Nuclear Thermal Hydraulic Engineering Lab.

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OpenFOAM 이용 공기냉각 RCCS 상승관 내 열전달현상 예측을 위한 *Phit-f k-ε* 난류모델 개선

# Improvement of *Phit-f k-ε* turbulence model for the prediction of heat transfer phenomena inside an air-cooled RCCS riser using OpenFOAM

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# CONTENTS

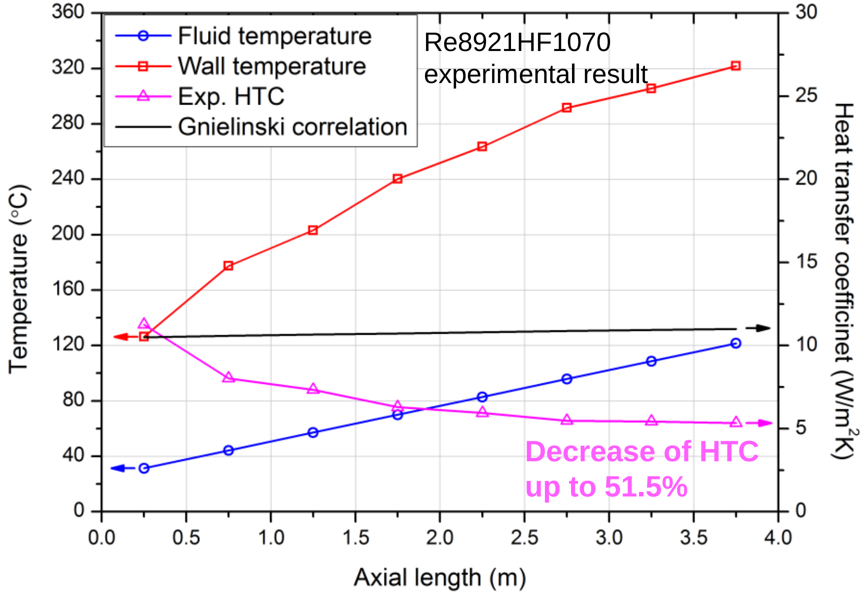
# Introduction

## Reactor Cavity Cooling System, RCCS

- Passive safety system of VHTR
- Reduced scale experiment; KAERI, ANL and University of Wisconsin
  - ✓ <u>Heat transfer regime were changed</u> with decreased inlet velocity

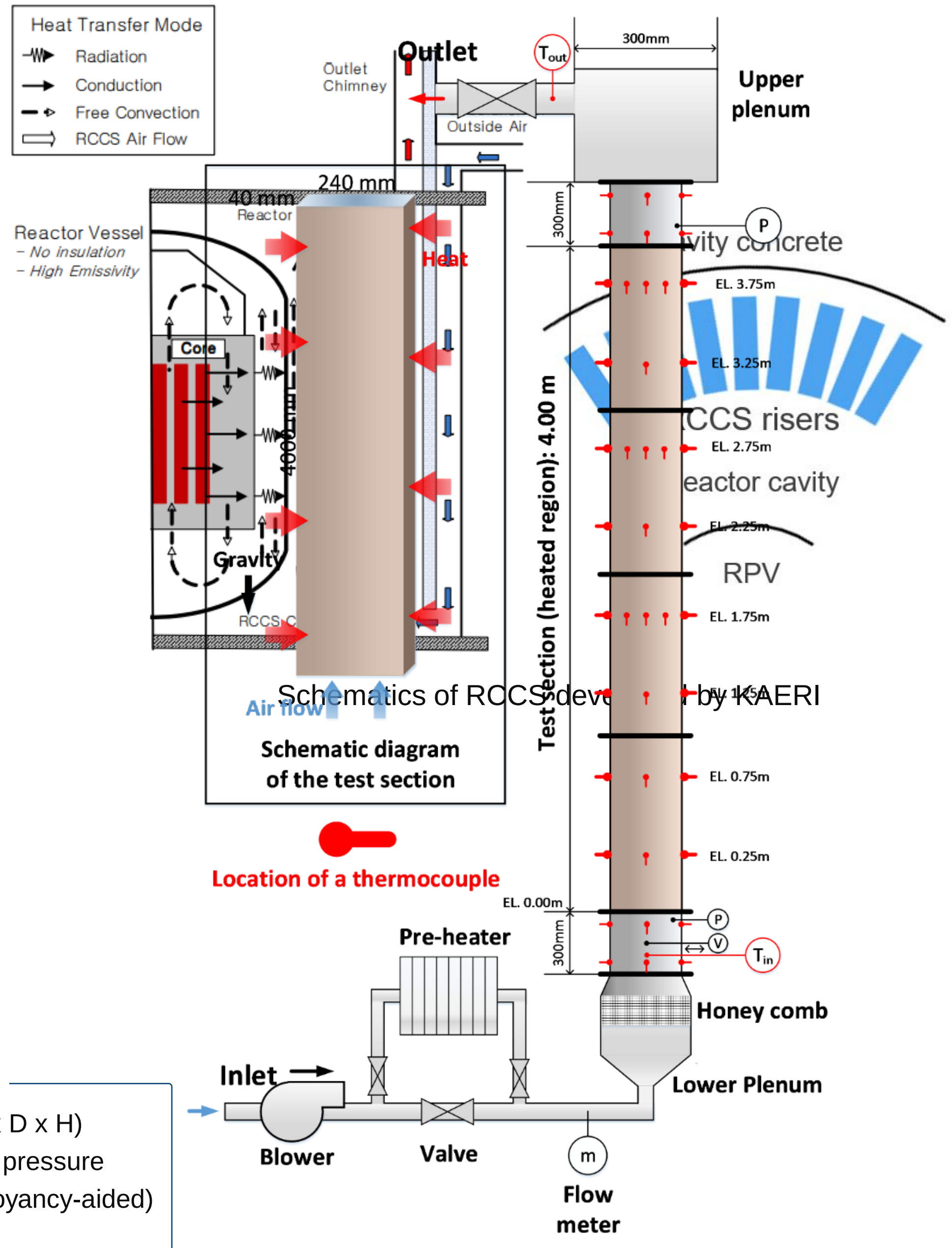
## Riser Heat transfer Experimental Facility, SNU-RHEF

- Heat transfer phenomena inside a <u>single rectangular RCCS riser</u>
  - Local heat transfer coefficient along the elevation
- ✓ Heat transfer deterioration under mixed convection heat transfer




**Design parameters of RHEF**

- 240mm x 40 mm x 4000mm (W x D x H)
- Working fluid : air in atmospheric pressure
- Flow direction : Upward flow (Buoyancy-aided)
- Inlet Re: 3000 – 16000
- Heat flux: 300 – 1800 W/m$^2$



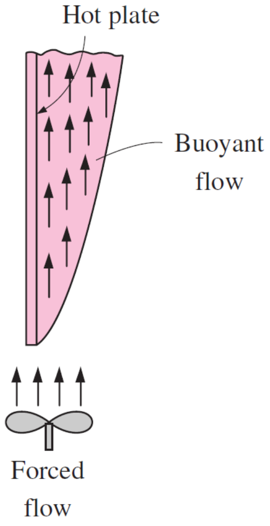
Schematics of RCCS developed by KAERI

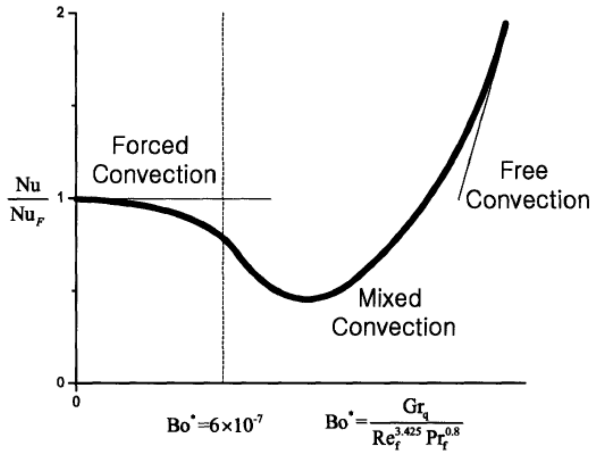
Design of SNU-RHEF [D.-H. Shin]

# Introduction

## Mixed convection heat transfer

- Complicated heat transfer mechanism
  - Thermo-physical property variation
- Buoyancy-aided flow
  - ✓ Heat transfer deterioration
  - Natural circulation from chimney effect

