Flow characteristics and pressure losses at a junction weld and in a spirally welded pipe

Contents

1. Introduction

The topic of pressure losses in welded pipes is apparently not well covered in existing documentation. In addition, calculation cannot be performed simply with analytical equations considering the number of parameters involved. While the case of longitudinal welds does not need to be studied (no flow disturbance), the case of junction and spiral welds need to be analysed to determine their disturbance on gas transport.

For the two weld types causing pressure losses, calculations may be performed using Reynolds Average Navier Stokes codes based on turbulence models. Compared to a junction weld case for which a two dimensional modelling is sufficient (flow axis symmetry), the case of spirally welded pipes is more complex considering the three dimensional displacement of the flow. Also the spiral weld periodicity requires the modelling of sections not fully cylindrical (no radial planes for inlet and outlet) to permit an extensive use of structured grids.

Turbulence models are first compared to determine their suitability and also their relative computing cost. The grid construction being particularly complex, its incidence on the final results needs to be evaluated, for instance, by comparing results with a different grid construction (cylindrical versus non cylindrical models also grids with different helix angles...).

Considering the large number of parameters influencing the pressure losses, the flow parameters (pressure, temperature, molecular weight, viscosity and flow) are reduced to one: the Reynolds number. The suitability of this parameter is verified by comparing results with a constant Reynolds number for different flow conditions.

Following the analysis of the flow characteristics, pressure losses at a spiral weld are calculated for several parameters: Reynolds number, pipe internal roughness, weld height and width, helix angle and pipe diameter.

2. Generalities

2.1. Types of welds in a pipeline

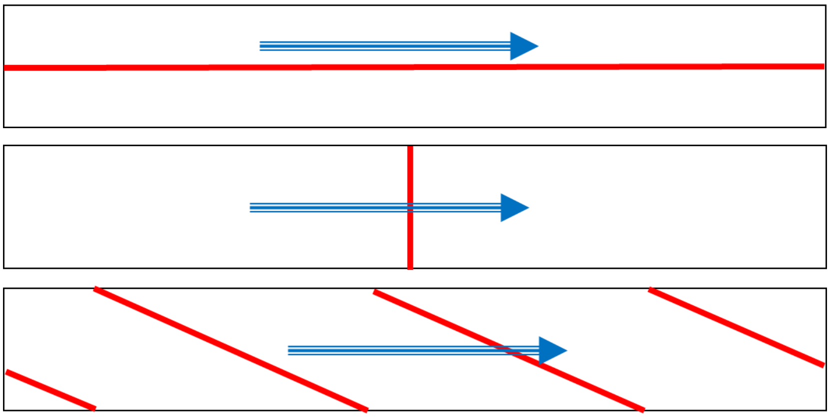
Different types of welds may be encountered in a pipeline:

- A longitudinal weld (a) in figure 2.1. It is encountered in the manufacturing of tubes made from rolled forged plate. These tubes are particularly used for high pressure applications and are generally 12m long. These welds are made in manufacturing plants.
- A junction or a radial weld (b) in figure 2.1. It is fabricated on land site or on a barge (sea pipeline) for connecting tubes.
- A spirally welded tube (c) in figure 2.1. It is produced from rolled plates for the manufacturing of long tubes (18 to 24 m). These tubes are rather used for medium pressure applications. These welds are made at the vendor shops.

Their incidence on the flow is different

- In a longitudinal weld case, the flow, parallel to the weld, is not disturbed by the weld.
- In a radial weld case, the flow, normal to the weld, is disturbed locally and circumferentially by the weld.
- In a spiral weld case, the flow, oblique to the weld, is disturbed locally with intensity dependent mostly on the helix angle.

In the second and the third cases, the disturbance is dependent on the flow characteristics mostly the Reynolds number.



a) Longitudinal weld

b) Junction or radial weld

c) Spiral weld

Figure 2.1 – Different types of welds which may be encountered in a pipeline

2.2. Pressure losses due to a change in the cross section area of a pipe – Case of a junction weld

2.2.1. Sudden enlargement

When there is a sudden increase in the area of the section perpendicular to the main flow, chock losses are produced. For a Reynolds number greater than 3500, the corresponding friction factor is given by: $\xi = H/(\rho v^2/2) = \left(1 - \frac{F_1}{F_2}\right)$ where F_1 and F_2 are respectively the upstream and downstream cross section areas, $\rho v^2/2$ is the kinetic energy and H the corresponding energy losses.

According to this equation, often called the Borda – Carnot equation, energy losses are only dependent on the opening ratio $n=F_1 / F_2$.

2.2.2. Flow restriction in a pipe section

It is considered here an opened wall separating two channel sections 1 (upstream) and 2 (downstream). When the flow approaches the opened wall, particles are deviated towards the channel centre due to their own inertia. This causes a reduction in the flow area F_c which becomes smaller than the area of the opened wall F_0. Downstream of the restriction, particles tend to fill the available volume and energy losses corresponding to a brusque enlargement are then generated. For a Reynolds number greater than 100 000, the corresponding friction factor may be estimated from (I.E. Idel'cik - 1986) :

$$\xi = H/(\rho v^2/2) = \xi'\left(1 - \frac{F_0}{F_1}\right) + \left(1 - \frac{F_0}{F_1}\right)^2 + \tau\sqrt{1 - \frac{F_0}{F_1}}\left(1 - \frac{F_0}{F_2}\right) + \xi_f$$

where ξ' is a coefficient dependent on the upstream shape of the opened wall, τ is determined by the thickness of the opened wall and the inlet shape and ξ_f is defined by the wall thickness and the flow conditions.

