

Numerical Analysis of Turbulent Flow in a Square Duct with 45 Degree Ribs

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Introduction

Ribs are sometimes located periodically on duct walls to provide active heat transfer. It is the one of effective method to enhance heat transfer.

We develop a design code of heat exchangers with ribs for HTGR heat application systems.

Step

- 1 Experimental by using PIV and analytical results in 3D by Bonhoff et al.
- 2 Algebraic Reynolds stress model, the fixed turbulent Prandtl number and algebraic turbulent heat flux models reducing calculated load for engineering application are examined



Manifestation

- To **clarify** turbulent flow structure, and correlation between momentum and heat transfer
- To validity availability of the analytical model

Targeted Object and Definition of Coordinate System

- One **side** length of the square duct

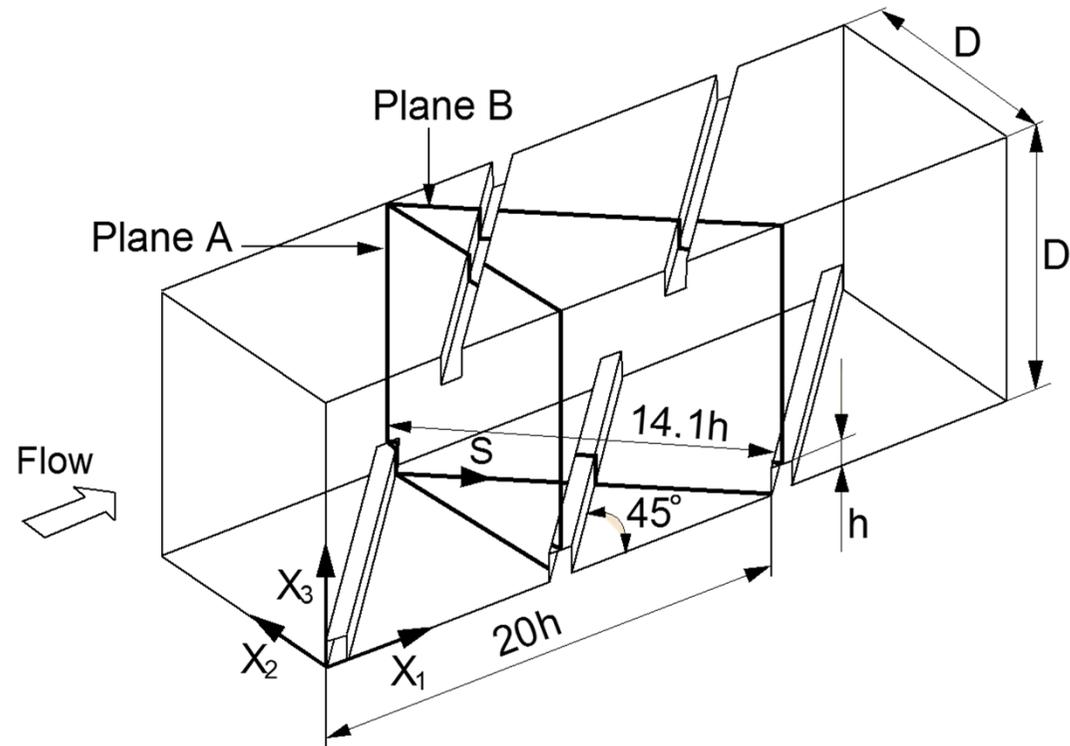
$D=100\text{mm}$

- One **height** of the rib

$h=10\text{mm}$

- **Reynolds number**

$Re=5.0 \times 10^4$



Model Equations

- Algebraic Reynolds Stress Model

Transport equation of Reynolds stress

$$\frac{D\overline{u_i u_j}}{Dt} - Diff_k = \frac{\overline{u_i u_j}}{k} (P_k - \varepsilon) = P_{ij} + [\pi_{ij} + \pi_{ji}]_1 + [\pi_{ij} + \pi_{ji}]_2 - \frac{2}{3} \delta_{ij} \varepsilon$$

- Algebraic Turbulent Heat Flux Model

Transport equation of turbulent heat flux

$$\frac{D\overline{u_i T'}}{Dt} = - \left(\overline{u_i u_k} \frac{\partial T}{\partial x_k} + \overline{u_k T'} \frac{\partial U_i}{\partial x_k} \right) - \frac{\partial}{\partial x_k} \left\{ \overline{u_i u_k T'} + \frac{P}{\rho} T' \delta_{ik} - \nu \frac{\partial u_i}{\partial x_k} T' - a u_i \frac{\partial T'}{\partial x_k} \right\} + \frac{P}{\rho} \frac{\partial T'}{\partial x_i} - (\nu + a) \frac{\partial T'}{\partial x_k} \frac{\partial u_i}{\partial x_k}$$

