Hands-on session 5 – Natural convection in enclosure

Abstract

This session will introduce you to the solution of a buoyancy driven flow. For this purpose, a simple 2D problem is studied and compared to experimental results. Two geometry configurations will be analyzed and compared to spot the major differences.

Goal

The aim of this hands-on session is to approach the modeling of a buoyancy driven flow in a 2D geometry and compare the results obtained with different geometrical configurations and the degree of agreement against experimental data. The user will get familiar with the Boussinesq approximation.

1. Introduction

Kuehn and Goldstein [1,2] have conducted an experimental study of natural convection in a cylinder annulus, using both concentric and eccentric configurations (Figure 1). A heated cylinder is placed inside another cylinder, trapping air in the resulting annular cavity. The inner cylinder is placed in four configurations, one in which the cylinders are concentric and the others in which the inner cylinder is displaced upward, downward or rightward. As the inner cylinder is hotter than the outer, buoyancy-induced flow results and natural convection occurs. Their results serve as a good benchmark for the natural convection heat transfer modeling capabilities. In this session two configurations are examined: one in which the inner cylinder is displaced downward (Figure 1c) and one in which the inner and outer cylinders are concentric (Figure 1a).

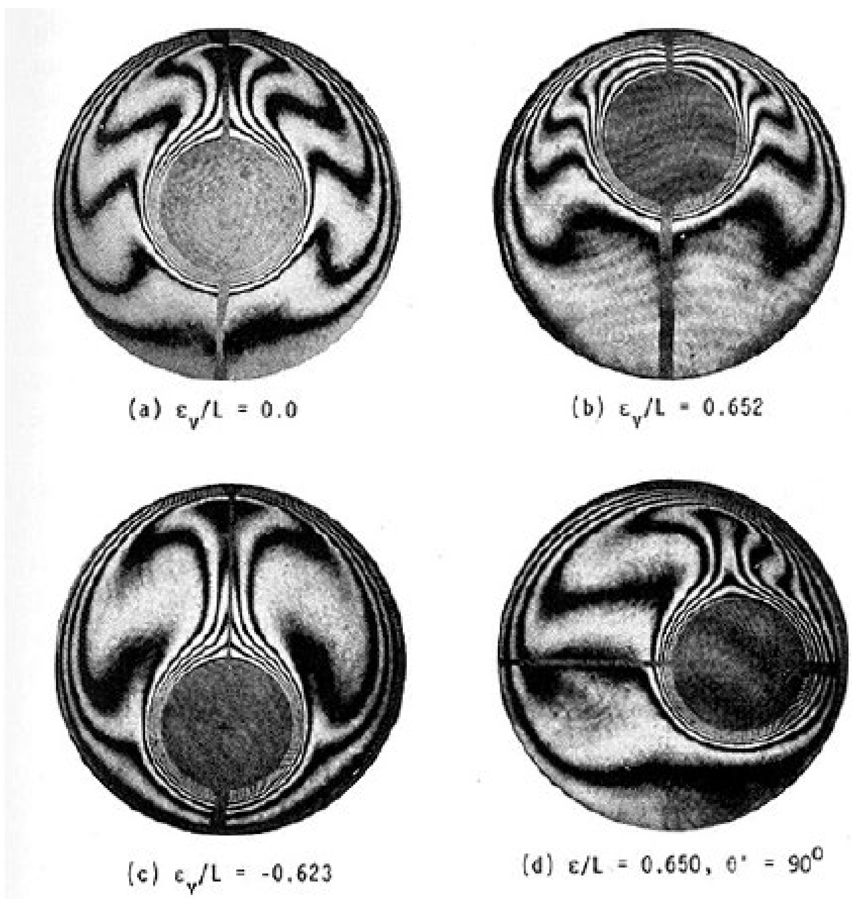


Figure 1: (a) Natural convention in a concentric annulus, (b) – (c) – (d) Different eccentric annulus configurations. Kuehn and Goldstein 1978

The purpose of this test is to compare the numerical prediction of temperature profiles along the symmetry lines with the experimental results of Kuehn and Goldstein for the eccentric and concentric case. The test also compares the numerically predicted heat flux from the surface of the inner and outer cylinders for the eccentric and concentric cases with the experimental results. The excel file *Lab10_ExperimentalData.xlsx* contains the experimental results. The modelling has to be approached with a **steady state analysis**.

1. Kuehn, T.H. and Goldstein, R.J., An Experimental Study of Natural Convection Heat Transfer in Concentric and Eccentric Horizontal Cylindrical Annuli, *Journal of Heat Transfer*, 100:635–640, 1978.
2. Kuehn, T.H. and Goldstein, R.J., An Experimental and Theoretical Study of Natural Convection in the Annulus Between Horizontal Concentric Cylinders, *Journal of Fluid Mechanics*, 74:695–719, 1976.