2.2.3. Junction weld

Pressure losses due to the presence of a junction weld (circular ring) between two pipe sections (12 m length each) have been calculated carrying out flow simulations with a CFD code using

RANS turbulence models (mostly k-ε models). This study was performed for several shapes and height values of junction welds and for several conditions of pipe Reynolds number and internal wall roughness.

An example of calculation results is presented on figure 2.2.1 for a semi-circular weld for two extreme Reynolds numbers. It may be seen from this figure that in addition to the obvious effects of the weld parameters (height mostly) and to some extent to the pipe diameter, the relative pressure loss is very dependent:

- on the pipe Reynolds number, particularly in the case of a smooth wall
- and on the internal pipe wall roughness. For instance, at the largest Reynolds number, the roughness may cause a variation of the relative pressure loss ranging from 1.6 to 4.2 %. In the lowest Re Nb, the relative effect of the wall roughness is smaller.

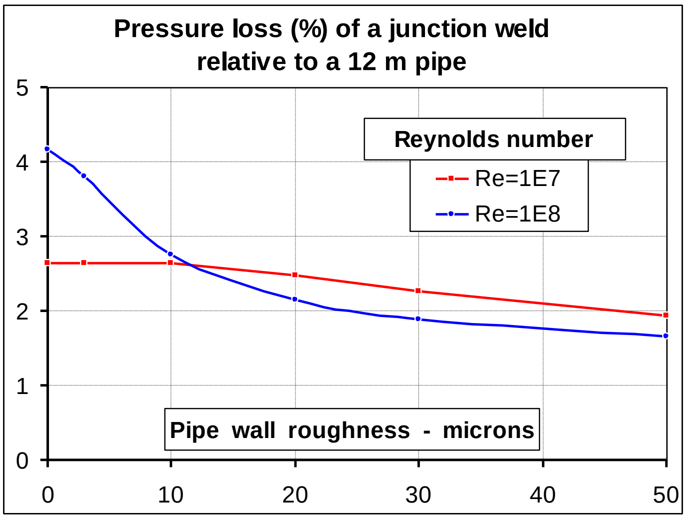


Figure 2.2.1 – Typical results for the relative pressure loss at a junction weld and for two extreme cases of Reynolds number. Results obtained in the case of a semi-circular weld.

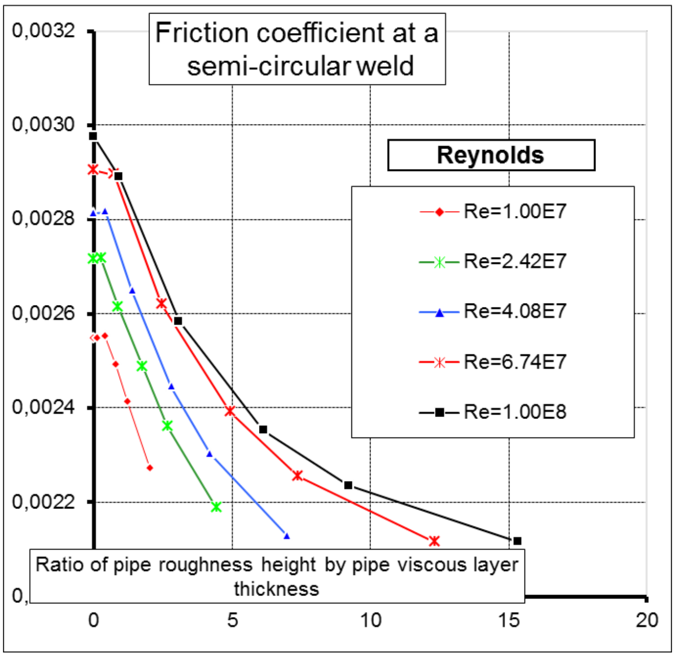


Figure 2.2.2 – Typical results for the friction coefficient versus the Reynolds number and the ratio between the roughness height and the viscous layer thickness - Semi-circular weld.

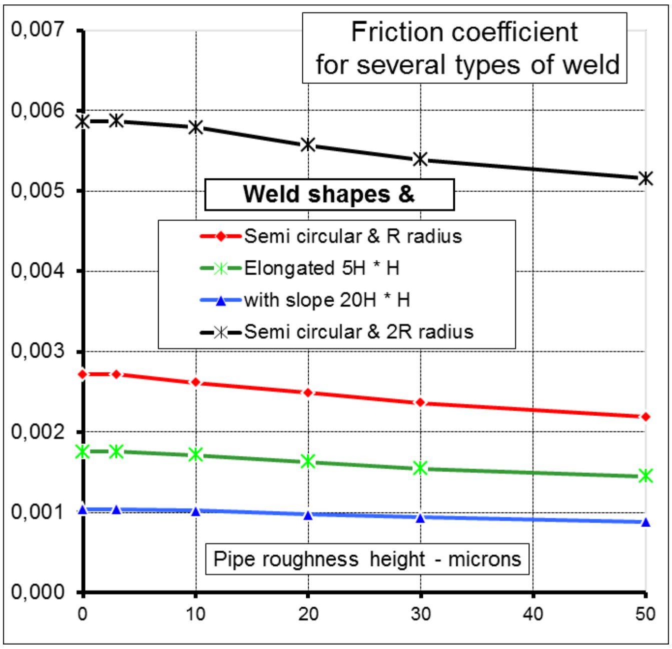


Figure 2.2.3 – Typical results obtained for several sizes and shapes of welds, semi-circular with radius R and 2R, elongated with length 5 times the height and a weld with decreasing height over 20 times the height.