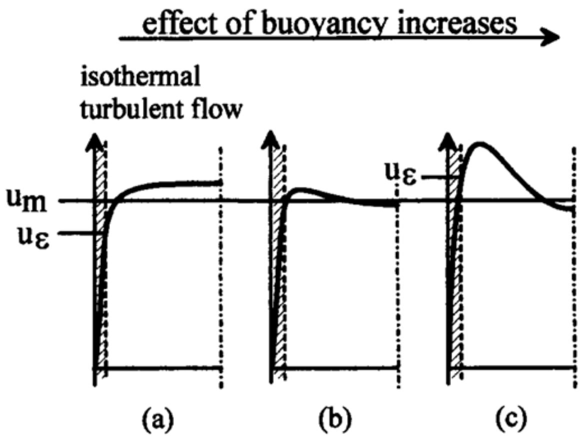


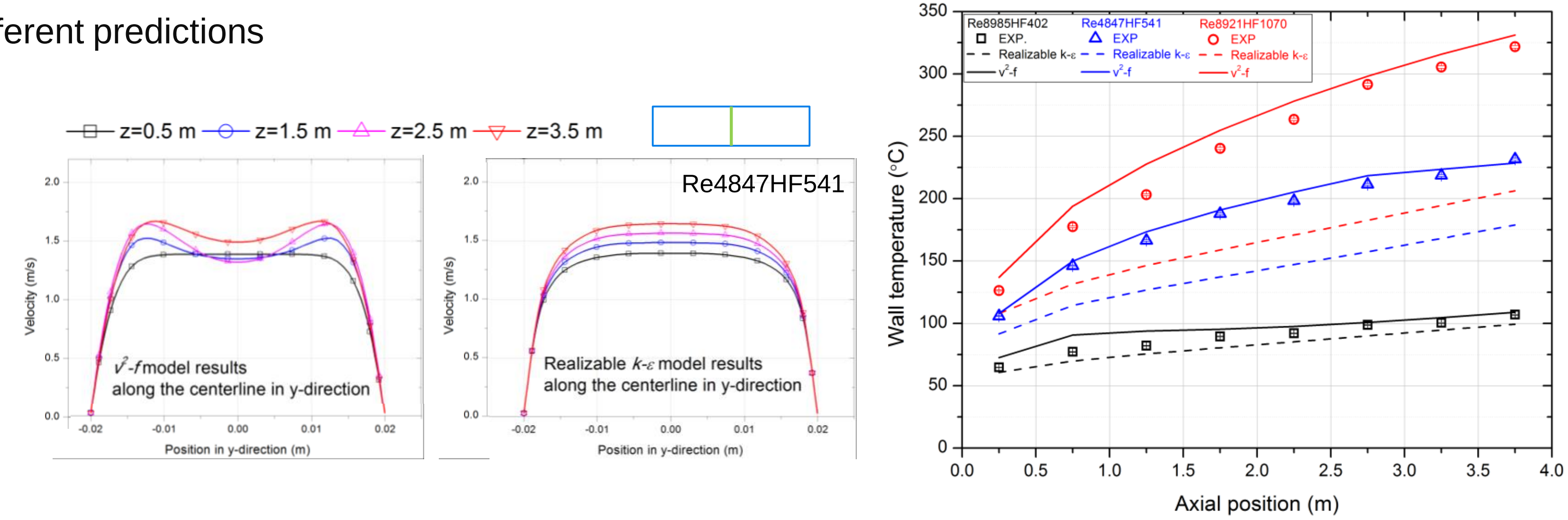

Mixed convection heat transfer correlation [Jackson et al., 1989]

## Local flow characteristics under mixed convection

- Heat transfer mechanism needs to be investigated.
- Depending on the turbulence model, different predictions

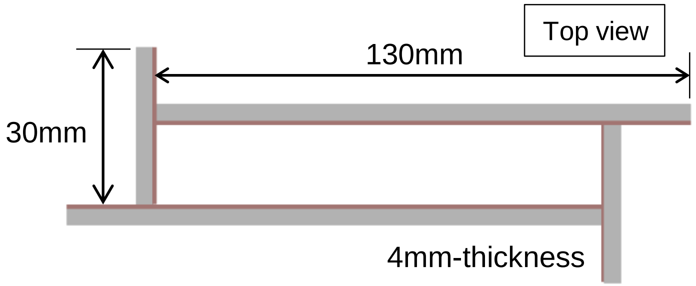



Near-wall velocity according to buoyancy [Aicher, 1997]



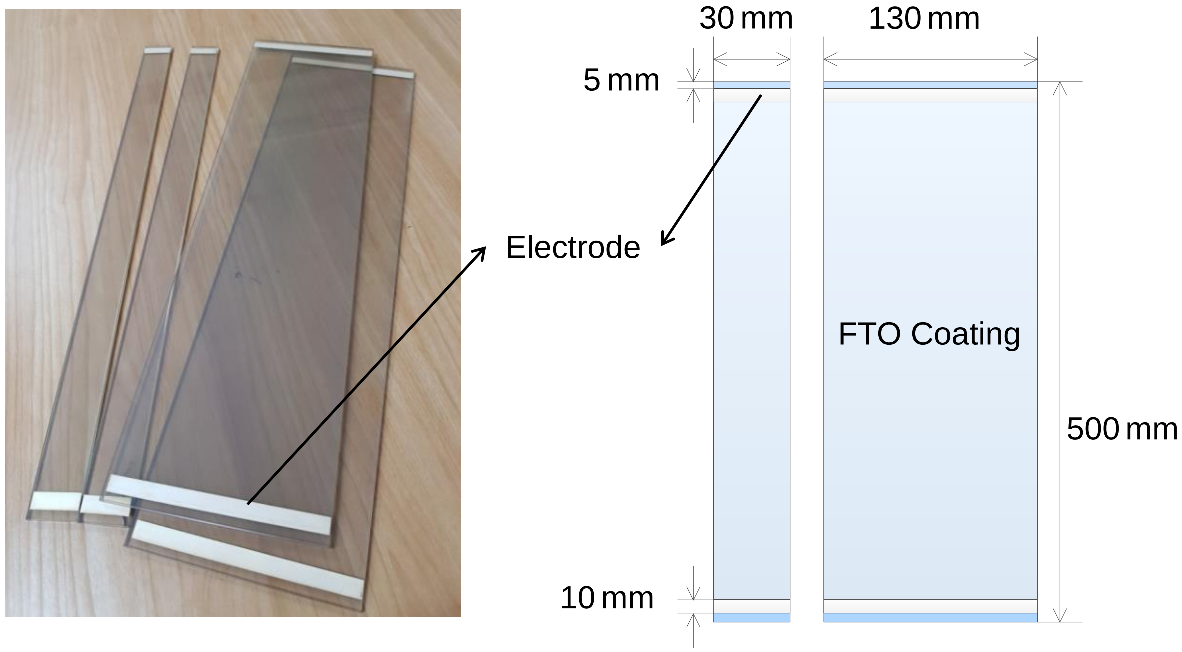

CFD analysis results for SNU-RHEF experimental conditions [Kim et al., 2021]

# Airflow visualization experiment

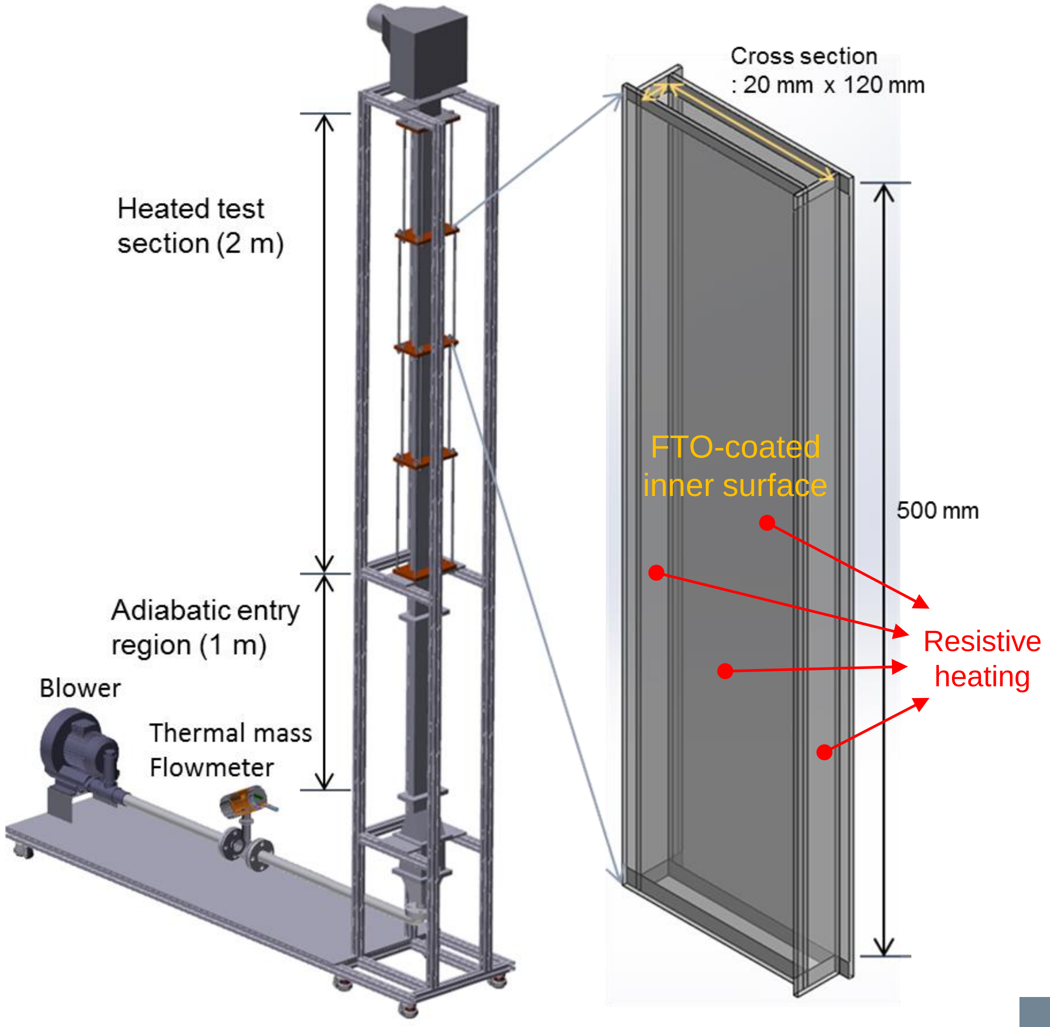



## FROVE; Four-Side Heating Riser Flow Visualization Experiment Facility

- Transparent test section for flow visualization
  - Heating region: 2.0 m (≈ 60 $D_h$), Entrance region (PVC): 1.0 m (≈ 30 $D_h$)
    - Inner test section: 120 mm × 20 mm × 2000 mm
    - Half sizes of the cross-section of prototype RCCS riser
  - FTO (Fluorine doped Tin Oxide) coated heat-resistant glass
    - FTO: Transparent conducting material for resistive heating
    - Heating power ← Power supply, control panel (~ 300 °C)



