FOSSEE, IIT Bombay
OpenFOAM Case Study Project
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Forced Convection through Helical Pipe with Constant Wall Temperature

Varun Pathak
Department of Mechanical Engineering, IIT Bombay

Abstract

This report aims to study the flow and heat transfer characteristics of flow through a helical pipe. Helical pipes are used to enhance the heat transfer between the fluid and the wall as compared to a straight pipe. The flow is characterized by the Reynolds number and the Dean Number. BuoyantSimpleFoam solver is used to study the steady state velocity and temperature profiles. An increase in nusselt number is observed as the dean number increases and the vorticity responsible for the increased heat transfer is qualitatively shown.

1 Introduction

Helically coiled tubes are used in applications involving compact heat exchangers such as food processing, nuclear reactor cooling and heat recovery systems.The reason for this prevalence is the hightened heat transfer characteristics that helical pipes provide over stright tubes. This enhancement is because of the centrifugal forces due to vorticity in the fluid leading to the development of a secondary flow transverse to the primary flow which leads to better heat transfer.

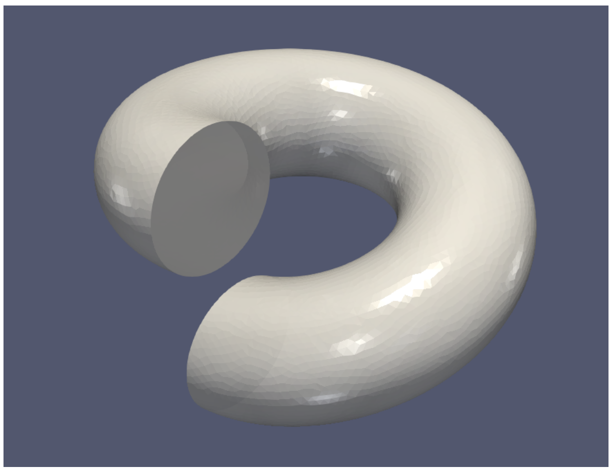


Figure 1: Helical Pipe

2 Problem Statement

The problem statement is to simulate the laminar flow of a fluid through a helical pipe with constant wall temperature and study the heat transfer characteristics of the flow in OpenFOAM-9. The flow is characterized by the Reynolds number and the Dean number. The Dean number is varied from 4000 to 10000 and the geometry should be such that the Reynolds number is lesser than the critical Reynolds number for helical pipes as given by Schmidt (1967).

$$Re_{Cr} = 2300[1 + 8.6(\frac{r}{Rc})^{0.45}]$$

Here r is the radius of the pipe and Rc is the pitch circle radius of the helix. The results obtained here are compared with results obtained by Jayakumar et. al. in [1].

3 Governing Equations and Models

Steady state compressible Navier Stokes equations are used to model the flow through the pipe and the energy equation governs the heat transfer.

$$\nabla \cdot \rho u = 0$$

$$\nabla \cdot (\rho u u) = \mu \nabla^2 u - \nabla p + \rho g$$

$$(u \cdot \nabla)T = \alpha \nabla^2 T$$

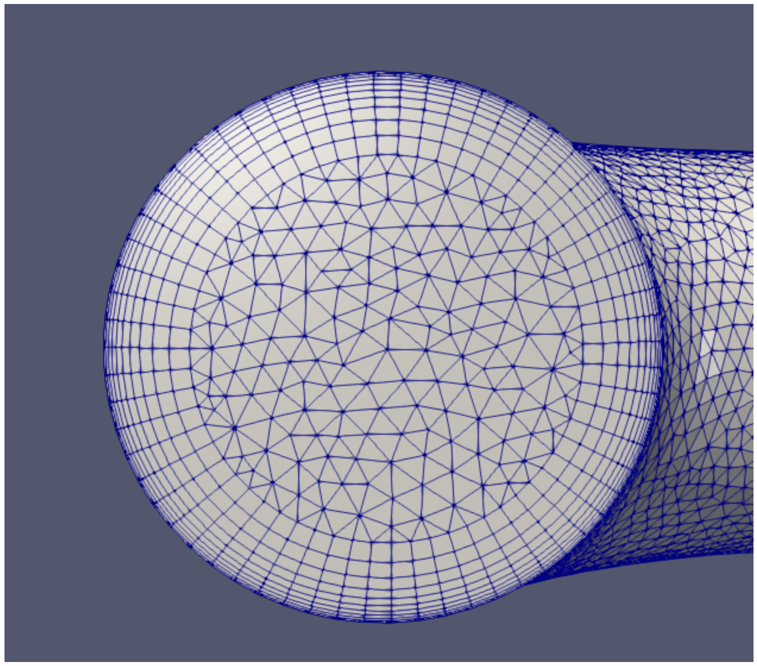
BuoyantSimpleFoam solver is used as it is a steady state, compressible solver capable of solving the energy equation. It can also model turbulence but this study only deals with laminar flow. Thermophysical and turbulence properties for the fluid are specified in the constant folder.

