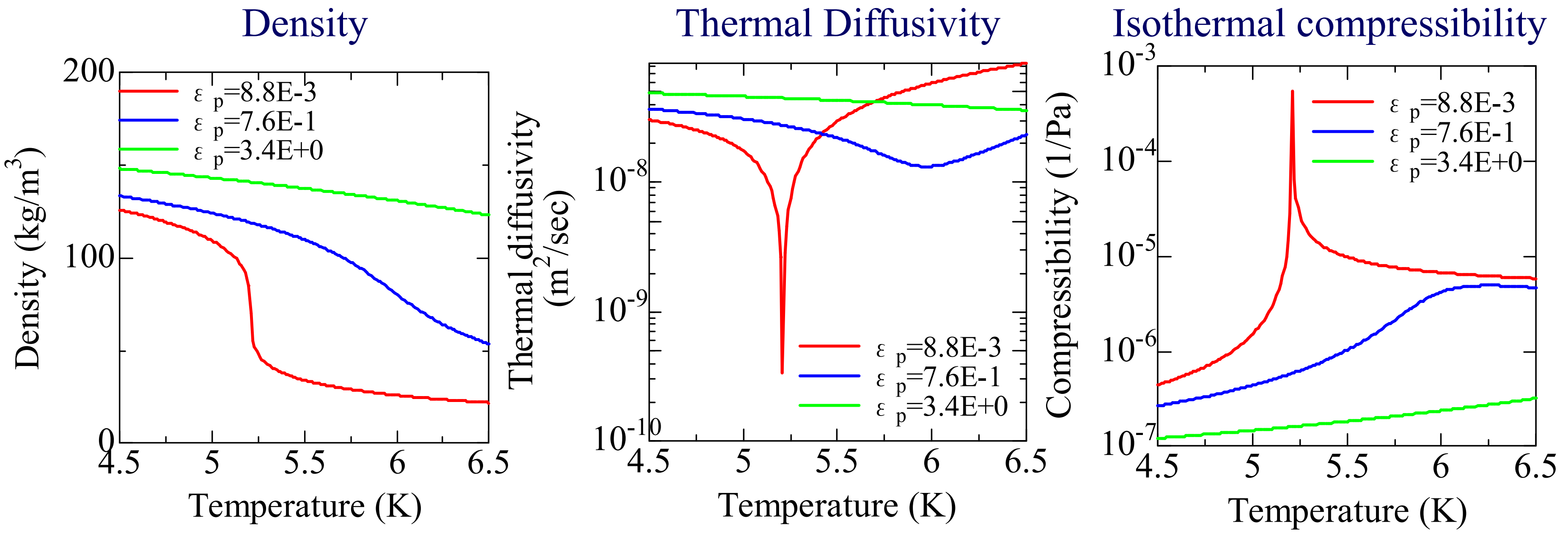


Properties of SuperCritical Helium (SCHe)

- Critical point (T_c = 5.19 K, P_c = 0.224 MPa @ Helium)



p=0.4 MPa (much higher than the critical pressure 224 kPa)

p=0.229 MPa (slightly higher than the critical pressure 224 kPa)

Near the critical point, properties strongly depends on the temperature.
- Low thermal diffusivity (Large heat capacity at constant pressure)
- Large compressibility

Depending on the system condition, there is possibility that peculiar phenomena such as plume & piston effect occur due to the drastically change of thermo physical properties.

■ Background

Superconducting magnets are often cooled by forced flow helium under the supercritical pressures.

It is important to clarify not only forced convection but also natural convection heat transfer because cooling channel may have some kind of dead end such that forced convection does not occur in the cooling channel.

Laminar turbulent transition processes in the case of vertical channel system with and without riblet are introduced in order to clarify followings.

1. **transition process to turbulent**

2. **appropriate passive turbulent control methods which has the possibility of heat transfer enhancement even in the dead end such that forced convection does not occur.**

■ System conditions in this study

- **Turbulent field induced by thermal plume in a open system is considered in this study. By considering open system, interaction between turbulence and piston effect induced in the case of closed system can be almost neglected.**

Initial conditions of the SCHe

$$T(\mathbf{r},0) = 5.25\,\mathrm{K} \longrightarrow \epsilon_T := T/T_c - 1 = 7.7 \times 10^{-3} > 1 \times 10^{-4}$$

$$\mathbf{u}(\mathbf{r},0) = 0\,\mathrm{m/sec}$$

$$\rho(\mathbf{r},0) = 47.96\,\mathrm{kg/m^3}$$

$$\langle\, p(\mathbf{r},0)\,\rangle = 228\,\mathrm{kPa} \qquad < \cdots > \overset{\mathrm{def}}{=} |\Omega^3|^{-1} \int_{\Omega^3} \cdots d^3\mathbf{r}$$

Maximum Rayleigh number is larger than critical Rayleigh number

$$Ra_{L_3} \overset{\mathrm{def}}{=} \frac{g\beta\nabla T \cdot \mathbf{e}_3 L_3^4}{\nu D} \qquad Pr_o = \nu_o/D_o = 5.17$$

Maximum Rayleigh number in the case of vertical channel.

$$Ra_{L3} = 1 \times 10^{12}$$

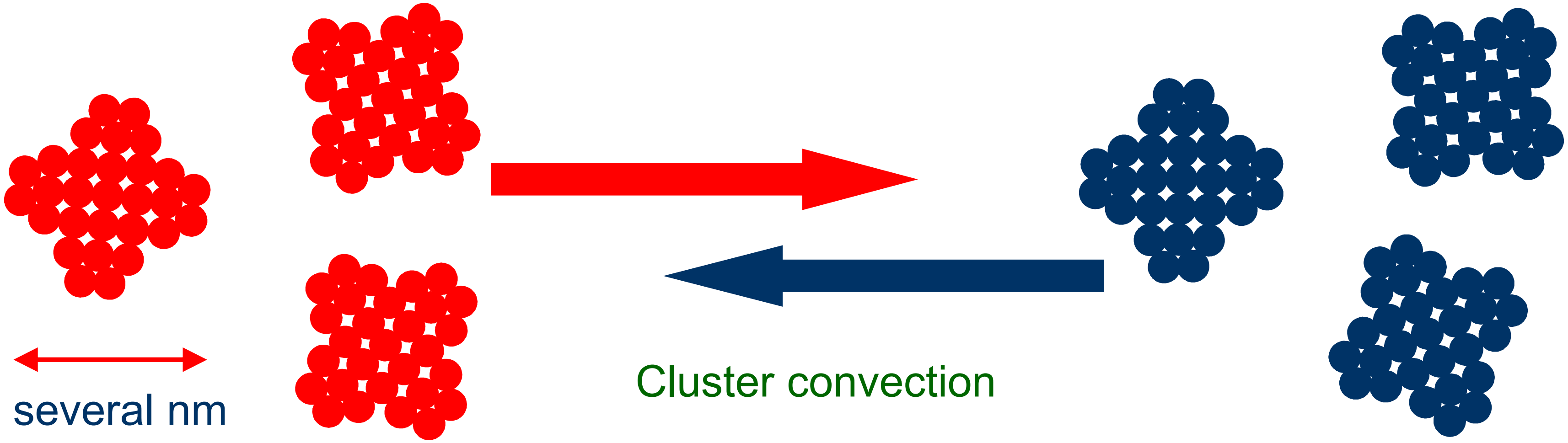
Violation of the continuum hypothesis & Stokes assumption

Reduced temperature $\epsilon_T := T/T_c - 1$

When the value of the reduced temperature is less than 10^{-4},

- **Violation of the continuum hypothesis will be generated.**
- **Bulk Viscosity becomes to be finite value. (order of several Pa-sec)**

In this case, the molecular structure of the fluid consists of several nm clusters and the nontrivial convection called “cluster convection” will be generated.



(Ref: A. Onuki , phase transition dynamics ,Cambridge University Press)

Basic Equations

- Compressible hydrodynamics equations.

$$\partial_t \rho + u_j \partial_j \rho = -\rho \partial_j u_j$$

$$\partial_t u_i + u_j \partial_j u_i = -\rho^{-1} \partial_i p + \rho^{-1} \partial_j \tau_{ij} - g,$$

$$\partial_t e + u_j \partial_j e = -\rho^{-1} \partial_j q_j - (p/\rho)\, \partial_j u_j - (\tau_{ij}/\rho)\, \partial_j u$$

- Thermal equation of state → HEPAK (thermal properties program of the helium)

$$dp = (\partial p/\partial \rho)_e \, d\rho + (\partial p/\partial e)_\rho \, de$$

※ *Constructive equations*

$$\begin{cases} \tau_{ij} := 2\mu S_{ij} - (2/3)\mu S_{kk}\delta_{ij}, \\ 2S_{ij} = (\partial_j u_i + \partial_i u_j) \end{cases}$$

- Theory of dynamic critical phenomena and Green-Kubo formula predicts that bulk viscosity which is usually treated as zero by Stokes assumption becomes finite value in the case that the reduced temperature is less than 10^{-4} .