- The fixed turbulent Prandtl number Model

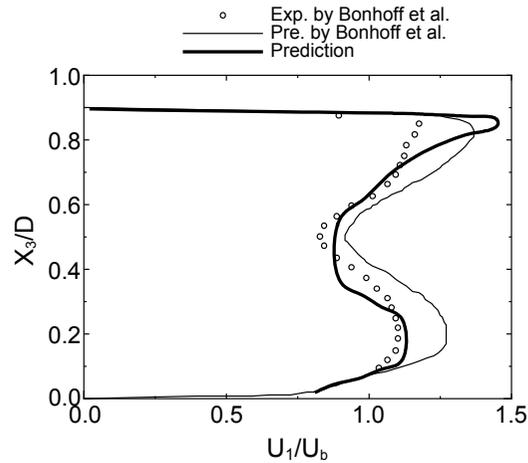
Diffusion model of gradient form

$$-\overline{u_i T'} = \alpha_t \frac{\partial T}{\partial x_i}$$

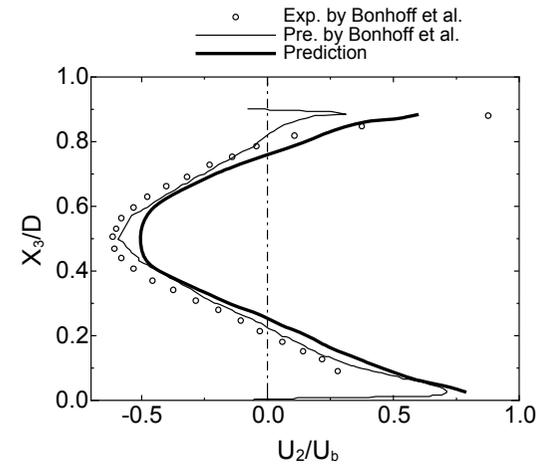
Numerical Analysis

Grid Points	$41 \times 31 \times 102 = 129,642$
Reynolds number	$Re = 5.0 \times 10^4$ (the same as experimental condition)
Numerical calculation	Difference method
Difference approximation of governing equation	QUICK (for convection term)
Boundary condition	Periodic boundary condition → the velocity and the wall temperature is set to be constant.
Turbulent model	High-Reynolds-number turbulent model The wall function method for k-ε
Grid point location	Regular Grid
Coordinate transformation method	Boundary-fitted coordinate system