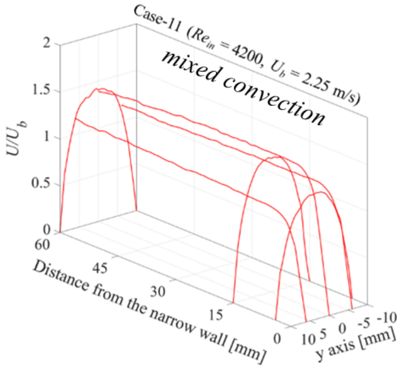

FTO coated heat-resistant glass and its design



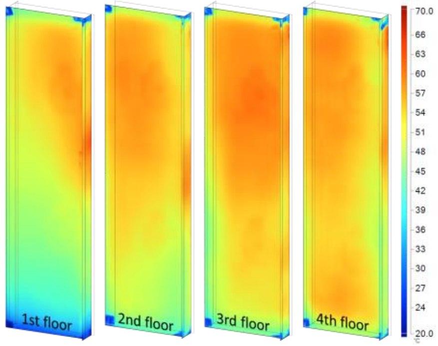

Schematics of airflow visualization experiment facility and its test section

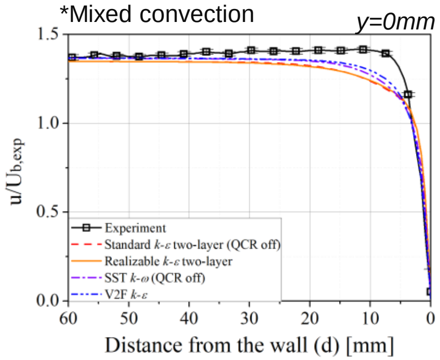
# Research works

## Previous researches



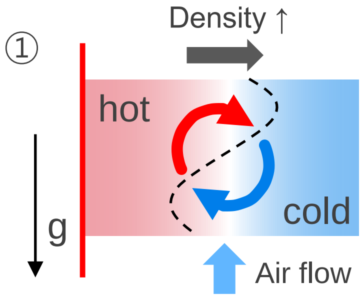

- ✓ Airflow visualization experiment
  - – Local velocity fields inside a heated rectangular riser

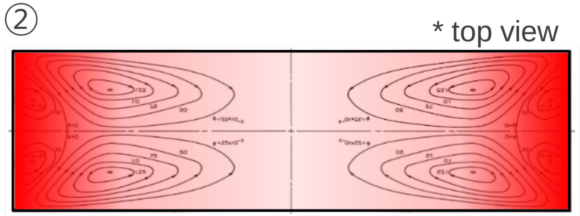


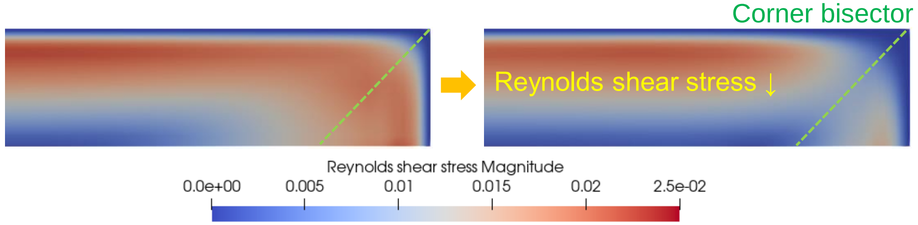

- ✓ CFD analyses with experimental conditions
  - – Turbulence model assessment (Limitations)

## In the present study




- ✓ Findings from the experiment
  - ① Density-gradient induced vortex motion
  - ② Flow laminarization preceding near the corners



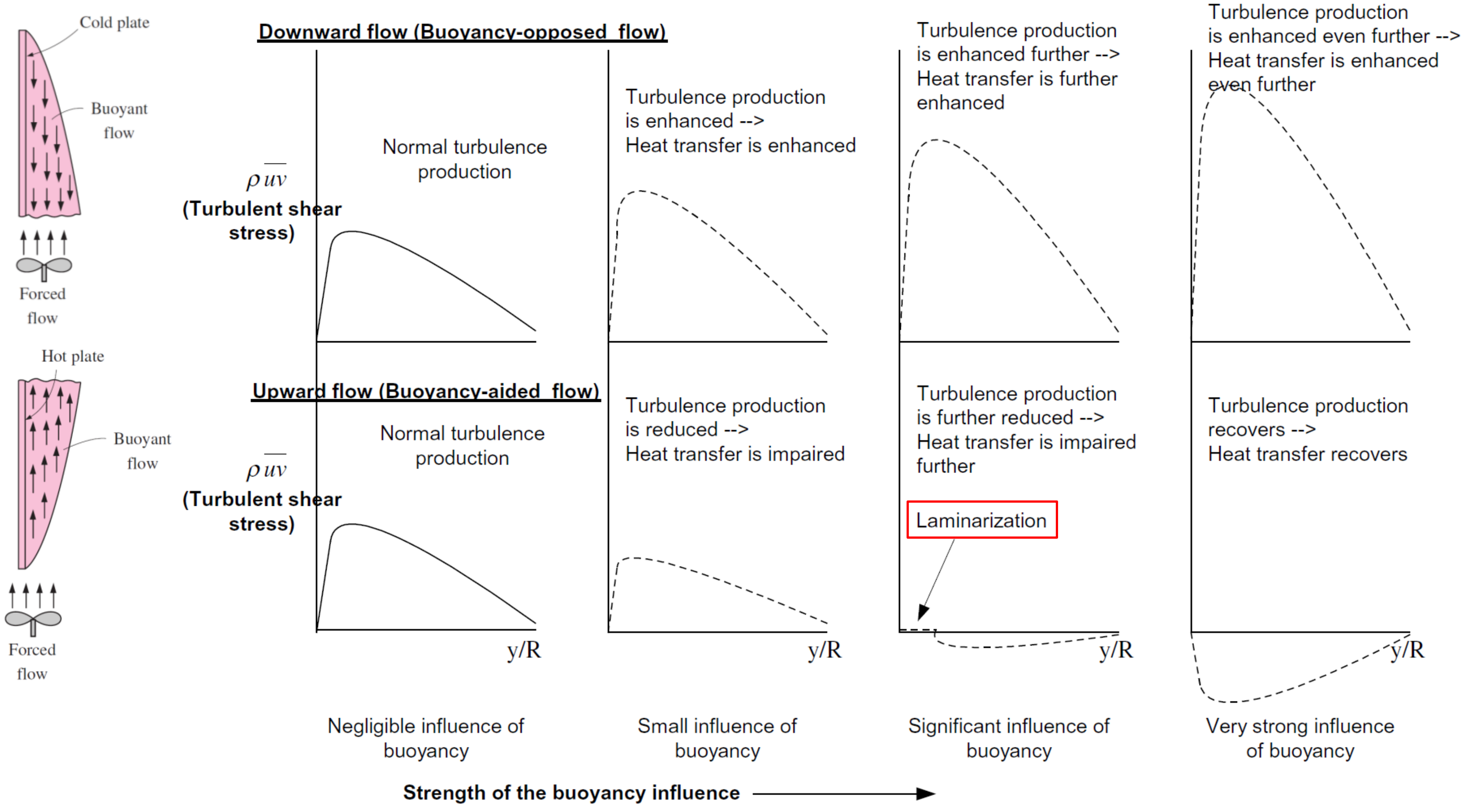

- ✓ Improvement of RANS turbulence model
  - ① Turbulence production related to the density-gradient
  - ② Flow characteristics along corner bisectors
- – Calculations with modified turbulence model
  - – Improved predictions for the experimental data