These effects are not predicted with sufficient accuracy by handbook equations designed for the prediction of the pressure loss at a flow restriction inside a pipe section. If the Reynolds number tends to be taken into account by some equations, no predictive equations could be found covering the case of the pipe wall roughness (figure 2.2.2). Also the shape of a junction weld is very specific and very different to the shape of orifice plates used for flow monitoring and for which many equations are available (figure 2.2.3).

In conclusion, no equations can predict with sufficient accuracy the pressure loss due to a junction weld. Considering the greater complexity of a spiral weld, a specific study is required for predicting the effect of this type of weld.

2.3. Key parameters for the pressure loss at a spiral weld

2.3.1. Inventory of key parameters

For calculating pressure losses due to a spiral weld, the following parameters need to be known:

- the pipe characteristics : the internal diameter (D), the internal wall roughness (ε) and the angle of the spiral weld (α) -Figure 2.3.2 that is **3 parameters**
- the weld characteristics : height (h) and width (w)- Figure 2.3.4 that is **2 parameters**
- the flow conditions : the gas pressure (P), temperature (T), molecular weight (Mw), velocity (V or flow Q) and the absolute viscosity (μ) that is **5 parameters**

Analysing the effect of all these parameters on the pipe pressure loss requires carrying out calculations in varying only one parameter at a time and using as an average 4 values for each parameter. It may be verified that in some cases the variation of the pressure loss is far from linear and that 4 values may be considered a minimum for representing the correct trend. See for instance, figures in sections 3 and 4.

On this basis, the number of calculations is $\mathbf{4^{10}}$ **that are approximately one million**. These calculations cannot be performed analytically. They are the results of flow simulations with the use of CFD codes. Considering an average of 3 days for each calculation (grid definition and computation time), several thousands of years would be required to perform all calculations.

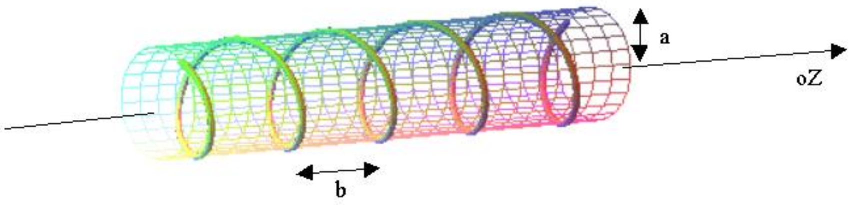


Figure 2.3.1 – overall shape of a spiral weld

Hopefully, the number of parameters can be reduced significantly by using the Reynolds number $Re = \frac{VD\rho}{\mu}$ where ρ is the gas density. Flow conditions resuming to a single parameter, the overall system reduces to 6 parameters: three for the pipe definition, two for the weld characteristics and one for the flow. **The total number of calculations is still very large:** $\mathbf{4^6}$ **that are approximately 4000**. Therefore, a preliminary analysis is required to determine the degree of influence of individual parameters (sensitivity analysis) and to establish the overall trend shape (degree of non linearity, location of maximum / minimum).

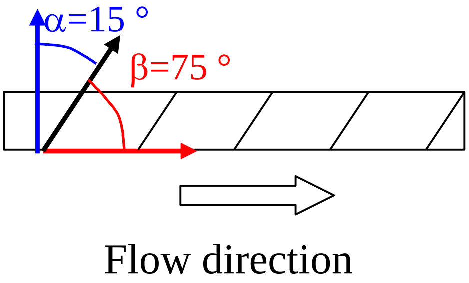


Figure 2.3.2 – Definition of the helix angle

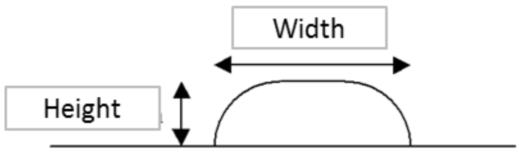


Figure 2.3.3 – Definition of weld height, width and overall shape

The benefit of the Reynolds number can be demonstrated by considering different values, for instance, of gas velocity and density and by comparing pressure loss calculation results.

It can be seen from the table below that for constant Reynolds number and wall roughness values:

- the friction factor is constant
- the pressure gradient in a straight pipe is directly proportional to the gas velocity
- the pressure gradient in a spirally welded pipe is equally proportional to the gas velocity
- the relative pressure loss due to a spiral weld is not dependent on the gas velocity nor on the gas density as long as their product is constant (Reynolds number unchanged).