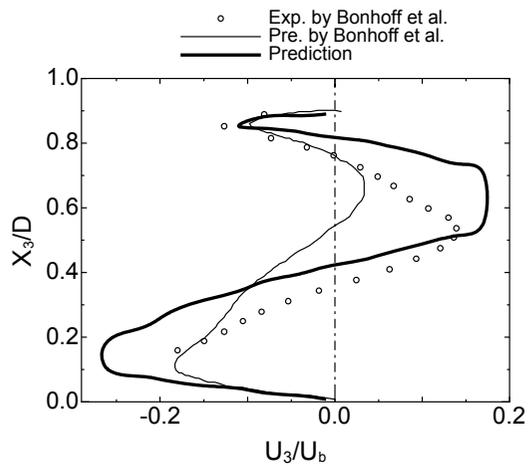
Velocity Profiles



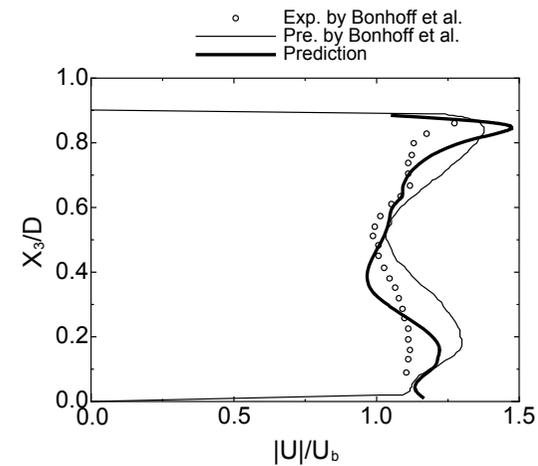
Streamwise velocity



Spanwise velocity

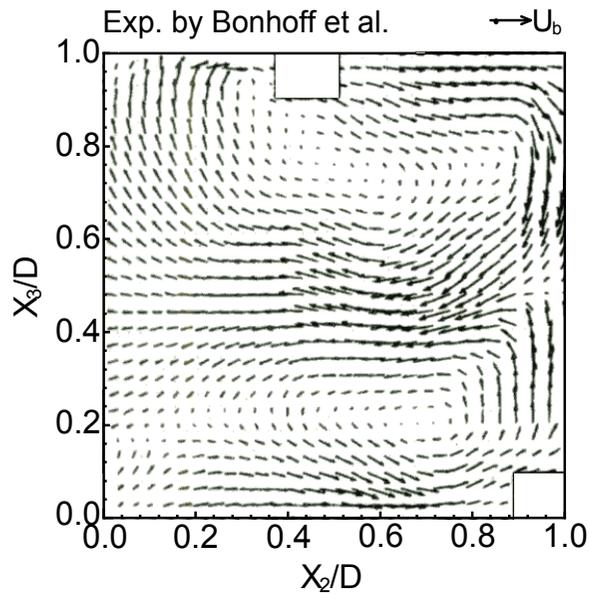


Vertical velocity

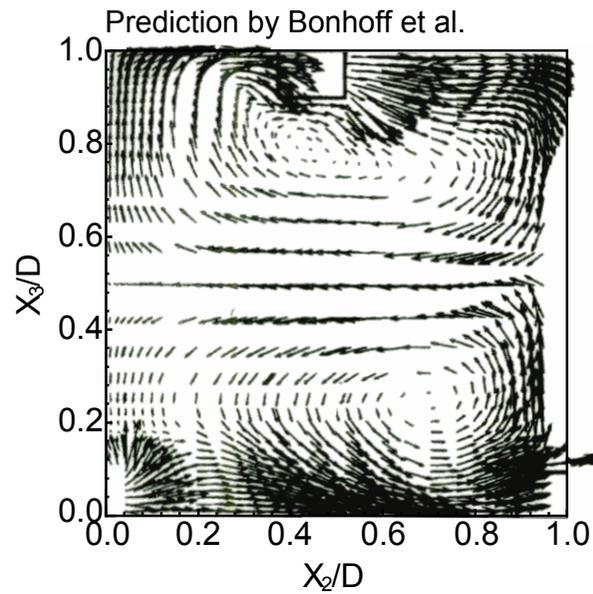


Velocity Magnitude

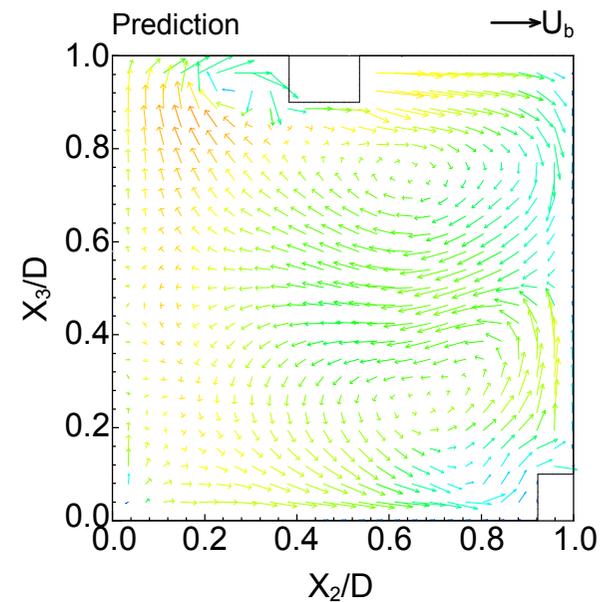
Secondary Flow Vectors



Experiment

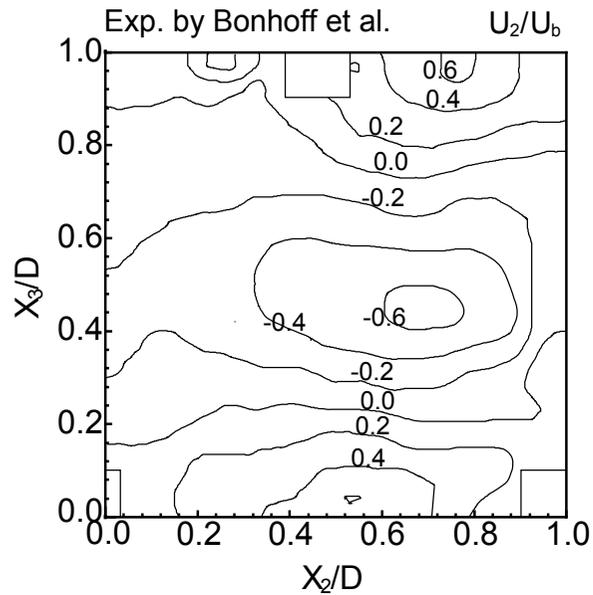


Prediction by Reynolds stress model