Bulk Viscosity : Stokes assumption is applied to the simulations

Part I: SCHe flow characteristics of natural convection on vertical heating system

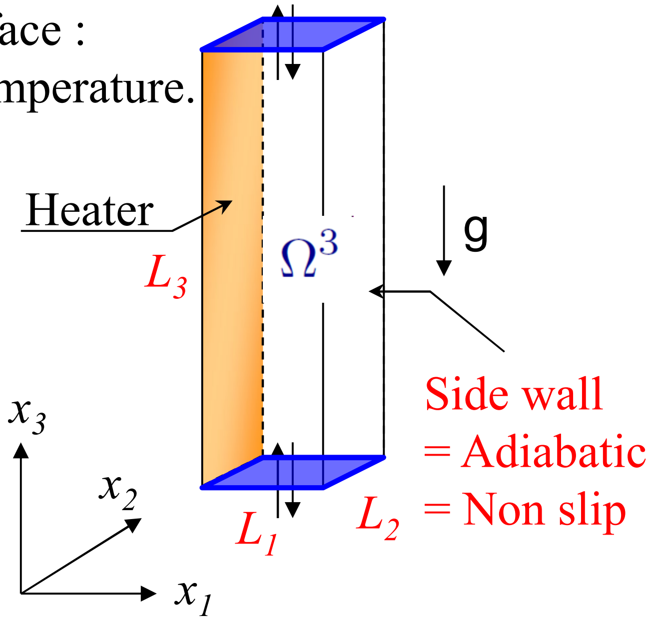
Shape of the channels and methods

- Vertical flat plate system
  - Inlet / outlet of the channel. =“Neumann BC.”
  - Side wall of the channel = “non slip wall”

  - Time & Spatial evolution → *“FDM”*

$$\boxed{L_3/L_1 = L_3/L_2 = 14.4}$$

$$\Omega^3 \overset{\text{def}}{=} [0, L_1] \times [0, L_2] \times [0, L_3]$$

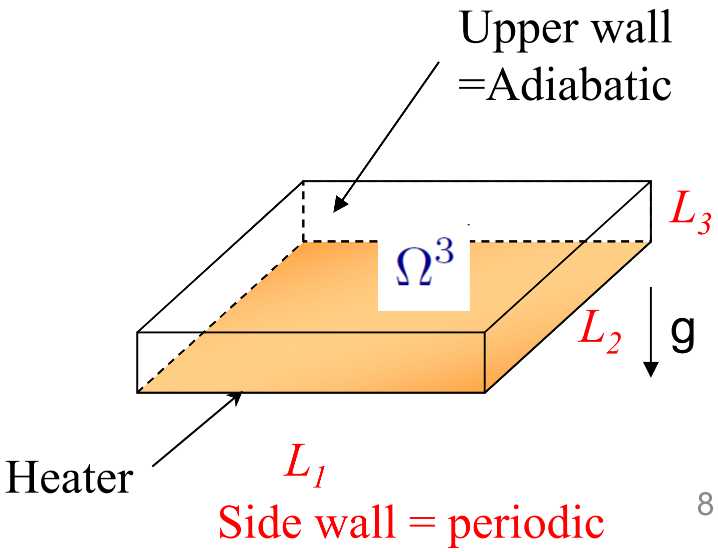


Heater surface : constant temperature.

Side wall = Adiabatic = Non slip

- Horizontal flat plate system
  - Horizontal direction. = “periodic BC.”
  - Time evolution → “PSM + FDM”

$$\boxed{L_3/L_1 = L_3/L_2 = 0.25}$$

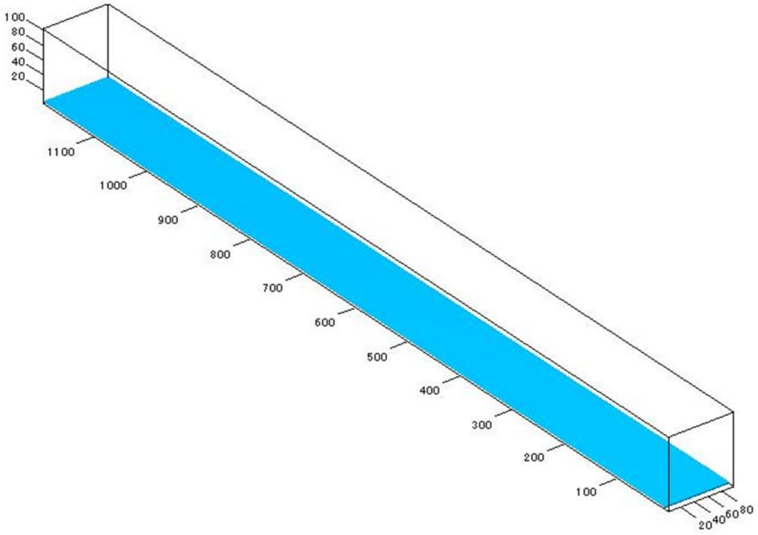


Upper wall =Adiabatic

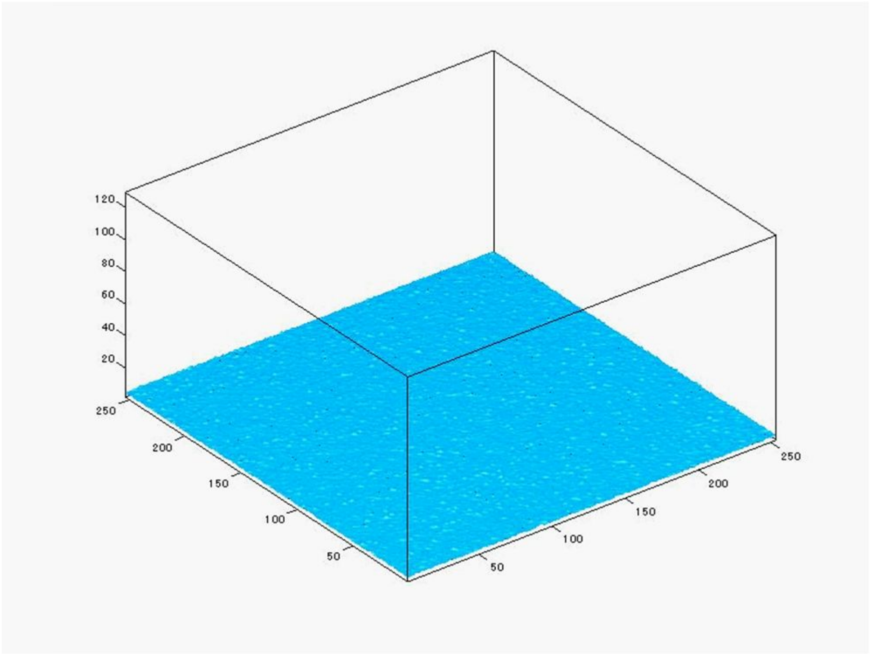
Side wall = periodic

■ Time evolution of the temperature field

Vertical heater system (3/4 Ω^3)



Horizontal heater system (1/4 Ω^3)



1) Spanwise thermal plume is generated.
due to K-H instability

1) Mushroom thermal plume is generated
due to R-T instability

2) Flow field becomes complicated structure in both cases.
due to secondary instability

■ Vortex definition

Definition of vortex

There are two kinds of Vortex → "Vortex tube" & "Vortex layer"

"Vortex tube" : "Rotation" >> "Strain velocity"

$$\|\boldsymbol{\Omega}\| \gg \|\mathbf{S}\|$$

i.e. Low pressure field ~ vortex tubes

In order to obtain vortex tubes in the fluid, we can find the locations such that above relation is satisfied in the whole convective field.

Mathematical Expression of the vortex tube → *Q* criterion

Second invariant, $\mathit{\Pi}(u_{i,j})$ of velocity gradient tensor, $u_{i,j}$

$$|\ \partial_j u_i - \xi\delta_{ij}\ | = 0$$

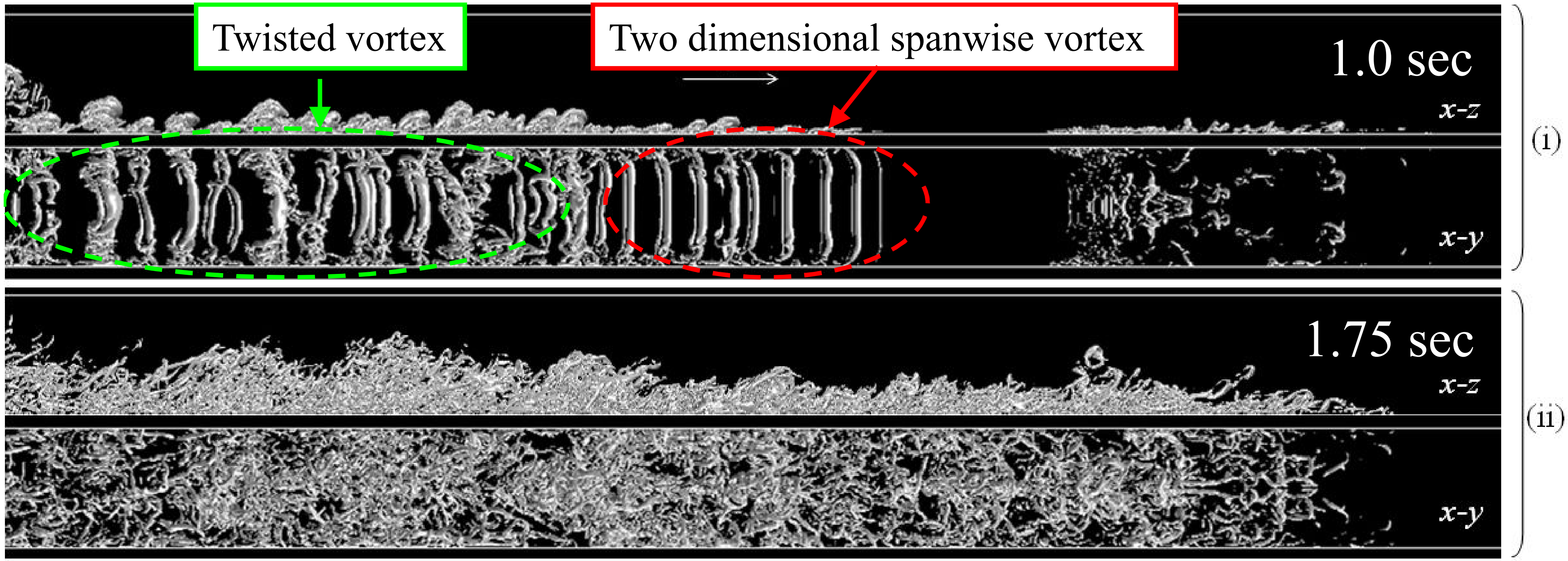
$$\mathit{\Pi}(u_{i,j}) = \xi_1\xi_2 + \xi_2\xi_3 + \xi_3\xi_1$$

Vortex tubes can be expressed as a positive value of the second invariant.

$$\boxed{\mathit{\Pi} \gg 0, \quad \text{i.e.} \quad \|\boldsymbol{\Omega}\| \gg \|\mathbf{S}\|}$$

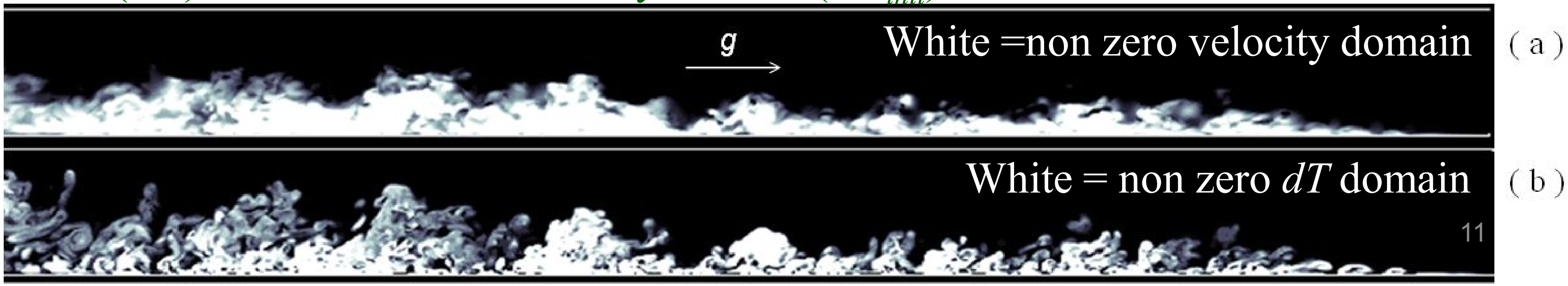
■ Vortical structures (vertical heater)

Side (x-z) & top (x-y) view of vortical structures at 1.0sec and 1.75 sec.