Flow conditions	Friction factor Nikuradse Prandtl	Diff. pressure Nik..dse/Prandtl No weld - Pa/m	Code Diff. pressure - No weld - Pa/m	Code Diff. pressure - With weld Pa/m	Relative pressure loss of a spiral weld
85.90 kg/m3; 4m/s; Re=1.8E7	0.00742 0.00745	8.35 8.39	8.34	14.25	70.9 %
42.95 kg/m3; 8m/s; Re=1.8E7	0.00742 0.00745	16.7 16.8	16.70	28.60	71.3 %

Same demonstration could be done by modifying three parameters at the same time (velocity, density and viscosity) and keeping the Reynolds number constant. In these situations, despite absolute values would change significantly, the relative effect of the spiral weld would be unchanged.

2.3.2. Domain definition – range of parameters

Industrial companies have provided data concerning characteristics of spirally welded pipeline and conditions of operation. Operating conditions may vary from a low Reynolds number of the order of 7.7E6 to a large one of 1E8.

Concerning the pipe data, the diameter ranges from 0.61 m to 1.32 m and the internal wall roughness from a relatively smooth (2 µm assumed) to a relatively rough condition (45µm).

Concerning the weld characteristics, three types of weld may be considered:

- Weld 1: S1 mm height with S2 mm width – Small weld
- Weld 2: M1 mm height with M2 mm width – Medium weld
- Weld 3: L1 mm height with L2 mm width – Large weld

In the present study, a weld profile is defined in its middle part by a horizontal line edged by two quarters of a circle with a radius equal to the weld height (figure 2.3.3).

The helix angle is varied from 15 to 60 degrees (angle α made by the helix and the radial plane). It corresponds to a variation of 75 to 30 degrees if the angle between the helix and the pipe axis is considered (angle β) – figure 2.3.2.

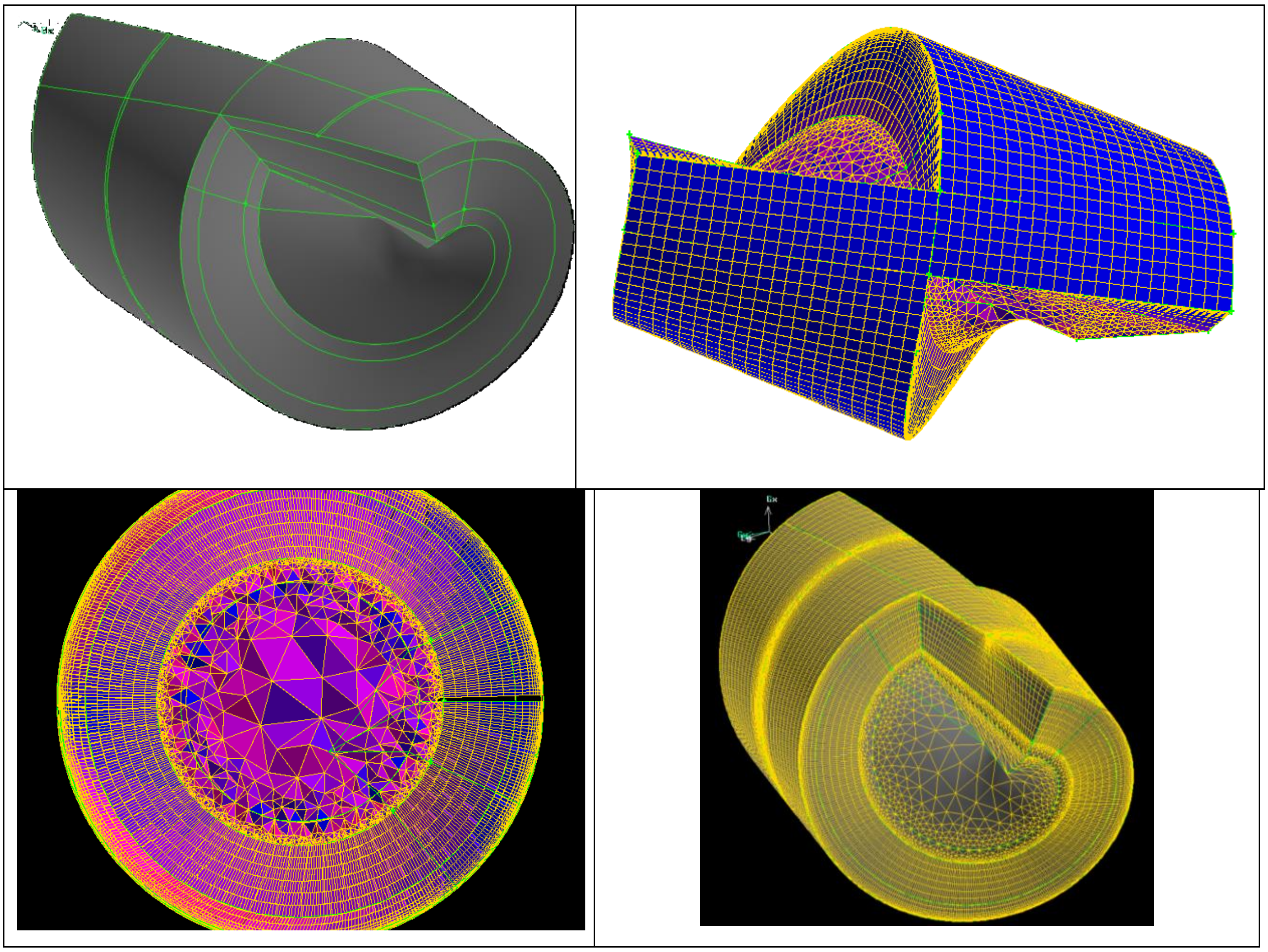
2.4. Computational Flow Dynamics simulation

2.4.1. Pipe modelling

Upstream, at and downstream a junction weld, the displacement of the main flow (not the flow fluctuations) occurs in a meridian plane. This may be designated as a two dimension flow. As a consequence, flow simulations may simply be studied in a meridian plane carrying out simulations on two dimension models with the pipe axis acting as a symmetry line.