# Reynolds shear stress

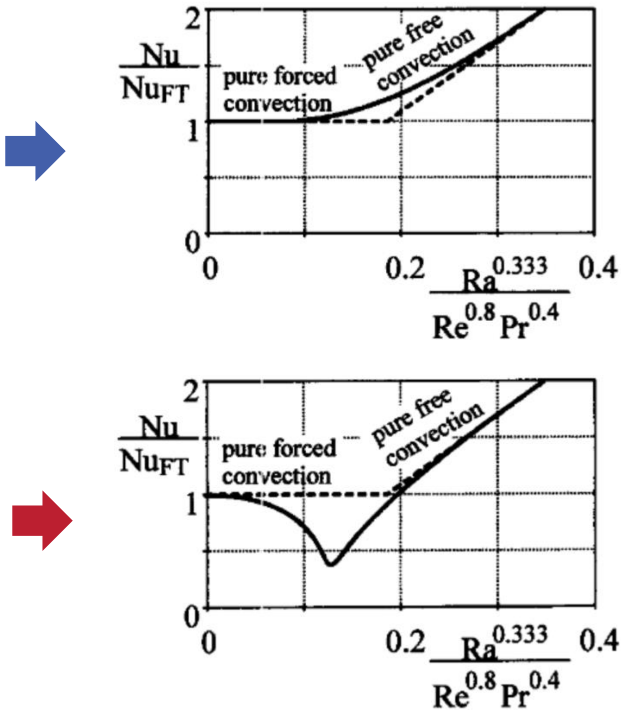
## Mixed convection heat transfer

– Explanation for the heat transfer deterioration and enhancement

; Changes in Reynolds shear stress distributions




Reynolds shear stress for buoyancy-opposed and buoyancy-aided flow [Kim et al., 2008]




Schematic diagram showing heat transfer for opposing (up) and aiding (down) mixed convection [Aicher and Martin, 1997]

# Discussions

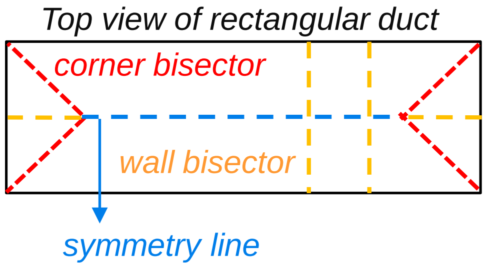
## Overestimation of heat transfer in mixed convection with RANS turbulence models

– Heat transfer phenomena not included in RANS turbulence modeling

### ① Density gradient in the radial direction

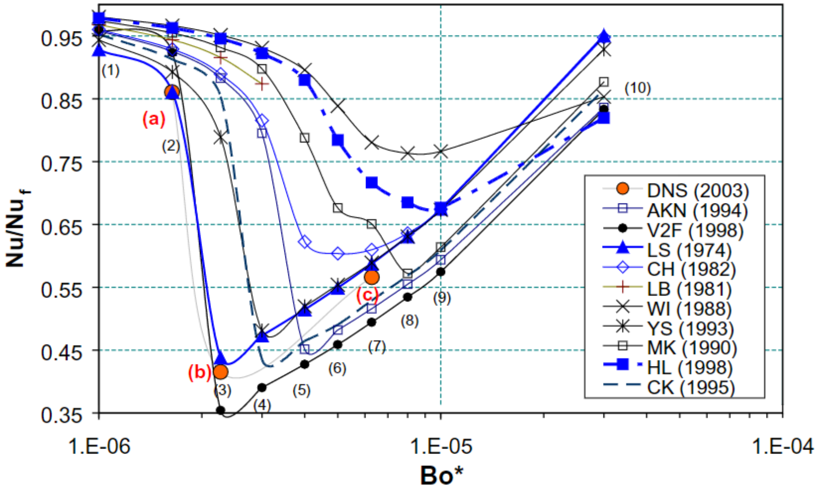

- ✓ Mean temperature gradient (← Reynolds averaging)
  ; Buoyancy production, $G_b = \beta \frac{\mu_t}{\mathrm{Pr}_t} (\nabla T \cdot \vec{g})$ is negligible in the vertical direction.
- ✓ In the developed region, axial mean $\nabla T \ll$ radial mean $\nabla T$

### ② Flow characteristics near the corner regions

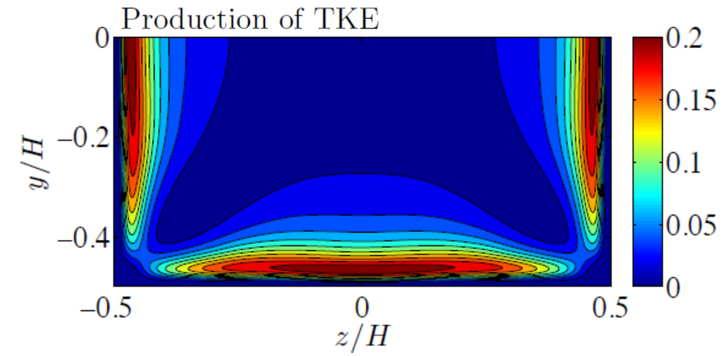



- ✓ Near wall distance
  → Influence of multiple walls is not considered.
- ✓ Reduced turbulence production near the corners from the experiment and DNS results

✓ More decrease of Reynolds shear stress; ① With heating ② Near corners




Influences of buoyancy on heat transfer in a tube from simulations using RANS turbulence models and DNS calculations [W. S. Kim et al., 2008]




Distribution of turbulence production
[DNS, Marin et al. from Zhang et al., 2016]

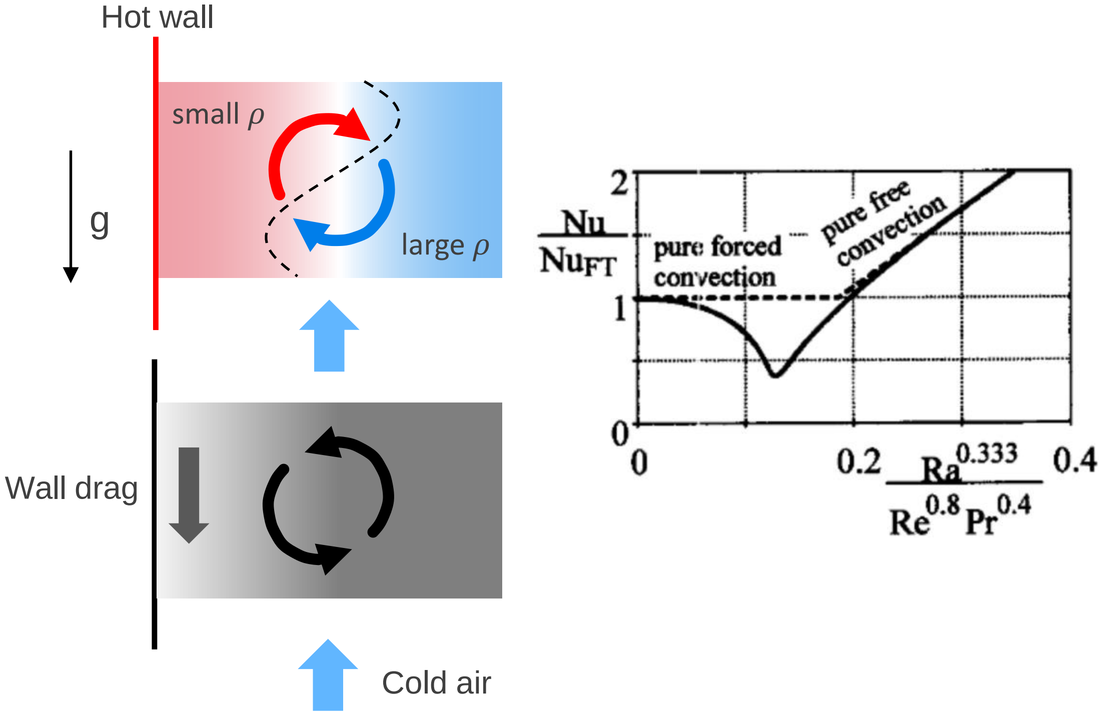
# Discussion 1. Density-gradient induced vortex

## Heating effect near the wall

– Temperature gradient along the wall-normal direction

✓ Large density gradient in the viscous sublayer → Another repetitive vortex motion independent of the wall-bounded vortex

