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On a more rigorous study of pipeline erosion in bends focused on fluid-particle interaction dynamics
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1. OVERVIEW

The present project has two main goals (two fronts). First, develop for the first time a state-of-the-art parallel code to rigorously simulate the complicated multiscale particle-laden flow phenomena in a pipe and a bend for future detailed fundamental studies of the erosion in pipelines. Second, develop general mechanistic design rules for different pipe bend configurations to reduce erosion based on how the bend modification affects the non-trivial secondary flows that significantly contributes to drag particles to the wall.

FIRST FRONT: For this front, the method used is the Lattice Boltzmann Method (LBM). In this year, we decided to focus on the boundary conditions to be applied to moving particles. The interpolated bounce-back scheme and the immersed boundary method are the two most popular algorithms in treating a no-slip boundary on curved surfaces. While those algorithms are frequently implemented in the numerical simulations involving complex geometries, their performances have not been compared systematically over the same local quantities within the same context.

SECOND FRONT: One phenomenon that contributes in the erosion of pipelines is the secondary flows. This year, we decided to focus on investigating what triggers them. The behavior of the secondary flow in the elbows of a pipe can be described as swirls, that is, a rotational motion occurring within the walls of the elbow. These eddies are called vortices of Dean in honor of W.R Dean. In 1927, this author inferred that the appearance of these secondary flows in the form of vortices is due to the centrifugal acceleration causing a pressure gradient in the cross section of the elbow. Over the years there have been numerous studies and compendiums of work on secondary flow behavior in elbows and curvatures varying certain variables such as Reynolds number, Dean number and radius of curvature. None of them takes a different approach to refute or complement that theory. It is intended, therefore, in the present research work, to take a different approach as stipulated by Dean, to observe and analyze the initiation of secondary flows.

2. METHODS

FIRST FRONT:

Originally created to model fluid mechanics, LBM was created with inspiration from the Lattice Gas Automata (LGA) method. In LBM a known amount of "pseudo-particles" are used to simulate the collision and movement of particles in a system with a fluid in motion. Each pseudo-particle represents a varying number of actual particles in the system that collides with other pseudo-particles at a known velocity at prescribed locations. At each collision one calculation is done for every possible direction the actual particles could go, the amount of directions is set to be known and controlled resulting in more efficient use of power and resources. In the LB scheme we track a particle density function and is a straightforward 3 steps procedure (see figure 1). First, we allow the pseudo particles to collide after which the particle density function f_i value of each "pseudo-particle" change its magnitude. The rules of the collision are a key element step since the collision rule determines the physics being solved. Next it is streaming, we move the direction-specific density functions to the nearest neighbor lattice nodes. With the updated distribution functions, computation of the macroscopic variables.

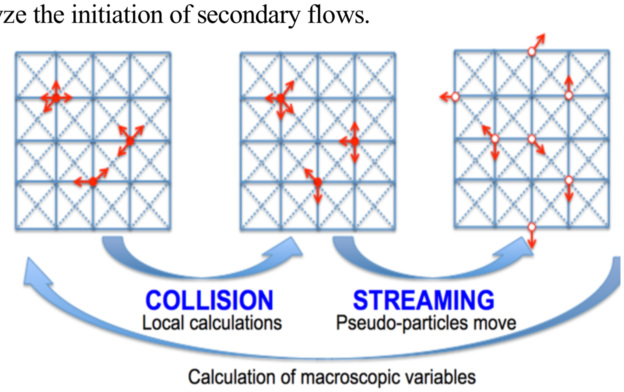

Figure 1. Theory of Lattice Boltzmann Method

SECOND FRONT:

In a regular computational fluid dynamics study, the governing equations are based in three fundamental principles: conservation of mass, conservation of momentum and conservation of energy. Throughout this study no energy balance was considered as isothermal conditions were assumed. The mathematical model consists of the set of Navier-Stokes equations and continuity equation. Two cases were studied, one laminar (Re=100) and one turbulent (Re=100.000). For the turbulence model, a k-ε model was used. At the inlet, a predetermined velocity value was imposed (that matched the Reynolds number). A prescribed value of 0 Pa was set at the outlet. A mesh sensitivity analysis (for both element size and wall resolution) was carefully performed. Due to computational constraints up to 5% of error was allowed. The boundary element size

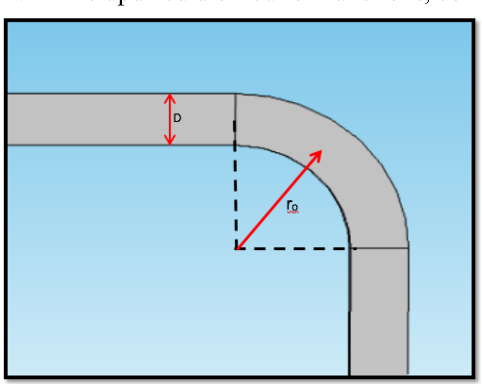

Figure 2. Typical domain in the study

was adjusted in order to decrease wall lift-off (Y+) to values lower than 20 (viscous unit). The physical domain consists of a square pipe with 3 sections (as shown in figure 2). The first section consists of a straight part with a length of 1 m, then a section of elbow of 90° with a radius of curvature r_o and finally the last section as straight square pipe, also of length of 1 m.