- Spanwise vortex street occurs due to Kelvin-Helmholtz instability
- Buoyant flow is generated very near the heated surface because of low thermal diffusivity.

Side (x-z) view of non zero velocity and $dT=(T-T_{init})$ field at 1.75 sec.



■ Discussion1 (transition process to turbulence)

Transition process to turbulence with respect to the natural convection SCHe

Developed turbulence takes place after two kinds of instability.

- "First" instability

  ↓ appearance of 2D structure (vortex ring & spanwise vortex)

  Horizontal heater → Vortex ring : Rayleigh-Taylor instability

  Vertical heater → Spanwise vortex : Kelvin-Helmholtz instability

- "Secondary" instability

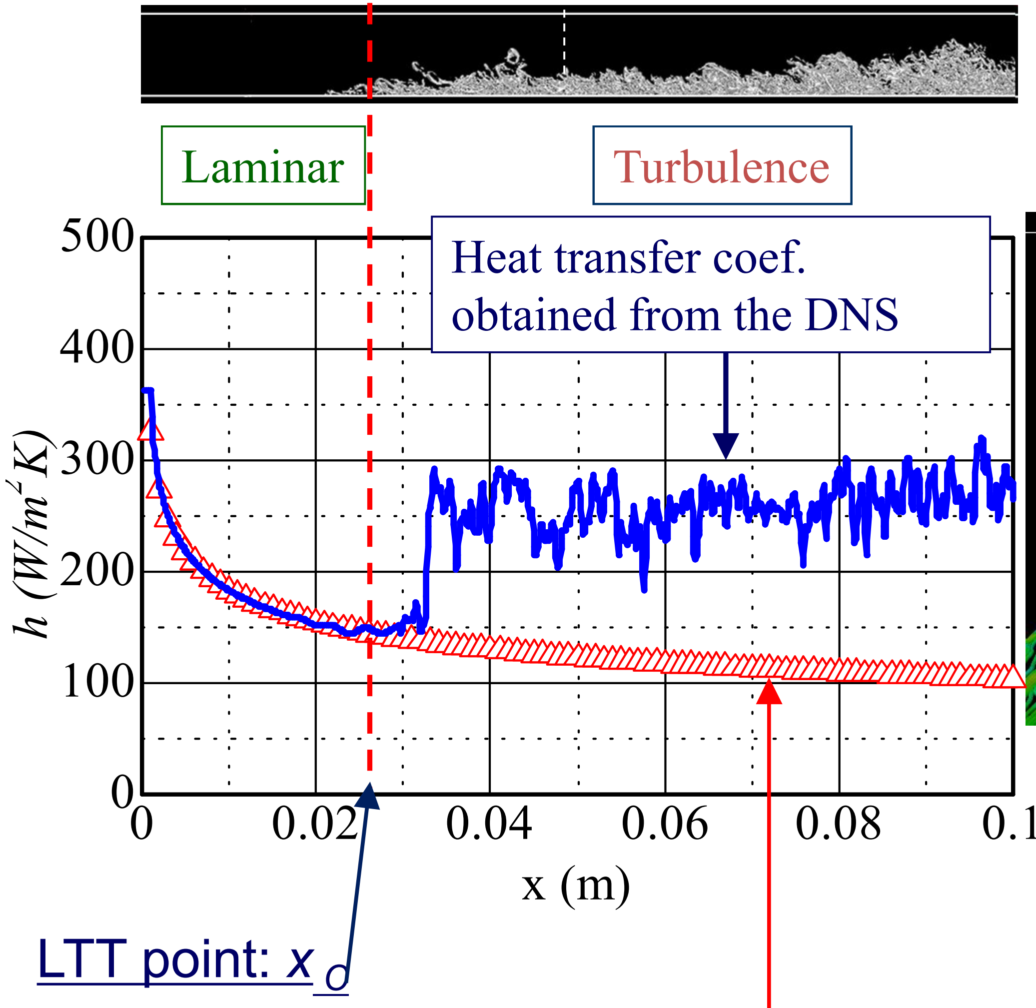
  ↓ appearance of 3D structure due to twisted vortex.

  - Twisted vortex is generated because of the interaction between vortices and non-slip wall.

- Fully developed turbulence

Transition process is almost same as jet and mixing layer.

■ Spatial evolution of local heat transfer coef.

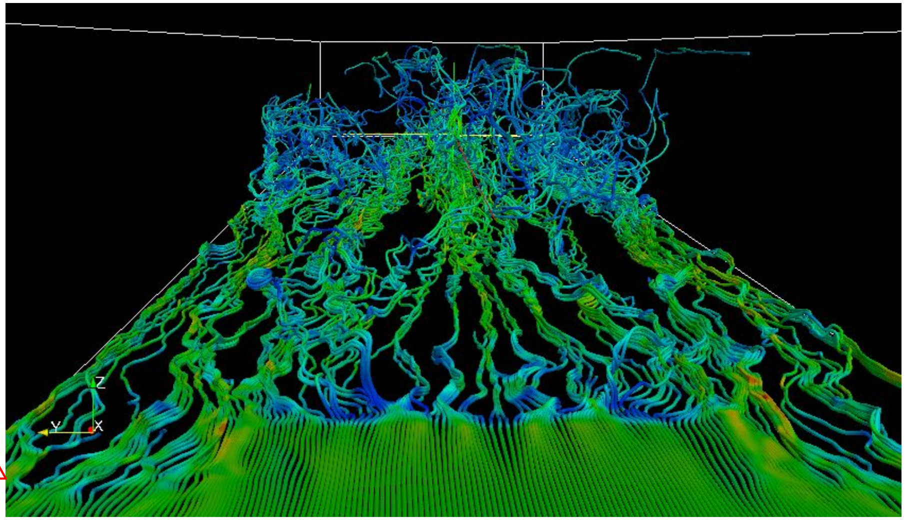


Heat transfer coef. obtained from the DNS

LTT point: x_O

Analytical solution for Laminar flow from boundary layer approximation.

Streamline aspect near the transition point

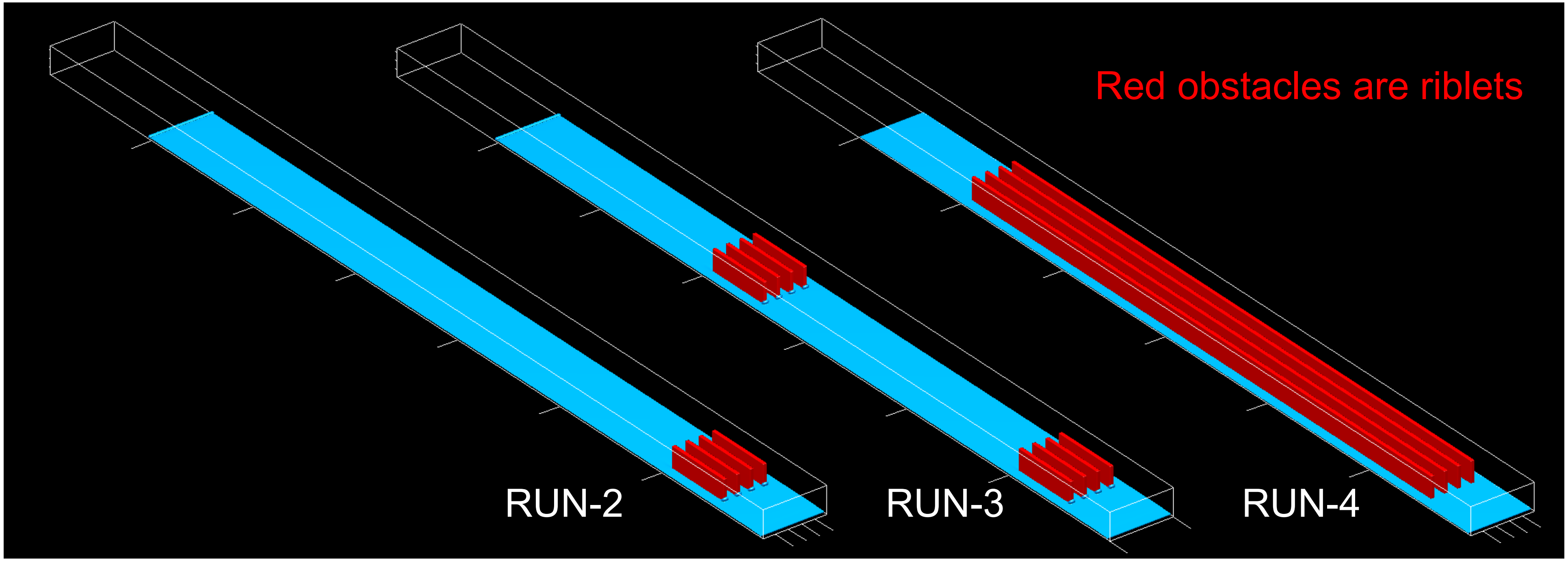


Near the transition point, stream line changes from straight to bending shape.