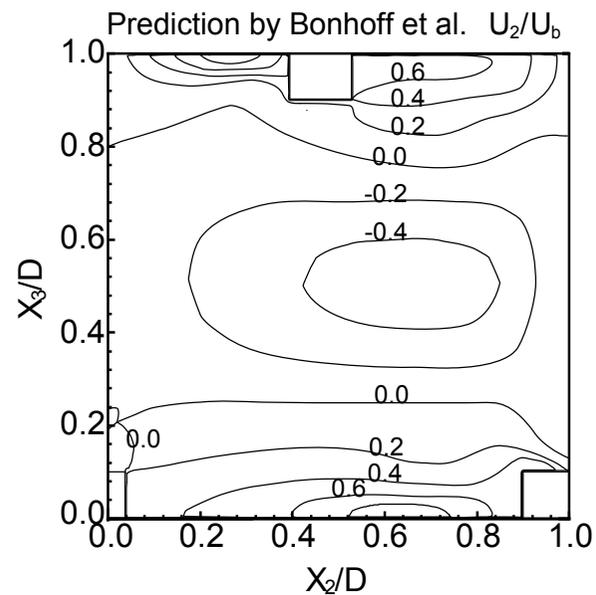


Prediction by algebraic Reynolds stress model

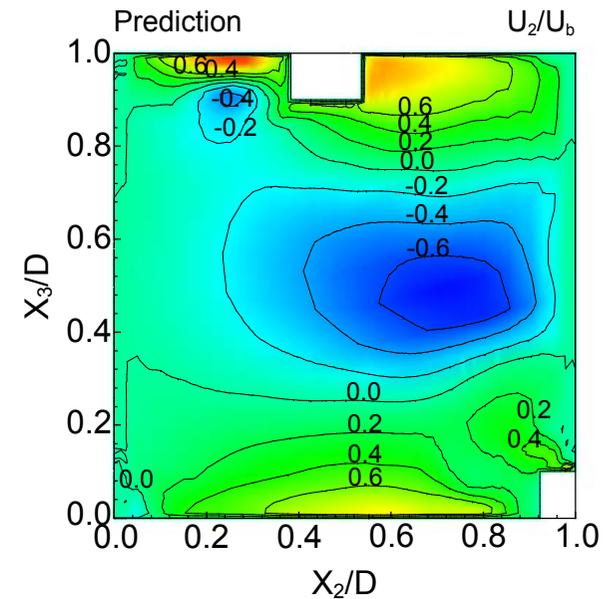
Spanwise Velocity Distribution



Experiment



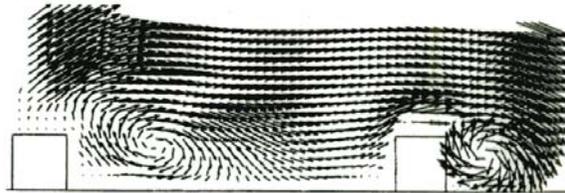
Prediction by Reynolds stress model



Prediction by algebraic Reynolds stress model

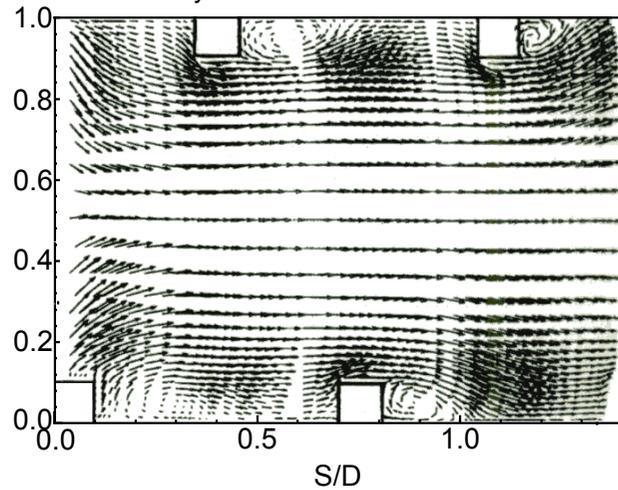
Vectors in Plane B

Exp. by Bonhoff et al.