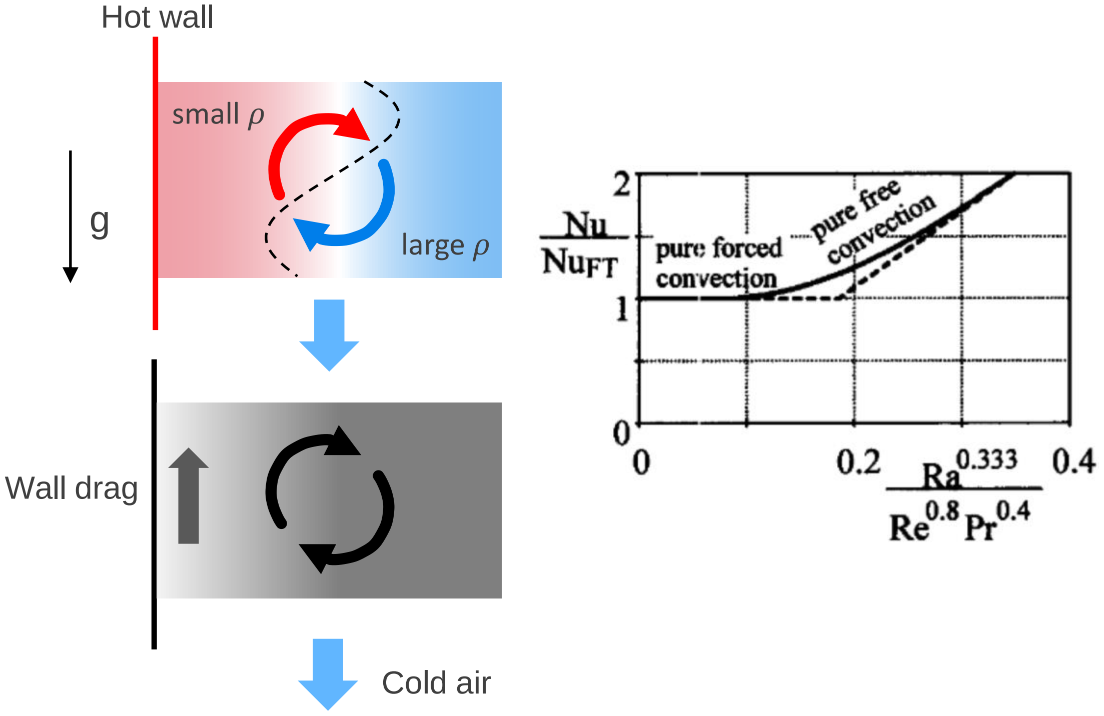
### Buoyancy-aided flow




Buoyancy ∥ Flow → Heat transfer deterioration with $R_{xy}$ ↓

∵ Wall-bounded vortex ↔ Density-gradient induced vortex

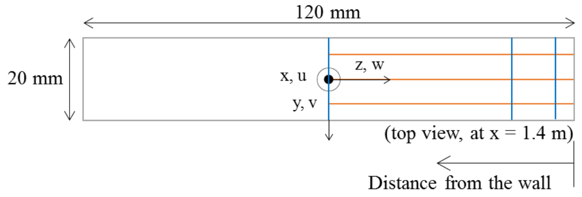
### Buoyancy-opposed flow




Buoyancy ↔ Flow → Heat transfer enhancement with $R_{xy}$ ↑

∵ Wall-bounded vortex ∥ Density-gradient induced vortex

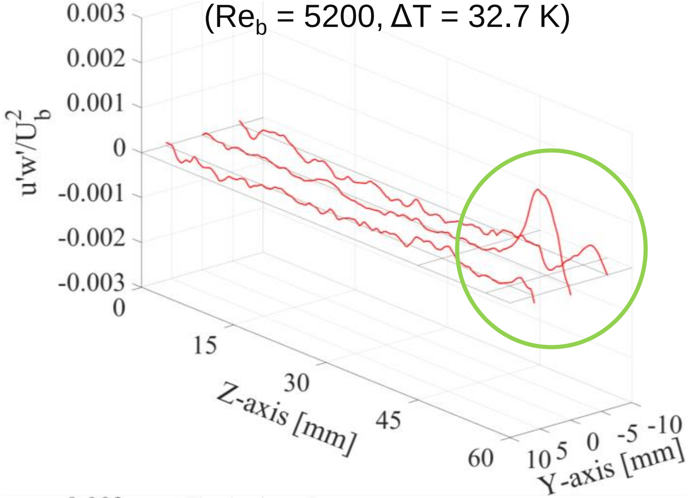
# Discussion 2. Flow characteristics along corner bisectors

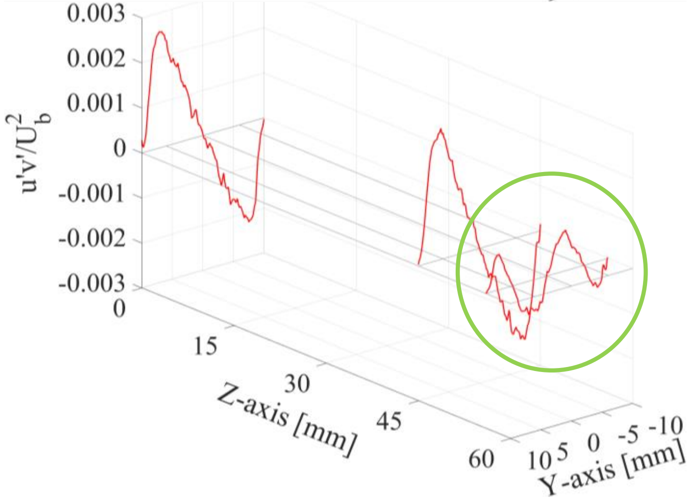



## Primary Reynolds shear stresses

– Complex and low distribution near the corners

Case-5 [Forced convection]
($Re_b$ = 5200, ΔT = 32.7 K)

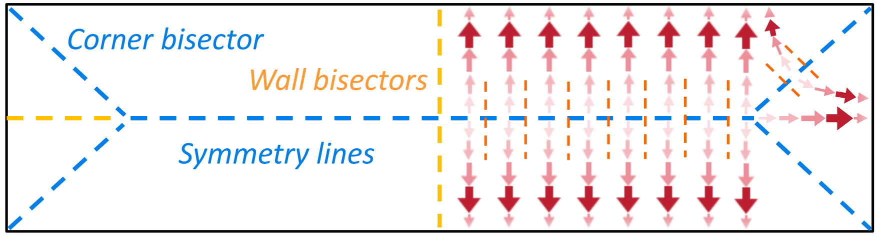



✓ Schematic diagrams for intuitive understanding of primary Reynolds shear stresses, $\overline{u'w'}$ and $\overline{u'v'}$

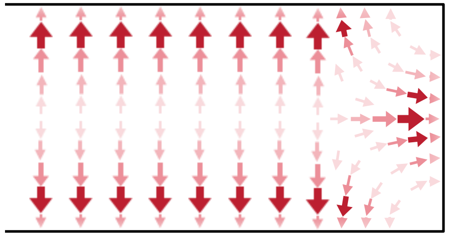
① The shear stress distribution is formed along the wall-normal direction.

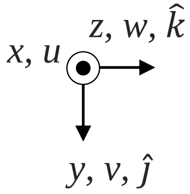
② On the line of symmetry (corner bisector), they cancel each other formed from opposite (orthogonal) walls.

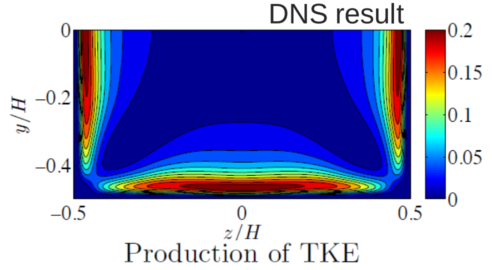



* top view

➢ It can be described with a newly defined vector; $\overline{u'v'}\hat{j} + \overline{u'w'}\hat{k}$

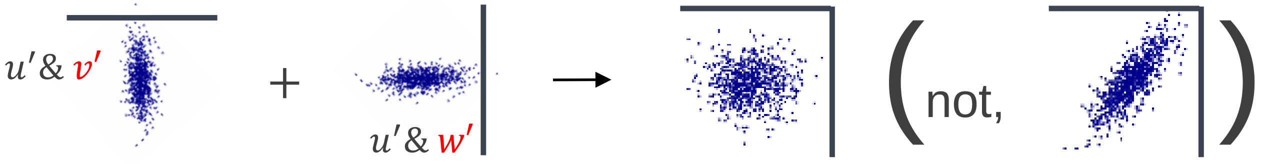





➢ Along the corner bisectors, the Reynolds shear stress is canceled in reality, rather than superposed.

