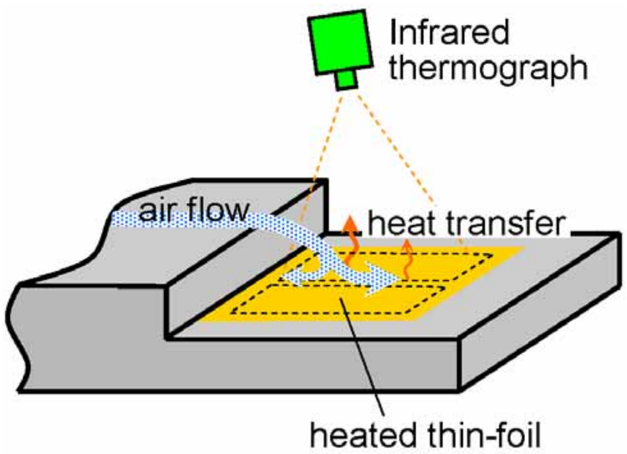
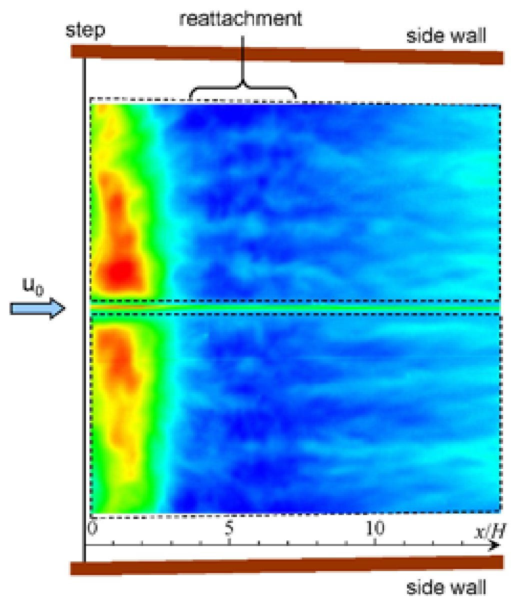
European Mechanics Society Colloquium 631
Control of skin friction and convective heat transfer in wall-bounded flows
Madrid, Spain, March 18-20, 2024

Development of spatiotemporal heat transfer measurements in wall-bounded flows

Hajime Nakamura

(Dept. of Mech. Eng., National Defense Academy, Japan)





Outline

1. Measurements of air flows
- Delay in temperature fluctuation
- Verification of the measurements using IRT
- Reattached flow behind a backstep
- Simultaneous measurements combining IRT and PIV

2. Measurements of water flows in a pipe
- Verification of the measurements
- Reattached flow behind an orifice
- Heat transfer enhancement by swirling the flow
- Sudden acceleration and deceleration of flow

3. Measurements of boiling
- Flow boiling in a mini-channel

4. Concluding Remarks

Turbulent temperature field measurements using IRT

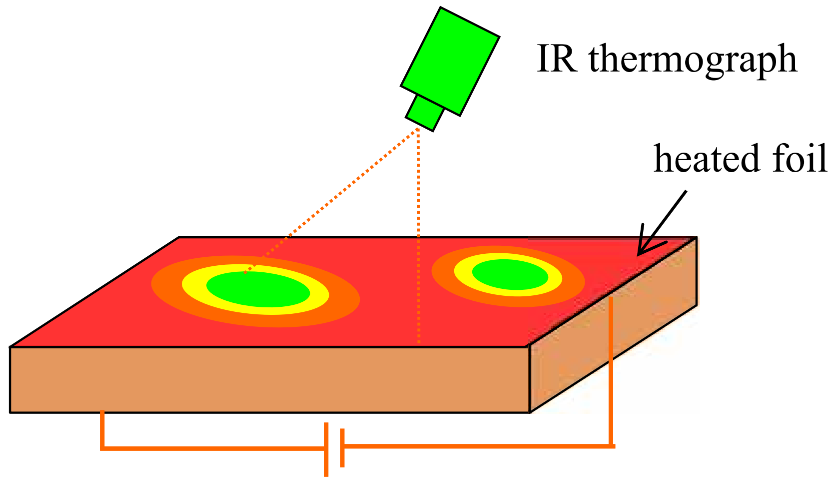
IR thermograph has been widely used to measure wall heat transfer due to flow turbulence

Time average measurements

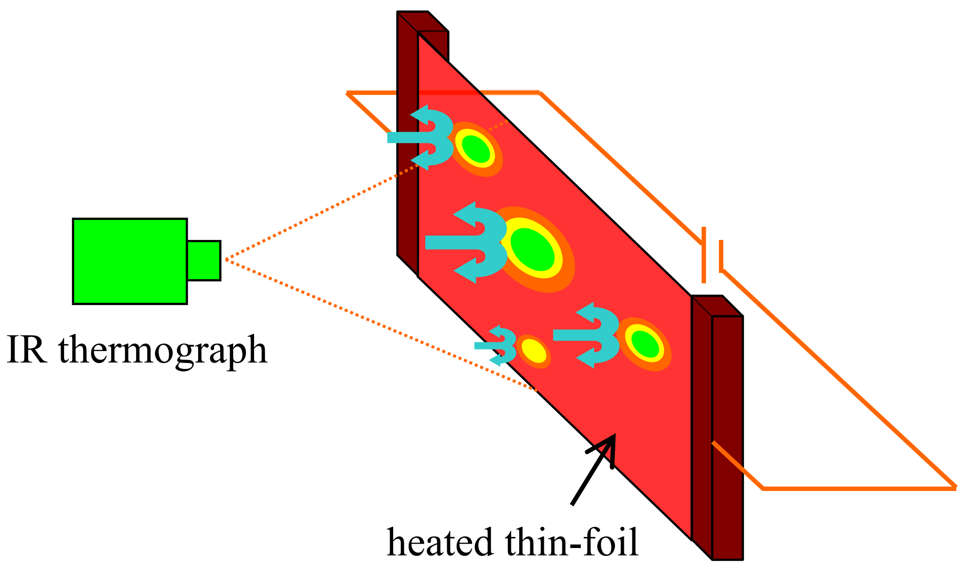
- Carlomagno & Luca (impinging jet, air)
  Handbook of Flow Visualization (1989)
- and many others

Transient measurements

- Hetsroni and Rozenblit (turbulence, water)
  Int. J. Multiphase Flow (1994)
- Silvestri, et al. (turbulence, water)
  7th Int. Conf. QIRT (2004)
- Nakamura (turbulence, air)
  5th Int. Symp. TSFP (2007)
- Wagner and Stephan (pool boiling)
  J. Heat Transfer, 131 (2009)
- Golobic, et al. (pool boiling)
  Heat and Mass Transfer, 45 (2009)
- and others



Time average measurement

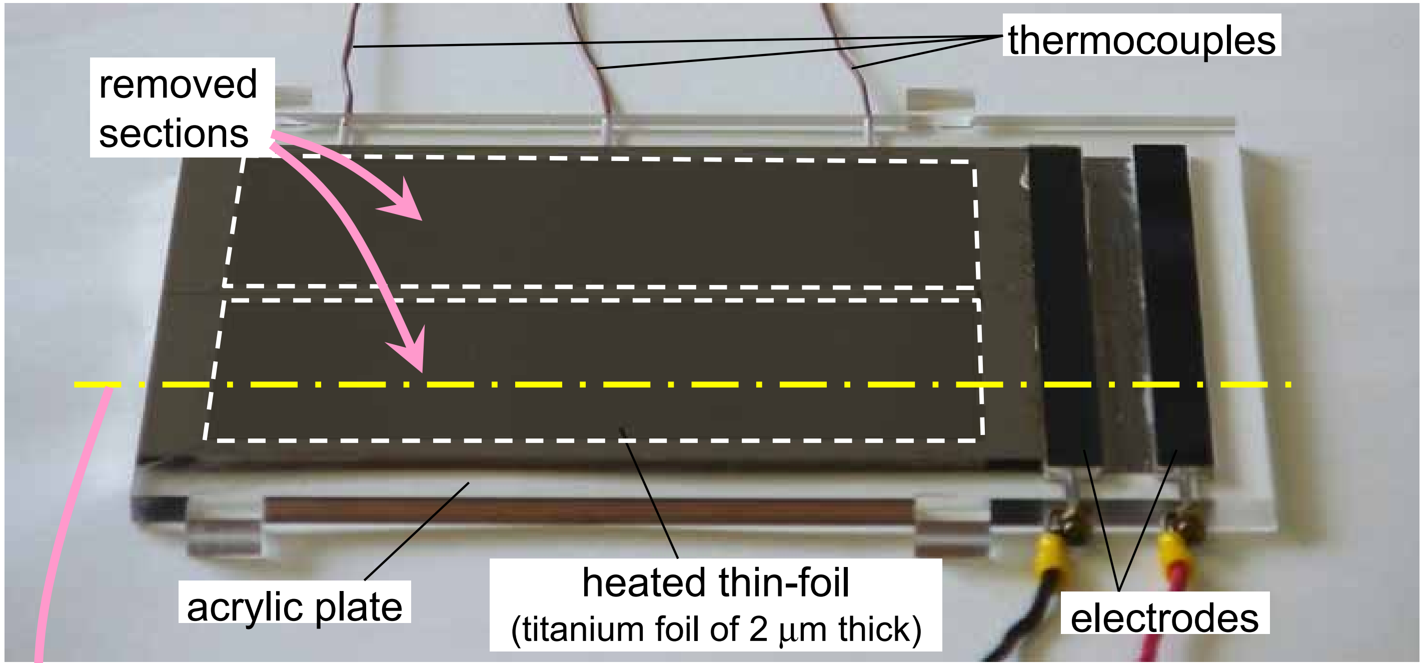


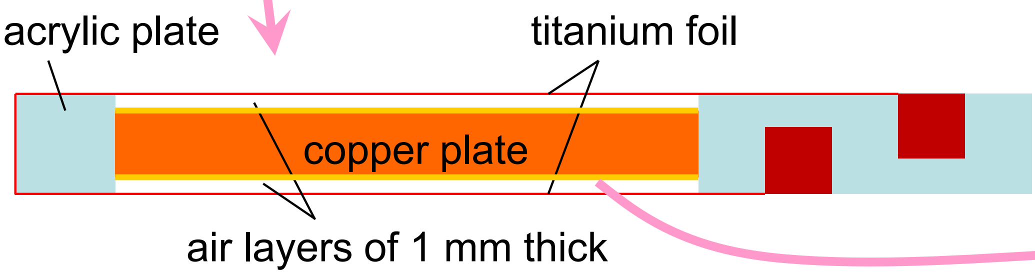
Transient measurement

However, this measurement has a serious problem:
"attenuation of temperature fluctuations"

Test plate to measure heat transfer fluctuation

Nakamura and Yamada,
Int. J. Heat Mass Transf., Vol. 64, 892-902 (2013)





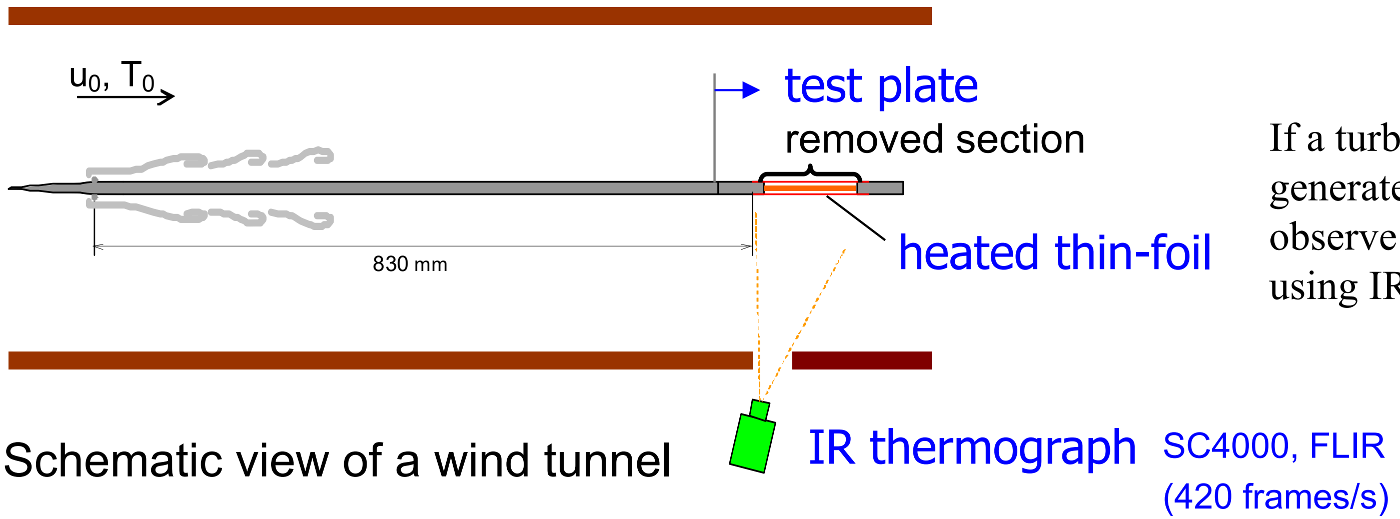
Cross-sectional view

Before covering titanium foil

Copper plate was shielded with gold leaf
to suppress radiation loss

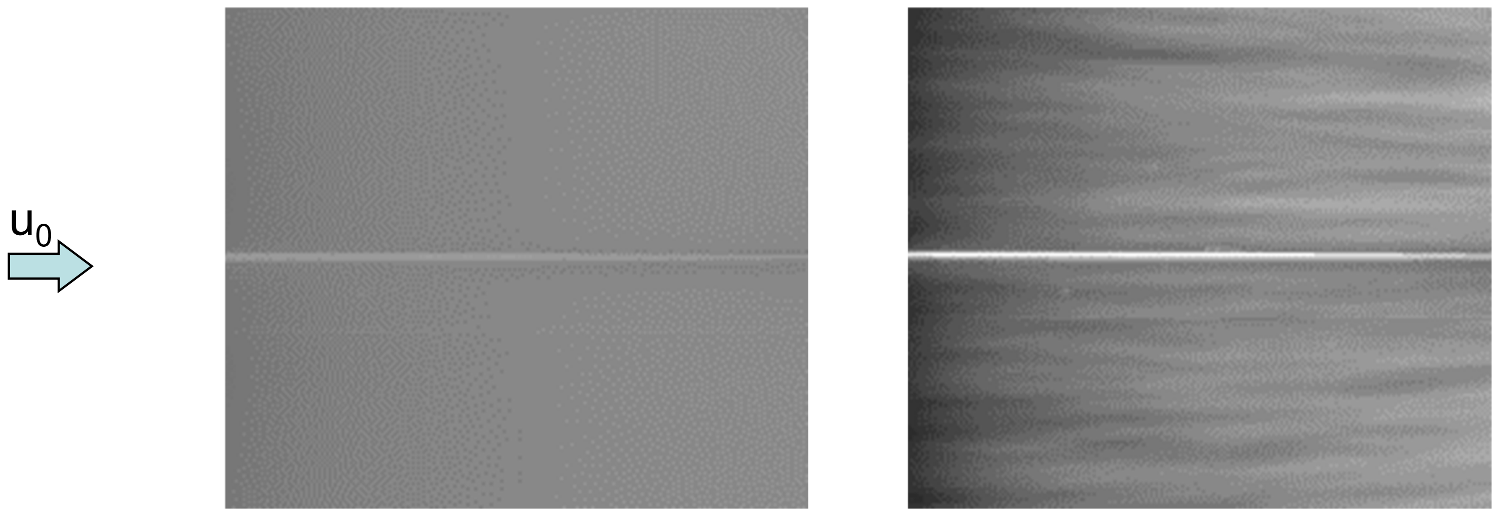
Photograph of the test plate (2μm thick titanium foil)

Validation of the measurements using IRT



Schematic view of a wind tunnel

If a turbulent boundary layer is generated on the plate, we can observe the temperature fluctuation using IR thermograph.



laminar, $u_0 = 1$ m/s

turbulent, $u_0 = 6$ m/s, $Re_\theta = 925$

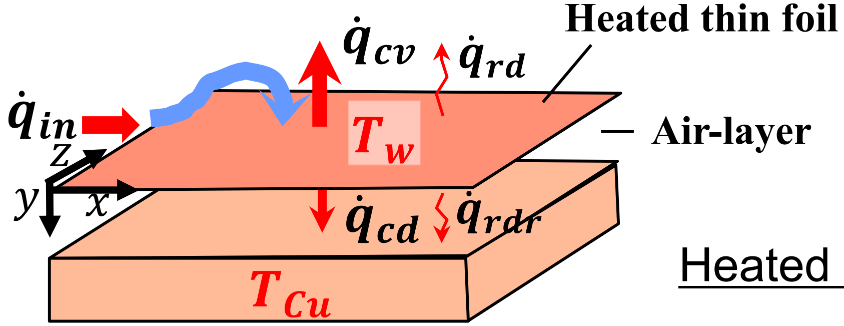
Thermal images measured using IRT

Playback speed 1/21

Measured temperature fluctuations are attenuated in time and space

How can the attenuation be restored?