2. Modeling approach

The radii of the outer and inner cylinders, respectively, are 46.3 mm and 17.8 mm. For the eccentric annulus case the eccentricity is ε = -0.6245, which is very close to the value of -0.623 reported in the experiment.
The eccentricity is the measure of the distance the inner cylinder is moved from the concentric position and is defined as $\varepsilon = \varepsilon_v / (R_o - R_i)$ (Figure 2). The inner cylinder wall is set to a temperature of T_i= 373 K and the outer cylinder wall to T_o= 327 K.
Only half of the domain needs to be modeled from symmetry considerations. The following air properties are assumed to be constant and are taken to be the values at the mean temperature (film temperature) of 350 K. They are:

- Viscosity μ= 2.081·10^{-5} Ns/m^2
- Thermal Conductivity k= 0.02967 W/mK
- Specific Heat c_p= 1008 J/kgK

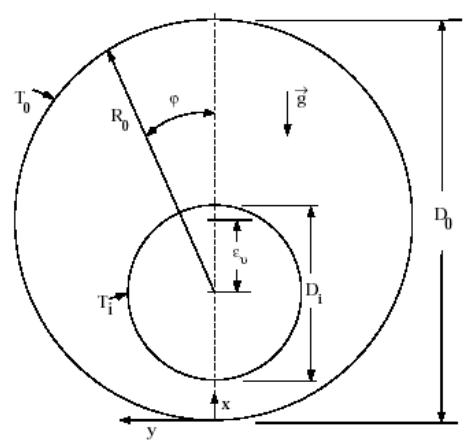


Figure 2: Problem description

where

- ε_v = -17.8 mm distance measured along the vertical axis
- D_o = 92.6 mm the diameter of the outer cylinder
- D_i = 35.6 mm the diameter of the inner cylinder

3. Solving procedure

The procedure for solving the problem is as follows:

1. Check the domain dimension and the mesh quality.
2. Analyze the problem (Rayleigh number).
3. Set the solver and the appropriate models.
4. Set the material properties and the operating conditions.
   It is suggested to use reference temperature for the lowest value of temperature inside a domain.
5. Set the appropriate boundary conditions.
6. Set up the solver and the convergence criteria.
7. Post-process the results and compare them with experimental ones.
   You have to compare the temperature profiles along the symmetry lines for the eccentric and concentric cases to the experimental data of Kuehn and Goldstein.
   The heat flux from the inner and outer cylinder surfaces for the eccentric and concentric cases must be compared with the experimental data.

4. Tips

4.1. Flow regime

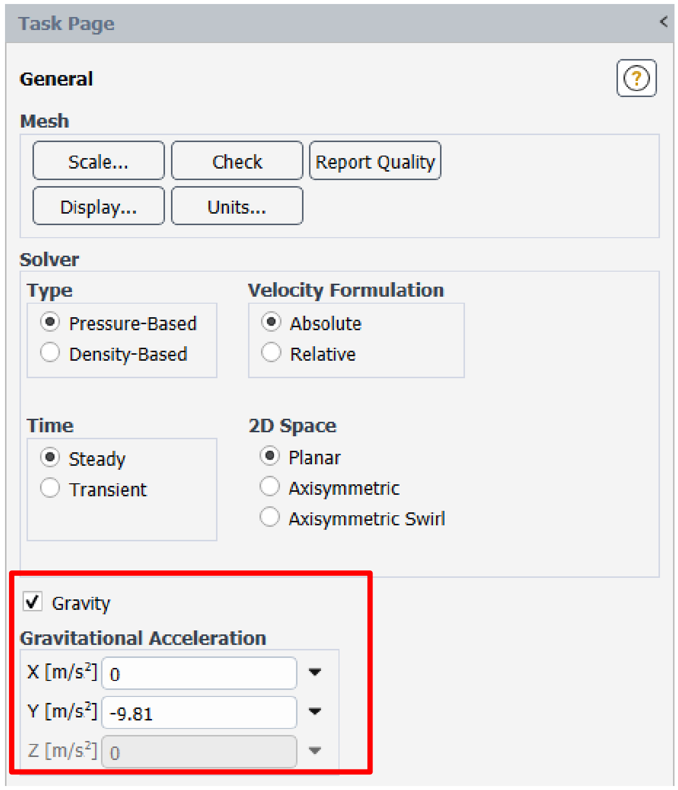
Based on Rayleigh number it is possible to fix the fluid dynamic regime (laminar or turbulent). The critical Ra number is around 10^9 and the transition to turbulent flow is between 10^6 and 10^{10}.

$$Ra_L = Gr_L \cdot Pr$$

$$Gr_L = \frac{\beta \cdot g \cdot L^3 \cdot \Delta T}{\nu^2}$$

4.2. Gravity

In order to account for the natural convection, the buoyancy effects have to be turned on in the solver. First, the gravitational acceleration has to be set up in the General tab by turning on the Gravity option and introducing the negative gravitational acceleration for a proper axis.

