FOSSEE, IIT Bombay
OpenFOAM Research Migration Project
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Study of laminar flow and heat transfer in a square channel with 30º inline angled baffle turbulators using OpenFOAM.

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Synopsis

This research migration project aims to do a Study of laminar flow and heat transfer in a square channel with 30 deg inline angled baffle turbulators using OpenFOAM. The geometry and mesh were defined using the `blockMesh` utility. The computations based on the finite volume method with the SIMPLE algorithm (`buoyantSimpleFoam`) have been conducted for the fluid flow in terms of Reynolds numbers ranging from 100 to 2000. The analysis executed by Pongjet Promvonge [1] using a commercial CFD simulator is taken as a reference.

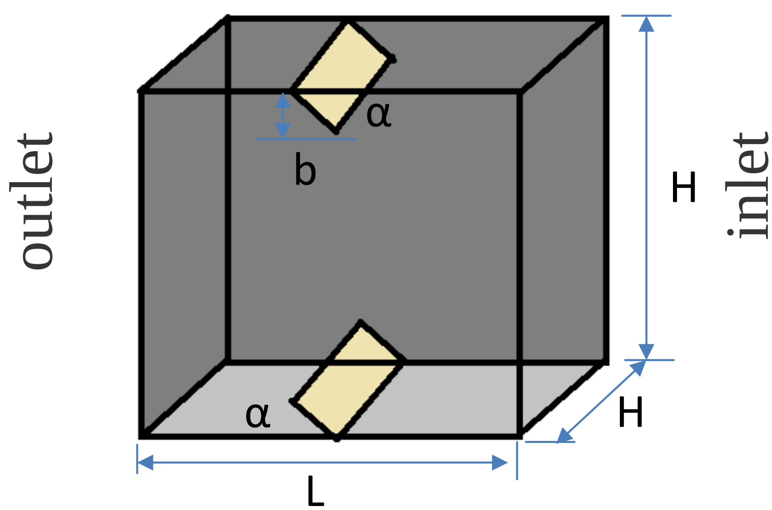

Figure 1*: Geometry and Dimensions*

The dimensions of the geometry stated in the figure 1 are: H=0.05 m, L=0.05 m, BR = 0.1 &0.2 for PR =1. Flowing fluid is entering from the inlet with a velocity of 0.316 m/s and exiting from the outlet. Fluid properties and boundary conditions are discussed in the report.

Reference

[1] Pongjet Promvonge*, Withada Jedsadaratanachai, Sutapat Kwankaomeng. “Numerical study of laminar flow and heat transfer in a square channel with 30° inline angled baffle turbulators”. In: *Applied Thermal Engineering 30 (2010) 1292e1303*. ISSN: 0098- 2202. DOI: https://doi.org/10.1016/j.applthermaleng.2010.02.014

1. Introduction

In the paper, the numerical computations are carried out for 3D laminar channel flows over a 30° angled baffle pair mounted in an inline arrangement on top and bottom channel walls. The main objective is to evaluate the changes in the flow and heat transfer behaviors. The use of the inline 30° angled baffles placed over the opposite walls of the tested channel is expected to generate a pair of P shape counter-vortex flows through the channel for the better mixing of flows between the core and the wall leading to a higher heat transfer rate in the channel.

2. Governing Equations and Models

The following assumption for fluid flow and heat transfer in the square channel are as follows:

- Steady 3D fluid flow and heat transfer.
- Flow is laminar and incompressible.
- Considering constant fluid properties.
- Viscous dissipation and body forces are neglected.
- Negligible radiated heat transfer.

