Virtual Experiments: Numerical Computations as a Powerful Tool for Engineers

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Abstract: An undergraduate course is developed to initiate future engineers to multiphysics numerical simulation by approaching concrete cases in various fields such as: heat transfers, fluid flow, mechanics, chemistry and electrostatics. The so called "Virtual Experiments" course consists of four projects given successively to students. Each project lasts about ten hours. The major notions related to numerical simulation are approached: physical model and associated boundary conditions, geometry, mesh, solving method and also postprocessing.

Keywords: undergraduate, course, heat transfers, fluid mechanics, simulation.

1. Introduction

Associated to the theory and the experiment, the numerical simulation is becoming the third necessary step in all the activities of development (industry, environment, health, transport, and energy). Indeed once validated from experimental measurements, a numerical model can be performed to simulate a large range of practical cases using a large range of parameter values in order to analyze and optimize the system of interest. The so called "Virtual Experiments" is an under-graduate course to initiate future engineers to multiphysics numerical simulation by approaching concrete cases in various fields such as: heat transfers, fluid flow, mechanics, chemistry and electrostatics. To these ends four different projects where given successively to students: natural convection in a pan (fig 1), application of buoyancy to airship (fig 2), hollow fiber cartridge to filter tap water (fig 3), heat exchanger (fig 4). Each project lasts about ten hours.

At first the student has to choose the adequate physical models, to build the geometry, to select the relevant physical parameters and the associated boundary conditions of the problem.

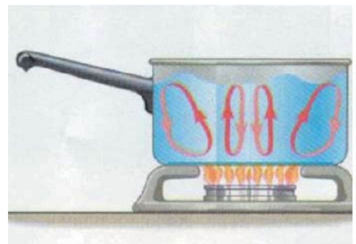

Figure 1. Rayleigh-Bénard Convection (www.nanoscience.info)

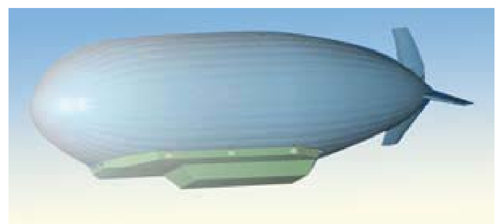

Figure 2. Airship (Aerospace Adour Technologie)

Figure 3. Filter cartridge on tap (Dom source)

Figure 4. Heat exchanger (http://www.directindustry.fr/)

Even if the geometry is generally simple, an important part of the course focuses on the mesh and more precisely on the element type (quadrangle or triangle) and on the boundary layer refinement. Identically the method of solving is particularly highlighted. At this stage the student must be sensitive to the size of the mesh regarding the accuracy of the numerical results taking into account the capability of the computer used. Then the student must also think about the best way to illustrate the virtual experiment both quantitatively and qualitatively using the post processing. As an engineer, the student is finally encouraged to use the virtual experiment as a tool of designing and dimensioning.

2. Use of COMSOL Multiphysics

Natural convection in confined geometry:

Natural convection in confined geometry is illustrated in the case of a pan full of water, heated from the bottom, before vapor bubble formation. Water is heated near the bottom of the pan and then rises to the surface thanks to buoyancy and promotes recirculation motions. This is the well known natural convection phenomenon. In this example, the “fluid thermal incompressible flow” in Comsol Multiphysics application mode is used as the physical model. This model considers the combined incompressible Navier Stokes equations and convection diffusion heat transfer equation. The geometry is 2D axisymmetric and the pan wall is either conductive (tin) or insulating (pyrex). A heat flux is assumed at the bottom of the pan while water surface is kept at ambient temperature. A typical result of flow streamlines are shown in fig 5.

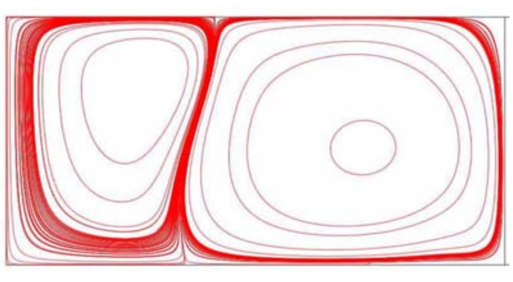

Figure 5. Natural convection in a pan heated from the bottom

Buoyancy force and application to airship:

From the previous project of natural convection, the idea is to study the buoyancy force in order to combine both phenomena for the designing of an airship.

In a first part, buoyancy force is estimated around a sphere in a quiescent liquid. The 2D axisymetric problem is solved with Comsol using the Navier-Stokes equations. The students are invited to analyze the pressure map and to compare it to trivial solution of hydrostatic. The pressure profile (fig. 6) around the sphere is then integrated on the whole surface to obtain the total buoyancy force projected on Z axis: $F_{pz} = \iint - p.n_z\,dS$. The radial component of the force is also calculated and discussed with student.