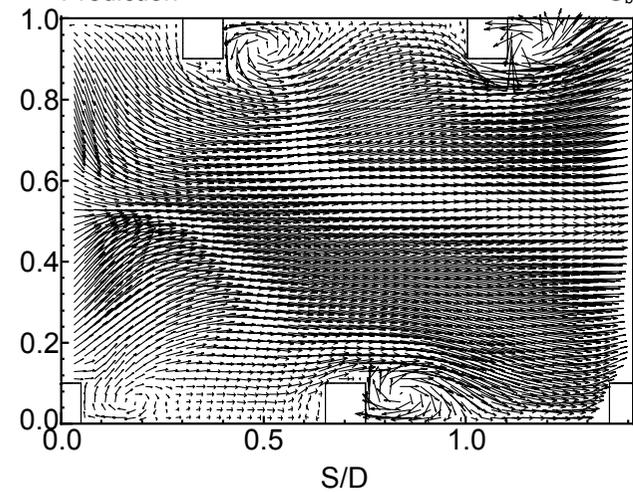
Experiment

Prediction by Bonhoff et al.



Prediction by Reynolds stress model

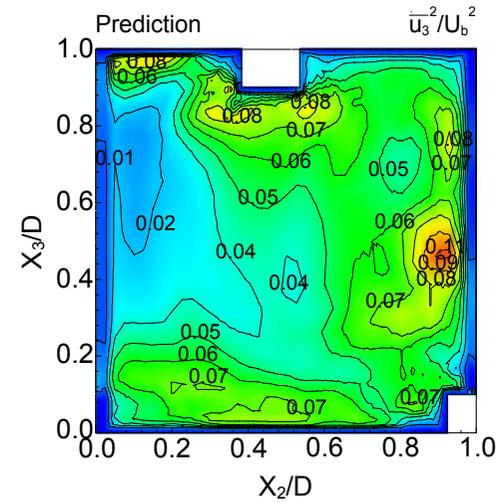
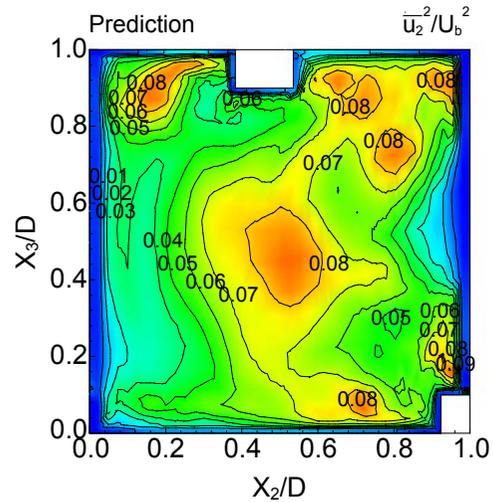
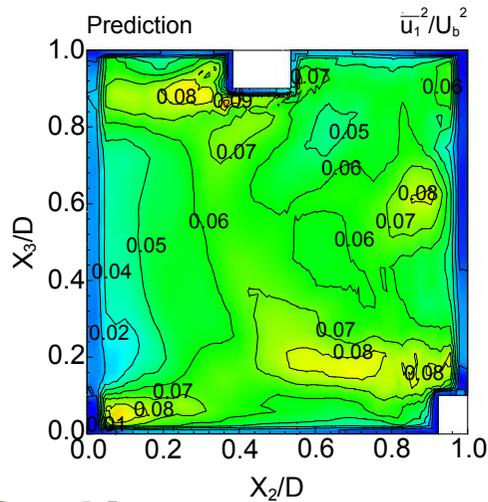
Prediction