Part II: Influence of thermal flow filed due to obstacles

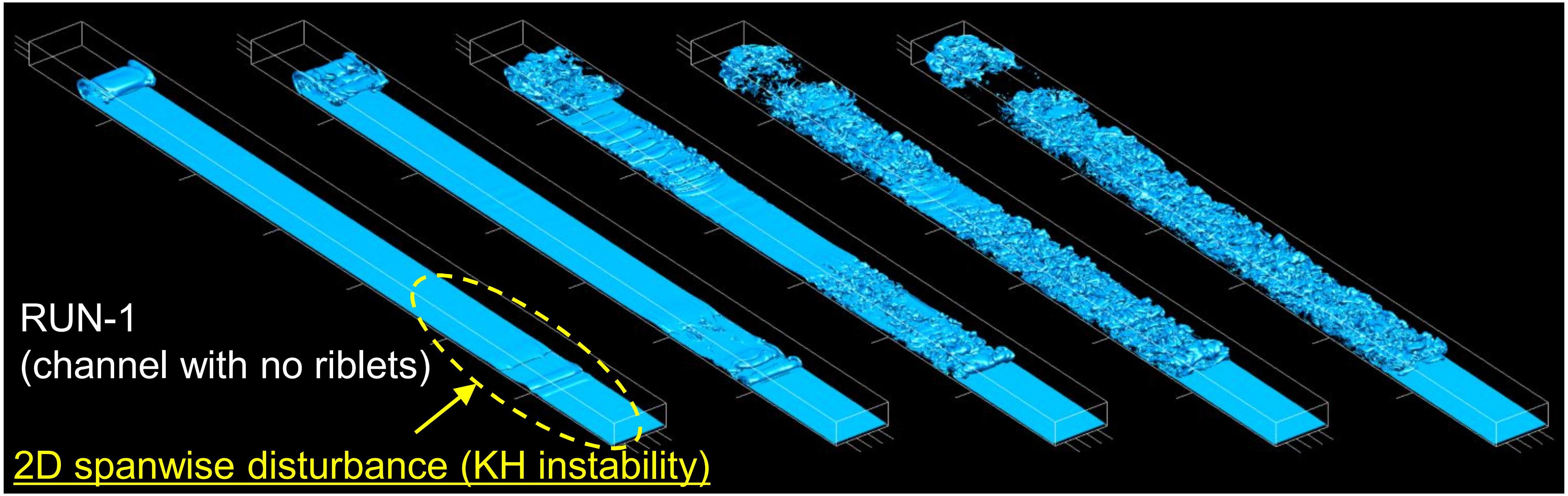
■ Shape and location condition of riblets

Three kinds of simulations are performed in order to clarify the channel shape dependence of transition process and heat transfer characteristics.



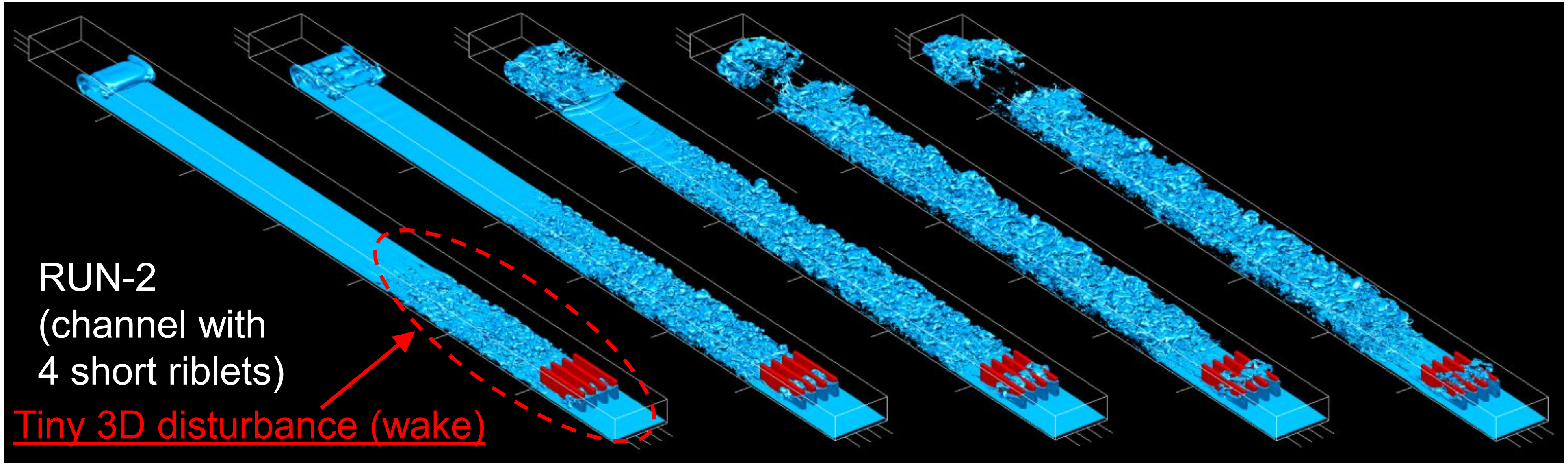
RUN-1: no riblet
RUN-2: 4 riblets（short riblets located near the leading edge）
RUN-3: 8 riblets（short riblets located near the leading edge and center of the channel）
RUN-4: 7 riblets（long riblet）

■ Comparison between RUN-1 and RUN-2



RUN-1
(channel with no riblets)

2D spanwise disturbance (KH instability)

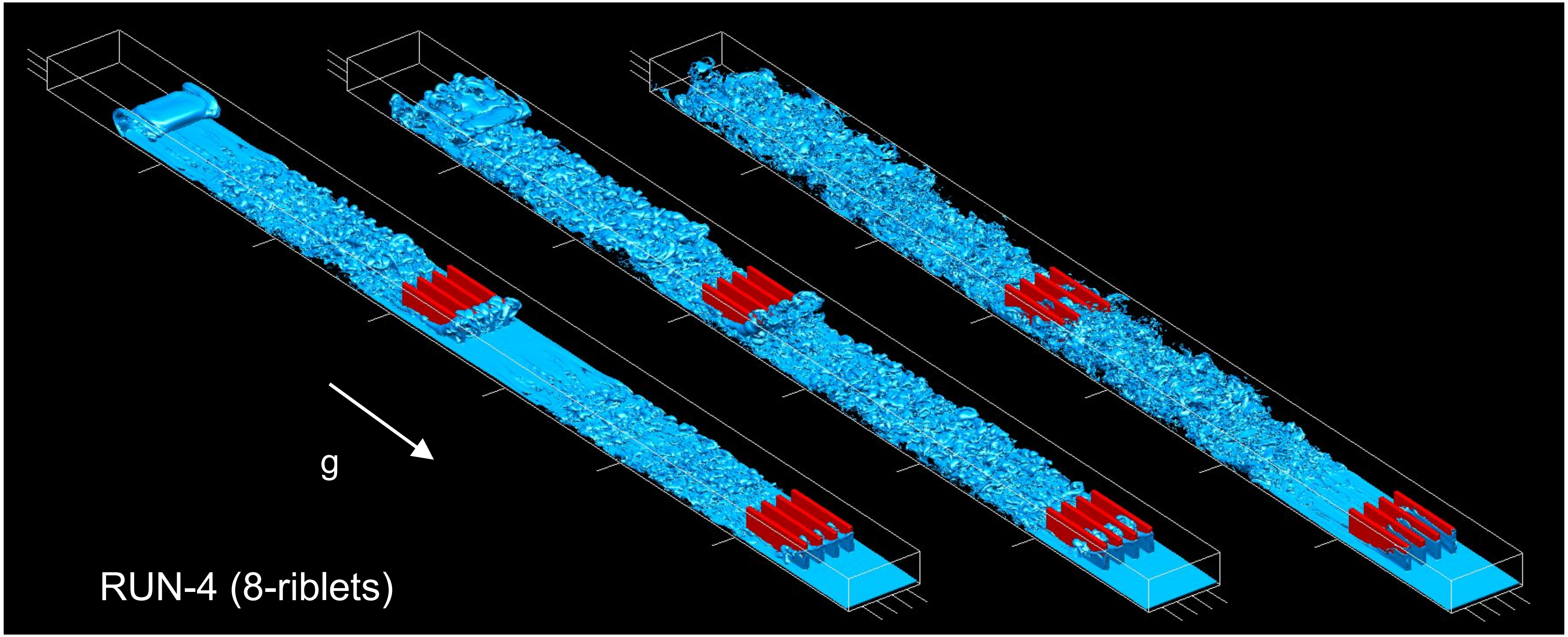


RUN-2
(channel with
4 short riblets)

Tiny 3D disturbance (wake)

t=1.0 sec, 1.2 sec, 1.4 sec, 1.6 sec, 1.8 sec

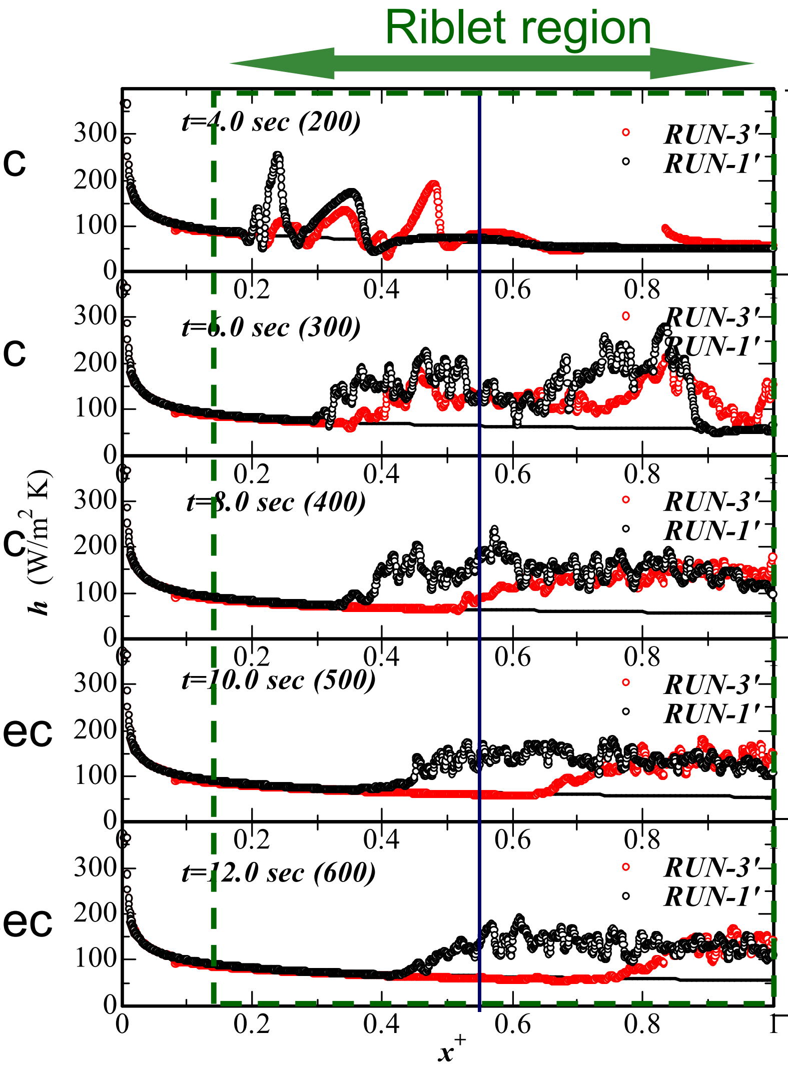
■ In the case of the many short riblet in a channel



t=1.0 sec, 1.2 sec, 2.0 sec

- Short riblets contribute to vortex generation.
- Reduction of the transition time to turbulence can be realized by the short riblets.
- Installation of the riblet at adequate distance can lead the reduction of the transition ti