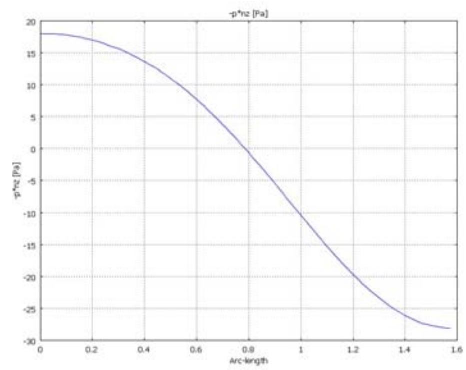

Figure 6. Axial component of the pressure along the arc-length of the sphere.

The exercise is then extended to other virtual experiments with other fluids, shapes, sizes in order to rediscover the Archimedes law.

In a second part, the virtual dimensioning of an airship is proposed and a comparison between several technologies is asked. The student can choose the size and the shape of his airship. The buoyancy effect can be generated by helium or by heated air.

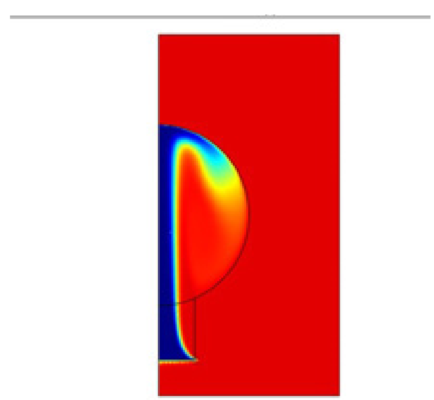

Figure 7. Gas density inside and outside the airship.

In this last case, the incompressible Navier-Stokes equations are combined with convection diffusion heat transfer equation with the Boussinesq assumption. A typical result presents the density in the airship on fig. 7. The inner weight of the airship is calculated with Comsol by a volume averaged integration of the density. Then the surface averaged integration of the pressure is used to estimate the net buoyancy force of the airship.

Filtration in a hollow fiber bundle:

The project aims to conceive a microfiltration cartridge, composed of a bundle of thousand hollow fibers, to improve the quality of the tap water for drinking. Hollow fibers are minitubes closed in an extremity (dead end filtration), having a porous wall made of synthetic material, pores of which are of the order of 0.1 microns. The cartridge should be directly placed on the faucet. The objective is to use the pressure of the distribution network (3.5 bars) to obtain a quantity of minimal filtered water of 2 liters per minute for a capacity of working corresponding to 2 000 liters before replacement of the cartridge. The characteristics of the hollow fibers are the following: 10 cm length, 1mm inner diameter, 0.3 mm wall thickness and 10^{-14} m^2 permeability.

In this project, the “laminar incompressible Navier Stokes equations” in Chemical Engineering module application mode is used as the physical model. This model is adequate as it is especially dedicated to fluid / porous coupled problems. Indeed the combined Navier Stokes equations and Darcy Brinkman equations with the associated interfacial boundary conditions, i.e. velocity and pressure continuity, are considered. The geometry is 2D axisymmetric. A pressure driven filtration flow is imposed using pressure as inlet and outlet boundary conditions.

At first students are required to simulate the working of one single fiber to determine how many fibers are required to obtain a flow rate of 2 l/min. Here the geometrical domain consists of an inner fluid subdomain bounded by an annulus porous subdomain where filtration takes place.

Then they study the case of a bundle of fibers taking into account the packing density and its impact on filtration performance. To this end an additional annulus fluid subdomain is considered around the annulus porous subdomain to account for packing effect. This model is known as Happel model. At this stage some recent experimental results [1] are given to students to test the accuracy of their results.

Finally they have to account for particle accumulation at the inner surface of the fibers, which is responsible for progressive filter fouling and flow rate reduction. For simplicity it is assumed that particles follow the streamlines and the permeability of the cake is calculated by Kozeny Carman equation. The size and the concentration of particles are given. Students have to detrmine if it is necessary to replace the cartridge after the filtration of 2000 l of water. In this final part of the project, the “moving mesh ALE” model is added to simulate the growth of porous subdomain due to particle capture.

Most of students achieved the expected results (Figure 8) but some of them failed to simulate a large range of packing density because of a bad choice of mesh. However they all succeed in illustrating progressive clogging of inner hollow fiber using the animation tool of the postprocessing.

