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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:

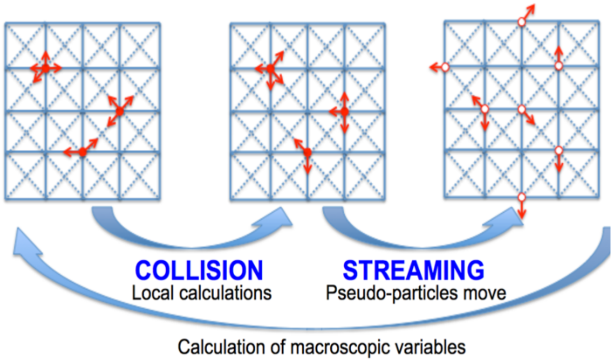

Figure 1. Theory of Lattice Boltzmann Method

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.

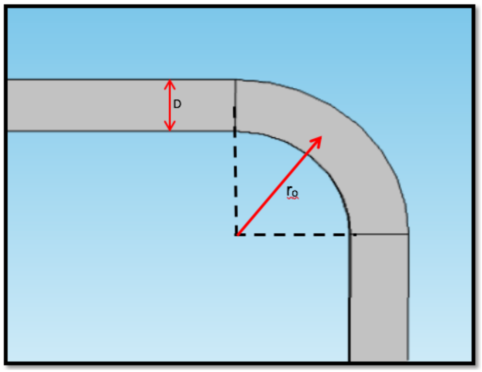

Figure 2. Typical domain in the study

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 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:

The previous 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. This work was published in a journal paper (it was accepted). This year we did similar study for turbulent flow cases. The major problem of the immersed boundary method revealed by the present study is its incapability in computing the local velocity gradients inside the diffused interface, which can result in significantly underestimated dissipation rate and viscous diffusion locally near the particle surfaces. Otherwise, both categories of the no-slip boundary treatments are able to provide accurate results for most of turbulent statistics in both the carrier and dispersed phases, provided sufficient grid resolutions.

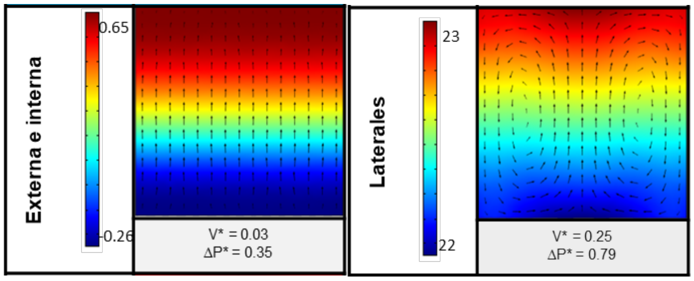

Figure 3. Pressure field and velocity vectors on a 45^o plane in an elbow (Reynolds 100 y r/D=2.5). Left: slip in external and external walls. Right: slip in lateral walls.

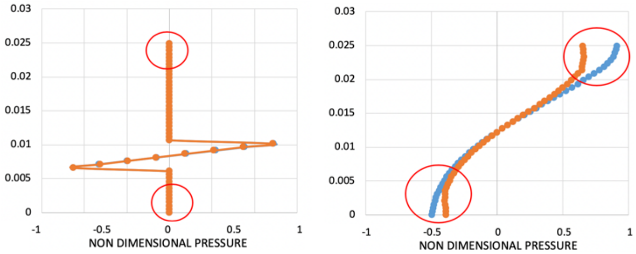

Figure 4. Pressure distribution along center line (blue) of the plane and along the lateral wall (orange). Left: slip in external and external walls. Right: slip in lateral walls.

SECOND FRONT:

The previous year after a series of new numerical studies varying the wall conditions (non-slip and slip conditions) in the pipe-elbow system to observe how they affect the appearance of secondary flows, 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. This work was presented in a conference and published in its proceedings. We further looked into the effect of wall conditions. We played with the NON-SLIP condition on the lateral walls and the external/internal elbow walls. On figure 3 we can observe that there are no formed vortexes form when the non-slip condition is applied only to the external and internal walls (while slip condition is applied to the lateral walls). On the other hand, the vortexes are fully formed when the non-slip condition is only applied to the lateral walls (while slip condition is applied to the external and internal walls). We realized that the reason for that is the centrifugal acceleration is exactly equation to zero at the lateral walls when the non-slip condition is applied to them, while the centrifugal acceleration is in full effect at the core of the elbow. This create an unbalance of pressure, or transversal pressure drop that pushes the flow to move sideways. This can be observed in figure 4. To the left of figure 4 the pressure along the center line in a plane is exactly equal to the pressure along the wall (when slip condition is applied to it). To the right of figure 4, we notice the transversal pressure differential that triggers the initiation of the secondary flow. In addition to the detailed secondary flow studies, we also started to look into the erosion in elbows. We looked at the effect of the secondary flow alone in erosion. Preliminary results show that the secondary flows might be responsible of up to 50% of the total erosion (this depends on the strength of the secondary flow and the particle properties).

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.