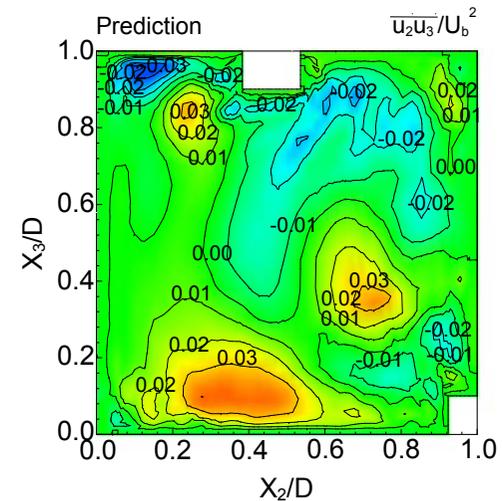
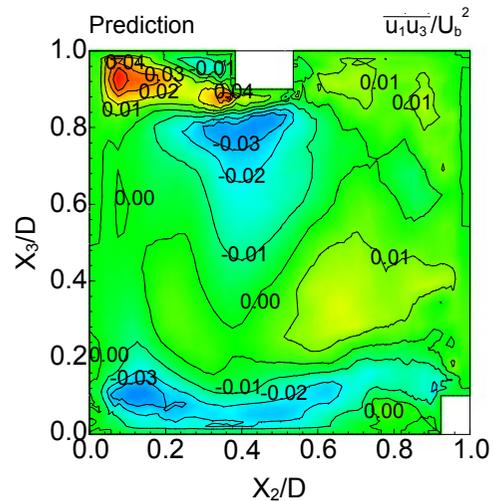
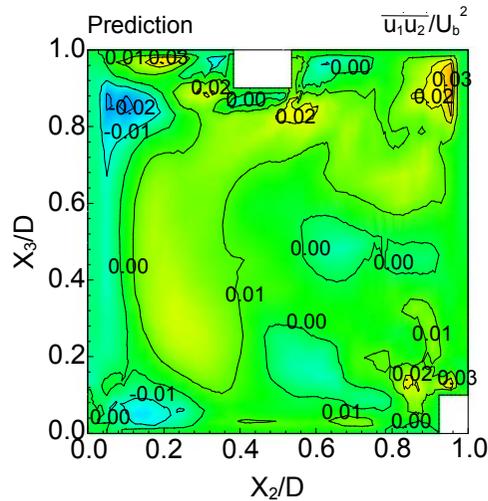
Prediction by Algebraic Reynolds stress model