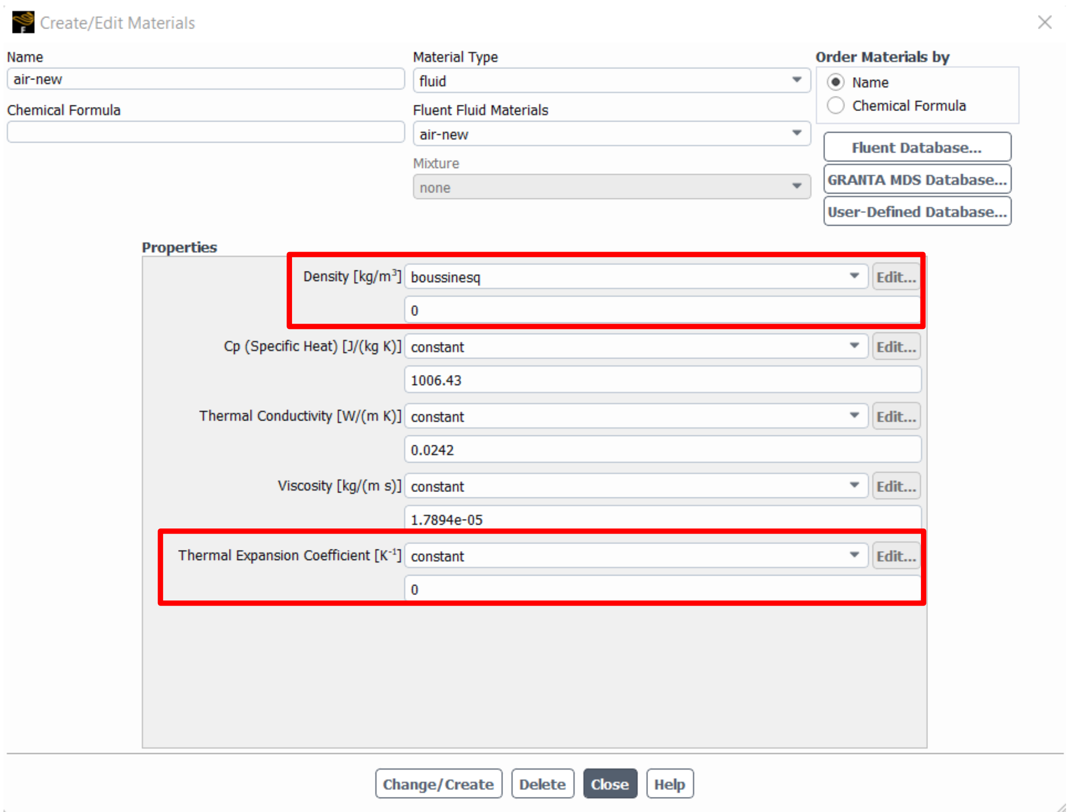


4.3. Boussinesq approximation

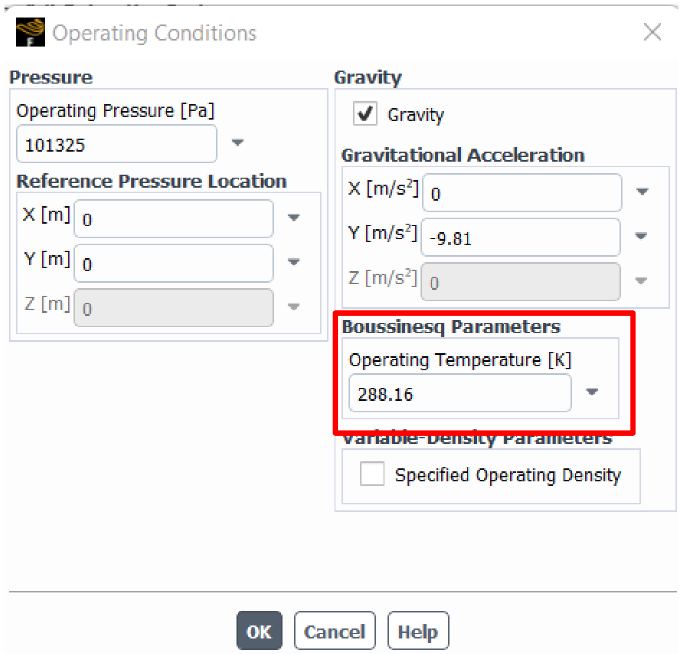
Next, for the simplification of the case, the Boussinesq approximation is used, which assumes constant density for all the governing equations apart from the buoyancy term in the momentum equation, where the density is defined using equation:

$$\rho = \rho_0(1 - \beta(T - T_0))$$

where ρ_0 is operating (constant) density, β is thermal expansion coefficient and T_0 is operating (constant) temperature. To turn on the Boussinesq approximation and introduce the properties to Fluent, go to Materials and change the Boussinesq in the density list and introduce there the ρ_0 value calculated for the reference temperature. Also the thermal expansion coefficient β calculated for the average temperature of the problem.



To specify the operating temperature T_0, go to Cell Zone Conditions -> Operating conditions -> Boussinesq parameters, and introduce there the temperature for which the operating density and all the other fluid constant properties were defined:



The operating density option in Variable-Density Parameters doesn't need to be turned on, as it's the operating density which would appear in other fluids body-force term of the momentum equation, which do not use the Boussinesq approximation. In our domain we use only one zone with single fluid.

4.4. Solver settings

Use the second-order-upwind discretization scheme, because natural convection produces large eddies that are not aligned with the grids. Enable Body Force Weighted or PRESTO! for the pressure discretization.