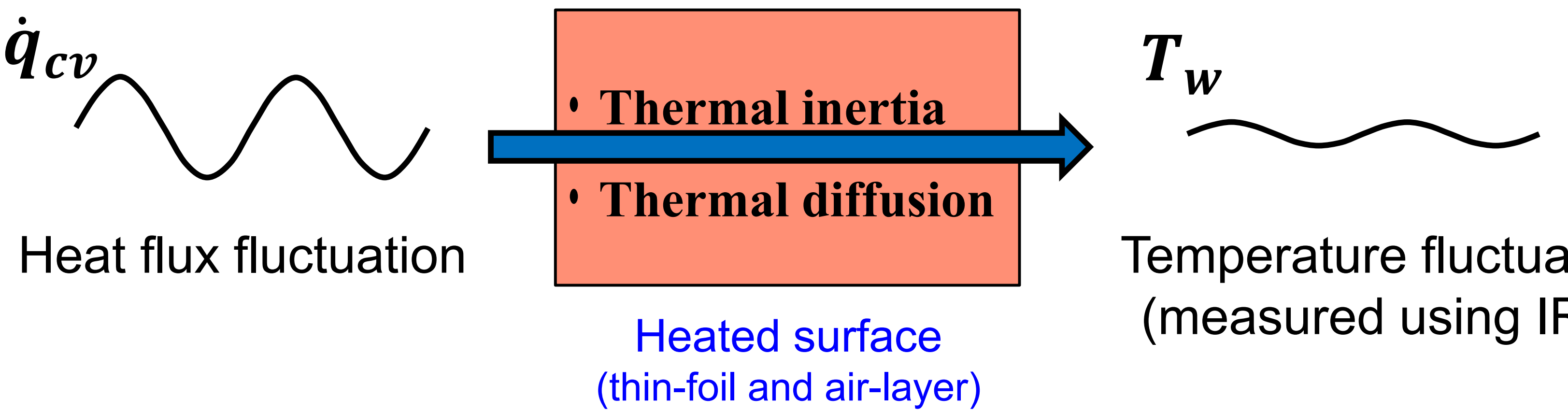
Nakamura, *5th TSFP*, 773-778 (2007)



Heated thin-foil test plate

2D unsteady heat conduction equation for the foil

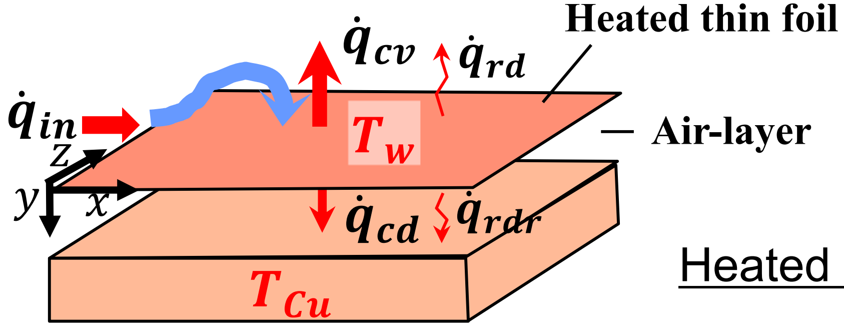
$$c\rho\delta\frac{dT_w(x,z,t)}{dt} = \lambda\delta\left(\frac{d^2T_w(x,z,t)}{dx^2} + \frac{d^2T_w(x,z,t)}{dz^2}\right) + \left(\dot{q}_{in} - \dot{q}_{cv}(x,z,t) - \dot{q}_{cd}(x,z,t) - \dot{q}_{rd}(x,z,t) - \dot{q}_{rdr}(x,z,t)\right)$$



Temperature fluctuation attenuates

How can the attenuation be restored?

Nakamura, *5th TSFP*, 773-778 (2007)

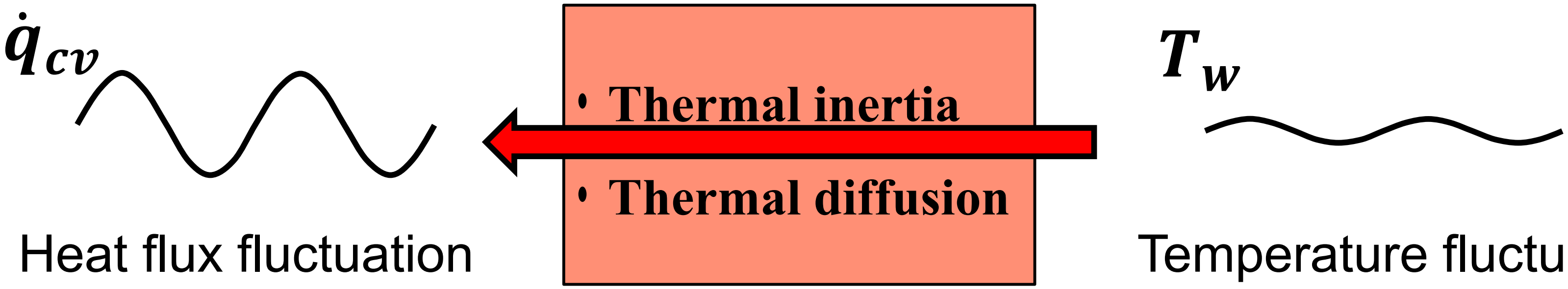


Heated thin-foil test plate

2D unsteady heat conduction equation for the foil

$$c\rho\delta\frac{dT_w(x,z,t)}{dt} = \lambda\delta\left(\frac{d^2T_w(x,z,t)}{dx^2}+\frac{d^2T_w(x,z,t)}{dz^2}\right)+\left(\dot{q}_{in}-\dot{q}_{cv}(x,z,t)-\dot{q}_{cd}(x,z,t)-\dot{q}_{rd}(x,z,t)-\dot{q}_{rdr}(x,z,t)\right)$$

To be calculated



Heat flux fluctuation

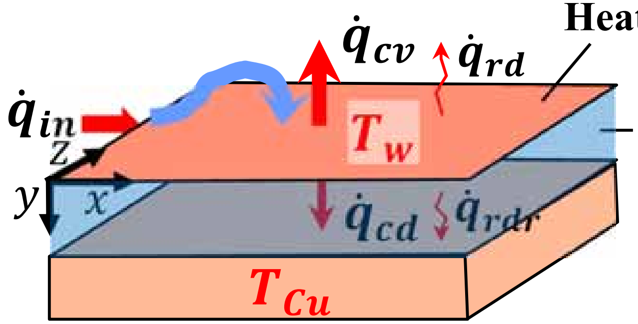
Heated surface
(thin-foil and air-layer)

Temperature fluctuation
(measured using IRT)

We can obtain heat flux fluctuation having no attenuation

How can the attenuation be restored?

Nakamura, *5th TSFP*, 773-778 (2007)



Heated thin-foil test plate

2D unsteady heat conduction equation for the foil

$$c\rho\delta\frac{dT_w(x,z,t)}{dt} = \lambda\delta\left(\frac{d^2T_w(x,z,t)}{dx^2} + \frac{d^2T_w(x,z,t)}{dz^2}\right) + \left(\dot{q}_{in} - \underbrace{\dot{q}_{cv}(x,z,t)}_{\text{To be calculated}} - \dot{q}_{cd}(x,z,t) - \dot{q}_{rd}(x,z,t) - \dot{q}_{rdr}(x,z,t)\right)$$

Spatiotemporal heat transfer coefficient

$$h(x,z,t) = \dot{q}_{cv}(x,z,t)/(T_w(x,z,t) - T_0)$$

$$= \frac{\underbrace{\dot{q}_{in}}_{\text{Given}} - \underbrace{\dot{q}_{cd}(x,z,t)}_{\text{Heat conduction to the air-layer}} - \boxed{\dot{q}_{rd}(x,z,t)} - \boxed{\dot{q}_{rdr}(x,z,t)} + \lambda\delta\left(\frac{d^2\boxed{T_w(x,z,t)}}{dx^2} + \frac{d^2\boxed{T_w(x,z,t)}}{dz^2}\right) - c\rho\delta\frac{d\boxed{T_w(x,z,t)}}{dt}}{\boxed{T_w(x,z,t)} - T_0}$$

$\dot{q}_{cd}(x,z,t)$ can be evaluated by heat conduction analysis in the air-layer by applying the thermal boundary conditions of $T_w(x,z,t)$ and T_{Cu}.

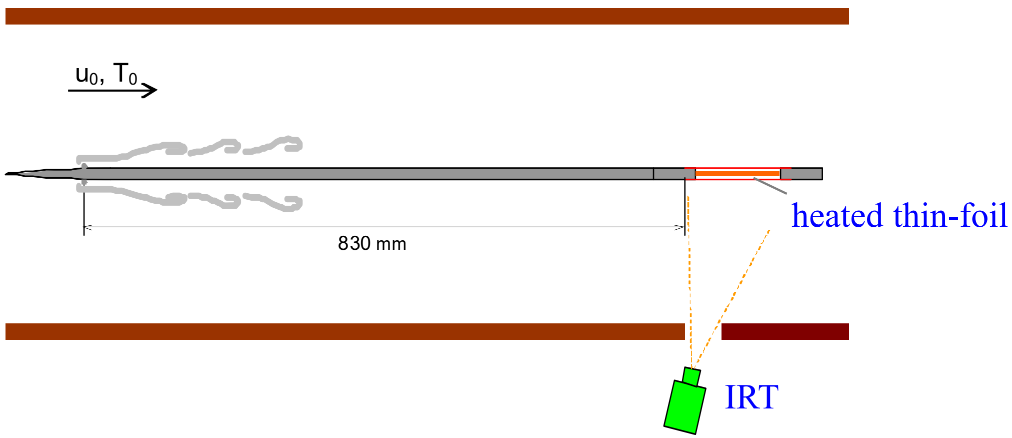
$\boxed{}$ can be determined by IRT measurement

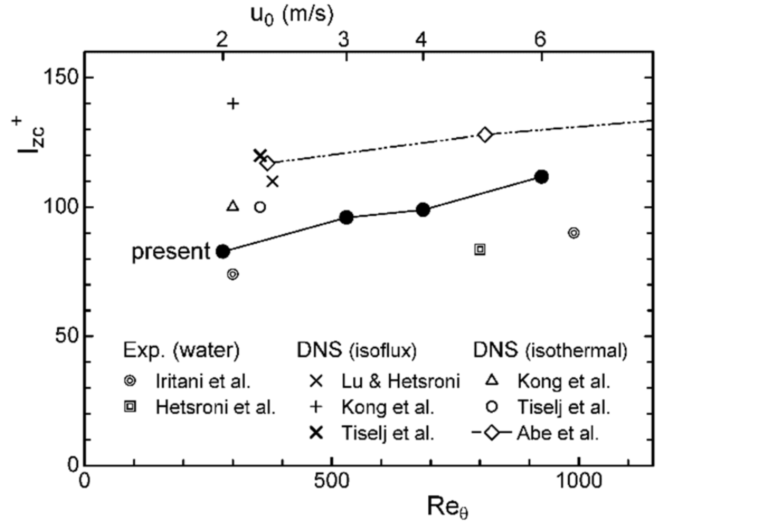
All terms in the above equation can be evaluated by IRT measurement

We can evaluate spatiotemporal heat transfer coefficient having no attenuation

Spatiotemporal heat transfer coefficient

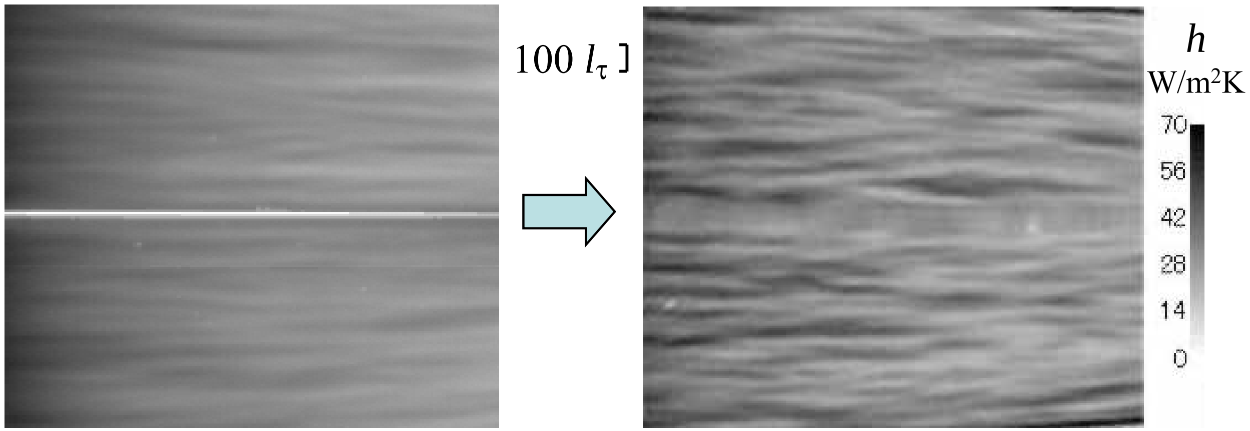
Nakamura and Yamada,
Int. J. Heat Mass Transf., Vol. 64, 892-902 (2013)





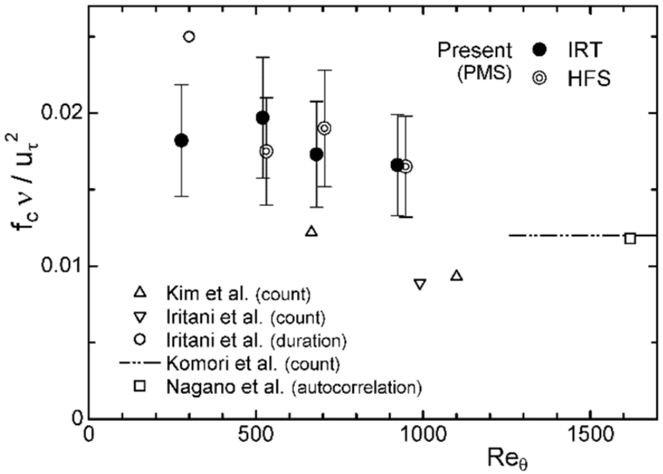
Mean spanwise wavelength of thermal streaks

Playback speed 1/21



Temperature fluctuation Spatiotemporal heat transfer

Spatiotemporal heat transfer of the turbulent boundary layer
($u_0 = 6$ m/s, $Re_\theta = 925$, $l_\tau = 0.068$ mm)

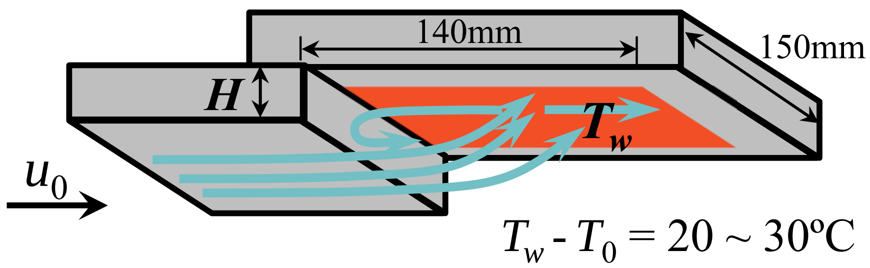


Characteristic fluctuating frequency

Spatiotemporal heat transfer can be quantitatively evaluated using IRT measurement

Reattached flow behind a backstep

Nakamura, *IHTC14*, 22753, (2011)

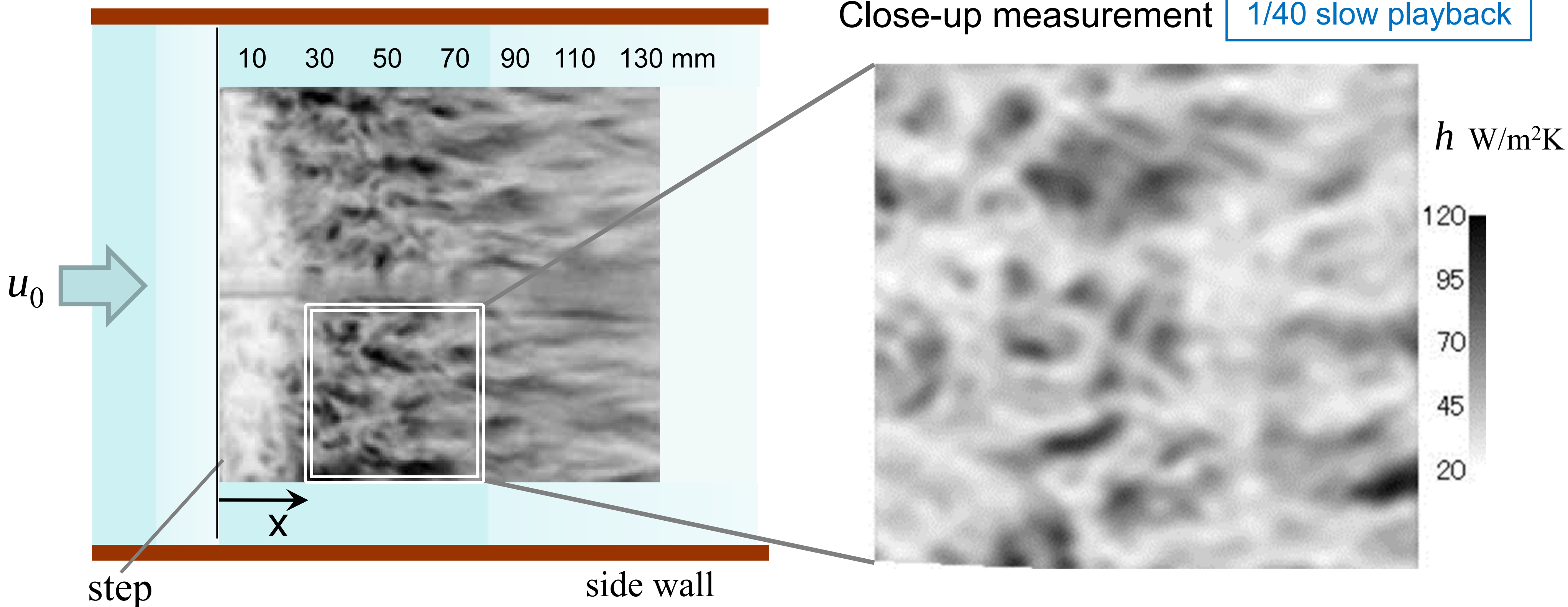


$H = 10$ mm
$u_0 = 6$ m/s
$\boldsymbol{Re_H = 3560}$

※ The backstep was flipped upside down to suppress the buoyancy effect

Wide measurement 1/21 slow playback

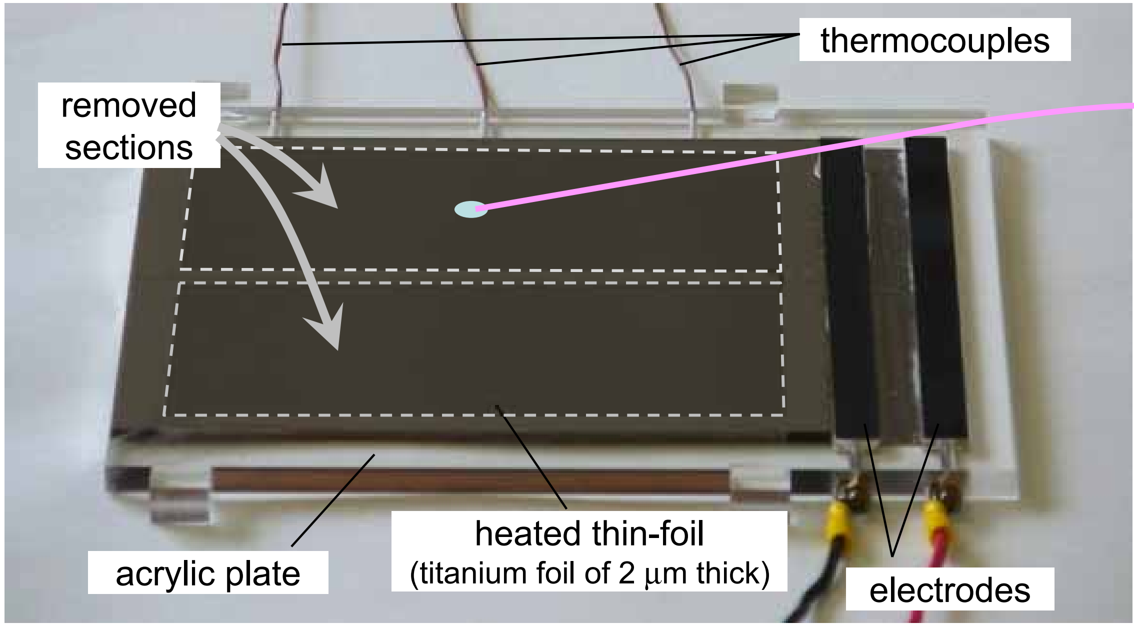
Close-up measurement 1/40 slow playback

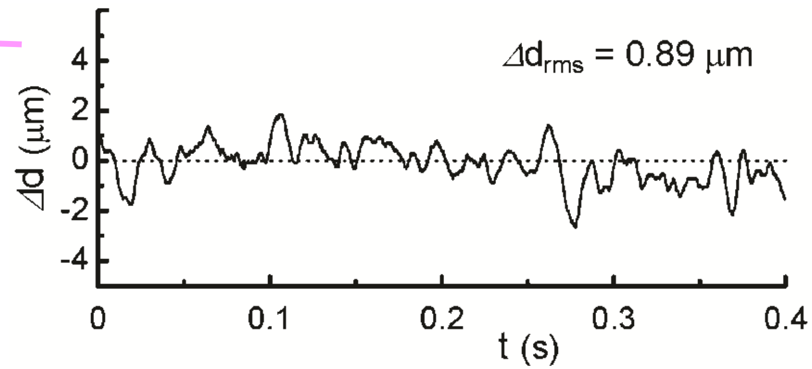


A mottled structure appears in the flow reattachment region, which is considered to be formed by many spot-like reattachments