4 Simulation Procedure

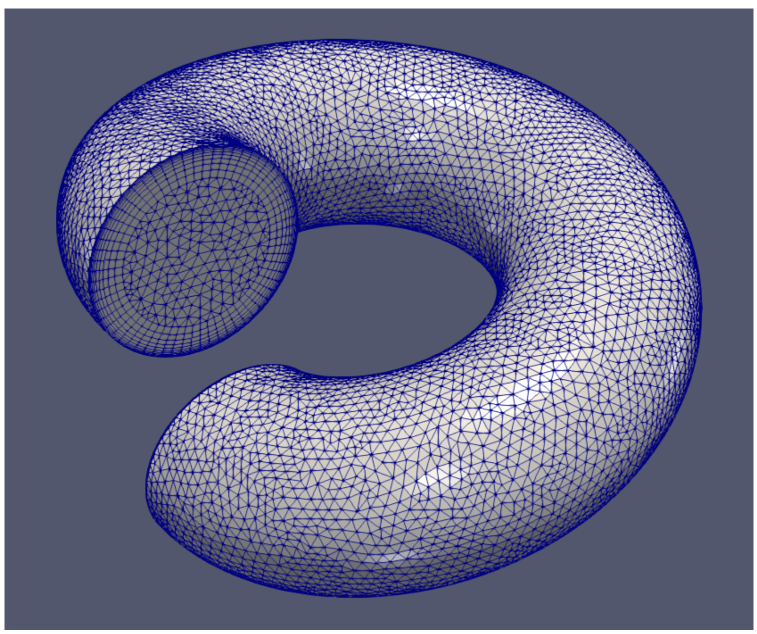
4.1 Geometry and Mesh

The domain is a helical pipe with a diameter of 10 mm. The pitch circle diameter of the helix is 20mm and the pitch is 12 mm. The geometry was generated in ANSYS Spaceclaim and the mesh was generated in ANSYS Meshing. The mesh consists of tetrahedral elements with a size of 0.5 mm and 10 inflation layers with a growth rate of 1.3 and a maximum thickness of 1.5 mm. The first layer height is calculated using the formula given below.

$$Total\ Thickness = First\ Layer\ Thickness \times \frac{g^{N+1} - 1}{g - 1}$$



Mesh with Body Sizing and Inflation layers



Full Domain Mesh

The mesh consists of 340,246 elements and 666,835 nodes. The maximum aspect ratio in the mesh is 11.72 and the maximum skewness is 0.81.

4.2 Initial and Boundary Conditions

Boundary	Temperature Initial Condition	Velocity Initial Condition	P_rgh Initial Condition
Inlet	fixedValue = 300	Fixed Value	fixedFluxPressure
Wall	fixedValue = 350	noSlip	fixedFluxPressure
Outlet	zeroGradient	zeroGradient	prghPressure = 0