Conversely, the displacement of the main flow inside a spirally welded pipe (helicoidally pipe) is tri dimensional and as such requires three dimension flow simulations.

Despite, it would have been possible to consider pipe sections using radial planes at inlet and outlet, this would have required practically a complete unstructured grid meshing with several associated disadvantages, to quote a few, a large number of meshes, a bad quality of the meshing and a large computing time.

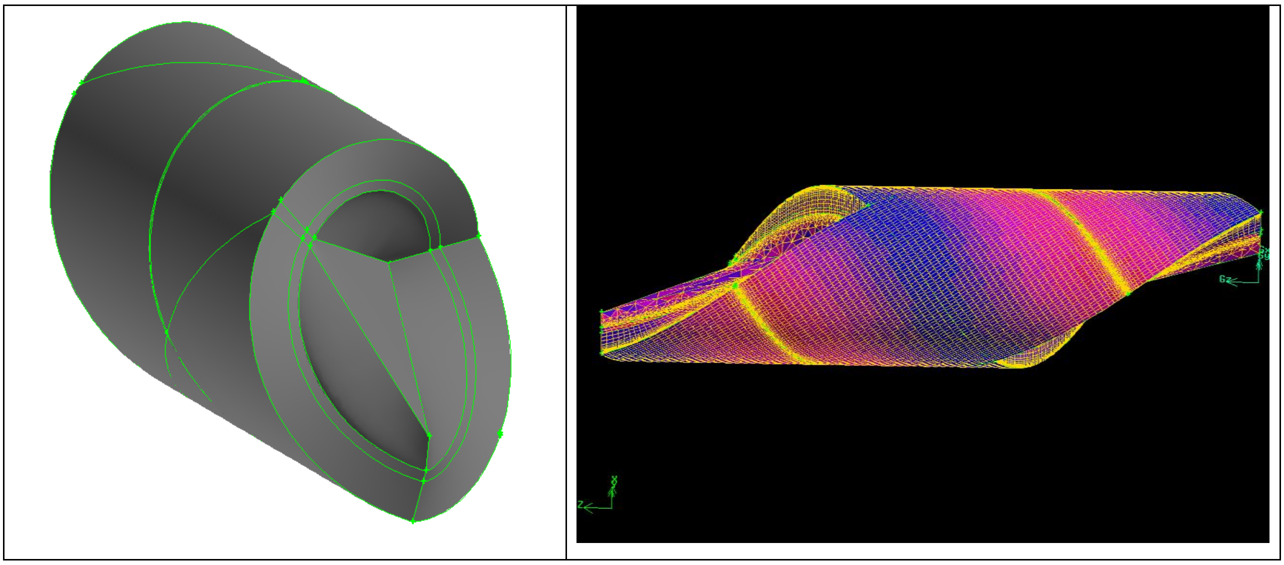


Figures 2.4.1 a, b, c and d (from upper left to lower right) : Grid construction for a 15° helix angle pipe section. a- Definition of the external volume including structured grid; b- Straight pipe section (no weld) with structured and unstructured grids; c- View of unstructured grid in the central core; d-Spirally welded section

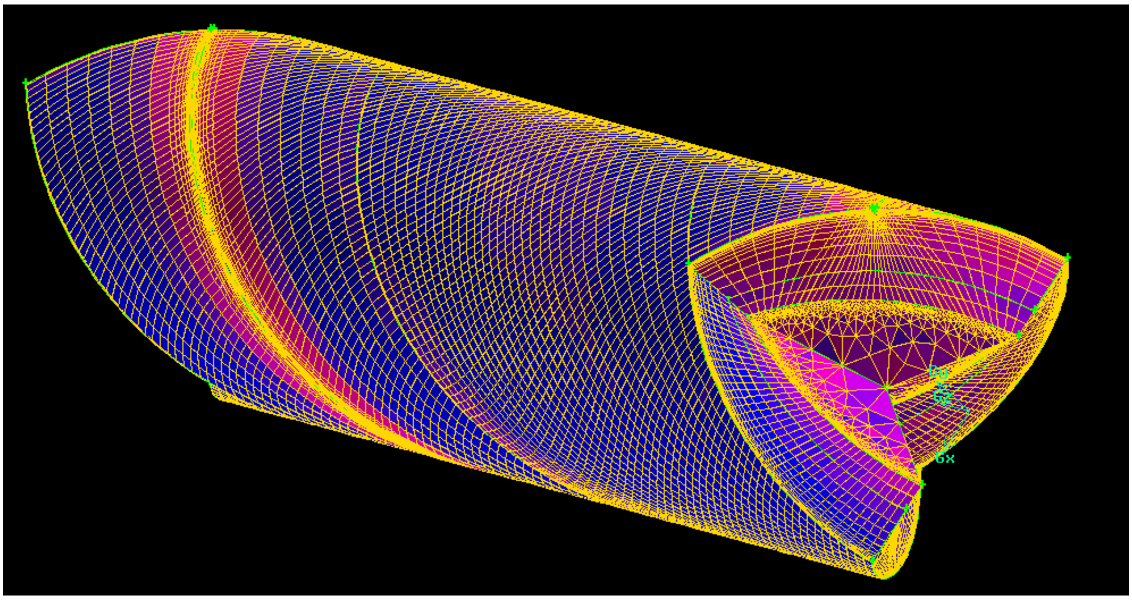
Instead, an apparently more complex geometry as been preferred. It consists of a volume limited cylindrically by the pipe wall and by inlet and outlet surfaces including planes either parallel or perpendicular to the spiral weld (figures 2.4.1 to 2.4.3). This permits to use of a structural grid on the external volume (figure 2.4.1.a and d including the weld volume) and of an unstructured grid in the central core where the grid definition is less critical (figure 2.4.1.c). The inlet and outlet faces are selected to represent a periodic section with the inlet section matching the outlet one by a simple axis translation. This provides the pressure losses (with and without weld) over a period. Pressure gradient and total pressure loss may be obtained, respectively, in dividing by the length of a period and in multiplying by the number of periods included in a pipe length.