Mechanical vibration of the foil

Since this measurement uses a very thin foil, there is a concern that the foil vibration due to flow turbulence may affect the measurement



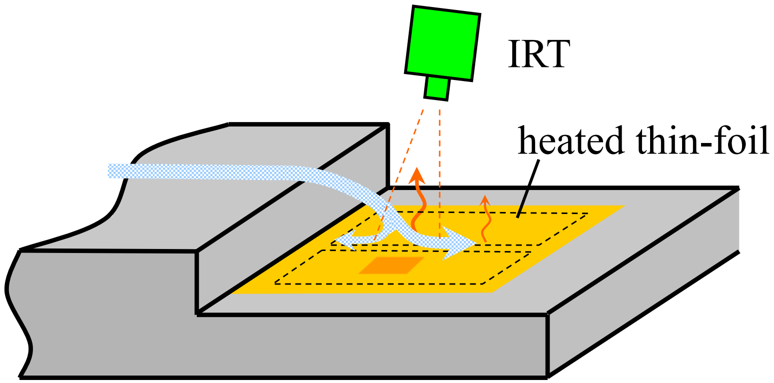


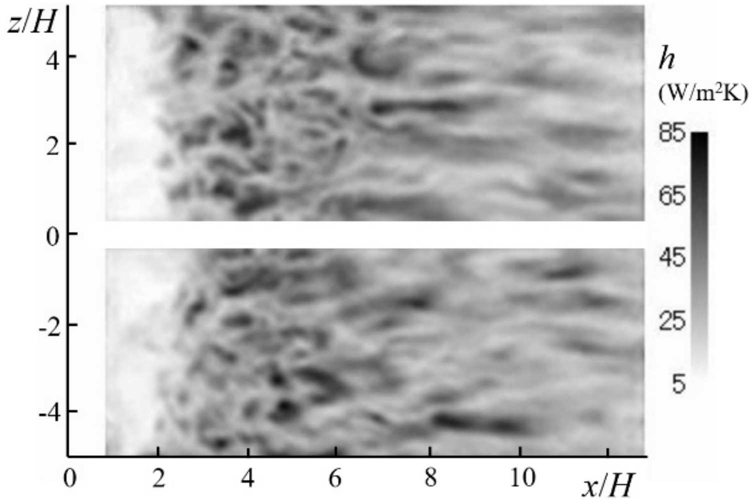
Vibration displacement of foil measured with a laser displacement meter

(Backstep at u_0 = 6 m/s)

Vibration displacement of the foil was on the order of 1μm even in the flow reattachment region

Comparison with DNS



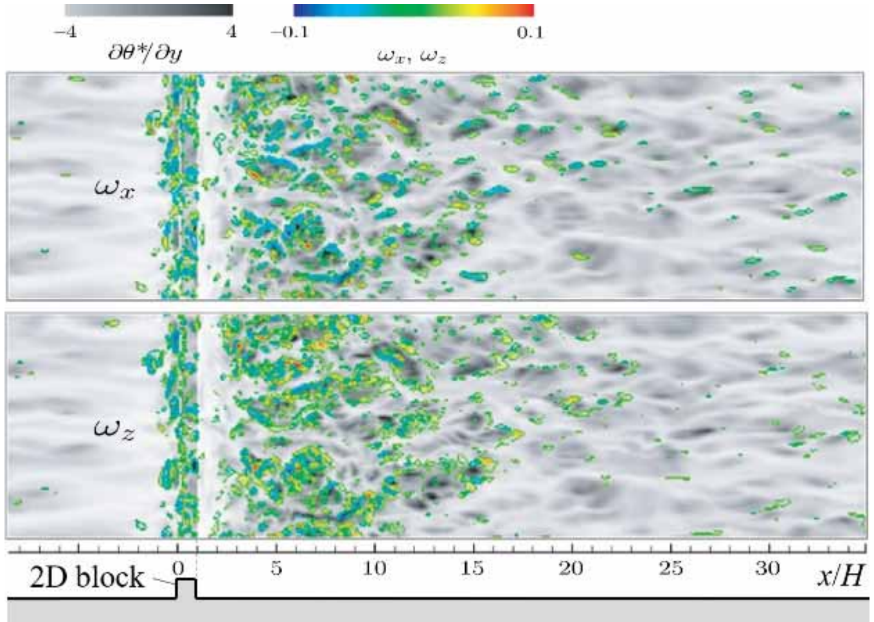


Spatiotemporal HTC

IRT measurement at $Re_H = 2500$

DNS

Hattori and Nagano, *Int. J. Heat and Fluid Flow*, 37, 81-92 (2012).

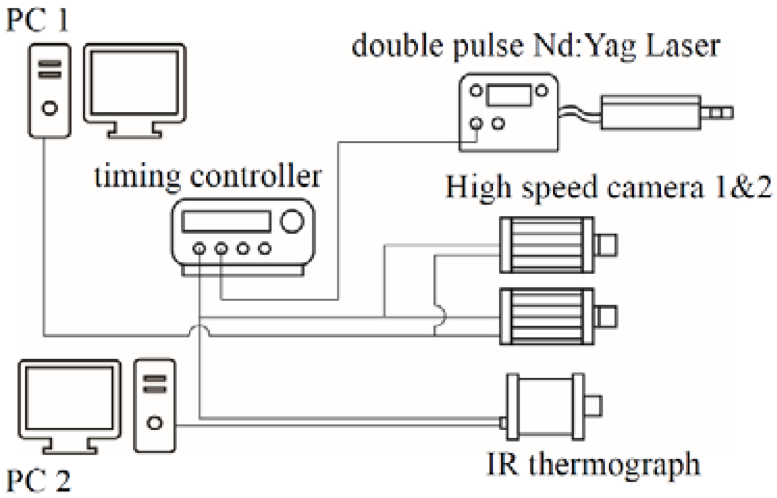


Heat flux and near-wall vortex structures

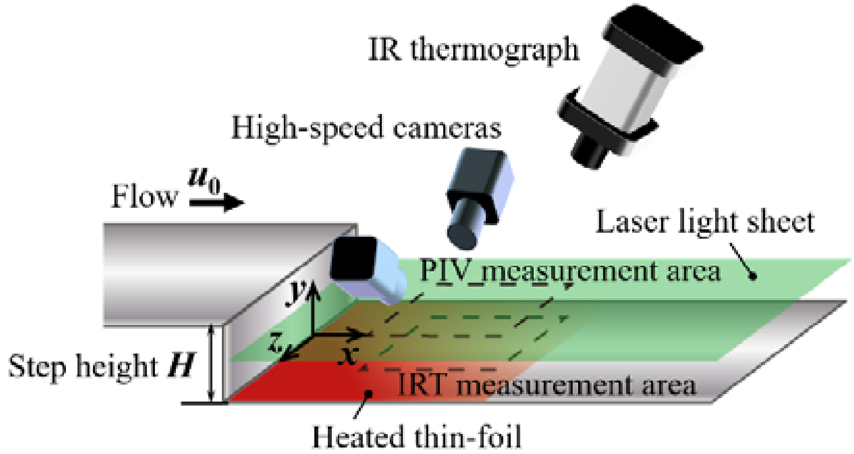
over a 2D block at $Re_H = 900$

The heat transfer feature in the reattachment region is very similar to that obtained by DNS

Simultaneous measurements combining IRT and PIV



Measurement system combining IRT and PIV



xz cross-section measurement by PIV

This is the case for a two-dimensional three-component (2D-3C) PIV measurement with a stereoscopic approach.

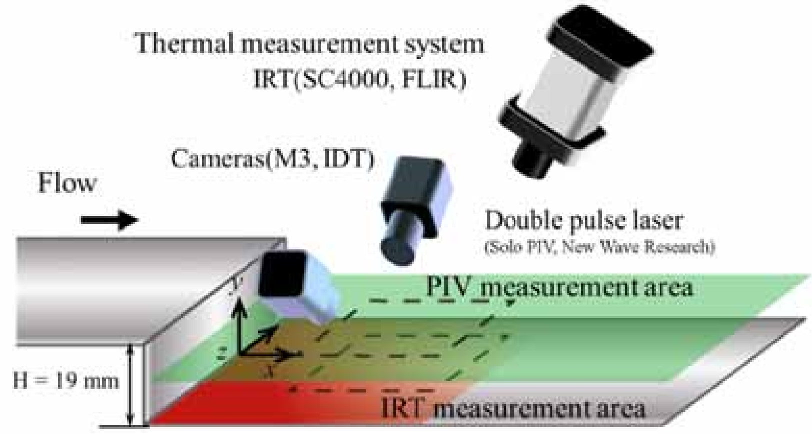
Two cameras and a double pulse laser are synchronized by a timing controller together with IR thermograph.

By irradiating a cross-section with a laser light sheet and performing PIV measurement together with IRT measurement, instantaneous heat transfer on the wall and its nearby instantaneous velocity field can be measured simultaneously.

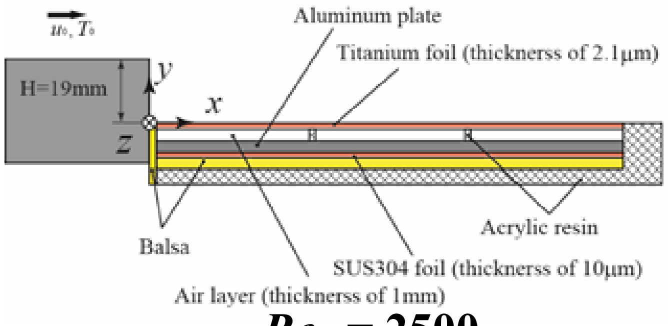
There is no interference between the two wavelengths of PIV and IRT

Only, care must be taken so that the laser does not heat the IRT measurement surface

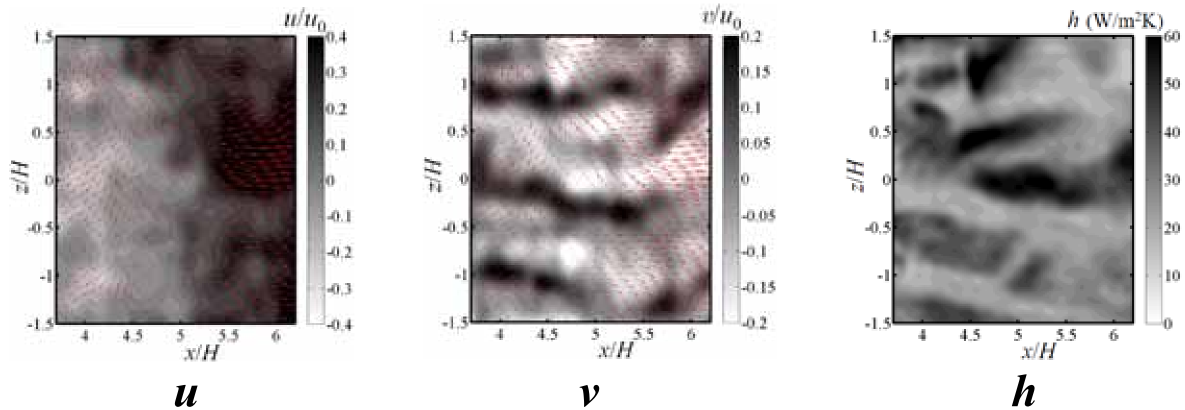
Yamada and Nakamura, *Int. J. Heat Fluid Flow*, 61, 174-182 (2016)



xz cross-section

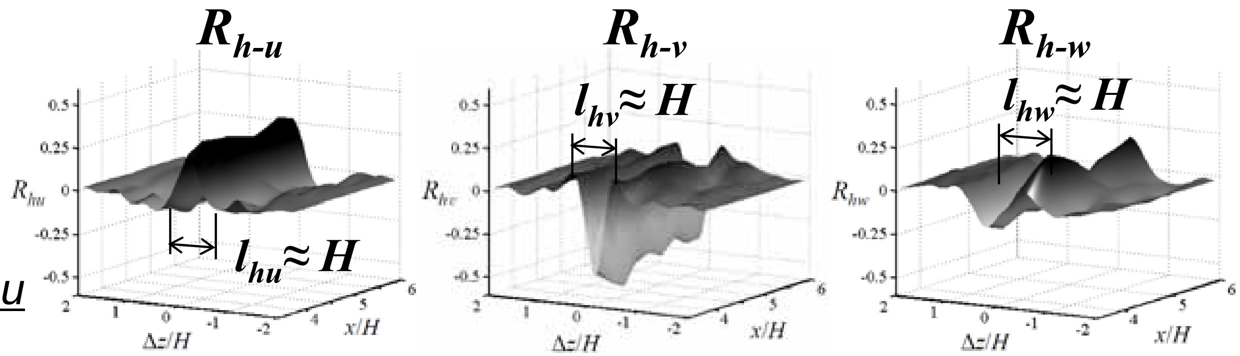


$Re_H = 2500$



Instantaneous velocity distributions ($y/H = 0.06$ in the xz plane) and the corresponding wall heat transfer coefficient

Instantaneous h tend to be higher when v is negative



Spanwise cross-correlation between h and u

$$R_{hu}(t,x,\Delta z) = \frac{\overline{h'(t,x,z)\cdot u'(t,x,z+\Delta z)}}{\sqrt{\overline{h'(t,x,z)^2}}\sqrt{\overline{u'(t,x,z+\Delta z)^2}}}$$

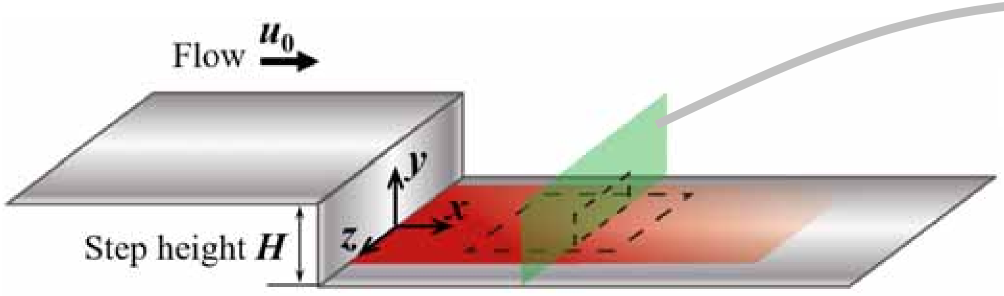
Spanwise cross-correlation between each velocity ($y/H = 0.06$) and heat transfer coefficient

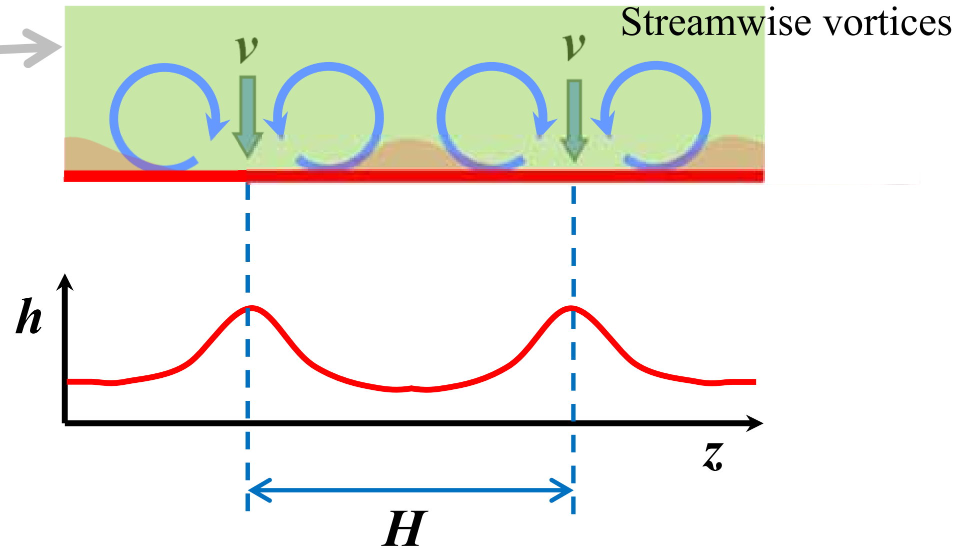
- **Relatively strong correlation between h and $-v$**
- **Regularity in the span (z) direction at an interval of H**