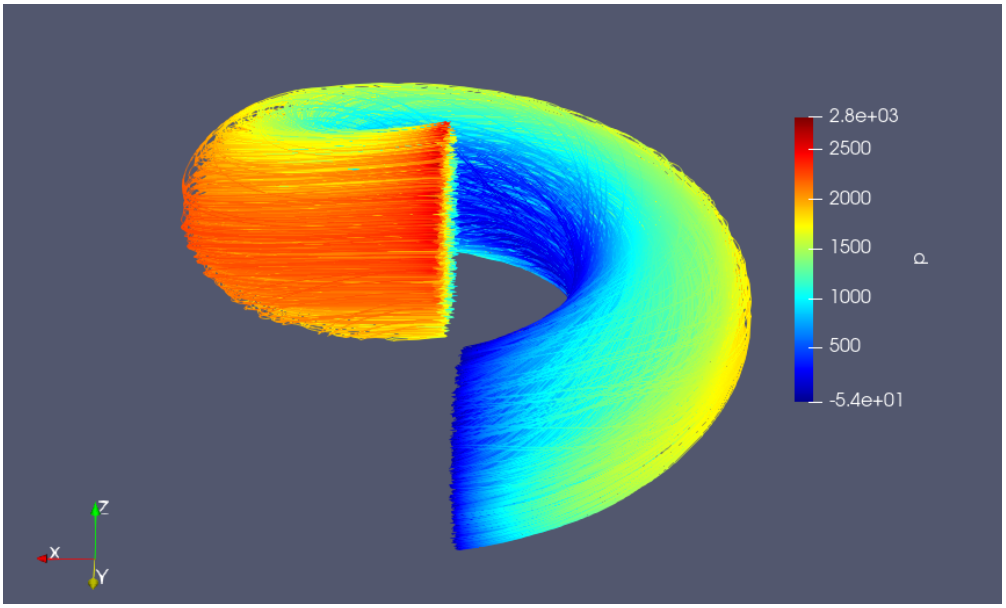
The velocity at the inlet is modified based on the Dean number and the Reynolds number for each case. Four values of Dean number are simulated(4000,6000,8000,10000) which correspond to Reynolds number varying from 5656.9 to 14142.1.

4.3 Solver

BouyantSimpleFoam is used as a solver in this case study. It is a steady state compressible, turbulent flow based solver. The solver uses SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm to evaluate NS equations. The solver follows a segregated solution strategy. It sequentially solves the NS equations followed by the Poisson equation for pressure and the Energy equation for temperature. The simulation is run for 1000 time steps with a time step of 1 second. A wallHeatFlux function is used to calculate the heat flux at the wall to calculate the heat transfer coefficient.

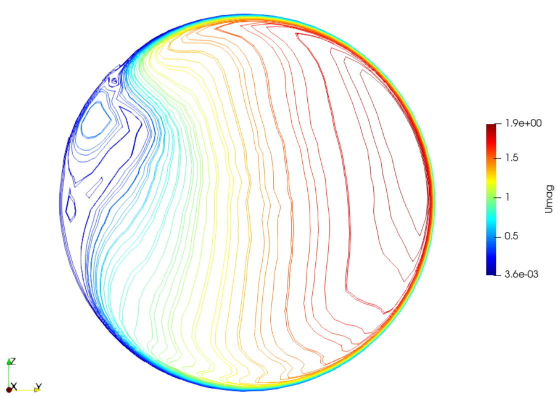
```
wallHeatFlux1
{
    // Mandatory entries (unmodifiable)
    type            wallHeatFlux;
    libs            (fieldFunctionObjects);

    // Optional entries (runtime modifiable)
    patches     (wall);
    qr          qr;

    // Optional (inherited) entries
    writePrecision  8;
    writeToFile     true;
    useUserTime     true;
    region          region0;
    enabled         true;
    log             true;
    timeStart       0;
    timeEnd         1000;
    executeControl  timeStep;
    executeInterval 1;
    writeControl    timeStep;
    writeInterval   1;
}
```