✓ *Cancellation of the linear relationships from orthogonal walls*



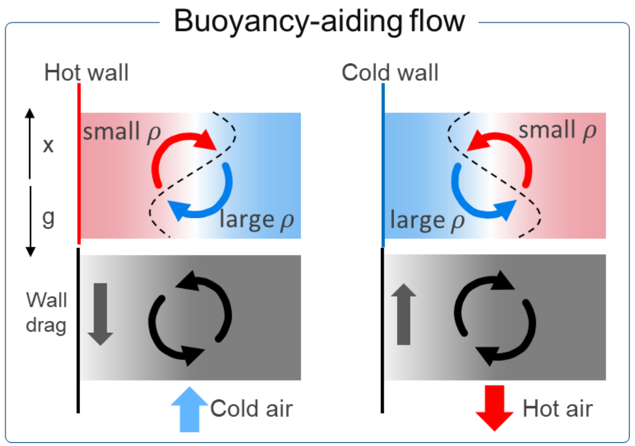
# Improvement of RANS turbulence model

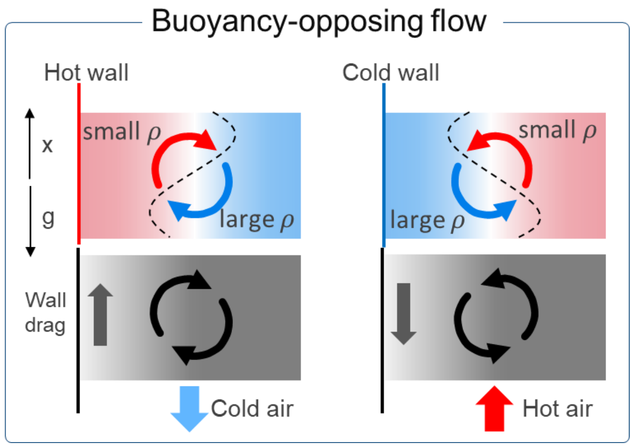
## Modification 1

**; Turbulence production by the density-gradient induced vortex**

- Magnitude; From the buoyancy production term, $G_b$
- Sign;
  - ① Gravity-perpendicular velocity gradient direction; $\frac{\nabla u_x}{|\nabla u_x|} = \frac{-\nabla(\vec{U}\cdot\hat{g})}{|\nabla(\vec{U}\cdot\hat{g})|}$
  - ② Density gradient direction

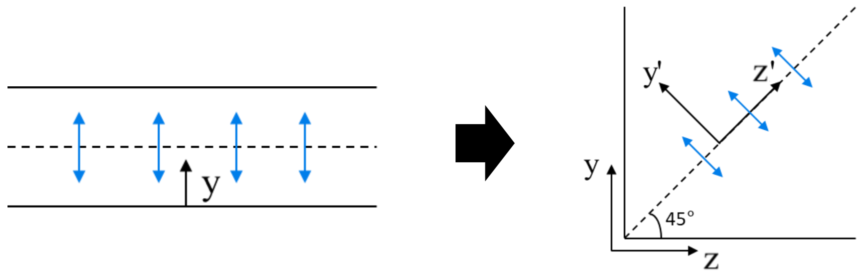
$$G_b = -\frac{\mu_t}{\mathrm{Pr}_t}(\nabla\bar{\rho}\cdot\vec{g})/\bar{\rho} \Rightarrow G_{gperp} = -\frac{\frac{\mu_t}{\mathrm{Pr}_t}|\vec{g}|\left(\nabla\bar{\rho}\cdot\frac{-\nabla(U\cdot\hat{g})}{|\nabla(U\cdot\hat{g})|}\right)}{\bar{\rho}}$$




## Modification 2

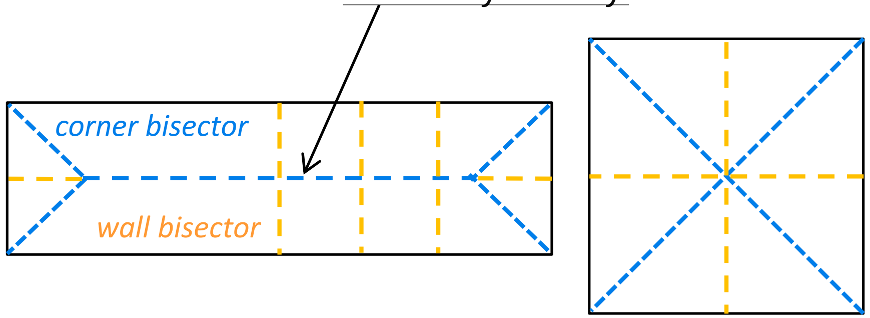
; **Derivation of additional term for the flow characteristics along the corner bisector**




$$\rightarrow L^2\left(\nabla^2 f - 2C_{corner}\left|\frac{\partial^2}{\partial y\partial z}f\right|\right) - f = -\frac{\Pi_{ij}}{k} - \frac{\left[\overline{u_i u_j}/k - \frac{2}{3}\right]}{T}$$

for elliptic relaxation equation of V2F *k-ε* model

Flow characteristics near corner region in a rectangular duct
✓Corner bisectors ≈ line of symmetry ≉ wall bisectors



# Improvement of RANS turbulence model

## **PhitF $k\!-\!\varepsilon$ model in OpenFOAM v.2012** (Laurence et al., 2004)

– Baseline model and modified model

*Transport equations of baseline model*

$k$;
$$\frac{\partial}{\partial t}(\rho k) + \nabla\cdot(\rho\vec{u}k) - \nabla^2\left(\rho\left(\nu + \frac{\nu_t}{\sigma_k}\right)k\right) = \rho G_k - \frac{2}{3}\rho(\nabla\cdot\vec{u})k - \frac{\rho}{T}k$$

$\varepsilon$;
$$\frac{\partial}{\partial t}(\rho\varepsilon) + \nabla\cdot(\rho\vec{u}\varepsilon) - \nabla^2\left(\rho\left(\nu + \frac{\nu_t}{\sigma_\varepsilon}\right)\varepsilon\right) = C_{\varepsilon 1}\rho\frac{G_k}{T} - \frac{2}{3}C_{\varepsilon 1}\rho(\nabla\cdot\vec{u})\varepsilon - C_{\varepsilon 2}\frac{\rho}{T}\varepsilon$$

$f$;
$$-\nabla^2 f = -\frac{f}{L^2} - \left((C_{f1}-1)\frac{\varphi - \frac{2}{3}}{T} - \frac{C_{f2}G_k}{k} + C_{f2}\frac{2}{3}\nabla\cdot\vec{u} - \frac{2\nu(\nabla\varphi\cdot\nabla k)}{k} - \nu\nabla^2\varphi\right)\frac{1}{L^2}$$

$\varphi$;
$$\frac{\partial}{\partial t}(\rho\varphi) + \nabla\cdot(\rho\vec{u}\varphi) - \nabla^2\left(\rho\left(\nu + \frac{\nu_t}{\sigma_\varphi}\right)\varphi\right) = \rho f - \rho\varphi\left(\frac{G_k}{k} - \frac{2}{3}\nabla\cdot\vec{u} - \frac{2\nu(\nabla\varphi\cdot\nabla k)}{k\sigma_\varphi\varphi}\right)$$

$$T = \max\left(\frac{k}{\varepsilon}, C_T\frac{\sqrt{\max(\nu,0)}}{\varepsilon}\right)$$

$$L = C_L\max\left(\frac{k^{1.5}}{\varepsilon}, C_\eta\left(\frac{(\max(\nu,0))^3}{\varepsilon}\right)^{0.25}\right)$$

*Transport equations of modified model*

$$\frac{\partial}{\partial t}(\rho k) + \nabla\cdot(\rho\vec{u}k) - \nabla^2\left(\rho\left(\nu + \frac{\nu_t}{\sigma_k}\right)k\right) = \rho\left(G_k + G_b + G_{gperp}\right) - \frac{2}{3}\rho(\nabla\cdot\vec{u})k - \frac{\rho}{T}k$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \nabla\cdot(\rho\vec{u}\varepsilon) - \nabla^2\left(\rho\left(\nu + \frac{\nu_t}{\sigma_\varepsilon}\right)\varepsilon\right) = C_{\varepsilon 1}\rho\frac{\left(G_k + C_{\varepsilon 3}\left(G_b + G_{gperp}\right)\right)}{T} - \frac{2}{3}C_{\varepsilon 1}\rho(\nabla\cdot\vec{u})\varepsilon - C_{\varepsilon 2}\frac{\rho}{T}\varepsilon$$

$$-\nabla^2 f = -2C_{corner}\left|\frac{\partial^2 f}{\partial y\partial z}\right| - \frac{f}{L^2} - \left((C_{f1}-1)\frac{\varphi - \frac{2}{3}}{T} - \frac{C_{f2}\left(G_k + G_b + G_{gperp}\right)}{k} + C_{f2}\frac{2}{3}\nabla\cdot\vec{u} - \frac{2\nu(\nabla\varphi\cdot\nabla k)}{k} - \nu\nabla^2\varphi\right)\frac{1}{L^2}$$

$$\frac{\partial}{\partial t}(\rho\varphi) + \nabla\cdot(\rho\vec{u}\varphi) - \nabla^2\left(\rho\left(\nu + \frac{\nu_t}{\sigma_\varphi}\right)\varphi\right) = \rho f - \rho\varphi\left(\frac{\left(G_k + G_b + G_{gperp}\right)}{k} - \frac{2}{3}\nabla\cdot\vec{u} - \frac{2\nu(\nabla\varphi\cdot\nabla k)}{k\sigma_\varphi\varphi}\right)$$

$$T = \max\left(\frac{k}{\varepsilon}, C_T\frac{\sqrt{\max(\nu,0)}}{\varepsilon}\right)$$

$$L = C_L\max\left(\frac{k^{1.5}}{\varepsilon}, C_\eta\left(\frac{(\max(\nu,0))^3}{\varepsilon}\right)^{0.25}\right)$$

# Calculation conditions

## OpenFOAM v.2012 (2020.12.)

– PhitF $k\text{−}\varepsilon$ turbulence model and with modifications

## Calculation geometry

– Quarters of the geometry with symmetry planes (average y+ < 0.5)

– Solid part (for the stability of calculation near the corners)