Supposed flow field in *yz* cross-section

From these results, it can be supposed that pairs of streamwise vortices are arranged in the span direction at an interval of approximately the step height

- **Relatively strong correlation between h and $-v$**





- **Regularity in the span (z) direction at an interval of H**

Although this is not the exact flow field,
this kind of modeling may be possible by focusing on the *yz* cross-section

Outline

1. Measurements of air flows

- Delay in temperature fluctuation
- Verification of the measurements using IRT
- Reattached flow behind a backstep
- Simultaneous measurements combining IRT and PIV

2. Measurements of water flows in a pipe

- Verification of the measurements
- Reattached flow behind an orifice
- Heat transfer enhancement by swirling the flow
- Sudden acceleration and deceleration of flow

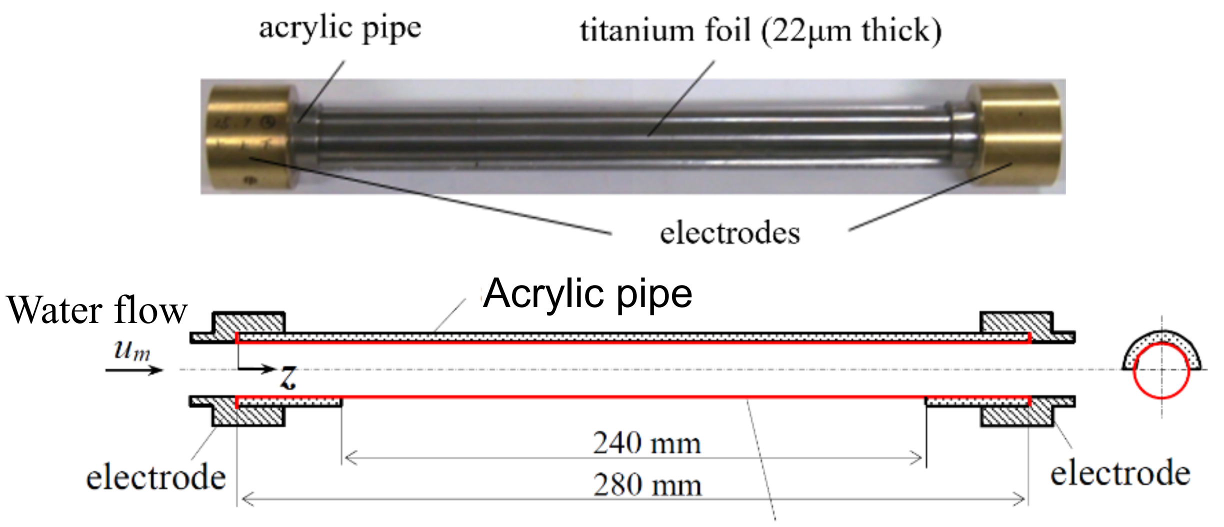
3. Measurements of boiling

- Flow boiling in a mini-channel

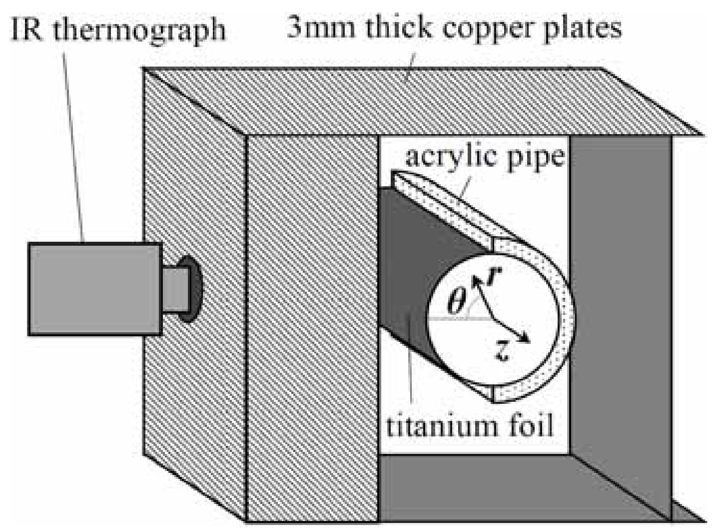
4. Concluding Remarks

Measurement of water flows in a pipe

Nakamura et al., *IJHFF*, Vol. 63, 46-55 (2017)



Test pipe



Measurement system

Test pipe devised to measure spatiotemporal heat transfer of water flows in a pipe

Spatiotemporal heat transfer coefficient

$$h(z,\theta,t) = \frac{\dot{q}_{in} - \dot{q}_{cvr}(z,\theta,t) - \dot{q}_{rdr}(x,z,t) + \lambda\delta\left(\frac{d^2T_w(z,\theta,t)}{dz^2} + \frac{d^2T_w(z,\theta,t)}{d(R\theta)^2}\right) - c\rho\delta\frac{dT_w(z,\theta,t)}{dt}}{T_w(z,\theta,t) - T_m(z)}$$

$$T_m(z) = T_{in} + \int_0^z \frac{2\pi R\langle\overline{\dot{q}_{cv}}\rangle_\theta(z)}{c_f\rho_f u_m \pi R^2}dz$$

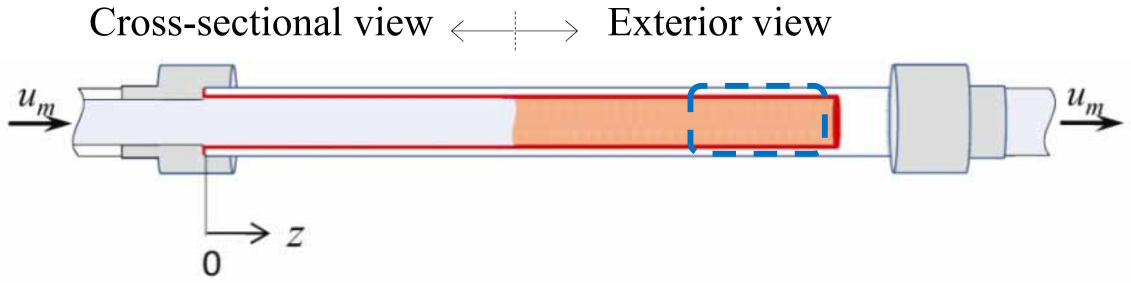
Mean heat transfer coefficient

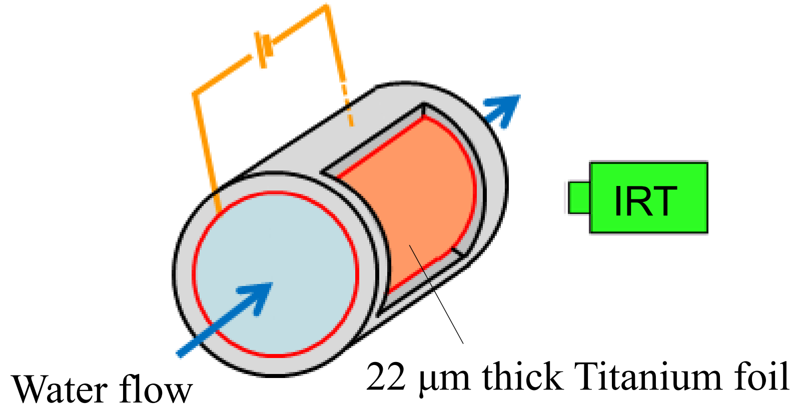
$$h_m(z) = \frac{\langle\overline{\dot{q}_{cv}}\rangle_\theta(z)}{\langle\overline{T_w}\rangle_\theta(z) - T_m(z)}$$

Nusselt number

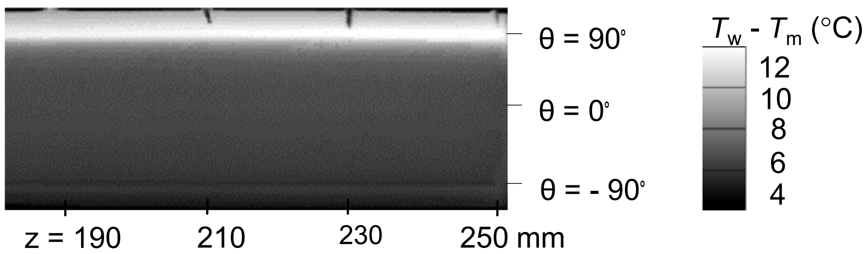
$$Nu(z) = \frac{h_m(z)\cdot D}{\lambda_f}$$

Validation of the measurements



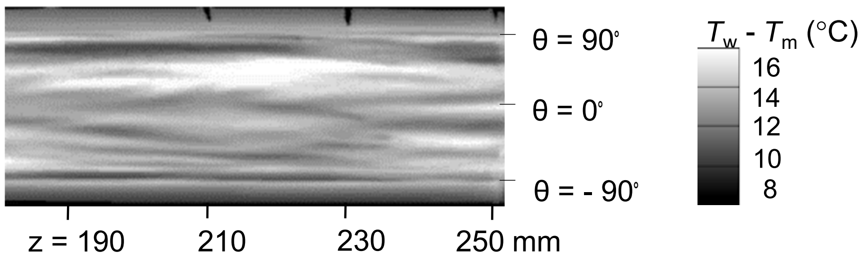


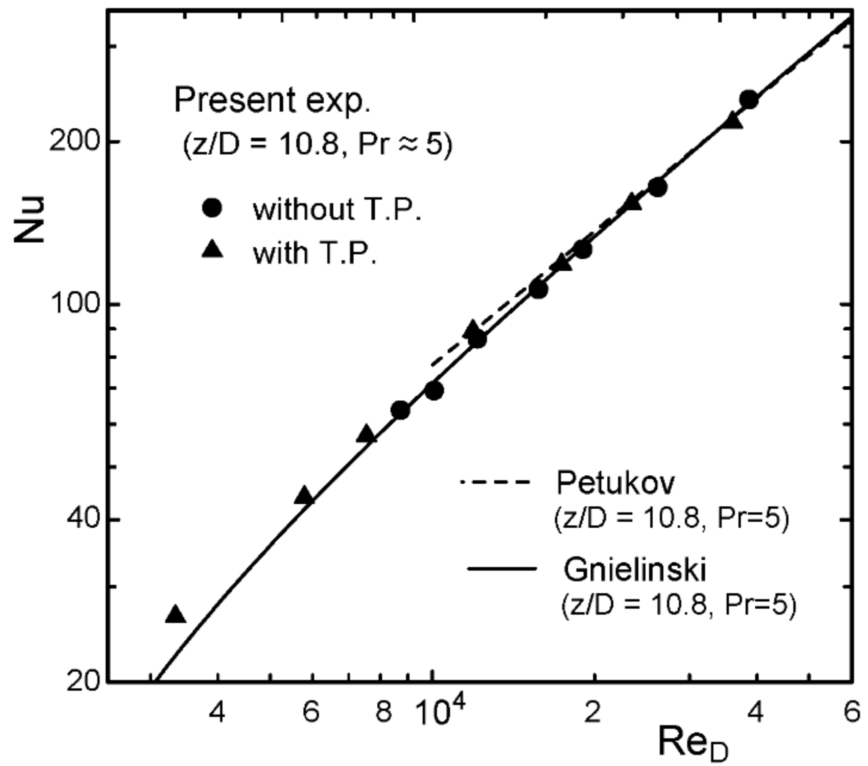
Re_D= 1100 (laminar)



Re_D= 8700 (turbulent)

1/30 slow playback



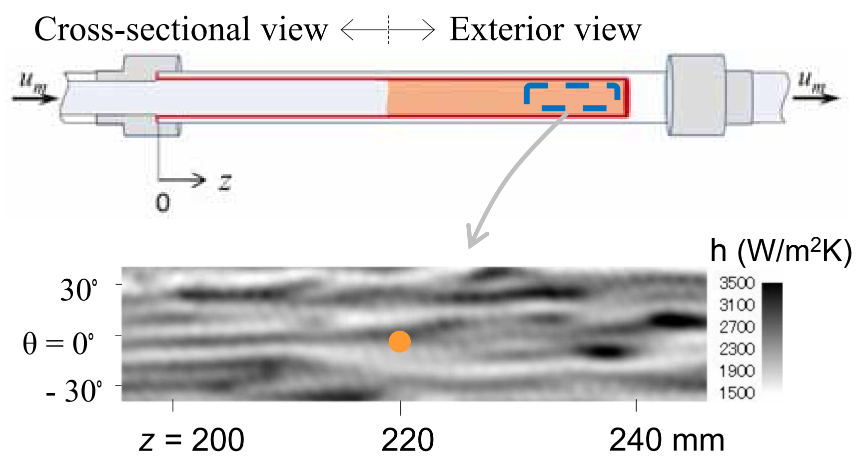


Nusselt number compared with empirical formula

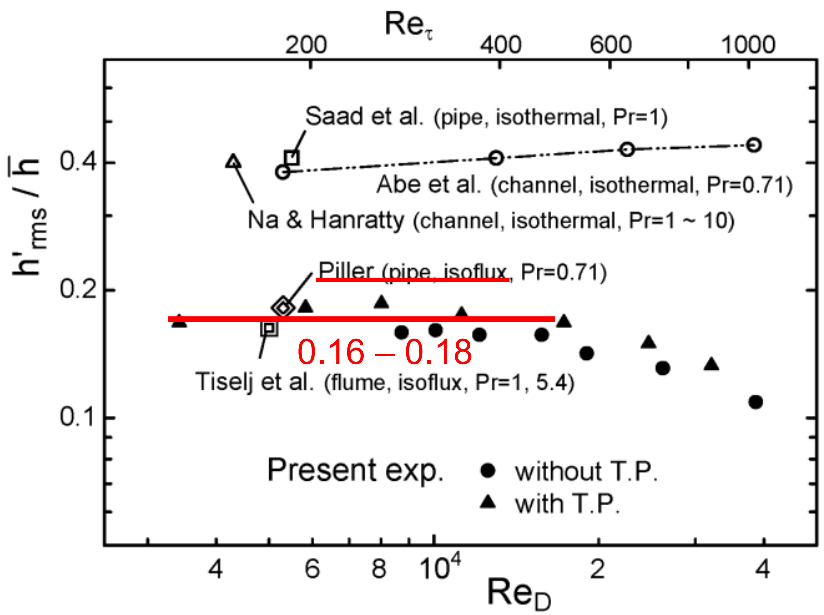
HTC measured using IRT is reliable at least for the time-averaged value

Validation of temporal fluctuation

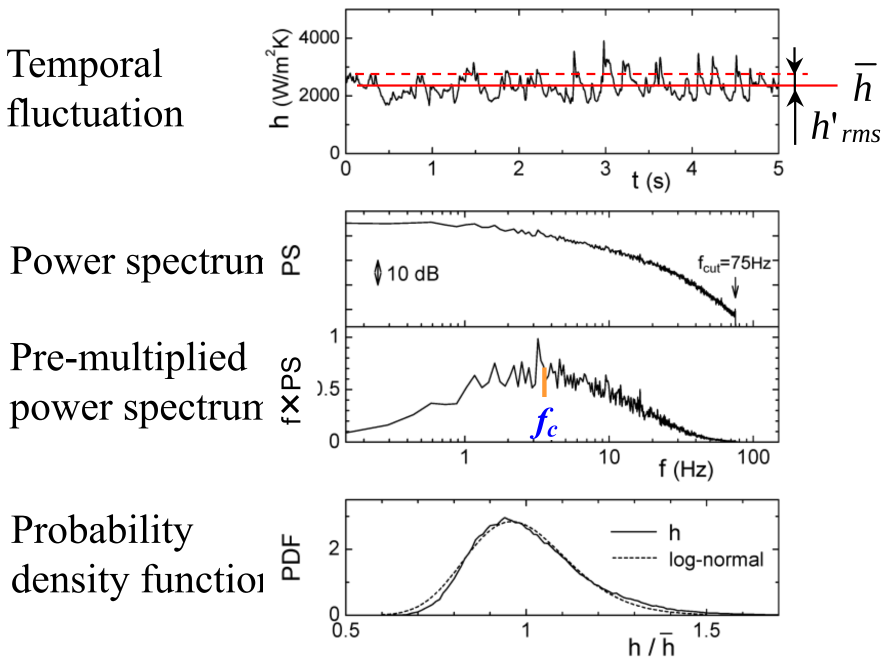
Nakamura et al., *Int. J. Heat and Fluid Flow*, Vol. 63, 46-55 (2017)

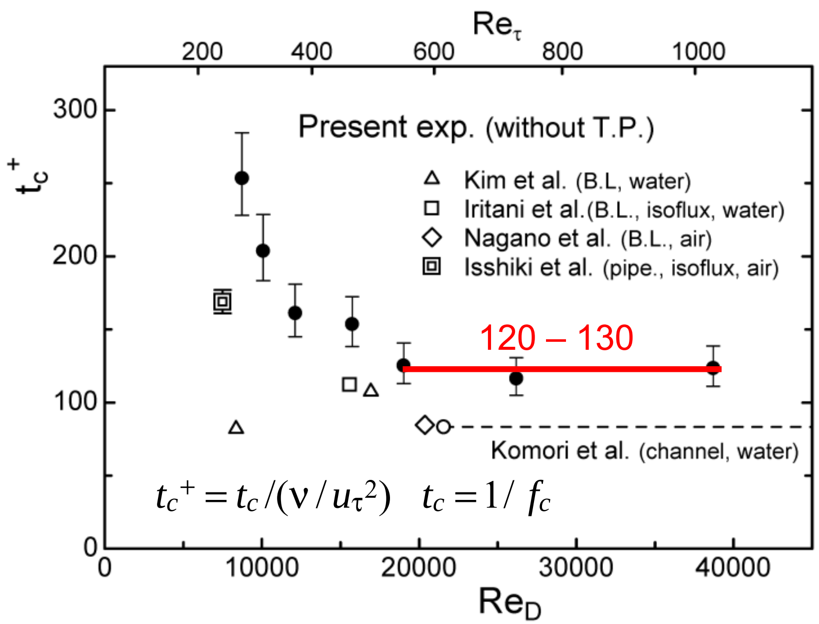


Instantaneous HTC (Re_D = 10100)