As per the assumptions, the governing equation for channel flow is continuity, Navier-Stokes equations, and energy equation. The equations can be written as follows:

<u>Continuity equation:</u>

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0$$

<u>Momentum equation:</u>

$$\frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right]$$

<u>Energy equation:</u>

$$\frac{\partial(\rho u_i T)}{\partial x_i} = \frac{\partial}{\partial x_j}\left(\Gamma\frac{\partial T}{\partial x_j}\right)$$

where Γ is the thermal diffusivity and is given by

$$\Gamma = \frac{\mu}{\Pr}$$

Apart from the energy equation, the governing equations were discretized by the power-law differencing scheme, decoupling with the SIMPLE algorithm, and solved using a finite volume approach.

k-ε Model

$$\frac{D}{Dt}(\rho k) = \nabla.(\rho D_k \nabla k) + P - \rho\varepsilon$$

$$\frac{D}{Dt}(\rho\varepsilon) = \nabla.(\rho D_\varepsilon \nabla\varepsilon) + \frac{C_1\epsilon}{k}\left(P + C_3\frac{2}{3}k\nabla.U\right) - C_2\rho\frac{\varepsilon^2}{k}$$

$$\nu_t = C_\mu\frac{k^2}{\varepsilon}$$

Here k is the turbulent kinetic energy, ε is the specific dissipation rate, P is the production term, Dk and Dε are the effective diffusivities for respective equations and νt is the turbulent viscosity. The default value of the coefficients C1, C2, C3, and Cμ are used here.

3. Simulation Procedure

3.1. Geometry and Mesh

In the present study, the main interest is in a horizontal square channel with inline angled baffle pairs placed on the upper and lower channel walls as shown in Fig. 1. The flow is considered in such a way that it attains a periodic flow condition in which the velocity field repeats itself from outlet to inlet in a cyclic pattern. The air enters the channel at an inlet temperature Tin, and flows over a 30^{o} angled baffle pair where b is the baffle height, H set to 0.05 m, is the channel height and b/H is known as the blockage ratio, BR. L is an axial pitch which is the distance between the baffle cells set to L= H, in which L/H is defined as the pitch ratio, PR. To investigate an arrangement effect of the interaction between baffles, the baffle blockage ratio, BR is varied from 0.1 to 0.2 and the baffle pitch ratio, PR is taken at 1 in the present investigation.

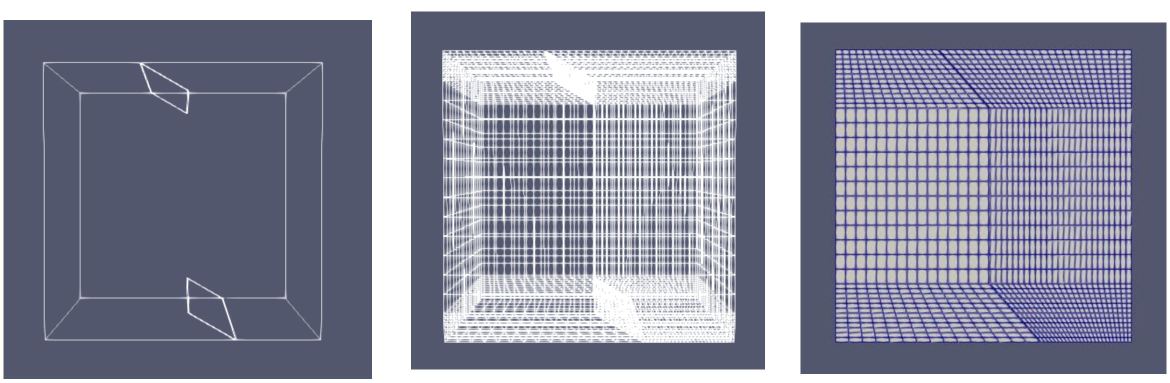

Figure 2: *Square channel with 30 deg inline angled baffle turbulators with b/H ratio 0.1 for PR 1*