The size of a mesh and therefore their total number is determined by the magnitude of the Reynolds number. At a Reynolds number of 7.8E6, for a gas velocity of 4 m/s and a 610 mm pipe diameter, the friction velocity is 0.13 m/s and the friction length 2.4E-6 m. According to CFD code documentation, the Standard Wall Function defining the velocity profile near the pipe wall is valid for $30<y+<500$ where y+ is the non dimension length (an absolute length divided by the friction length). This defines the absolute dimension in the normal direction of a mesh near the wall considering that we are always aiming at 100<y+. At this Reynolds number, the total number of meshes is:

- 81 000 without a spiral weld
- 800 000 with a spiral weld (450 000 and 350 000, respectively for the external – structured volume and the internal – unstructured volume).



Figures 2.4.2 a and b (from left to right): Grid construction for a 35° helix angle pipe section. a-Definition of external and internal volumes; b-Spirally welded section after grid construction.



Figures 2.4.3: Grid construction for a 60° helix angle pipe section

2.4.2. Turbulence models and wall velocity laws

Flow simulations are carried out using the Reynolds Average Navier Stokes calculation method (RANS code) using average turbulence models in the resolution of the Navier Stokes equations. Conversely, with DNS and LES CFD codes, turbulence equations are fully or partially resolved. These codes are not suitable for the present case considering the extremely large Reynolds number (up to 1E8 while DNS is limited to 5000 in Re) and because turbulence models have been sufficiently proven in similar situations with RANS models.

Four turbulence models have been tested in the case of a straight pipe (no welds) to verify the suitability of these models together with two wall velocity laws ("Standard wall treatment" and "Non equilibrium wall treatment") :

- k-ε Standard
- k-ε RNG
- k-ε Realizable
- k-ω

The flow simulations were carried out on the following conditions: 610 mm pipe diameter, 4 m/s gas velocity, 37.2 kg/m3 gas density and 1.17E-5 Pa.s absolute viscosity representing a Reynolds number of 7.8E6. Calculating the friction factor from the Prandtl equation (or Colebrook & White with hydraulic roughness = 0), the pressure gradient is 4.07 Pa/m.

The flow simulation results are as listed in the following table:

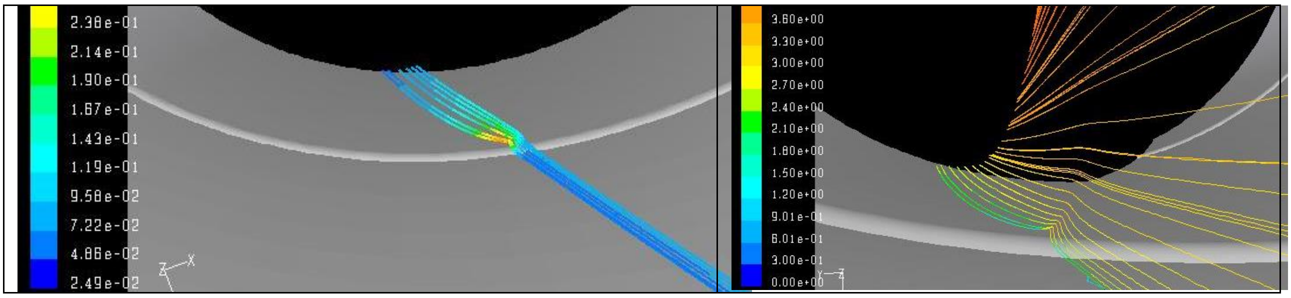
Turbulence model	Wall velocity law	Average Y+	dp/dl (Pa/m)	Difference
k-ε standard	standard	94	4.12	+1.08%
k-ε RNG	standard	91	3.82	-6.15%
k-ε realizable	standard	85	3.21	-21.2%
k-ω	standard	91	3.89	-4.58%
k-ε standard	non-equilibrium	90	3.82	-6.09%

The purpose of this exercise is to verify the order of magnitude provided by each model. It is not necessarily to retain the model providing the smallest difference with the Prandtl equation as nor the CFD code nor the Prandtl equation provide fully exact solutions. However, this does not mean that the CFD code is not suitable for providing exact trends and for analysing the effect of individual parameters. To the contrary, it can provide a high degree of sensitivity (when sufficient convergence has been reached) to the variation of individual parameters. This was verified and is reported in following paragraphs.