■ Heat transfer decreasing in the case of RUN4



RUN-4 channel with long riblets

t=4.0 sec
- ** RUN-1' Laminar*
- ** RUN-4 Turbulent*

t=6.0 sec
- ** RUN-1' Transition region*
- ** RUN-4 Transition region*

t=8.0 sec
- ** RUN-1' Turbulent*
- ** RUN-4 Transition region*

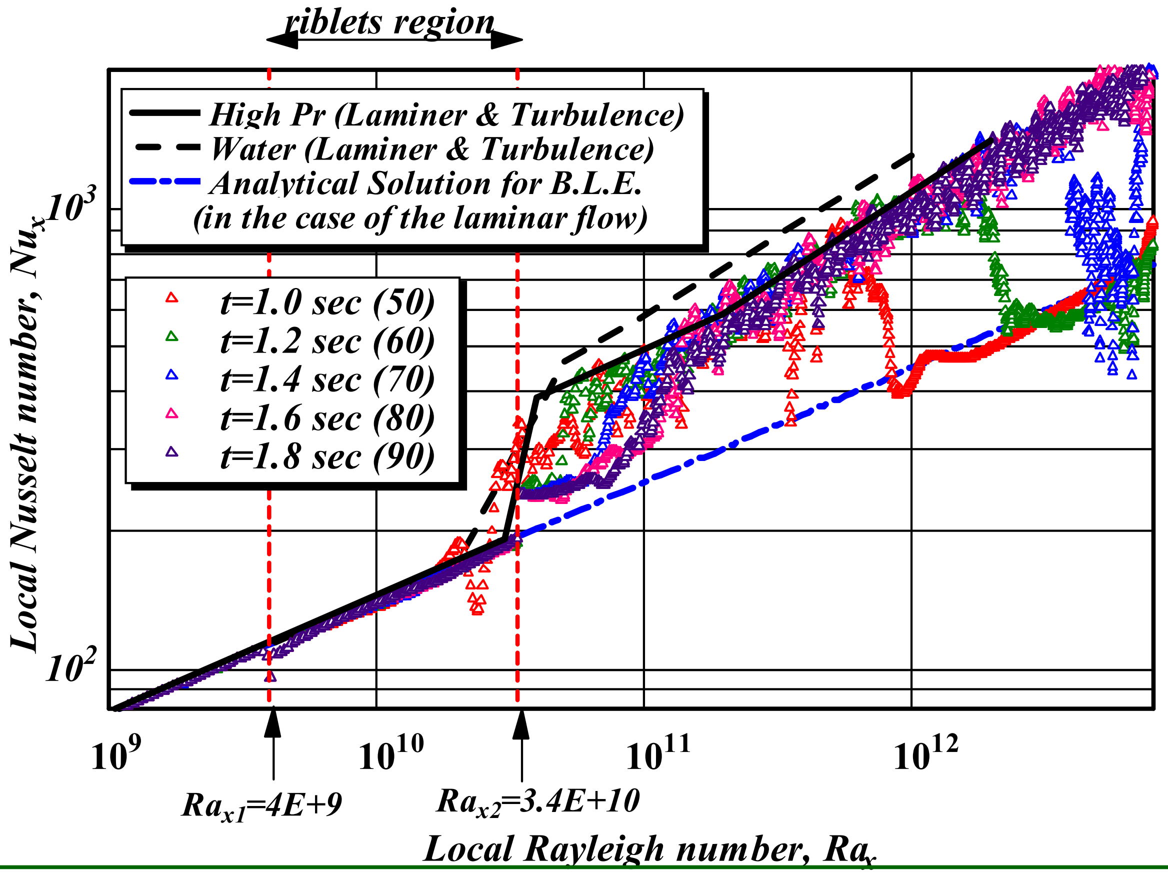
t=10.0 sec
- ** RUN-1' Turbulent*
- **** RUN-4 Relaminarization***

t=12.0 sec
- ** RUN-1' Turbulent*
- **** RUN-4 Relaminarization***

➢ After t=8.0 sec, as the time advances, heat transfer coefficient obtained from RUN-4 becomes small compared with that in the case of the RUN-1' at the downstream from $x^+ = 0.55$

➢ This is because mixing effects due to entrainment are restricted because of the existence of long riblets.

Local Heat Transfer Coef. (RUN-2)



Scaling law of the heat transfer obtained from RUN-2

$$Nu_x = C\,Ra_x^m \begin{cases} \text{Laminar region} & C = 0.502\left(\dfrac{Pr}{Pr+\sqrt{Pr}+0.5}\right)^{1/4} \quad m = 1/4 \\ \text{Turbulent region} & C = 0.11, \quad m = 1/3 \end{cases}$$

■ Conclusions

- **Developed turbulence occurs after two kinds of instability** in the case of channel shape without riblets.

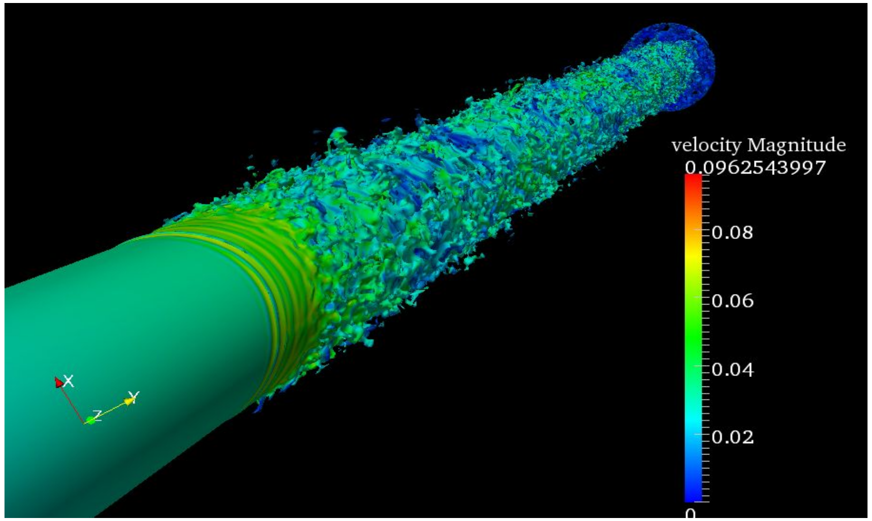
- In the case that **short riblets** are installed, developed turbulence take place instead of generation of the first instability. As a result, reduction of the transition time to turbulence can be realized by the short riblets.

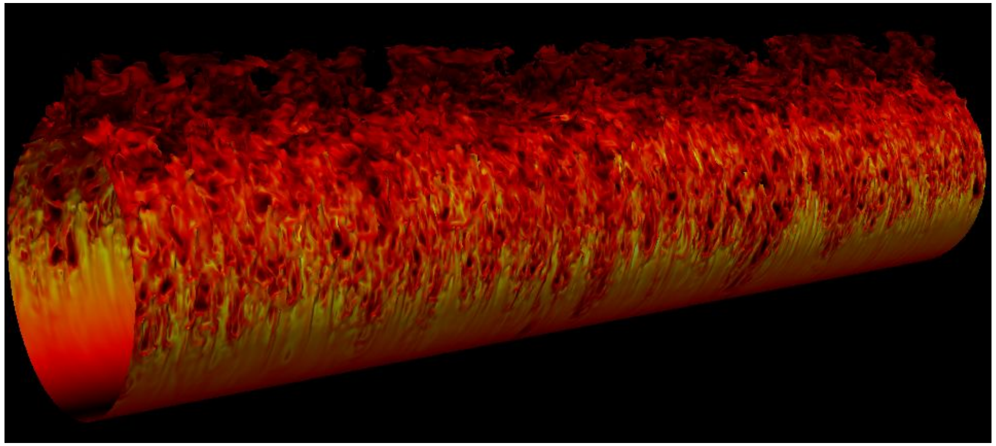
- In the case that the **long riblets** are installed, heat transfer degradation and relaminarization occurs due to the fact that mixing effect is restricted by the long side wall of the riblets.

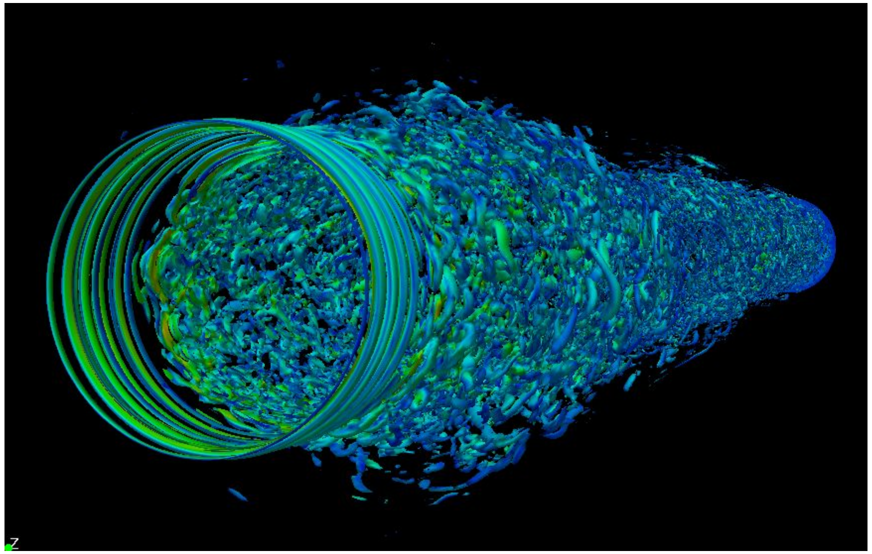
Future Plan

Now I’m trying to clarify turbulent properties of SCHe in the flow field induced by buoyancy

- ✓ Vertical cylinder system
- ✓ Horizontal cylinder system







In the case of Horizontal cylinder

In the case of vertical cylinder

Measurements of Helium Adsorption on Charcoals in Cryogenic Environment.