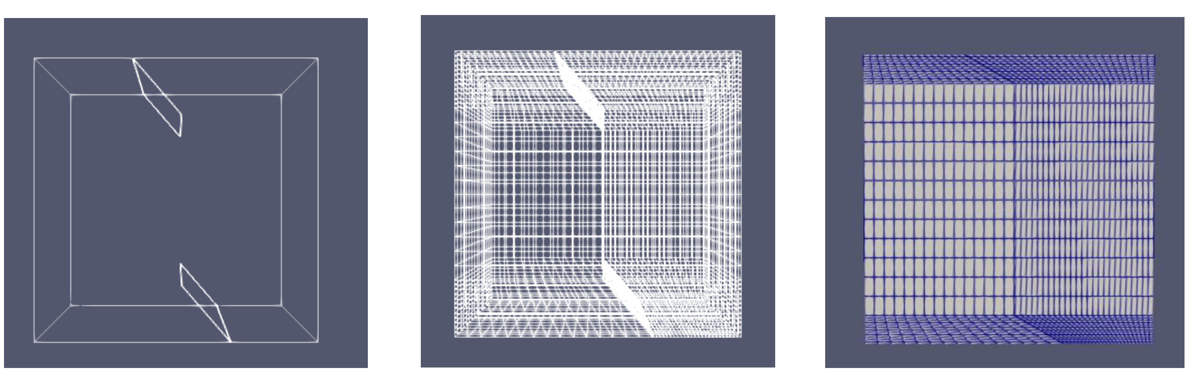

Figure 3: *Square channel with 30 deg inline angled baffle turbulators with b/H ratio =0.2 for PR 1*

Only hexahedral elements are used for structured meshing and the grid is refined near the baffle. It is a 3-dimensional mesh with around ~96000 cells. A mesh sensitivity analysis is carried out to obtain the most optimal results with a minimum number of cells in order to reduce computational time.

3.2. Initial and Boundary Conditions

Periodic boundaries are used for the inlet and outlet of the flow domain. The constant mass flow rate of air with 300 K (PR 0.707) is assumed in the flow direction rather than constant pressure drop due to periodic flow conditions. The inlet and outlet profiles for the velocities must be identical. The physical properties of the air have been assumed to remain constant at average bulk temperature. Cyclic boundary and no-slip wall conditions have been implemented over the channel walls as well as the baffle. The constant temperature of all the channel walls is maintained at 310 K while the baffle plate is assumed at adiabatic wall (high thermal resistance) conditions.

3.3. Solver

The solver used is “buoyantSimpleFoam”. This is a steady state solver for buoyant, turbulent flow of compressible fluids for ventilation and heat transfer. Here Boussinesq approximation is used by changing the equation of state to Boussinesq in the “thermoPhysicalProperties” file located in the “constant” folder to use this solver for the incompressible fluid.

All these algorithms are iterative solvers but PISO andPIMPLE are both used for transient cases whereas SIMPLE is used for steady-state cases. Here thermophysical properties (Thermo type) are shown below for this case to incorporate Boussinesq approximation in this buoyantSimpleFoam solver (for use this solver for a compressible fluid). This solver is used instead of simpleFoam in order to incorporate the gravity term.

3.4. Post-processing

The ParaView software can be used to visualize the simulation results in OpenFOAM. This can be run by typing the *ParaFoam* command line in the terminal to open the ParaView software and upload the case.

4. Results

In the following section, the contours of velocity in x and z directions are plotted in various planes and are compared with experimental data. From figure 4 and Figure 5, two different geometry having BR = 0.1 and 0.2 for the same PR = 1 is simulated using open foam. We can see the different velocity profiles for the same inlet velocity in the square channel. The vortex formation for BR = 0.2 is larger than BR = 0.1. Also, the velocity at the mid of the square channel for a higher BR ratio is reaching up to 0.0022 m/s whereas, for BR =0.1, the velocity is around 0.0016 m/s. So, we clearly observed an increase in BR realaffectect the flow inside the flow channel. The other objective of the study is to generate a pair of P shape counter-vortex flows inside the square channel as shown in Figure 6.