3. Flow characteristics

3.1. Particle tracking

This analysis was performed with the following conditions, Reynolds number: 7.8E6, wall roughness: 5 µm; pipe diameter: 610 mm, weld type: “M1;M2” and helix angle: 15 degrees.



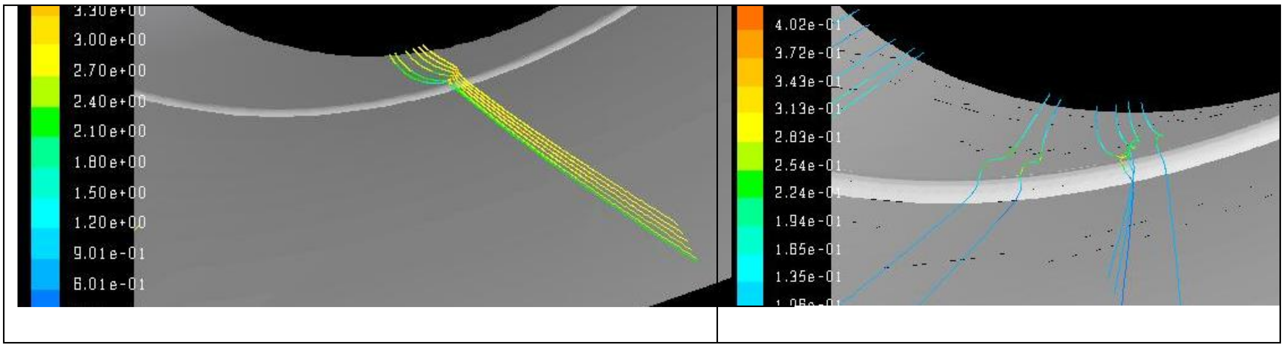


Figure 3.1 a, b, c and d (from upper left to lower right): flow streamlines near the pipe wall (figures a, c and d); flow streamlines from the pipe wall to the central core (figure b).

In figure 3.1.a, streamlines are coloured (intensity) by the turbulent kinetic energy. They range at a distance of the pipe wall from 0.5 to 5 mm.

In figure 3.1.c, as for above figure except streamlines are coloured by the velocity magnitude.

In figure 3.1.b, streamlines are coloured by the velocity magnitude. They range from the central core to the pipe wall.

In figure 3.1.d streamlines are coloured by the turbulent kinetic energy. They stand very close to the pipe wall showing the three dimension displacement of the particles near the weld.

3.2. Disturbance lengths

Downstream and, to some extent, upstream the weld, the flow is highly disturbed when passing over a weld (junction or spiral welds). Vortices are produced downstream the weld creating energy dissipation. The turbulent kinetic energy, the vorticity and the dissipation rate have been analysed to evaluate their incidence on pressure losses at a spiral weld. This was performed by comparing several situations of flow conditions (Reynolds number), weld height, weld helix angle and pipe diameter.

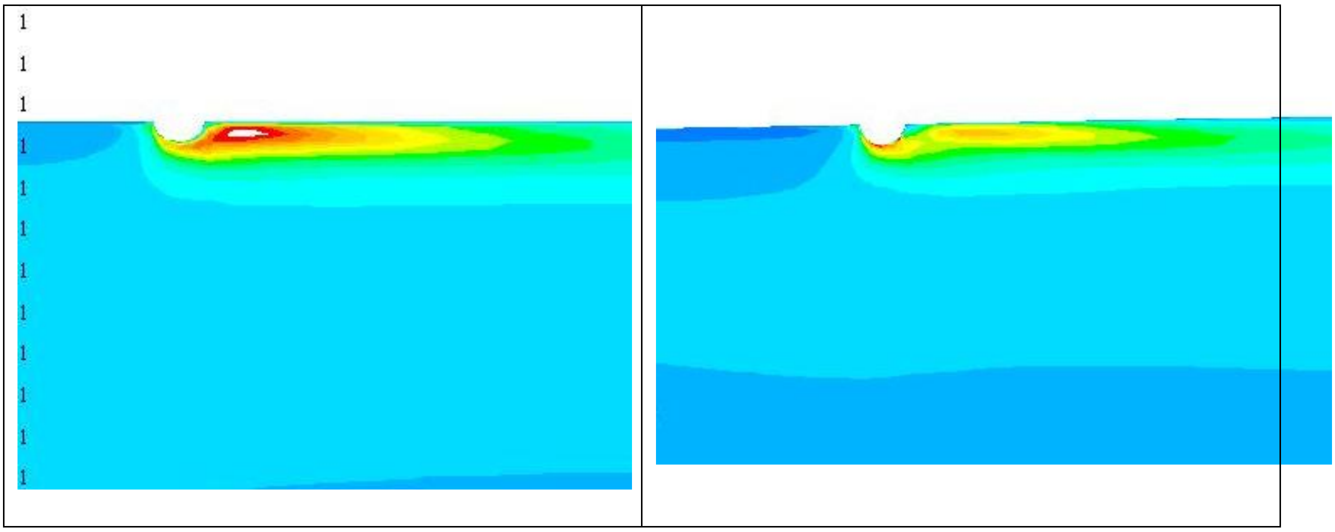


Figure 3.2.1 a and b – Flow disturbance ***for two Reynolds numbers****: 7.8E6 (left) and 4.3E7 (right). Iso surfaces for* ***turbulent kinetic energy, k****, ranging from 0.35 (red) to 0.001 m2/s2 (blue). Pipe dia = 0.61 m, helix angle = 15 deg, roughness = 15 µm; weld height = M1.*