Takahiro Okamura,
Ryutaro Okada, Hirokatsu Ohhata, Suguru Takada, Takayuki Tomaru,
Nobuhiro Kimura, Masashi Hazumi, Tsutomu Nakanishi, Syuichi Goto

KEK, High Energy Accelerator Research Organization
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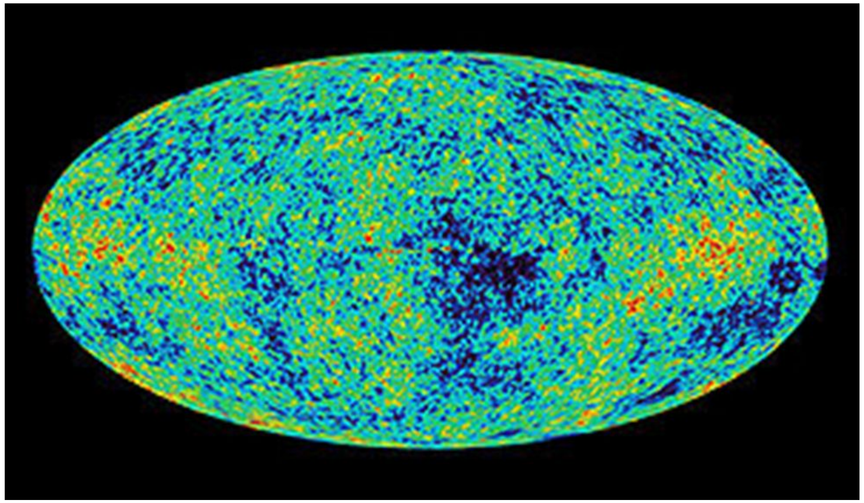
Background

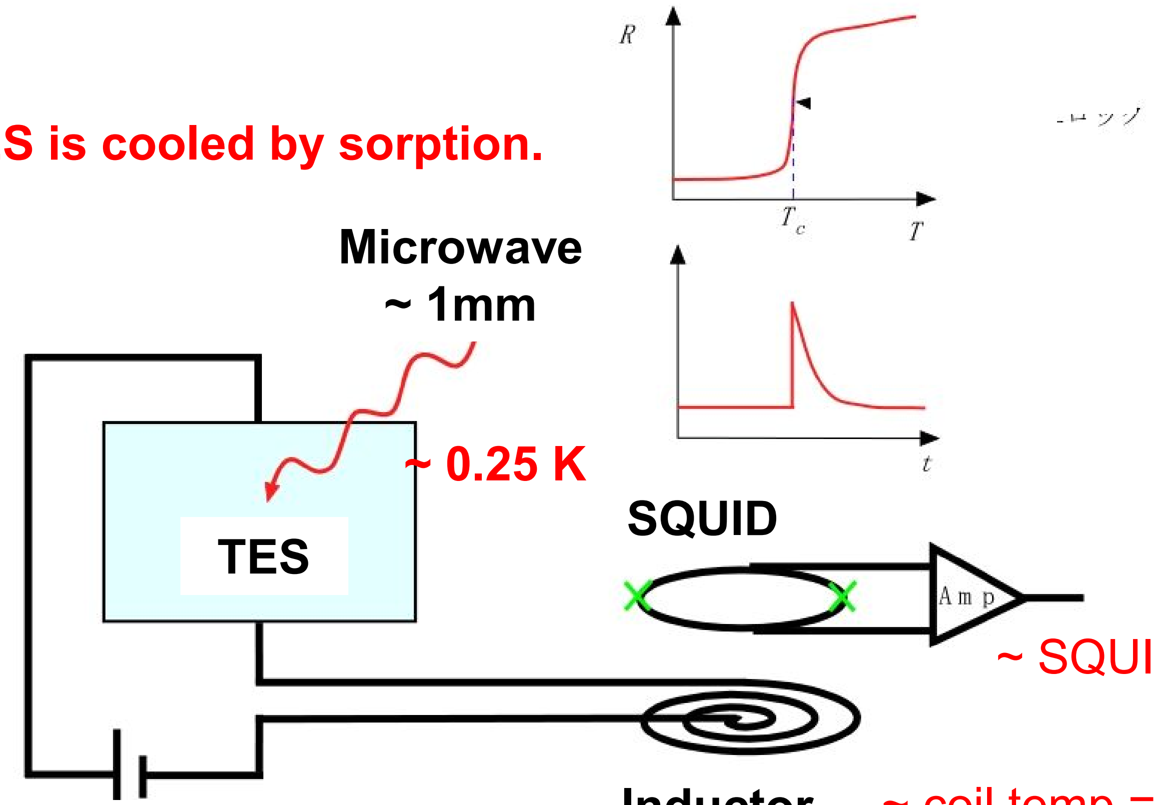
- KEK CMB group try to observe CMB (Cosmic Microwave Background) polarization by using telescope.
- Superconducting detectors is applied to detect microwave.
- Sorption fridges are used to cool down superconducting detectors such as TES to around 0.25 K in order to achieve required sensitivities.
- Sorption fridge takes advantage of He3 adsorption and desorption on charcoal .
- Gas Gap Heat SW is also employed in this sub-kelvin cooling system.

- KEK CMB cryogenic team is trying to develop
  - sorption and GGHS

    → It is important to clarify helium adsorption characteristics on charcoal.



Schematic view of TES Detector System



TES is cooled by sorption.

Microwave
~ 1mm

~ 0.25 K

~ SQUID temp = 4.2 K

Constant Voltage Bias

Inductor
(pickup coil)

~ coil temp = 4.2 K

Temperature of TES increases.

⬇

Phase transition from super to normal occurs in the TES.

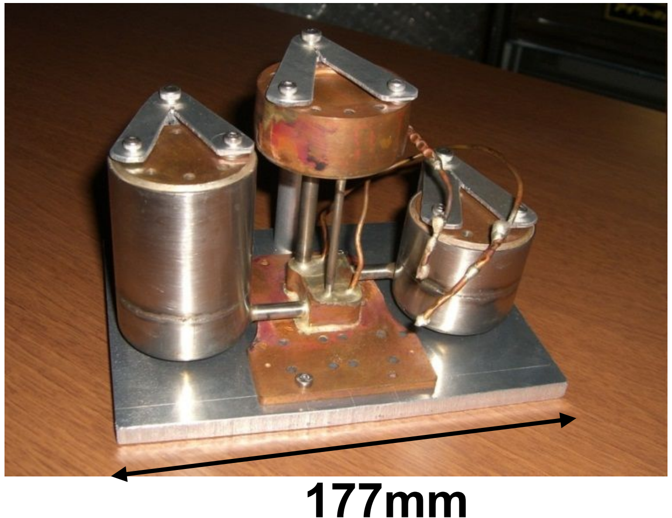
Resistance of TES also increases.

- **Current change in the circuit induces weak magnetic field by the inductor.**
- **Magnetic field induced by pickup coil can be detected by SQUID.**

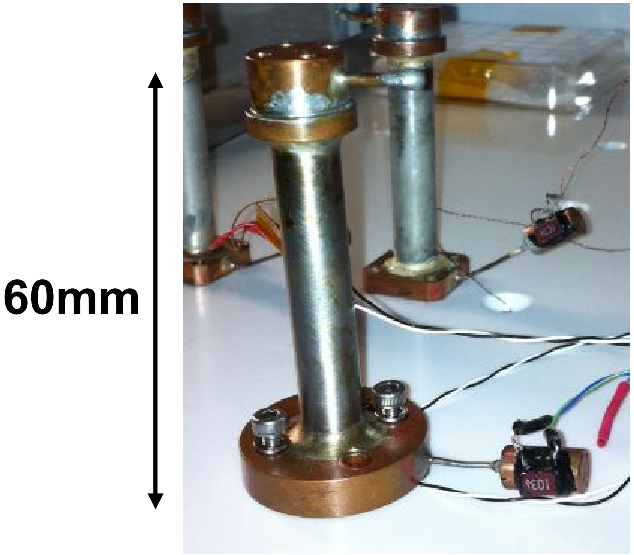
Cryogenic instruments using activated charcoal

- Activated charcoal is well known as excellent adsorbate.
- Following cryogenic application take advantage of helium adsorption and desorption on charcoal.

Sorption Fridge



Active Gas Gap Heat SW



- ■ Sorption Fridge

  0.25K can be obtained by decreasing saturated vapor pressure of 3He.