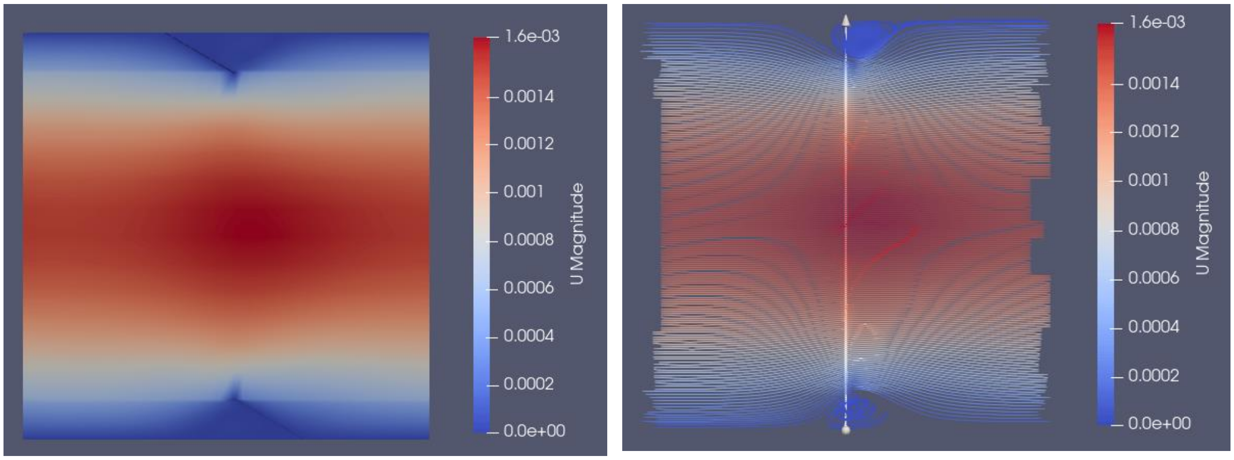

Figure 4: *Velocity contour and streamline Profile plotted for 30º baffle with b/H=0.1*

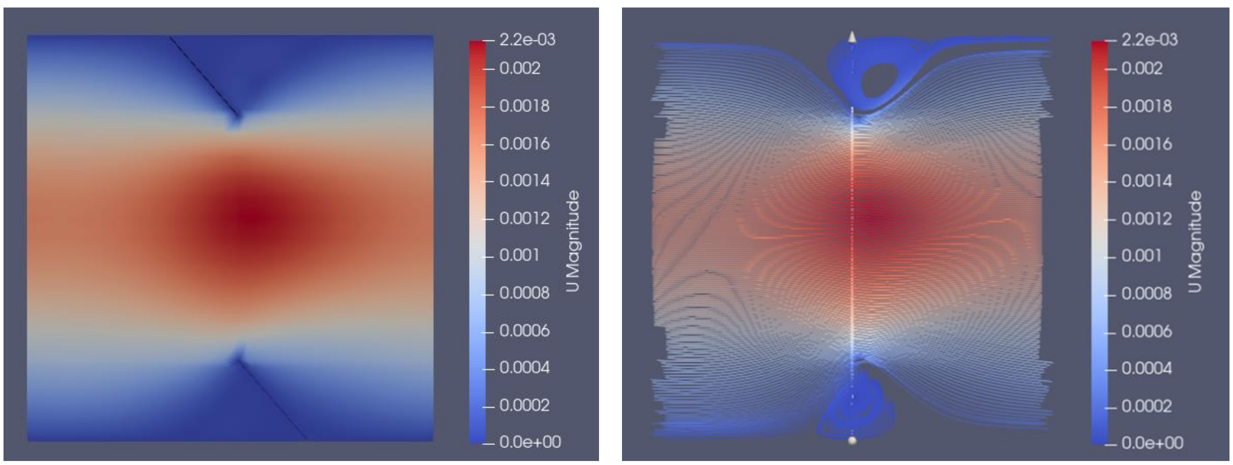

Figure 5: *Velocity contour and streamline Profile plotted for 30 deg baffle with b/H=0.2*