## Boundary conditions

– Temperature gradient on the outer wall

– Inlet average velocity with corresponding turbulence quantities

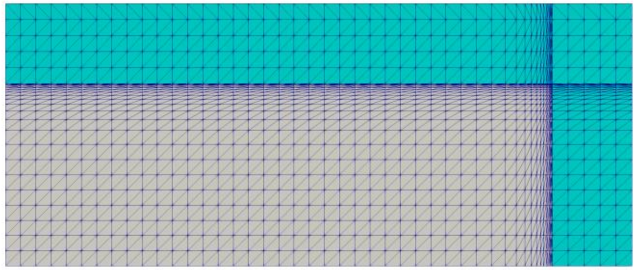
- Used meshes for the calculation geometry (Depth x Width x Length)

| | Mesh of fluid part | Mesh of total geometry |
|---|---|---|
| Cylinder | 120x40x500 (Whole) | 140x40x500 (Whole) |
| Aspect ratio = 6 | 20x60x1000 (Quarter) | 25x65x1000 (Quarter) |
| Aspect ratio = 3 | 21x45x1000 (Quarter) | 26x50x1000 (Quarter) |
| Aspect ratio = 1 | 30x30x1000 (Quarter) | 35x35x1000 (Quarter) |

- Example of the generated mesh (Aspect ratio = 3)

Solid part

Fluid part



- Physical models (Steady condition)

| | Fluid part | Solid parts |
|---|---|---|
| Solver | chtMultiRegionSimpleFoam (conjugate heat transfer) | |
| Thermo. type | heRhoThermo | heSolidThermo |
| Transport | $k, \mu$; polynomial | $k$; constIso |
| Thermo | $c_p$; hPolynomial | $c_p$; hConst |
| Equation of State | PengRobinsonGas | rhoConst |
| Energy | sensibleEnthalpy | sensibleEnthalpy |
| $Pr_t$ | 0.85 | - |

- Boundary conditions of properties of fluid

| | Wall | Inlet | Outlet |
|---|---|---|---|
| U | fixedValue; 0 | fixedValue | zeroGradient |
| $k$ | fixedValue; 0 | $\frac{3}{2}(IU_{in})^2$ | zeroGradient |
| $\varepsilon$ | epsilonWallFunction | $\frac{C_\mu^{3/4}k^{3/2}}{L}$ | zeroGradient |
| $f$ | fixedValue; 0 | zeroGradient | zeroGradient |
| phit | fixedValue; 0 | fixedValue; 0.66 | zeroGradient |
| nut | nutUWallFunction | calculated | zeroGradient |
| p_rgh | fixedFluxPressure | zeroGradient | FixedMean |

$I = 0.16\mathrm{Re}^{-1/8}, L = 0.07D_h$

# Validation for modified turbulence model (1/2)

**Comparison between the baseline and modified model** (including density-gradient induced vortex)

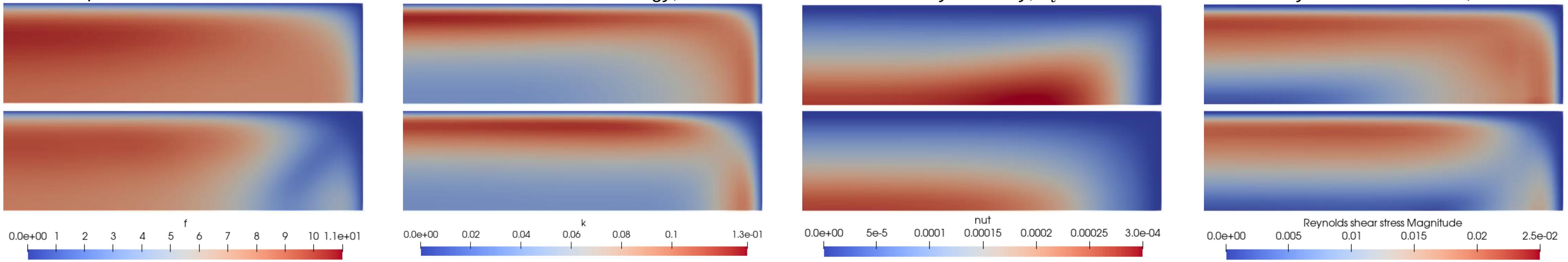
- PhitF *k*-*ε* model in OpenFOAM v.2012
- $C_{corner} \rightarrow 1.6$

➢ Without heating (Case-2 from FROVE experiment)

*elliptic relaxation function, f* | *turbulent kinetic energy, k* | *eddy viscosity,* $\nu_t$ | *Reynolds shear stress, R*

Baseline

Modified

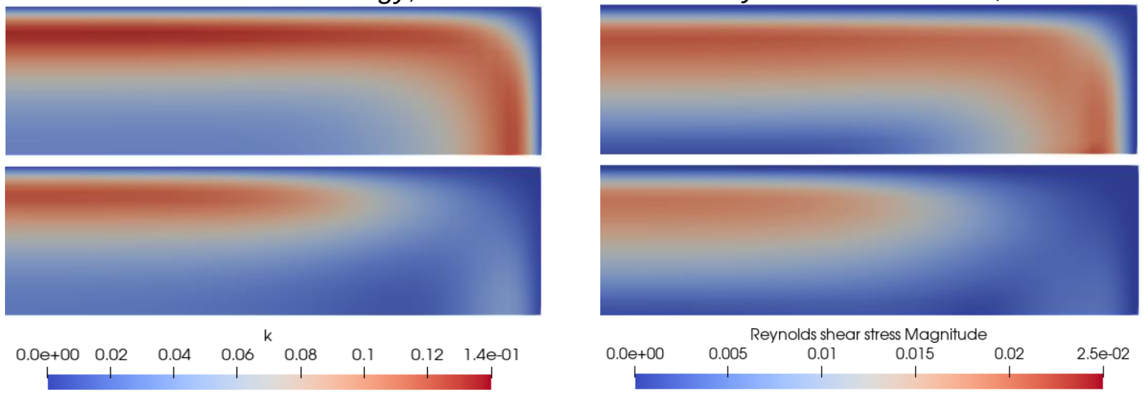


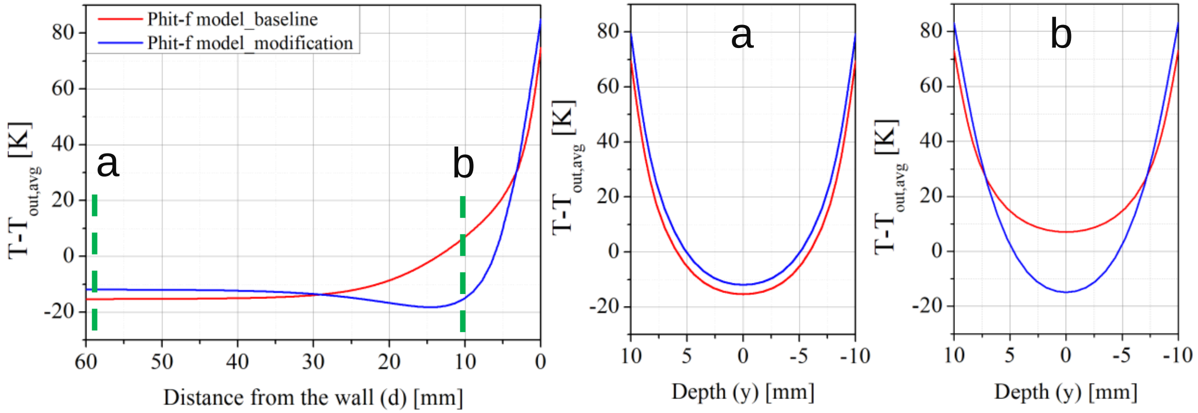

➢ In mixed convection (Case-9 from FROVE experiment); flow laminarization preceding near the corner