Reynolds Stress Distribution

● Normal stresses

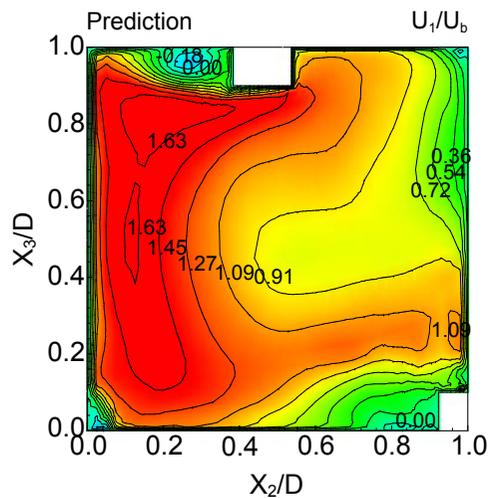


● Shear stresses



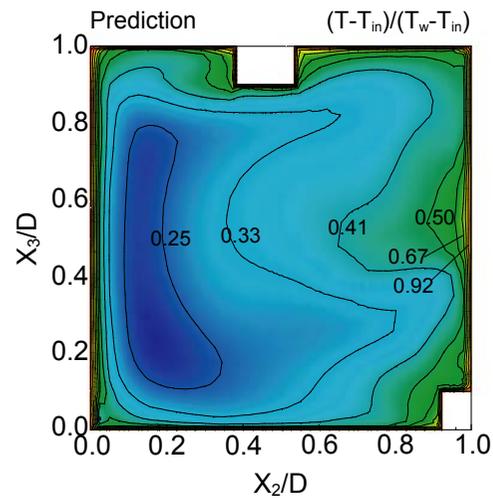
Temperature Profiles

Streamwise velocity profiles

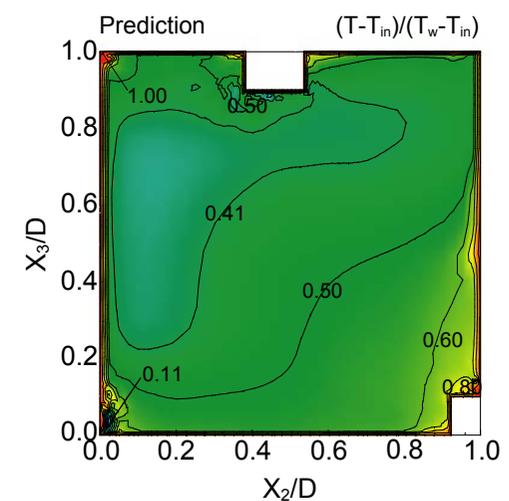


Algebraic Reynolds stress model

Temperature profiles



The fixed turbulent Prandtl number model

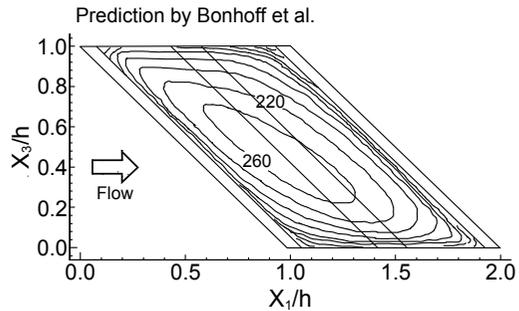


Algebraic turbulent heat flux model

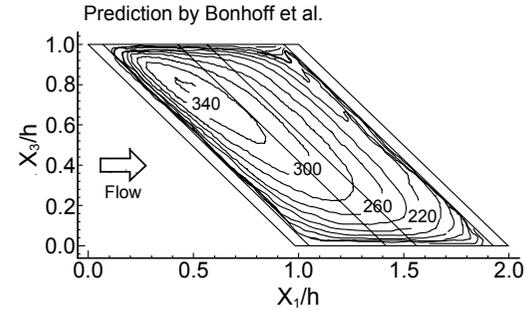
Compared results of the velocity profiles suggest...

- The fixed turbulent Prandtl number model
 - **confirm correlation** between momentum and heat transfer
- Algebraic turbulent heat flux model
 - **not confirm**

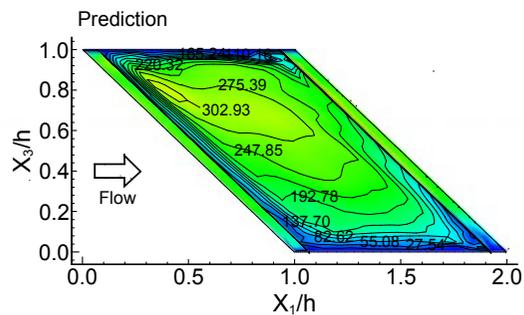
Predicted Distribution of Nusselt Number



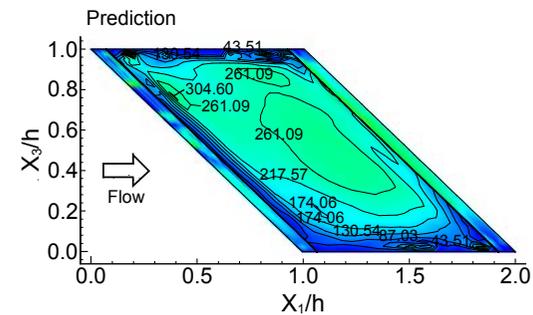
Reynolds stress model



k- ϵ model



The fixed turbulent Prandtl number model ($Pr=0.8$)



Algebraic turbulent heat flux model

Conclusions

A numerical analysis has been performed for turbulent flow with heat transfer in a square duct with 45 degree ribs by using the algebraic Reynolds stress, the fixed turbulent Prandtl number, and the algebraic turbulent heat flux models.

- ◆ **The presented method was able to predict three directional velocities except for vertical velocity, which tendency was the same as that obtained with the Reynolds stress model. Although the agreement with the experimental results were not perfect, characteristic features are realized by the algebraic Reynolds stress model.**
- ◆ **The algebraic Reynolds stress relatively well reproduces the streamwise flow, the vector pattern and the reattachment point in Plane B as well as those obtained with the Reynolds stress model. The algebraic Reynolds stress model can predict anisotropic turbulent flow in duct with 45 degree ribs to present six Reynolds stresses.**
- ◆ **The temperature contour map obtained by the algebraic turbulent heat flux model was not similar to velocity contour map. Since the algebraic turbulent heat flux model has potentiality to reproduce anisotropic temperature, correlation between momentum and heat transfer was not organized in this kind of turbulent field.**
- ◆ **The fixed turbulent Prandtl number and algebraic turbulent heat flux models predicted similar values of Nusselt number.**