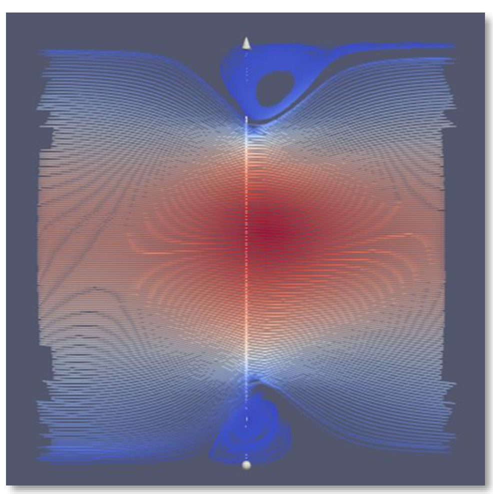

Figure 6: *P-Shape Counter-rotating vortex formation in Square channel with 30 deg inline angled baffle turbulators with b/H ratio =0.2 for PR 1*

In Figure 7 temperature profile is plotted. At the wall of the channel, the temperature is around 310 K whereas at the center of the domain the temperature is around 300 K. As we know mixing is more toward the wall hence temperature is more at the channel wall side rather than mid-portion. As the flow reaches the steady-state the fluid temperature will also reach wall temperature.

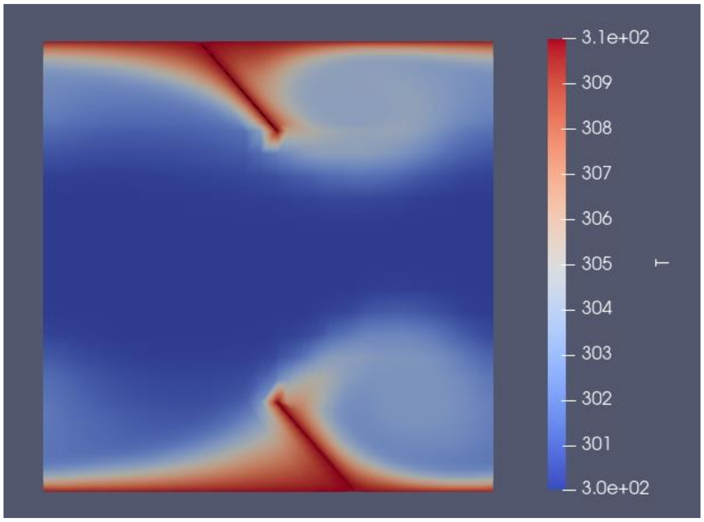

Figure 7: *Temperature Profile in a square channel with 30 deg inline angled baffle turbulators with b/H ratio =0.2 for PR 1*

5. Conclusions:

In this project, Numerical computations of laminar periodic flow and heat transfer characteristics through a domain with inline 30^o angled baffles placed over the opposite walls. The performance of the different models is compared with each other and experimental results using different parameters such as flow and heat transfer behavior are studied. The model was run for 1000 s with the time step of 0.001. From the results, we can see that due to changes in channel design (especially baffle height), there is a large vortex formation at the baffle side. The vortex formation also contributes to heat transfer behaviors inside the channel. Hence, we can conclude from the above results that for better heat transfer behavior large baffles are more favorable.

6. Other References

[1] P. Promvonge, C. Thianpong, Thermal performance assessment of turbulent channel flow over different shape ribs. International Communication in Heat and Mass Transfer 35 (10) (2008) 1327e1334.

[2] E.H. Ridouane, A. Campo, Heat transfer enhancement of air flowing across grooved channels: joint effects of channel height and groove depth. ASME Journal of Heat Transfer 130 (2) (2008) 021901.

[3] T. Chompookham, C. Thianpong, S. Kwankaomeng, P. Promvonge, Heat transfer augmentation in a wedge-ribbed channel using winglet vortex generators. International Communication in Heat and Mass Transfer 37 (2) (2010) 163e169.

[4] P. Promvonge, T. Chompookham, S. Kwankaomeng, C. Thianpong, Enhanced heat transfer in a triangular ribbed channel with longitudinal vortex generators. Energy Conversion & Management 56 (6) (2010) 1242e1249.
[5] S. Sripattanapipat, P. Promvonge, Numerical analysis of laminar heat transfer in a channel with diamond-shaped baffles. International Communication in Heat and Mass Transfer 36 (1) (2009) 32e38.