Rms value of the fluctuating heat transfer coefficient

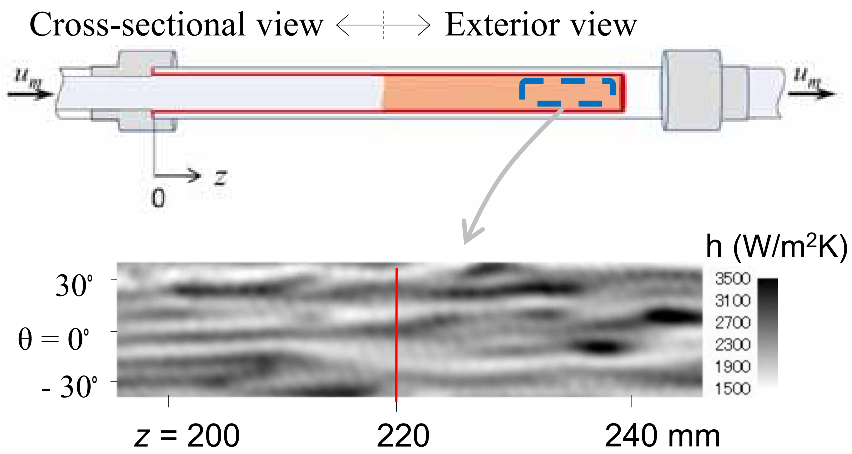




Characteristic period of the heat transfer fluctuation

Validation of spatial fluctuation

Nakamura et al., *Int. J. Heat and Fluid Flow*, Vol. 63, 46-55 (2017)

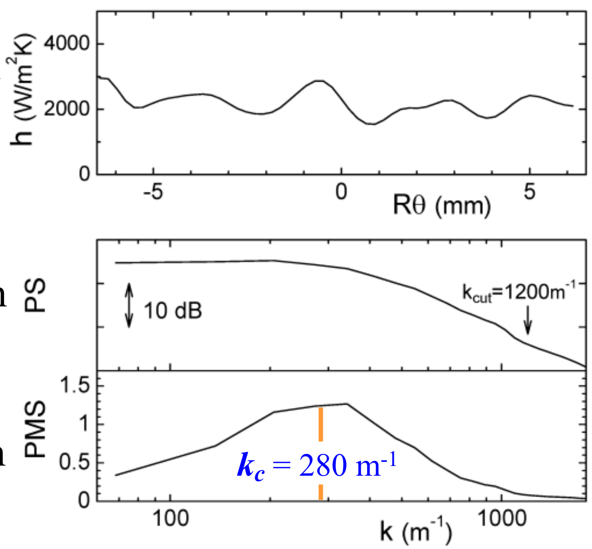


Instantaneous HTC (Re_D = 10100)

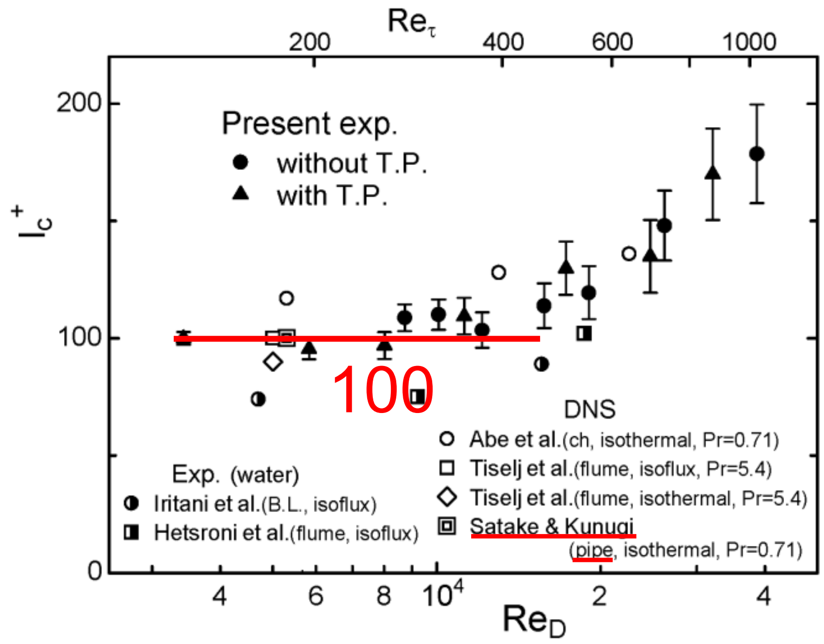
Circumferential distribution

Power spectrum

Pre-multiplied power spectrum



Mean spacing of the thermal streaks is reasonable compared to available experiments and DNSs at the lower Reynolds numbers where the streak spacing is sufficiently resolved.



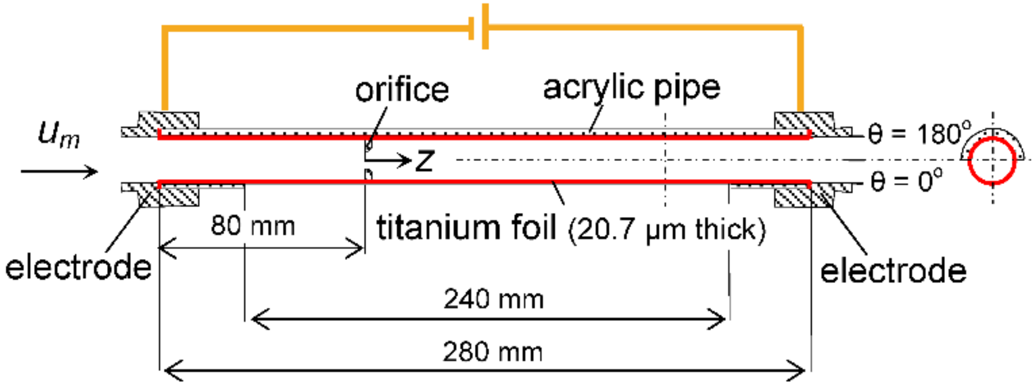
Mean spacing of thermal streaks

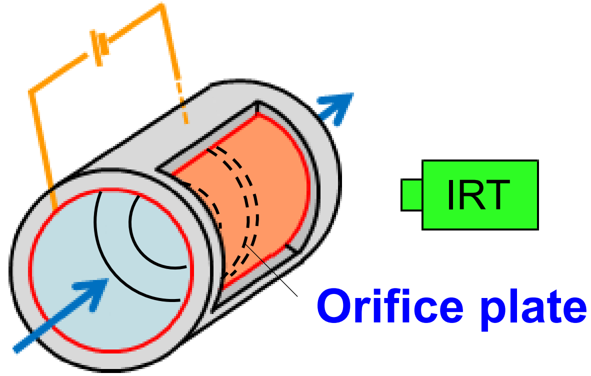
$$l_c^+ = l_c / (\nu / u_\tau)$$

$$l_c = 1 / k_c$$

Spatiotemporal heat transfer in a pipe can also be measured using IRT

Reattached flow behind an orifice

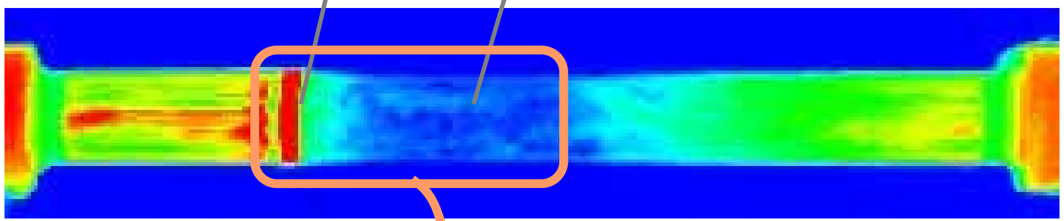




Orifice plate
(Flow separation)

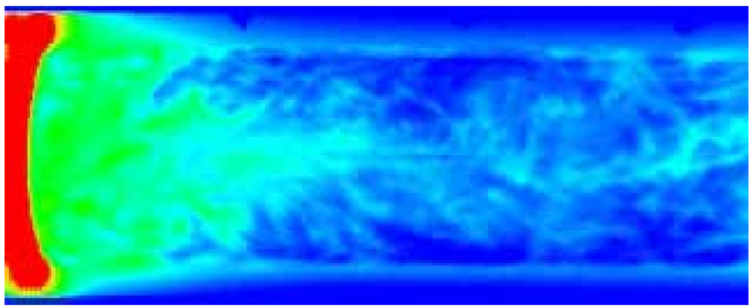
Flow reattachment

Real speed



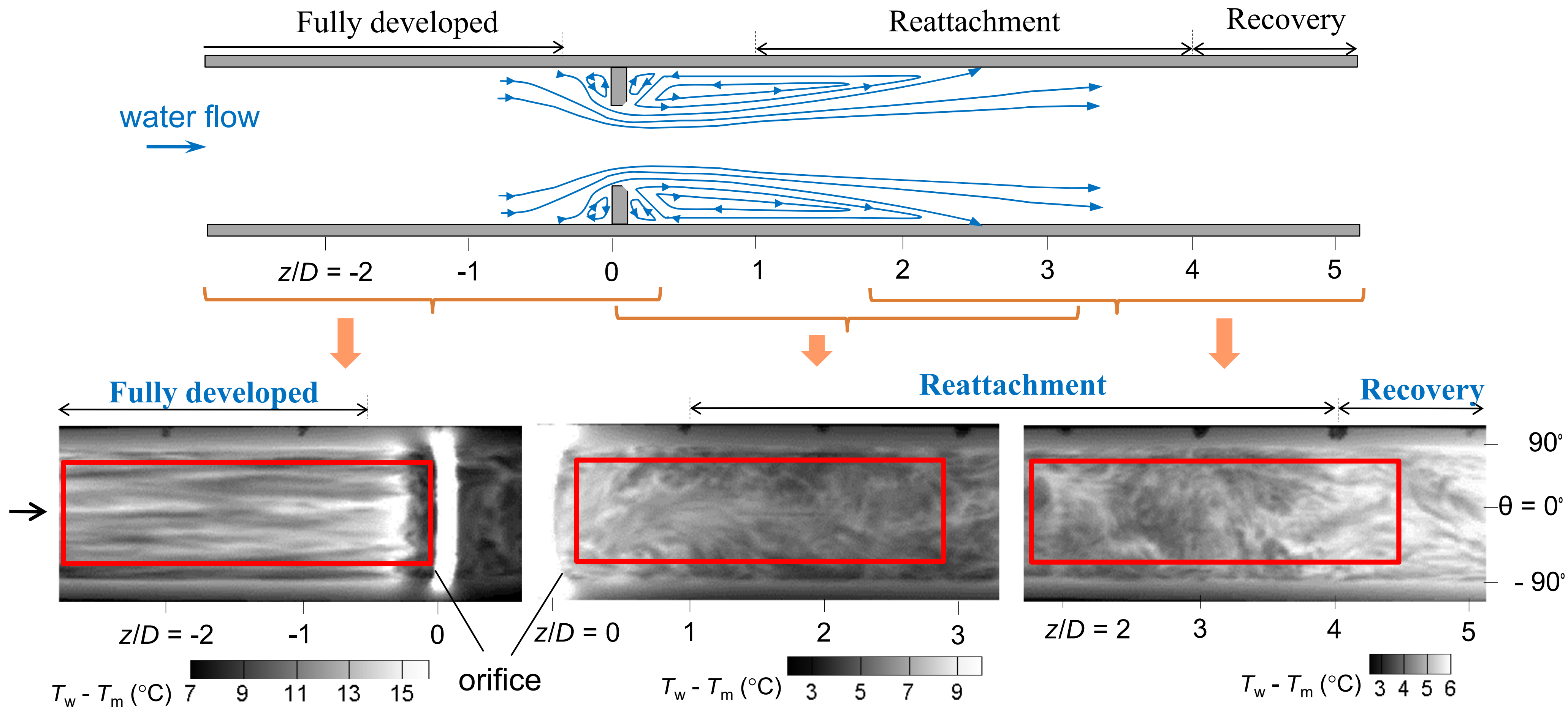
The temperature decreases suddenly behind the orifice plate due to the flow contraction and reattachment, and fluctuates rapidly

1/32 slow playback



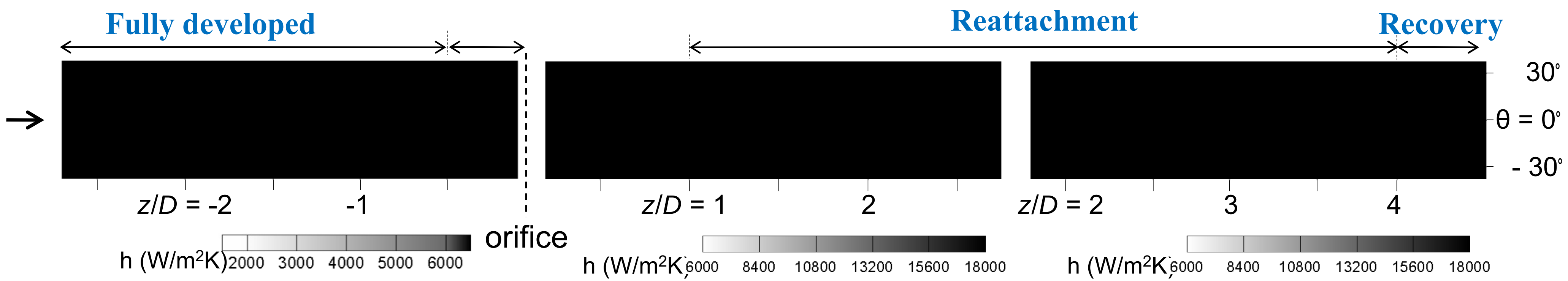
The temperature in the reattachment region fluctuates in a very complex manner as forward flow and reverse flow compete with each other

Thermal image behind an orifice plate at $Re_D = 12000$



Spatiotemporal heat transfer

In the flow reattachment region, a fine mottled structure appears, and fluctuates violently and complicatedly

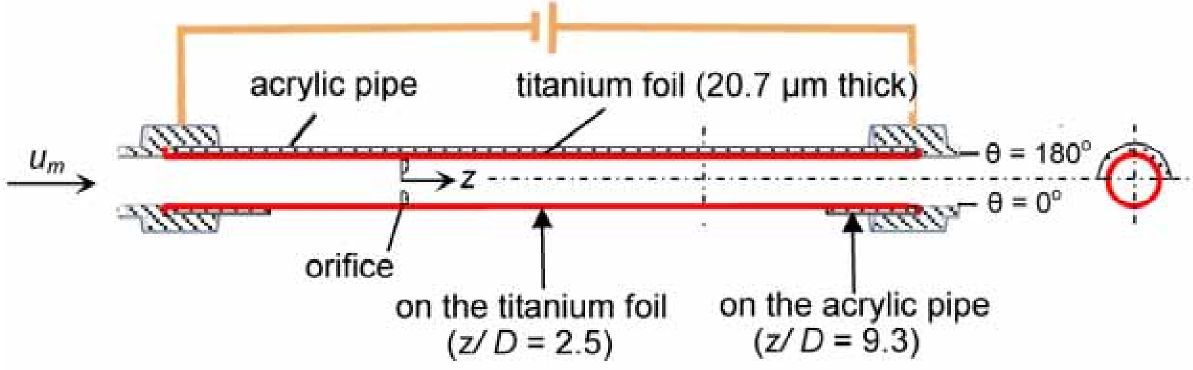


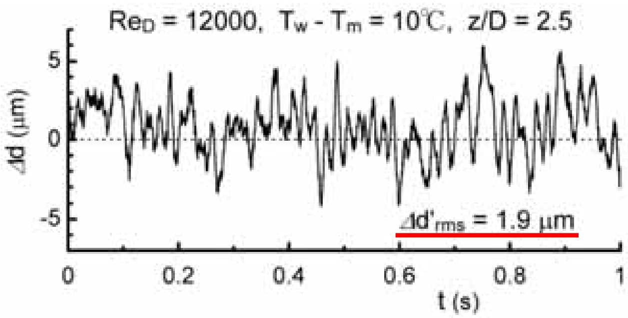
$Re_D \approx 12000$, $u_m \approx 0.5$ m/s, 1/80 slow playback

Shiibara, Nakamura, Yamada, *Mechanical Engineering Journal*, Vol. 2 (2015)

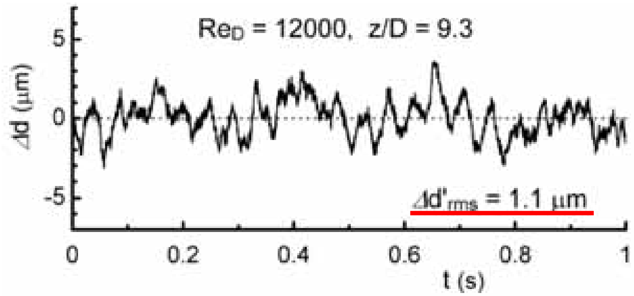
Mechanical vibration of the foil

Since there was a concern that the flow turbulence may vibrates the foil, we measured the mechanical vibration using a laser displacement meter.





(a) On a thin test surface at $z/D = 2.5$ and $\theta = 0°$



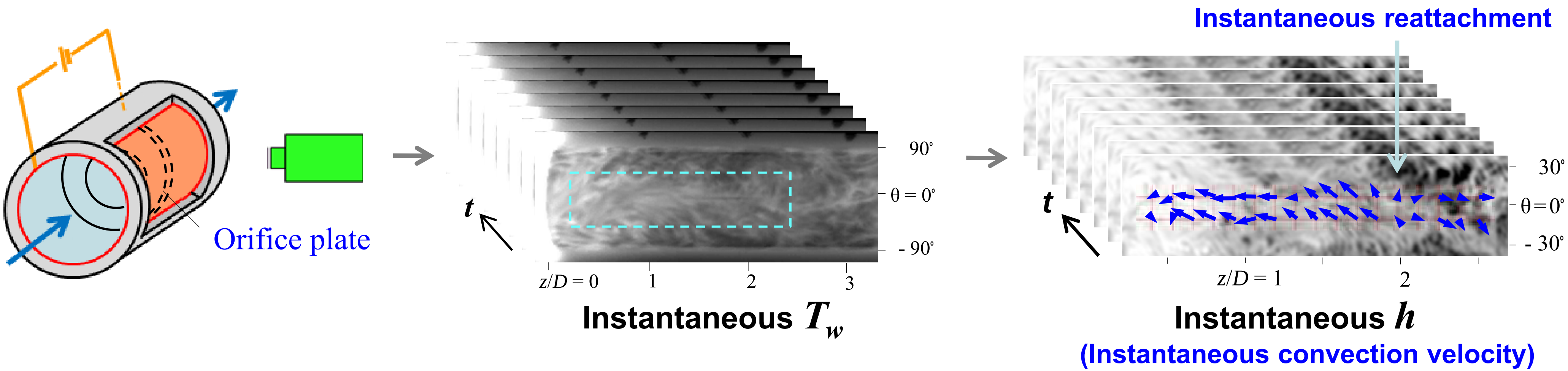
(b) On an acrylic pipe at $z/D = 9.3$ and $\theta = 0°$

Time trace of vertical displacement due to mechanical vibration at Re_D = 12000

Vibration displacement of the foil was on the order of 1 μm even when the water flow fluctuated violently and complicatedly.