3. RESULTS

FIRST FRONT:

This year we worked a systematic comparative investigation on some frequently used and most state-of-the-art interpolated bounce-back schemes and immersed boundary methods, based on both theoretical analyses and numerical simulations of four selected 2D and 3D laminar flow problems. Our analyses show that immersed boundary methods typically yield a first-order accuracy when the regularized delta-function is employed to interpolate velocity from the Eulerian to Lagrangian mesh, and the resulting boundary force back to the Eulerian mesh. This first order of accuracy is observed for both the local velocity and hydrodynamic force/torque, contrary to previous claims of having a second-order accuracy. On the other hand, the interpolated bounce-back generally possesses a second-order accuracy for velocity, hydrodynamic force/torque, and local stress field. The main disadvantage of the interpolated bounce-back schemes is its higher level of fluctuations in the calculated hydrodynamic force/torque when a solid object moves across the grid lines.

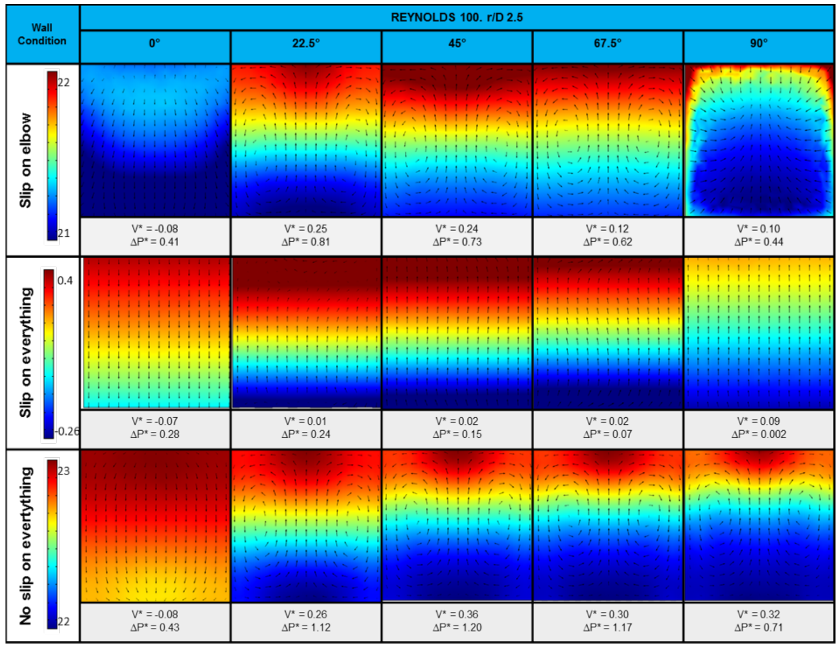

Figure 3. Pressure distribution and velocity vectors on each selected elbow planes for different wall condition combinations.

SECOND FRONT:

A series of new numerical studies were carried out varying the wall conditions in the pipe-elbow system to observe how they affect the appearance of secondary flows. Figure 3 show the results of the new numerical analysis for the case Re=100 and r/D=2.5. Slip wall and non-slip wall conditions were implemented in three scenarios: 1) slip wall condition only in the elbow (1st row), 2) slip wall condition in the elbow and pipes (2nd row), and 3) non-slip wall condition in the elbow and pipes (3rd row). This last scenario (3rd row) corresponds to the normal real-life case where secondary flows are clearly formed. When the slip wall condition was applied to the whole system (2nd rows), the pressure gradient is still present but weaker (see Δp^* values) and, more importantly, the typical recirculating secondary flows disappeared. There is still some flow however which is weaker. This means that despite the fact that there still is a centrifugal acceleration, the secondary flows are weaker and non-recirculating, contrary to what Dean proposed. A slip condition was placed in the elbow section, while the inlet and outlet pipes conserved their non-slip conditions. In the same figure it can be observed how the secondary flow vortices appear, although you can see certain differences with the position of the centers of vortices when comparing them with the case of non-slip. With this, we found that for the existence of secondary flows in elbows, two conditions are necessary: 1) the centrifugal force, and 2) the non-slip condition in the wall of the elbow that makes the centrifugal force zero at the walls.

4. IMPACT OF THE RESEARCH

PRF grant has fully supported two undergraduate students. They have gained a deeper understanding in this scientific area of pipeline erosion and valuable hands-on experience. The undergraduate students were trained to conduct independent research by getting heavily involved in activities such as: developing research plans, writing scientific papers, conducting research by using computational software, collecting and analyzing data, and presenting research results in group meetings. Students were trained on the use of the computer software COMSOL Multiphysics. During the course of the project the PI has met with participating undergraduate students twice a week to clearly state that week's goals and to collect results, summarize, and reflect on what was accomplished. Some other undergraduate students have joined the group to do other research activities (with other topics different to the one on this project) after they have heard what we have been doing. To this date, my research group has the largest number undergraduate students in the College. The PRF is my first external grant as a PI. It has made my tenure package stronger. The project has already resulted in two submitted conference papers over the last year and we are working on another one.