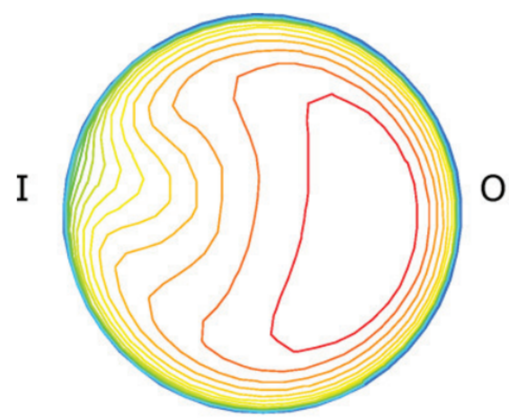
5 Results and Discussions



The streamlines below show the flow through the helix and the color represents the pressure along the streamlines. We can observe that the pressure is greater towards the outer part of the helix and lesser towards the centre. This pressure difference is what leads to mixing and better heat transfer due to mixing.

The velocity at the exit will be such that the the further a particle is from the centre of the helix, the higher its velocity will be. This can be seen from the contour plots of the exit plane. A comparison is done between the plots obtained in [1].

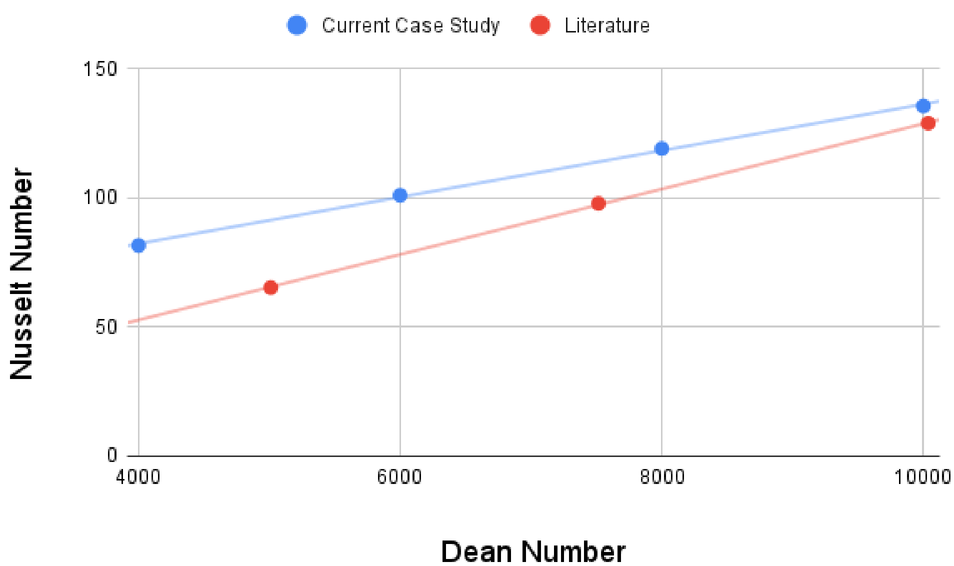




The values for Dean Number and Reynolds Number used for simulations listed below along with the inlet velocity. The average heat flux calculated for the wall is used to calculate the heat transfer coefficient. The heat transfer coefficient is calculated using the difference between the wall temperature and the bulk temperature.

Dean Number	Reynolds Number	Inlet Velocity	Average Flux through Wall	Heat Transfer Coefficient	Nu
		(m/s)	W/m2	W/mK	
4000	5656.9	0.498	261,222.0	5224.4	81.63
6000	8485.3	0.747	323,429.0	6468.6	101.07
8000	11313.7	0.996	381,211.3	7624.2	119.13
10000	14142.1	1.245	434,102.6	8682.1	135.66

A comparison is done between the values of Nusselt number obtained in the case study and the results presented in [1]. This nusselt number is significantly higher than the one achieved in a straight pipe for constant wall temperature (Nu = 3.66). An average error of 20 % is seen for the nusselt number. This error may arise due to the simulation not running for sufficient time steps.



Hence, we can see that there is a clear advantage in having helical pipe in heat exchanger systems and also that a higher dean number would lead to a higher nusselt number.

References

[1] Js, J., Mahajani, S., Mandal, J., Krishnan, V., and Bhoi, R. (2008). Experimental cfd estimation of heat transfer in helically coiled heat exchanger. *Chemical Engineering Research Design - CHEM ENG RES DES*, 86:221–232.