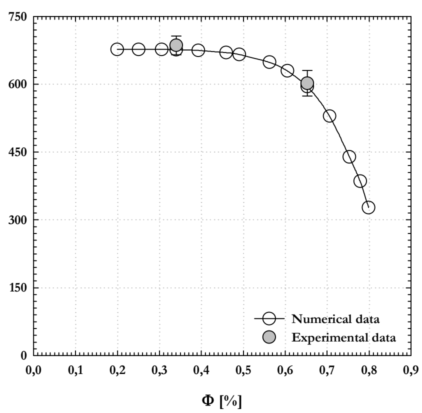

Figure 8. Reduction of filtrate flux with packing density [1]

Heat exchanger:

The heat exchanger consists of a heated cylinder cooled by a laminar fluid flow at lower temperature. The external flow is normal to the axis of the circular cylinder. This 2D model considers the combined incompressible Navier Stokes equations and convection diffusion heat transfer equation. Thus, there is a fluid-thermal coupling.

To begin with, the case of a flow around a circular cylinder without thermal exchange (isothermal hypothesis) is analyzed. With this common benchmark [2], students discover the effect of Reynolds number. Below Re = 40, two symmetric steady vortex are observed (fig. 9). Beyond Re=40, the flow becomes unsteady and a Karman vortex street is observed with a repeating pattern of swirling vortices. For example, for Re=100, the period of the vortex shedding is calculated. Thus, the Strouhal number can be calculated and compared to literature [2]. Other flow considerations can be observed, notably a stagnation point in front of the cylinder where a rise in pressure can be noticed (fig. 9-10).

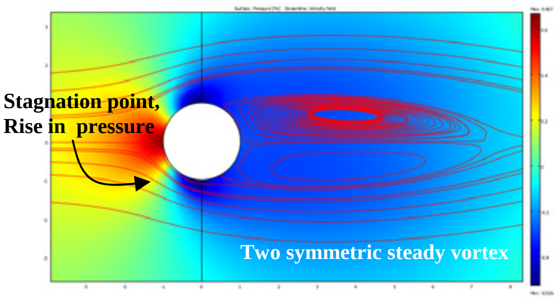

Figure 9. Pressure and streamlines on a circular cylinder in a cross flow (Re < 40)

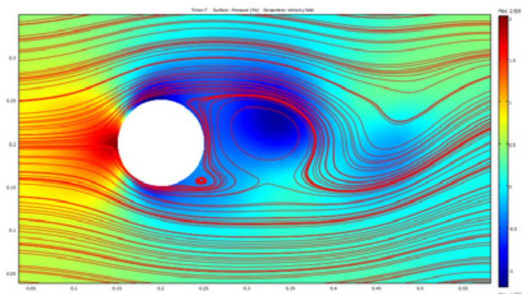

Figure 10. Pressure and streamlines on a circular cylinder in a cross flow (Re > 40)

Subsequently, thermal coupling is introduced. To simplify the problem, a steady flow is chosen ($Re < 40$). The aim is now to focus on the problem of computing heat transfer rates from a cylinder in an external forced flow and to compare Nusselt numbers obtained by simulation with classical correlation of the literature. Simulations are exemplified in fig. 11.

The analysis of the numerical results shows a maximum of the local heat flux at the stagnation point and then it decreases (Re<40). The total heat flux is calculated by integration of the normal local heat flux on the whole cylinder. The convective coefficient and the Nusselt number are then deduced. Correlations of the overall average Nusselt number may be obtained:

$$\overline{Nu_D} = C\ Re_D^m\ Pr^{1/3}$$

Several fluids are studied. Numerical results are compared to Hilpert Correlation [3] showing a very good agreement (fig. 12):

$$\overline{Nu_D} = 0.911\ Re_D^{0.85}\ Pr^{1/3} \text{ for } 4 < Re < 40 .$$

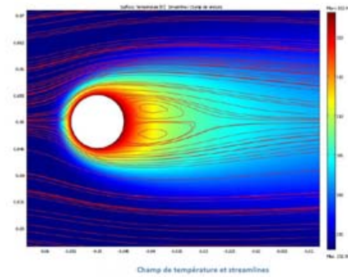

Figure 11. Temperature and streamlines in a flow around a heated cylinder

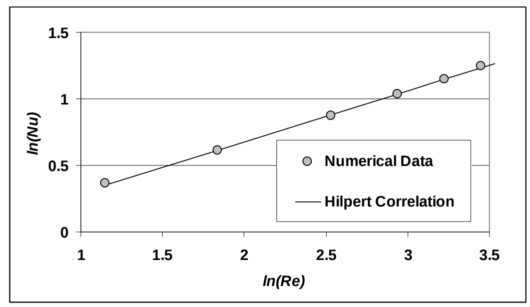

Figure 12. Nusselt number versus Reynolds number, comparison between numerical data and Hilpert correlation.

3. Conclusion

Comsol Multiphysics software appears to be an interesting tool for teaching. It is useful not only to illustrate physical phenomena but also to approach the techniques of numerical simulation. Finally even if the selected examples are quite simple, the students become aware that numerical simulation is a powerful tool for engineers.

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