  Vacuum pump = Helium adsorption on activated charcoal

- ■ Active Gas Gap Heat SW (AGGHS)

  Carrier of heat transfer = Helium gas

  - ・ Off condition ― Helium adsorption on charcoal （P~1E-2 Pa）
  - ・ On condition ― Helium desorption from charcoal

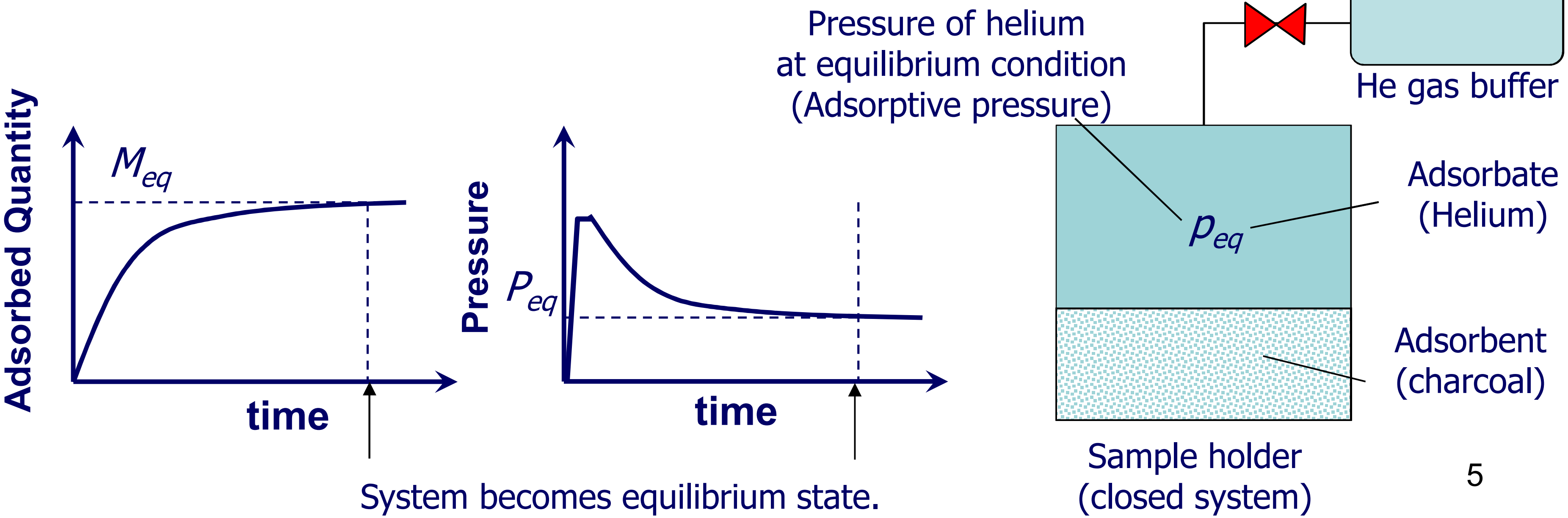
Helium Adsorption Characteristics on Charcoal

In order to develop sorption fridge and gas-gap heat switch,
we have to clarify the helium adsorption characteristics on charcoal.

We measured adsorption isotherm under various conditions.

T=300 K, 77 K, 4.2 K, 1.6 K

Adsorption Isotherm is the relation between adsorbed quantity, M_{eq} , and gas pressure, p_{eq} , at equilibrium state.



Adsorption Isotherm (I)

Adsorbed quantity is function of T, P and E.

$$M_{eq} = f(T, p_{eq}, E), \qquad E = E(T)$$

At constant temperature, ($T = const$)

Adsorption Isotherm

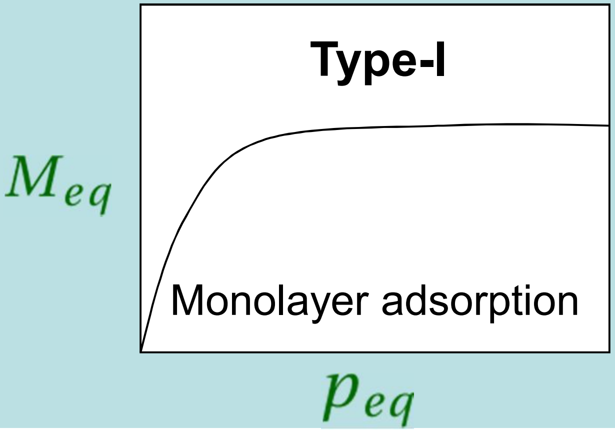
$$M_{eq} = f(p_{eq})$$

Purpose is to clarify Helium adsorption isotherm on charcoal under the cryogenic condition (1.66K to 300K)

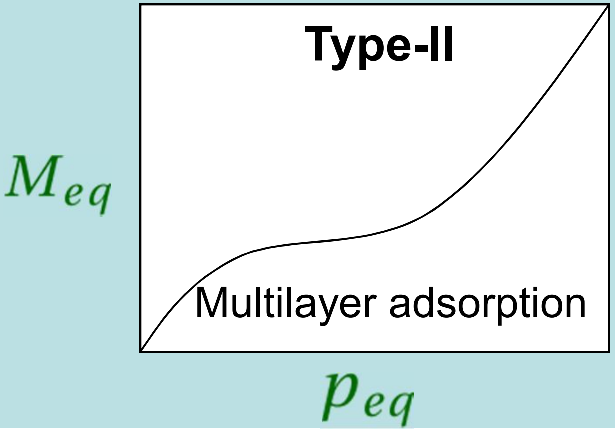
Adsorption Isotherms (II)

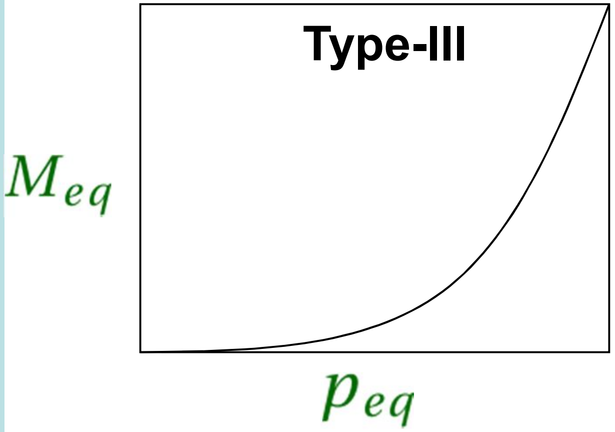
- **According to IUPAC, there are 6 kinds of Isotherms in the field of adsorption chemistry.**

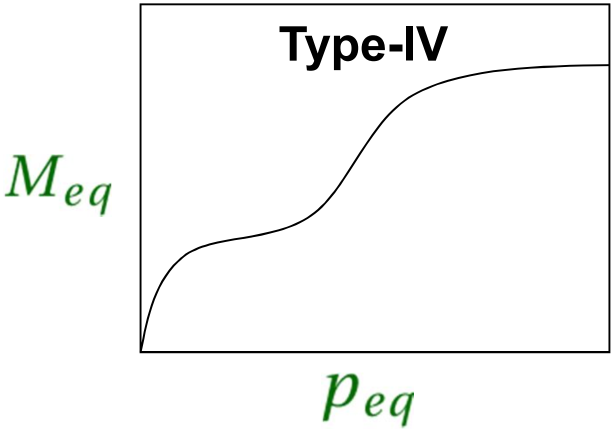
Langmuir type

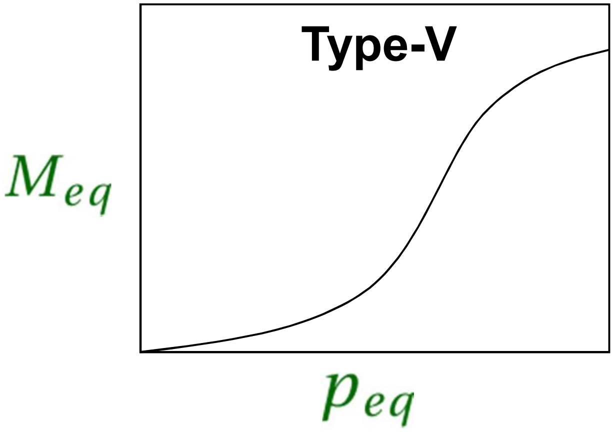


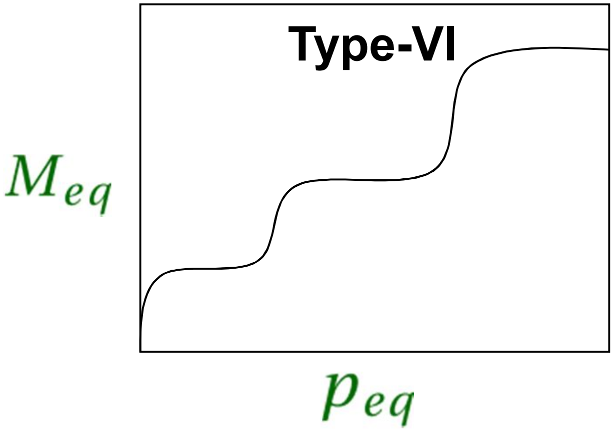
BET Type





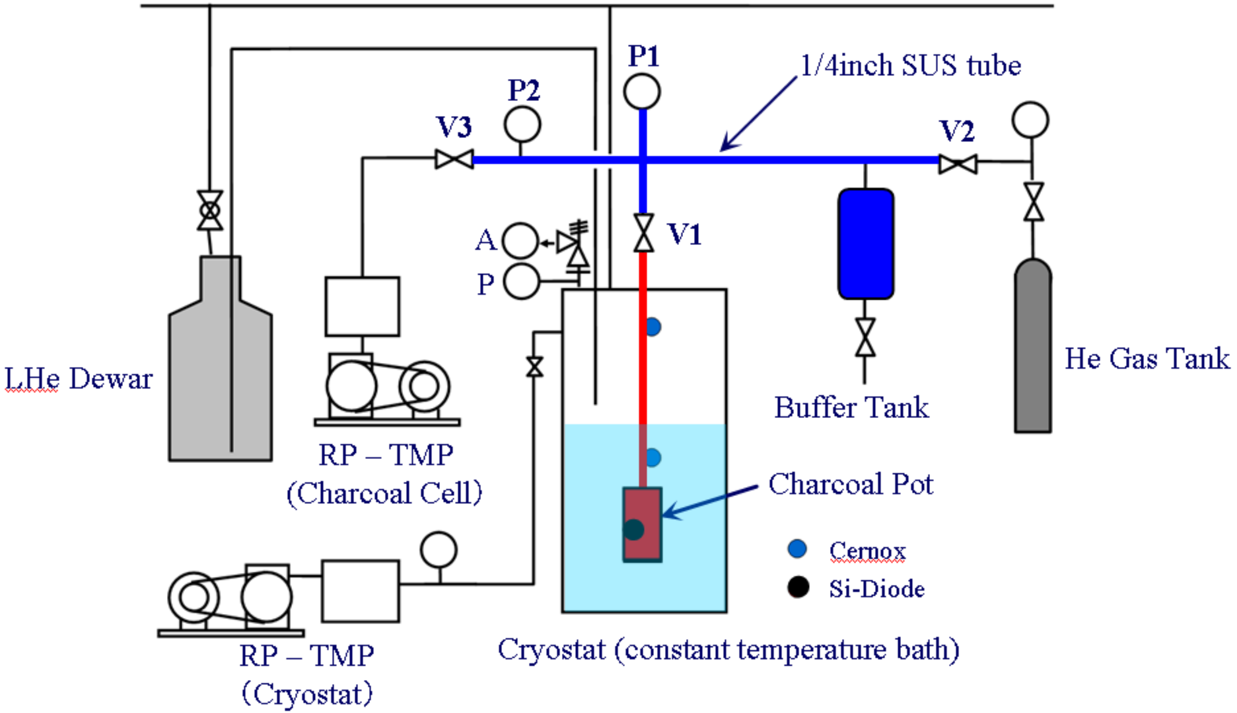






Which type in the case of the He adsorption on charcoal ?