Relation between flow reattachment and heat transfer

Shiibara, et al., *Trans. JSME*, 82, 16-00067 (2016), in Japanese

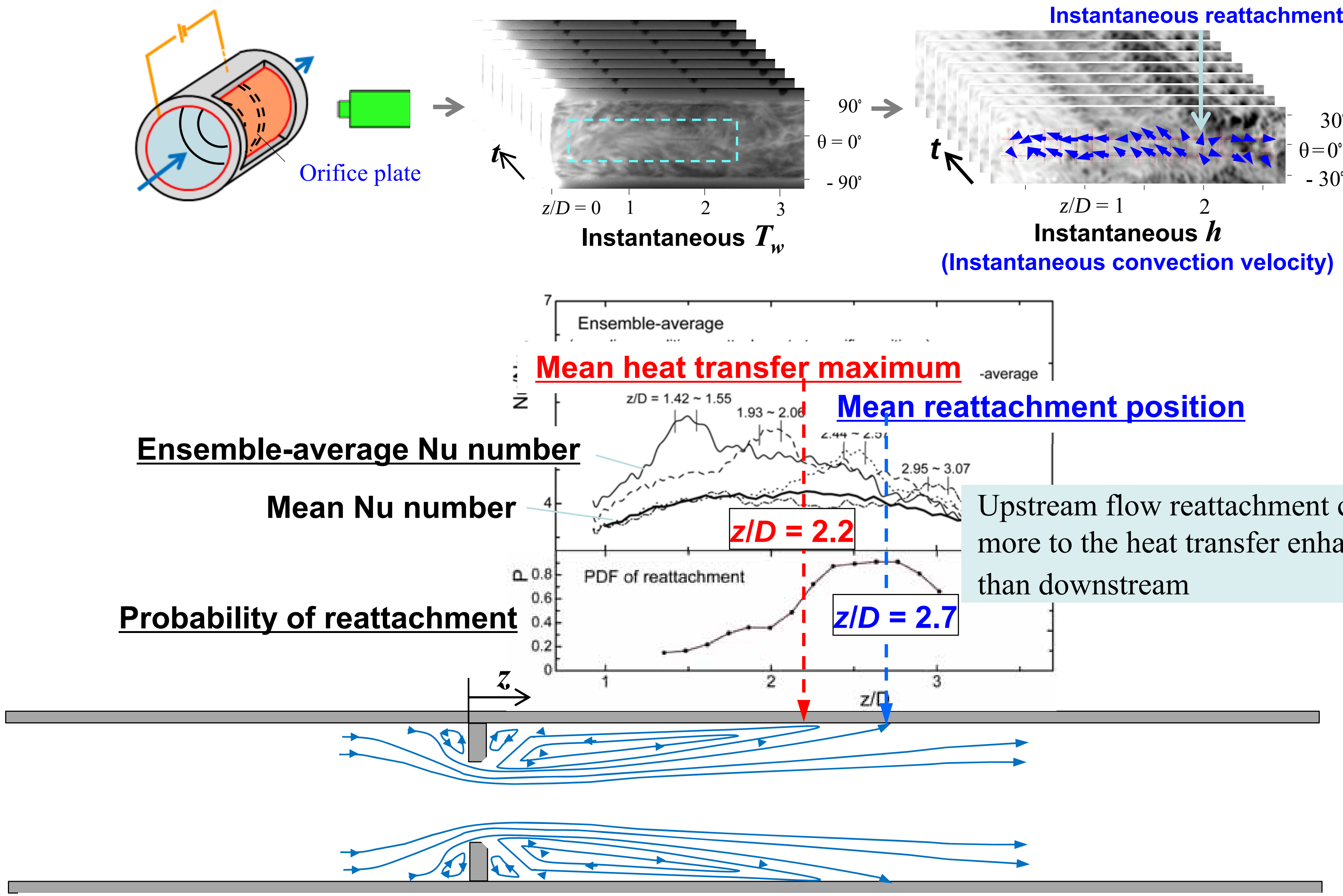


Since this measurement produces time-series data of the instantaneous heat transfer coefficient, we can calculate the convection velocity of the heat transfer using PIV software.

Using the calculated convection velocity, we can evaluate the instantaneous reattachment position where the streamwise convection velocity becomes zero.

Relation between flow reattachment and heat transfer

Shiibara, et al., *Trans. JSME*, 82, 16-00067 (2016), in Japanese

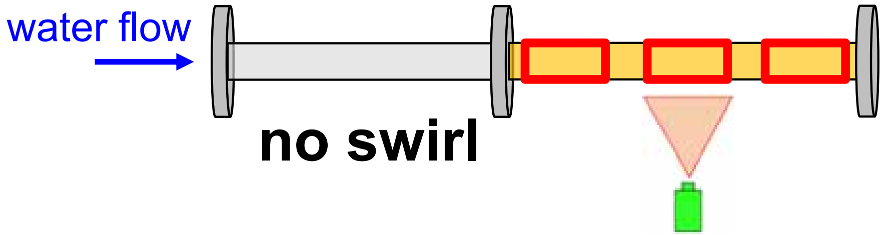


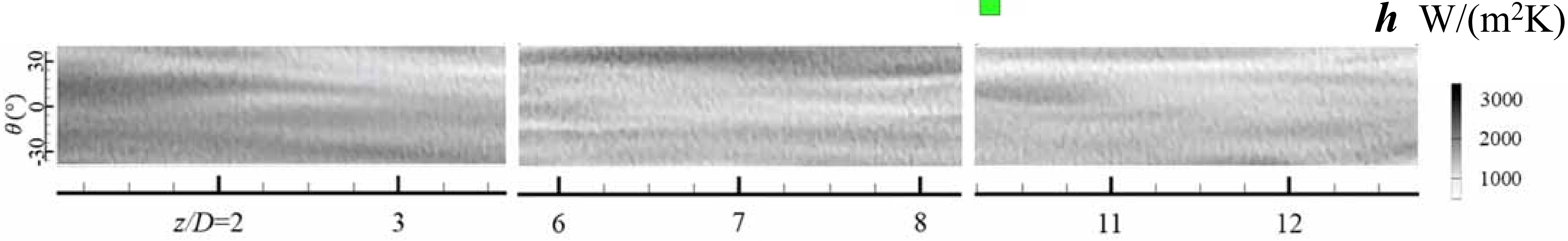
Upstream flow reattachment contributes more to the heat transfer enhancement than downstream

It is possible to investigate the relationship between heat transfer and flow field near a wall using IRT measurements

Heat transfer enhancement by swirling the flow

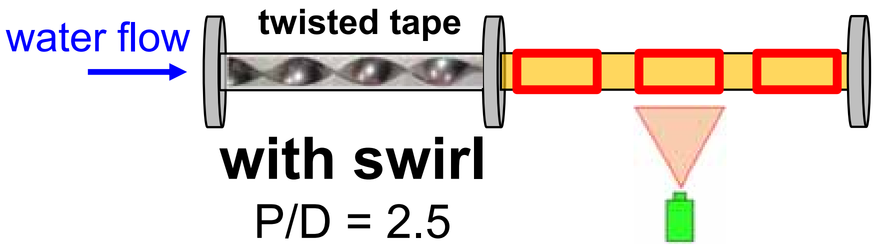
Re = 5800

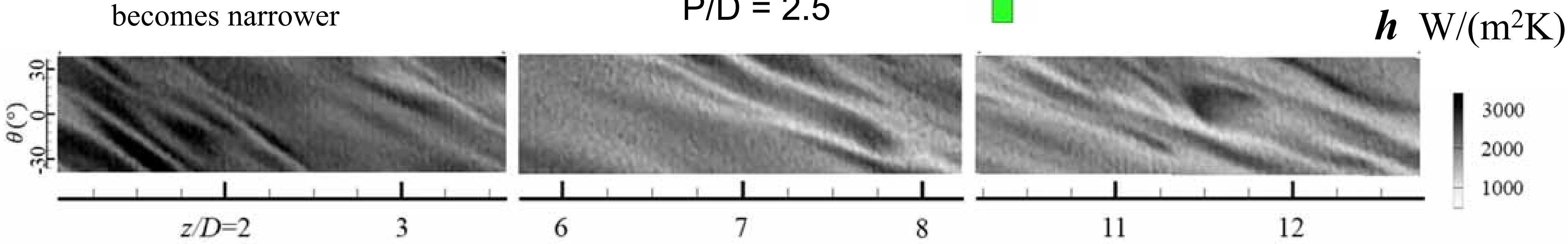




Instantaneous HTC (no swirl) 1/5 slow playback

The streaky structure inclines in the swirling direction, and the spacing of the streaks becomes narrower

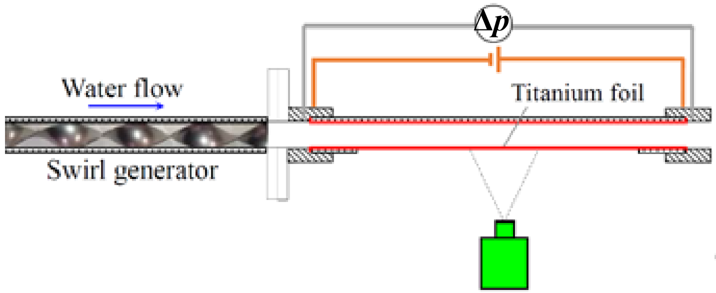




Instantaneous HTC ($P/D = 2.5$) 1/5 slow playback

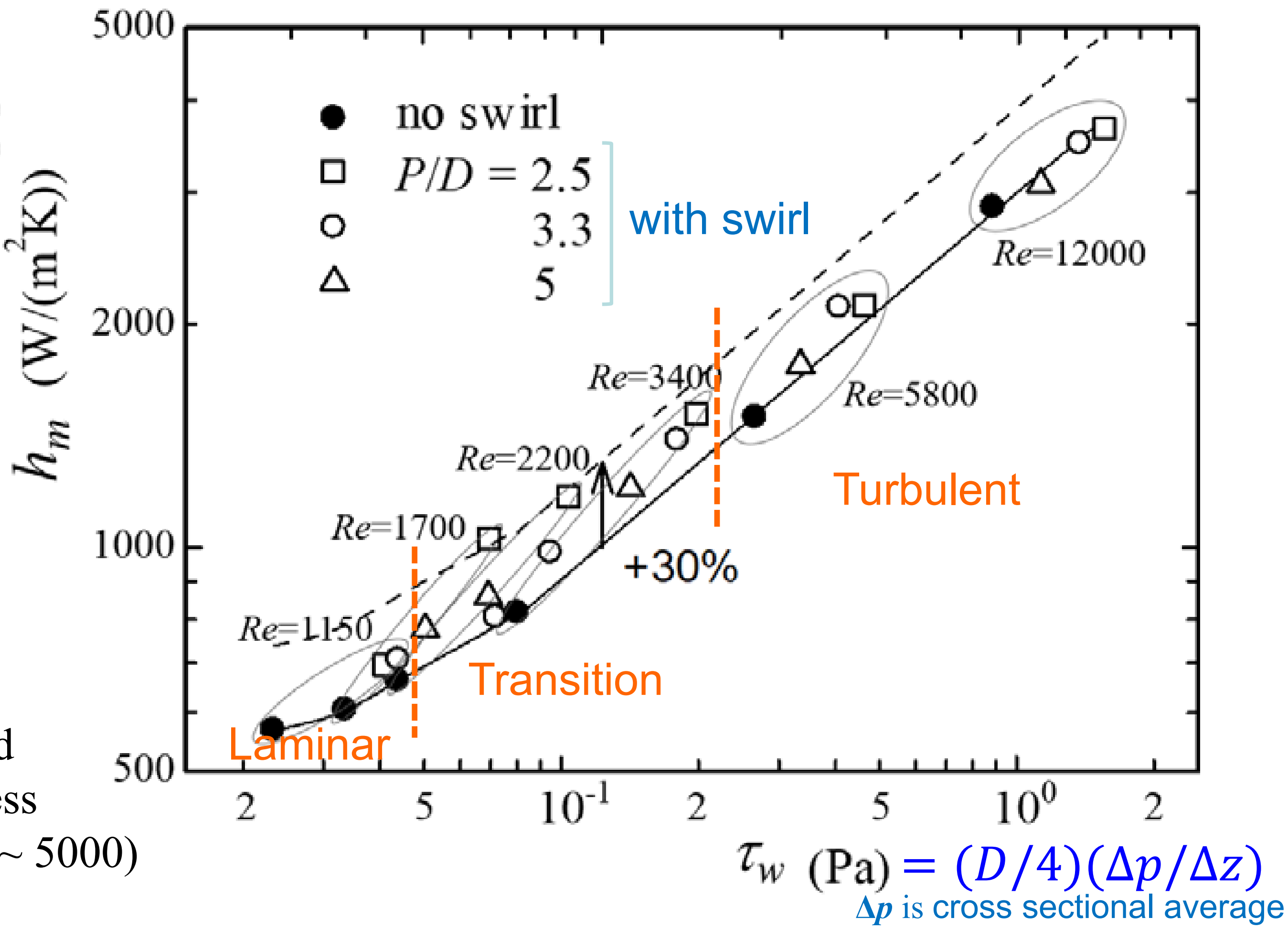
Dissimilarity between heat and momentum transports

Nakamura, et al., *IHTC17*, 333, (2023)



$$\frac{h_m}{\tau_w} \Rightarrow \frac{St}{C_f}$$

By applying the swirl, HTC increased up to 30% at the same wall shear stress in the transition regime ($\mathrm{Re_D} \approx 1500 \sim 5000$)



Mean HTC against wall shear stress

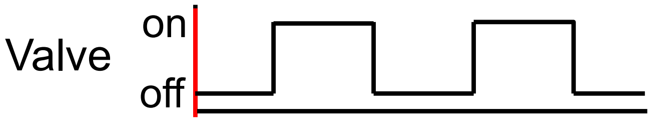
Dissimilarity appears between heat and momentum transports

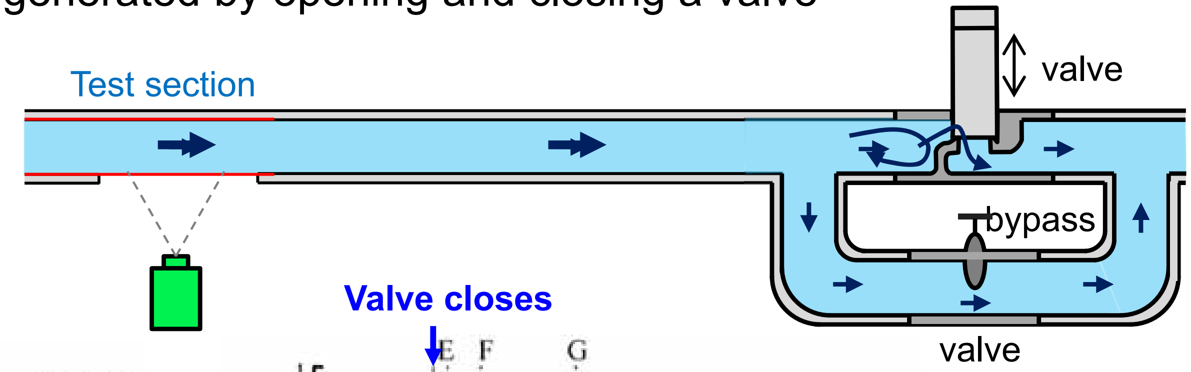
To clarify this mechanism, we are currently attempting to investigate turbulent shear stress and turbulent heat flux

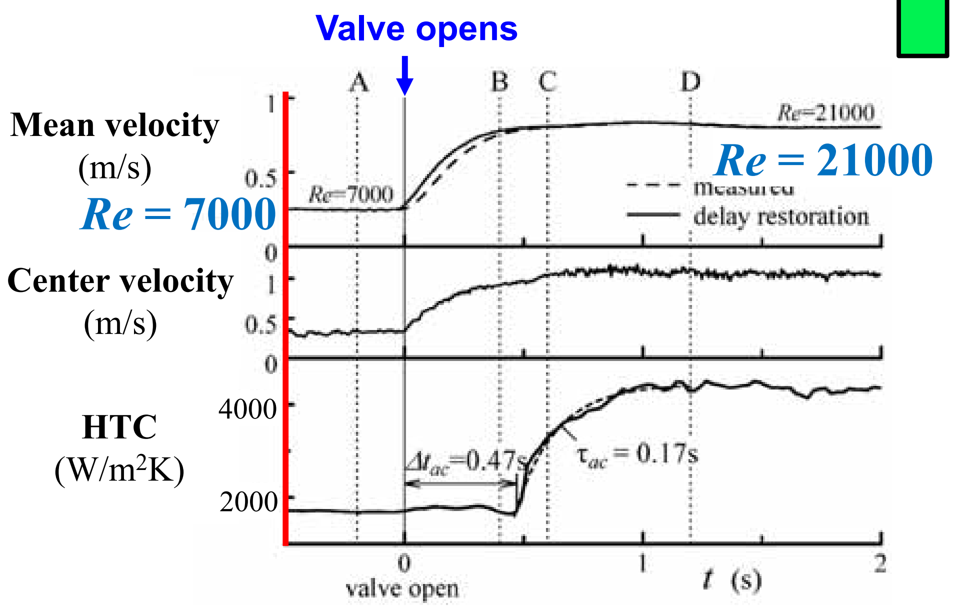
Sudden acceleration and deceleration of flow