*turbulent kinetic energy, k* | *Reynolds shear stress, R*

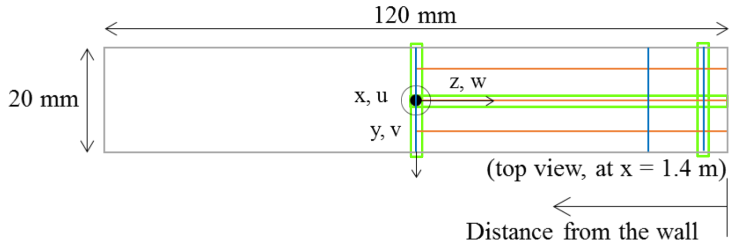
Baseline

Modified



# Validation for modified turbulence model (2/2)



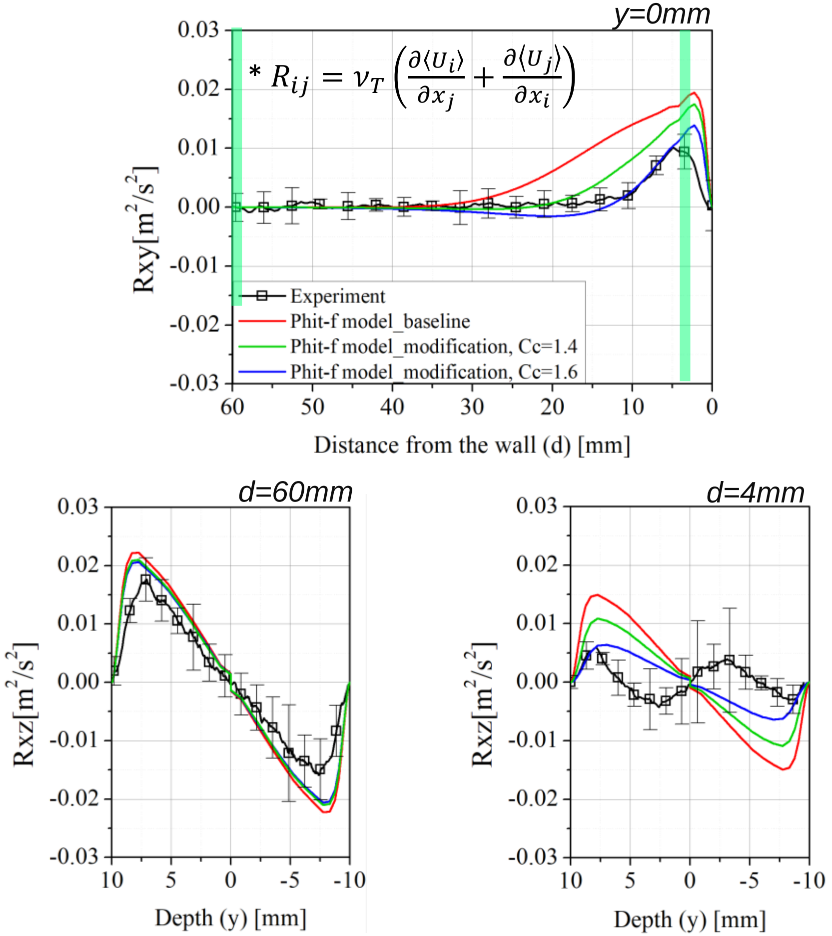

## Comparison with the experimental data

– Modified PhitF *k-ε* model predicts the experimental data closely.

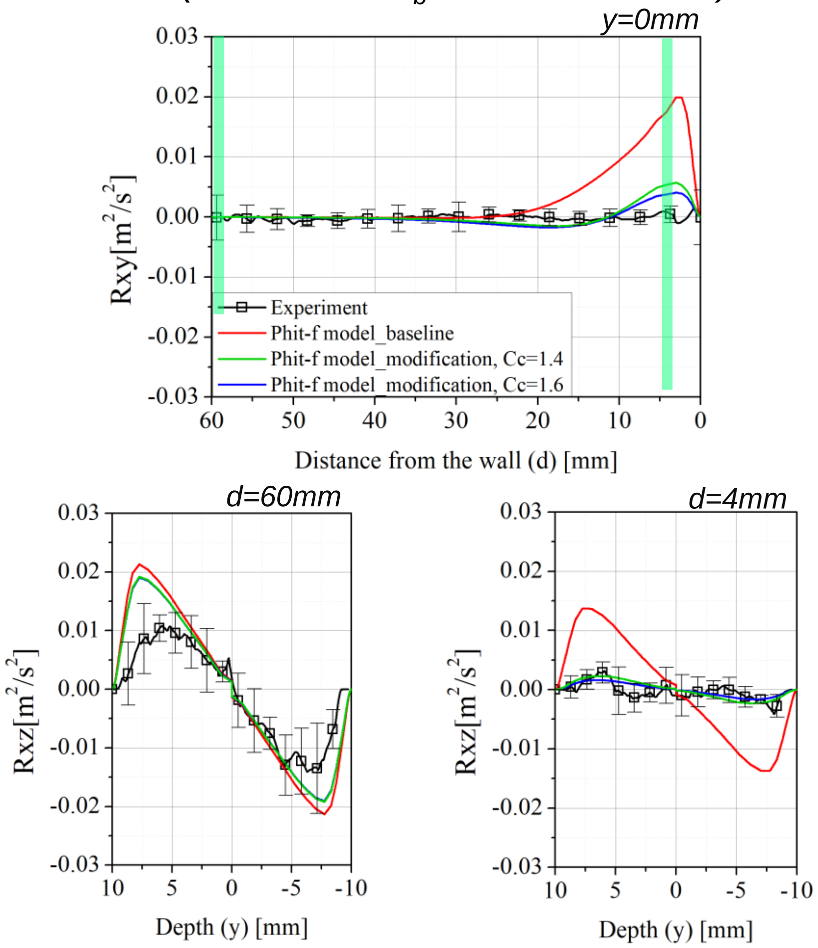
✓ $C_{corner} = 1.4 \text{ and } 1.6$

Modified PhitF *k-ε* model; $L^2\left(\nabla^2 f - 2C_{corner}\left|\frac{\partial^2}{\partial x \partial y} f\right|\right) - f = -\frac{\Pi_{ij}}{k} - \frac{\left[\overline{u_i u_j}/k - \frac{2}{3}\right]}{T}$

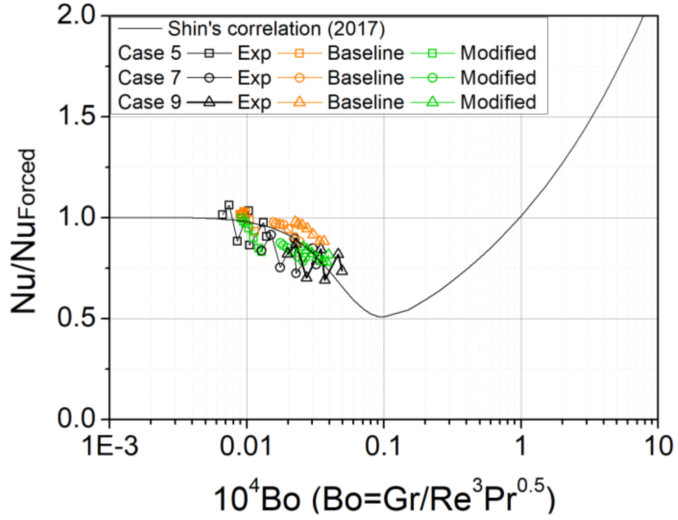
➢ *Case-2 (Re=5500, ΔT=0K)*




➢ *Case-9 (Re=5000, $Re_b$=4400, ΔT=81.5K)*



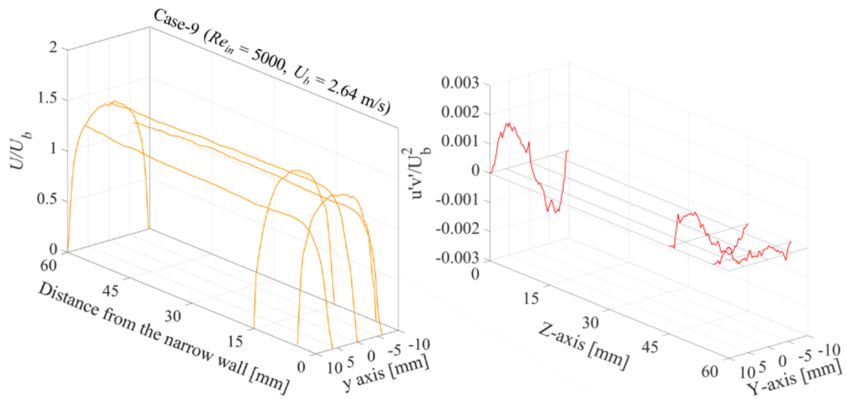

Heat transfer coefficient results



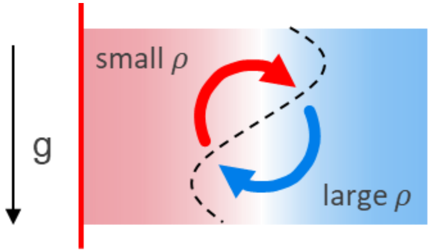
# Conclusions

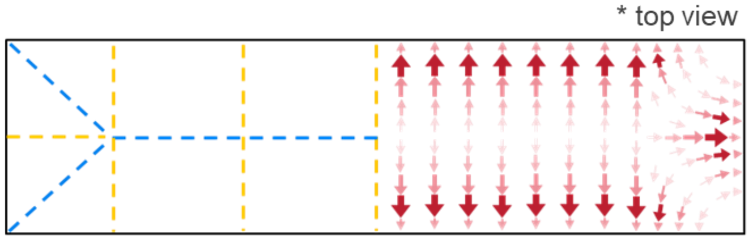
## Experimental researches

- ✓ **Experimental data in forced and mixed convection**
  - Local flow structure & turbulence quantities
- ✓ **Turbulence model assessment**




- ✓ **Gravity-perpendicular density-gradient induced vortex**
  - Explanation for the heat transfer mechanism in the mixed convection
- ✓ **Flow characteristics along corner bisectors**
  - Cancellation of Reynolds shear stress along corner bisectors
  - Laminarization preceding near the corner region




Schematic diagram of primary Reynolds shear stress distribution

## Improvement of turbulence model

- ✓ **Modification of RANS turbulence model**
  - Production term from the gravity-perpendicular density-gradient
  - Elliptic relaxation equation for the flow behavior near the corner
- ✓ **Improvement of the prediction with RANS turbulence model**
  - Local flow characteristics and heat transfer coefficients

*Reynolds shear stress*