Experimental Apparatus



- Red area (Charcoal pot) temperature ~ 4K （v_2=84.5 cm^3） T=room temp
- Buffer area room temperature （v_1=1083 cm^3） T=1.6K, 4.2K, 77K

＜Adsorbed quantity measurement method＞

Step1) Both regions are pumping and charcoal is reactivated at 473 K for 12hours.

Step2) Gate valve (V1) is closed.

Step3) Helium gas (P=Pb) is filled in buffer region. Charcoal pot keeps vacuum condition.

Step4) Gate valve is opened. Adsorption begins to occurs to charcoal.

Pressure becomes constant (equilibrium pressure=Pa<Pb).

Adsorbed quantity, M_{eq}, can be obtained from pressure difference between Pa and Pb.

Adsorbed Quantity

Adsorbed quantity can be obtained from mole number difference between step3 and step4

Adsorbed quantity can be obtained following equation.

$$M^{(1)} = \frac{22414}{R}\left(\frac{p_B^{(1)} v_1}{T_1} - \frac{p_{eq}^{(1)} v_1}{T_1} - \left\langle \frac{p_{eq}^{(1)} v_2}{T_2} \right\rangle\right)$$

Moles number in the buffer region.
(step3)

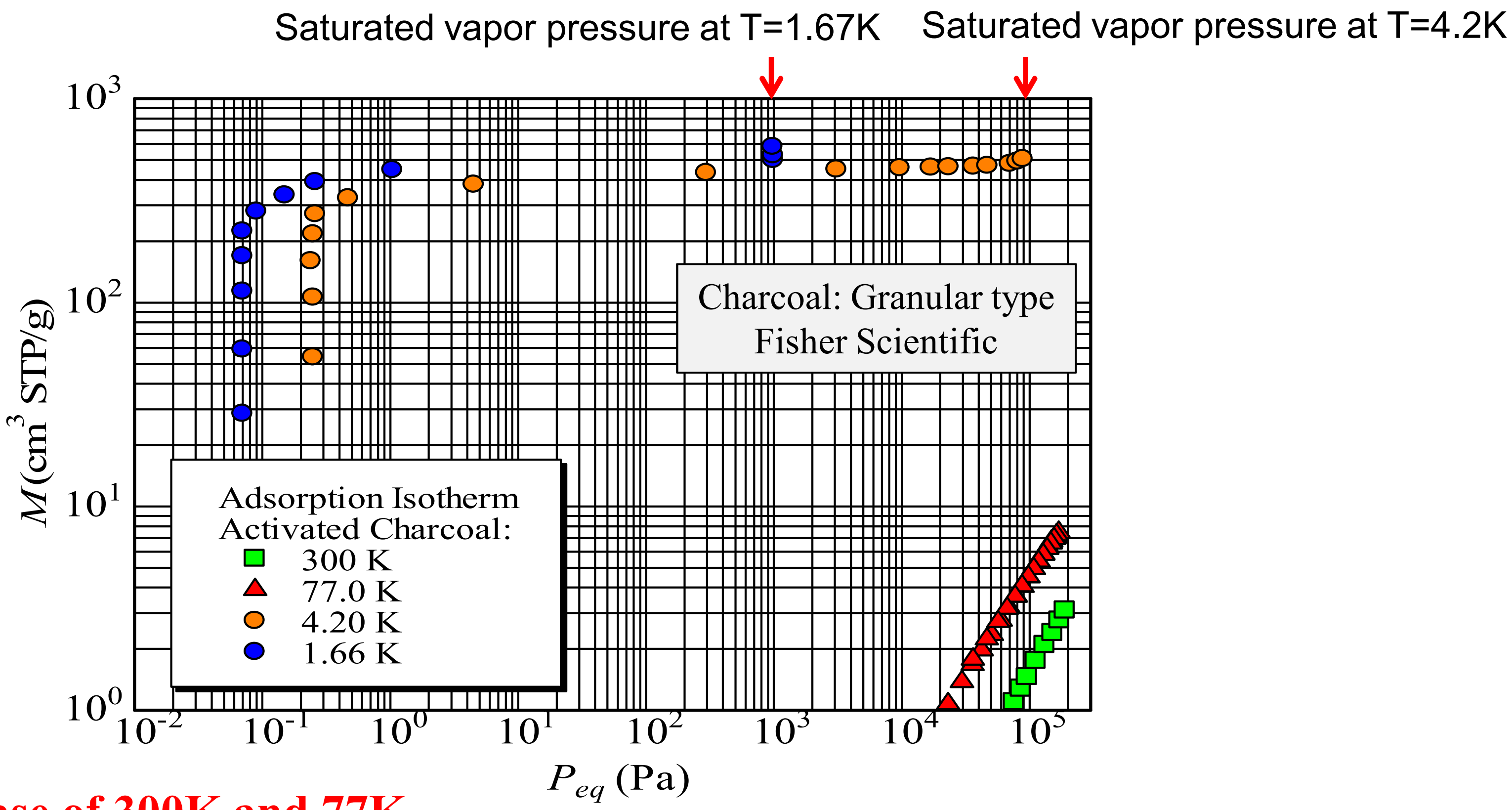
Moles number of residual helium gas
in the buffer and sample holder
after adsorption equilibrium (step4)

Generalized equation for Adsorbed quantity to obtain adsorption isotherm

$$M = M^{(1)} + \frac{22414}{R}\sum_{j=2}^{n}\left(\frac{p_B^{(j)} v_1}{T_1} + \left\langle \frac{p_{eq}^{(j-1)} v_2'}{T_2} \right\rangle - \frac{p_{eq}^{(j)} v_1}{T_1} - \left\langle \frac{p_{eq}^{(j)} v_2'}{T_2} \right\rangle\right)$$

$$\left\langle \frac{p v_2}{T_2} \right\rangle := \sum_{\alpha=1}^{N} \frac{p\Delta v}{\langle T\rangle_\alpha}, \quad \Delta v := \frac{v_2}{N}, \quad \langle T\rangle_\alpha := (T_\alpha - T_{\alpha-1})^{-1}\int_{\Delta l} T(x)\,dx$$

Experimental Results (adsorption isotherm)



In case of 300K and 77K,

- **Adsorption Isotherm = Henry Law**
- **interaction between helium and charcoal is very weak**

In case of 4.2 K and 1.66 K

- **Adsorption isotherm = Type I (Langmuir Type)**

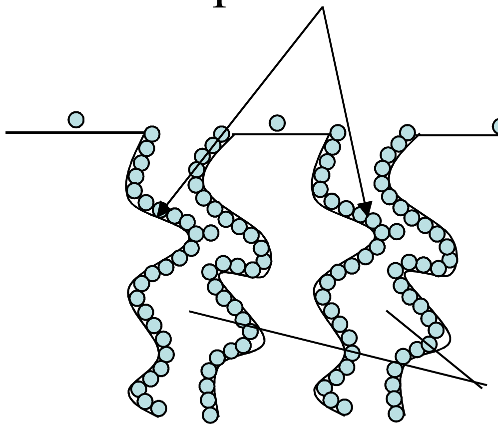
- **Saturated adsorbed quantity = 400 cm3/g @4.2 K**
  = 500 cm3/g @1.66K

Picture of helium adsorption isotherm at 4.2 K, 1.66K

Low pressure region (P<1Pa):

- Adsorption to micro pore in charcoal occurs (OD<2nm).

.



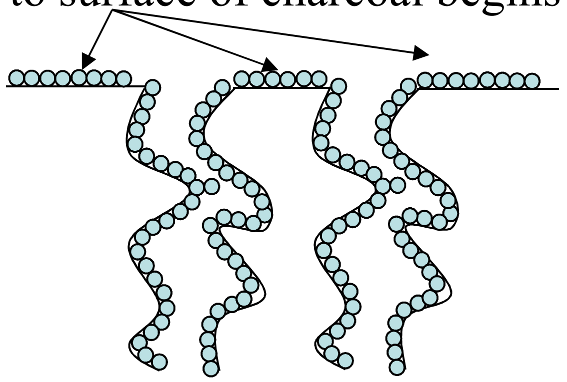
Micropore (Diameter< 0.2nm)

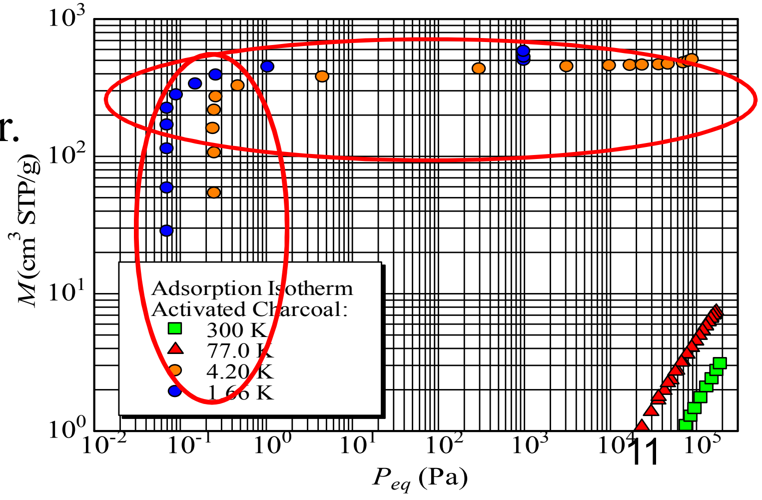
Surface ratio of Charcoal

$$\frac{A_{\mathrm{micro}}}{A_{\mathrm{surface}}} = 800 \sim 2000$$

High pressure region (P> 1Pa)

- Adsorbed quantity is slightly increasing,
  but almost constant compared with the case of P<1Pa
- This phenomenon indicates
  adsorption to micropore is saturated state.
  adsorption to surface of charcoal begins to occur.





Summary

- Adsorbed quantity is proportional to equilibrium pressure in the case of 300 K, 77 K.

- Adsorption isotherm can be classified as Type I isotherm which is identical to Langmuir Type.

- Adsorbed quantities and ability as vacuum pump at superfluid temperature are more excellent than that in the case of 4.2 K.