Nakamura et al., *Int. J. Heat and Fluid Flow*, 85, 108661 (2020)

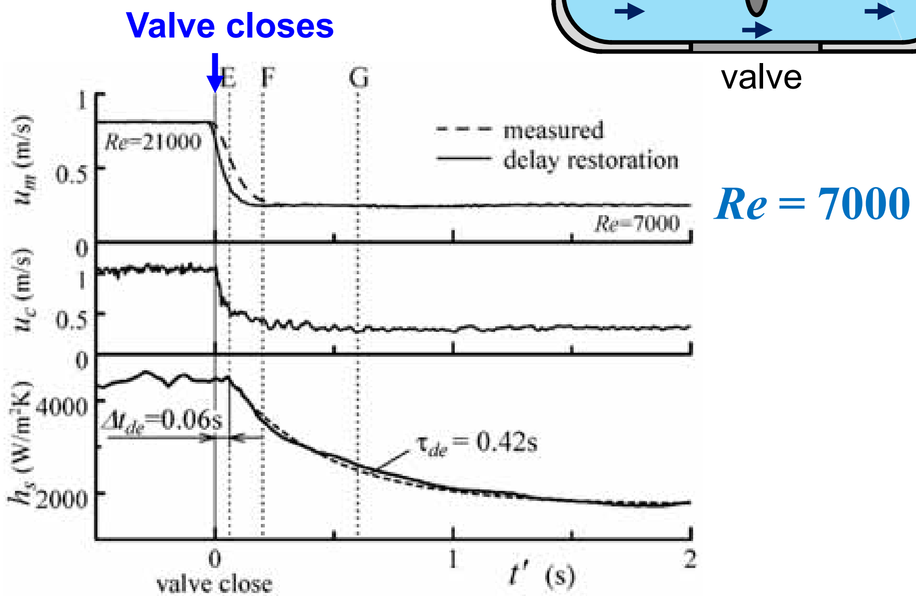
Flow acceleration and deceleration was generated by opening and closing a valve







Sudden acceleration



Sudden deceleration

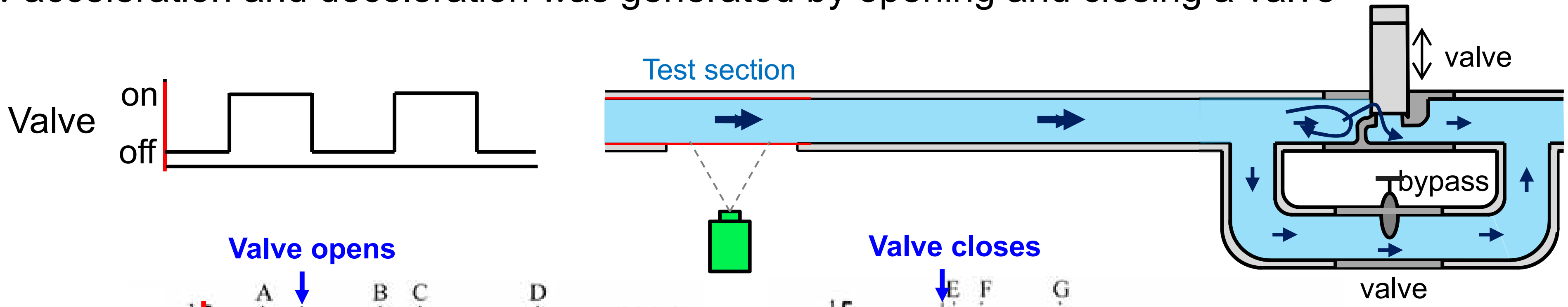
When the valve opens,
the velocities increase immediately,
but HTC has a delay
before it begins to increase.

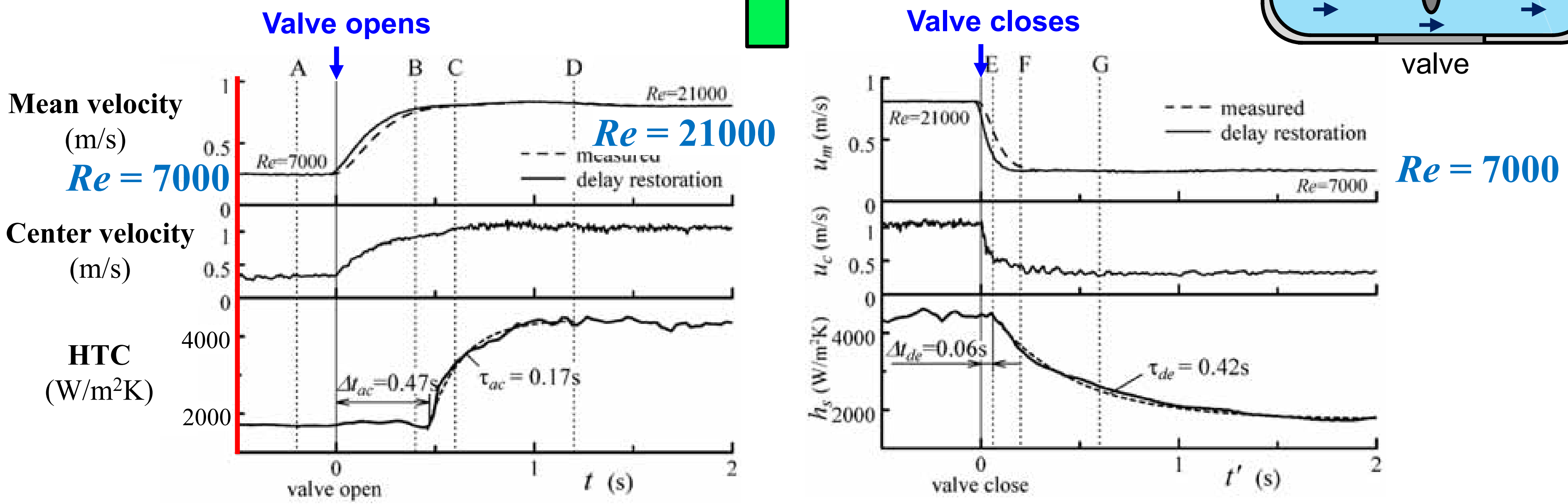
When the valve closes,
the velocities decrease immediately,
but HTC decreases gradually
after a short delay.

Sudden acceleration and deceleration of flow

Nakamura et al., *Int. J. Heat and Fluid Flow*, 85, 108661 (2020)

Flow acceleration and deceleration was generated by opening and closing a valve

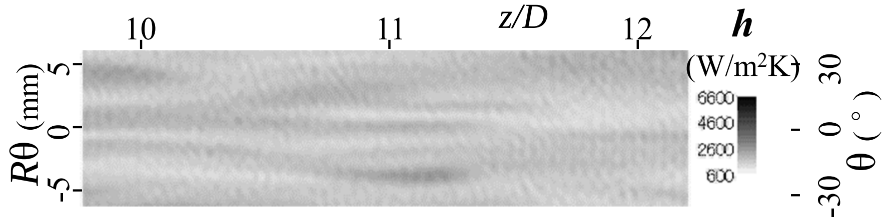




Sudden acceleration

Sudden deceleration

When the valve opens, the streaky structure is stretched, and after a while, the finer structure appears, and reaches the state of steady turbulence at Re = 21000.

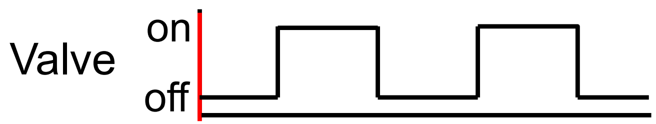


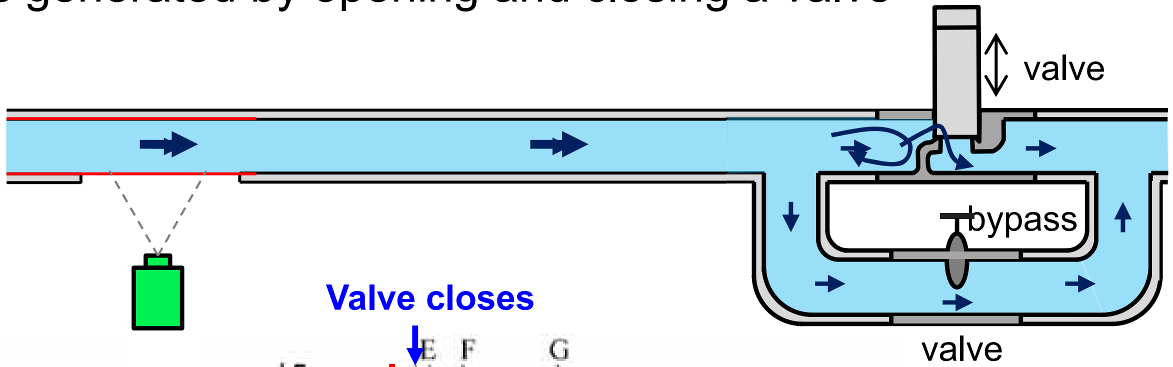
Instantaneous HTC

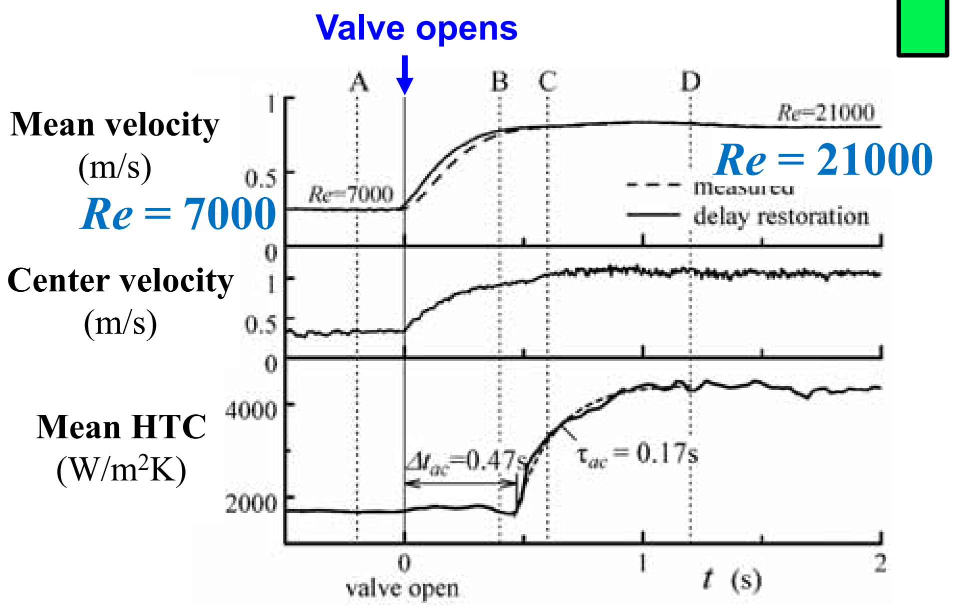
1/20 playback speed

Nakamura et al., *Int. J. Heat and Fluid Flow*, 85, 108661 (2020)

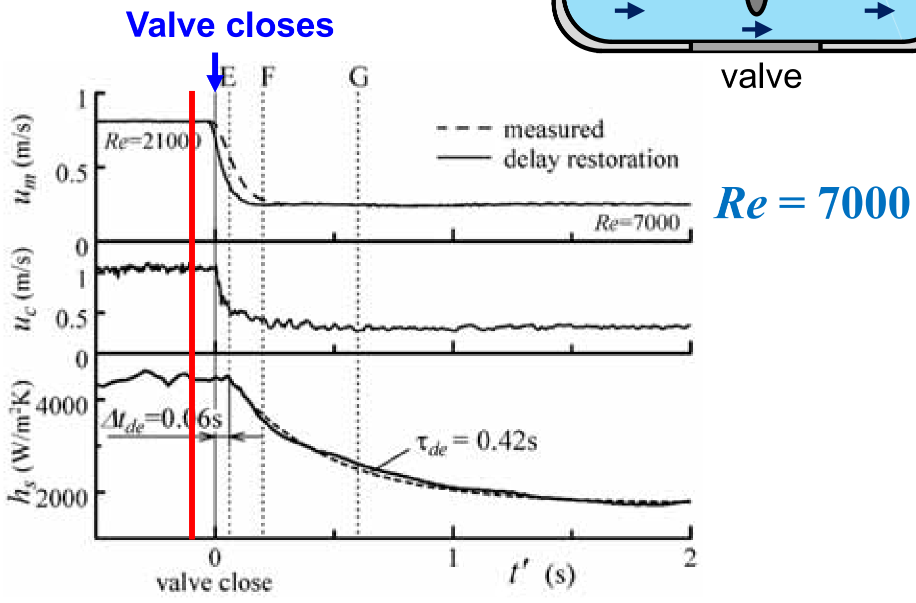
Flow acceleration and deceleration was generated by opening and closing a valve





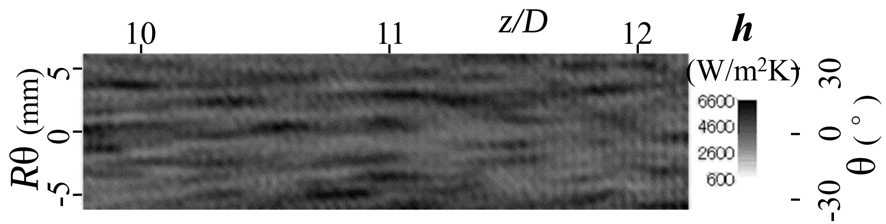


Sudden acceleration



Sudden deceleration

When the valve closes, the streaky structure crushes into a mottled structure, and this diffuses over time, resulting in a gradual decrease in HTC.



Instantaneous HTC

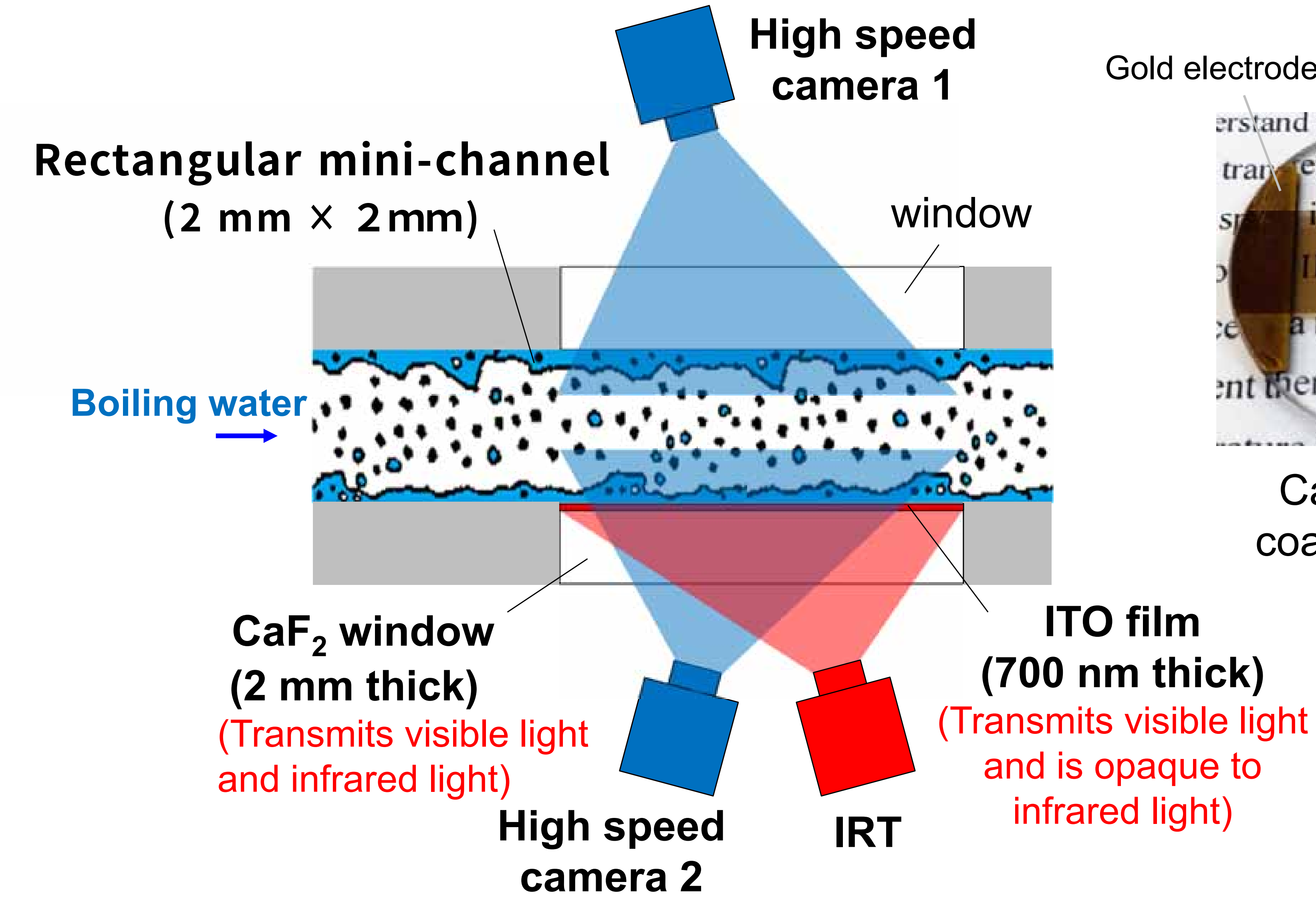
1/20 playback speed

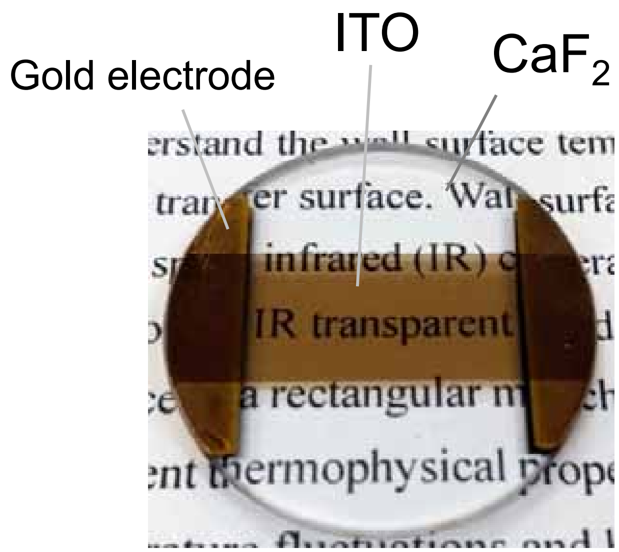
Dissimilarities appear between the flow field and heat transfer immediately after the acceleration and deceleration of flow

Outline

1. Measurements of air flows
    - Delay in temperature fluctuation
    - Verification of the measurements using IRT
    - Reattached flow behind a backstep
    - Simultaneous measurements combining IRT and PIV
2. Measurements of water flows in a pipe
    - Verification of the measurements
    - Reattached flow behind an orifice
    - Heat transfer enhancement by swirling the flow
    - Sudden acceleration and deceleration of flow
3. **Measurements of boiling**
    - **Flow boiling in a mini-channel**
4. Concluding Remarks

Flow boiling in a mini-channel



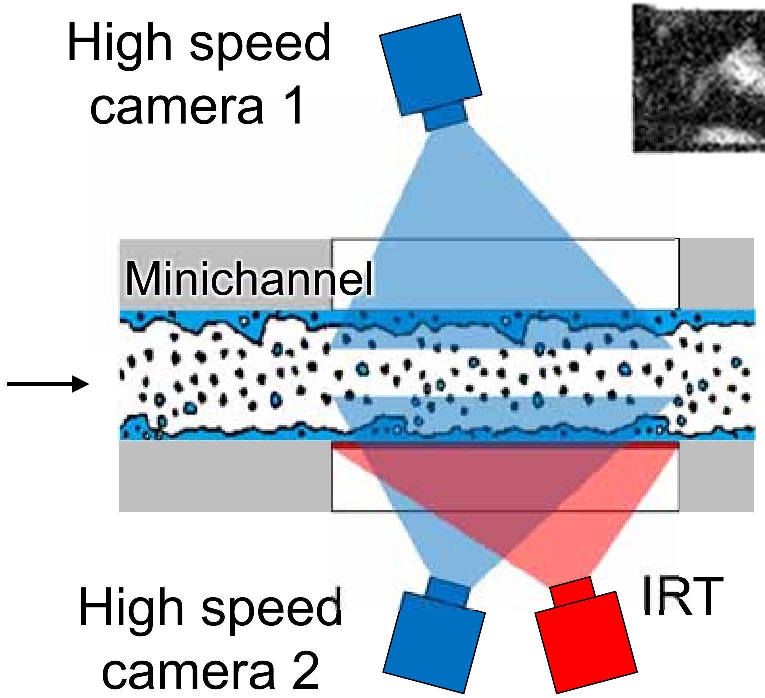


CaF_2 window coated with ITO

Schematic of spatiotemporal heat transfer measurement

Measurement example of boiling heat transfer

Yoshida, Yamada, Funami, Nakamura, *IHTC17*, 465, (2023)

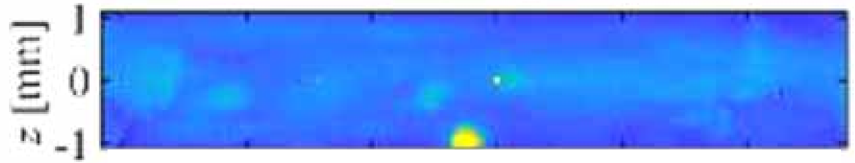


Visible image 1

1/70 slow playback

Fine and high-speed heat flux fluctuations are clearly captured caused by flow boiling

Visible image 2



Heat flux fluctuation

2000 fps, 25 μm resolution

In this research field, there have been very few measurements of heat transfer fluctuations, and DNS is currently not possible

It is expected that this measurement method will provide an opportunity to elucidate the flow boiling mechanism.

Concluding Remarks

IRT allows quantitative measurements of rapid and complex spatiotemporal fluctuations in convective heat transfer due to turbulence in both gas and liquid flows.

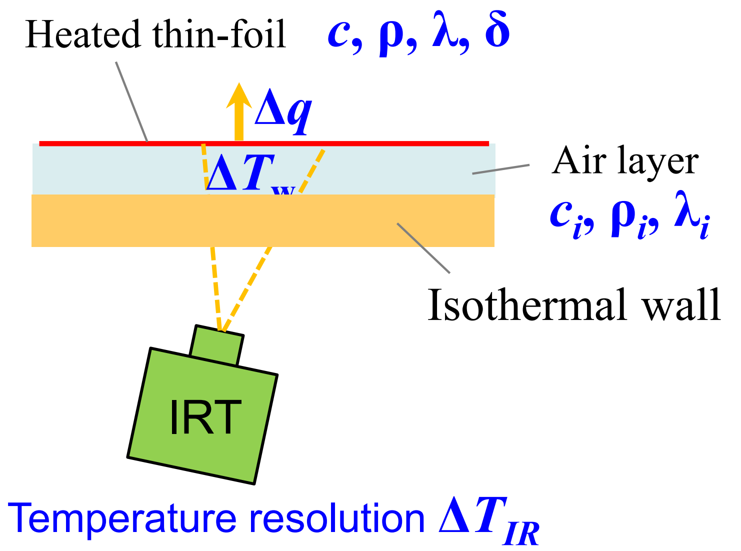
Also, IRT measurements make it possible to visualize flow patterns near a wall.

Simultaneous measurements combined with PIV provide a quantitative relationship between near-wall vortex motion and heat transfer fluctuations.

IRT measurements can also be extended to research fields where spatiotemporal heat transfer has been hardly understood, such as flow boiling.

Detectable temporal and spatial scales

Nakamura, *Int. J. Heat and Mass Transfer*, Vol. 52, 5040-5045 (2009)



Temporal fluctuation amplitude (f: frequency)

$$\Delta T_w \approx \frac{\Delta q}{2\pi c\rho\delta f + \sqrt{\pi}\sqrt{c_i\rho_i\lambda_i}\, f^{0.5}}$$

heat flux fluctuation (Δq); heat capacity ($c\rho\delta$); thermal effusivity of air-layer ($\sqrt{c_i\rho_i\lambda_i}$)

Spatial fluctuation amplitude (k: wavelength)

$$\Delta T_w \approx \frac{\Delta q}{\lambda\delta k^2 + \lambda_i k}$$

heat flux fluctuation (Δq); thermal conductance ($\lambda\delta$); Thermal conductivity of air-layer (λ_i)

※ ΔT_w becomes smaller as the spatio-temporal scale of fluctuation becomes smaller

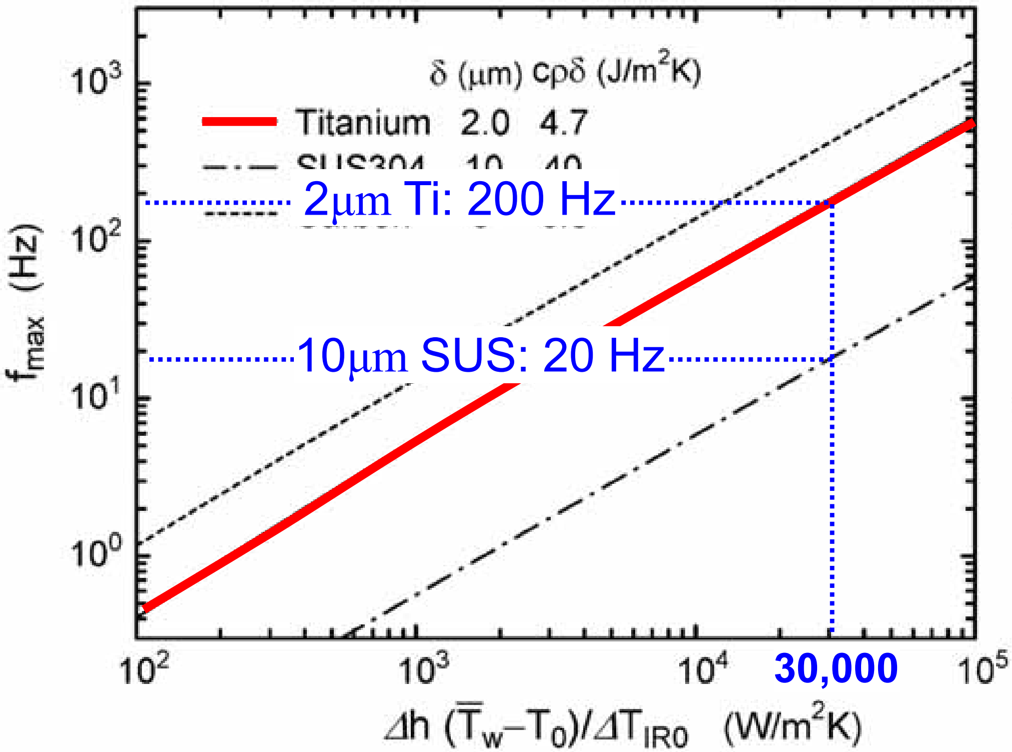
Fluctuation can be detected if $\Delta T_W > \Delta T_{IR}$

Even with a high-performance infrared camera,
fluctuations cannot be detected unless this condition is met!

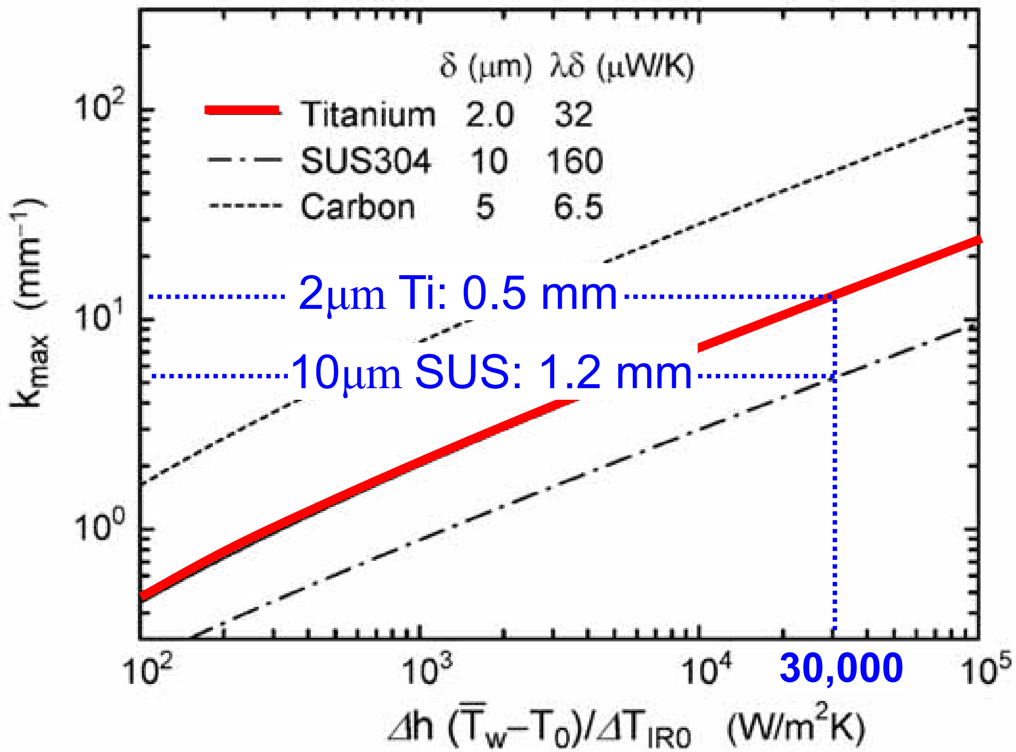
Detectable limits

$\Delta T_W = \Delta T_{IR}$ condition can be determined analytically

Nakamura, *Int. J. Heat and Mass Transfer*, Vol. 52, 5040-5045 (2009)



Detectable limit of fluctuating frequency



Detectable limit of spatial wavelength

Heat transfer fluctuation measurements in turbulent airflow:

$$\left.\begin{aligned}\Delta h &= 20\ \mathrm{W/m^2K}\\ (T_W - T_0) &= 30\ ^\circ\mathrm{C}\\ \Delta T_{IR0} &= 0.02\ ^\circ\mathrm{C}\end{aligned}\right\} \Rightarrow \Delta q/\Delta T_{IR0} = \Delta h(T_W - T_0)/\Delta T_{IR0} = \underline{30{,}000}$$

By using a 2 μm thick titanium foil, it is considered possible to capture temperature fluctuations on the wall due to turbulent airflow

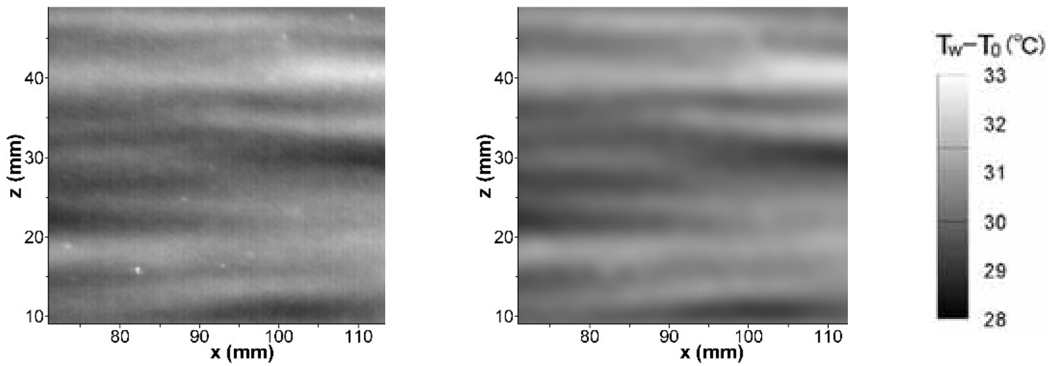
Noise Reduction

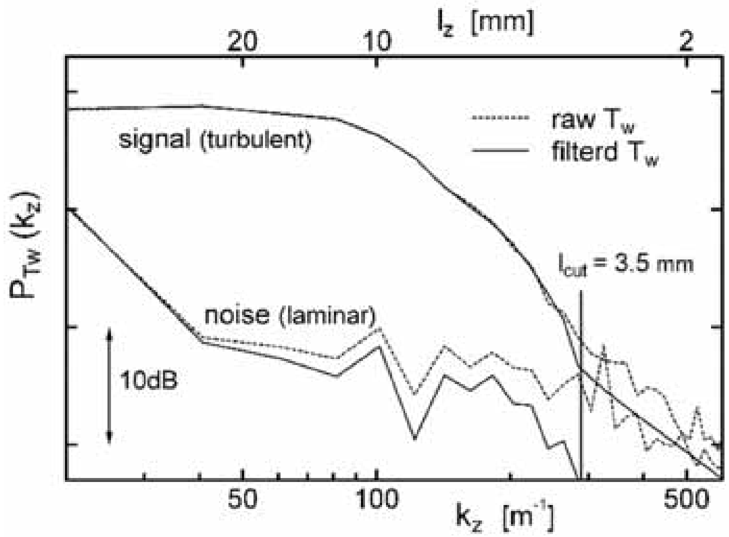
Nakamura and Yamada, *Int. J. Heat Mass Transf.*, Vol. 64, 892-902 (2013)

$$c\rho\delta\frac{dT_w(x,z,t)}{dt} = \lambda\delta\left(\frac{d^2T_w(x,z,t)}{dx^2} + \frac{d^2T_w(x,z,t)}{dz^2}\right) + (\dot{q}_{in} - \dot{q}_{cv}(x,z,t) - \dot{q}_{cd}(x,z,t) - \dot{q}_{rd}(x,z,t) - \dot{q}_{rdr}(x,z,t))$$

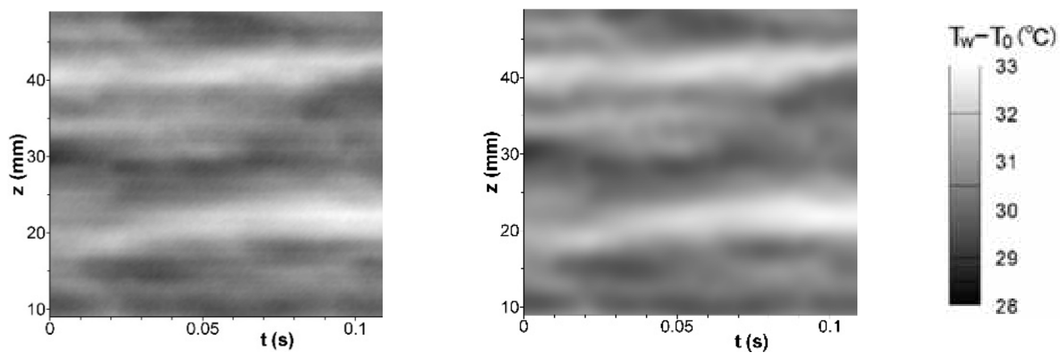
Low-pass filters with sharp cutoffs are applied in the time (t) and spatial (x and z) directions to suppress noise amplification in the calculation of the derivative terms.

Spatial noise reduction

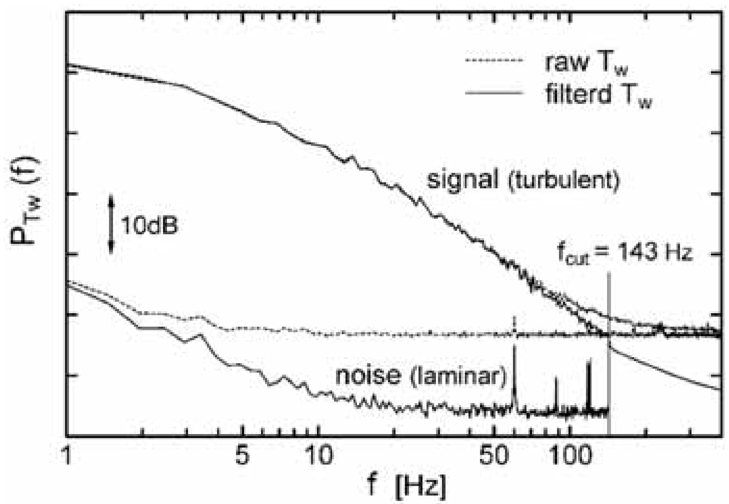




Temporal noise reduction



Measured temperature After applying low-pass filter



Turbulent boundary layer (u_0 = 4 m/s)

SN ratio of temperature fluctuation