Increasing the Reynolds number tends apparently to reduce the intensity of the turbulent kinetic energy downstream the weld (figure 3.2.1). This does not permit to predict a lower relative pressure loss of the spiral weld considering that the overall turbulent kinetic energy of a straight pipe also reduces as the Reynolds number is increased. However, the vorticity and the dissipation rate clearly increase with the Reynolds number (figures 3.2.2 and 3.2.3).

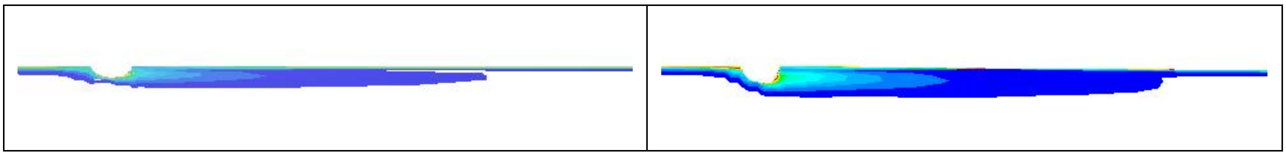


Figure 3.2.2 a and b – as above except iso surfaces stand for ***vorticity magnitude*** *in the weld vicinity, ranging from150 to 2500 sec^{-1}.* ***Reynolds numbers****: 7.8E6 (left) and 4.3E7(right)*

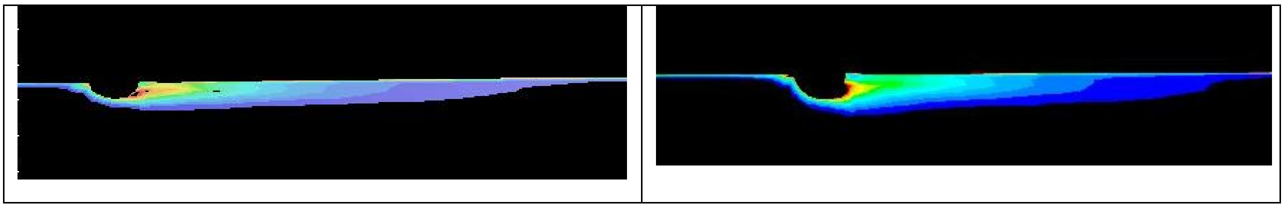


Figure 3.2.3 a and b – as above except iso surfaces stand for ***energy dissipation rate****, ε, in weld vicinity, ranging from10 to 100 m^2/s^3.* ***Reynolds numbers****: 7.8E6 (left) and 4.3E7 (right)*

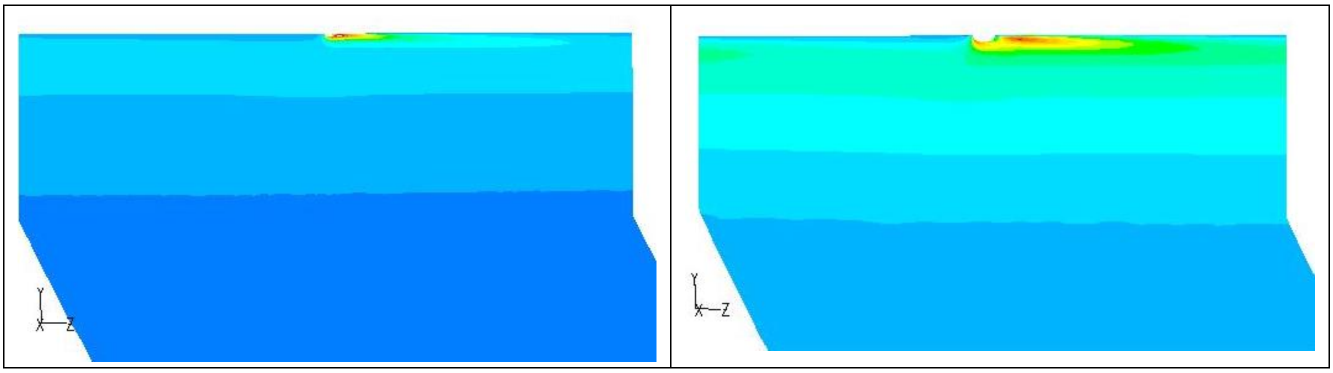


Figure 3.2.4 a and b – Flow disturbance ***for two weld heights****: M1(left) and L1 (right). Iso surface of turbulent kinetic energy ranging from 0.35 (red) to 0.001 m2/s2 (blue). Length=1 period, pipe dia = 0.61 m, helix angle = 15 deg, roughness = 15 µm. Reynolds number of 7.8E6*

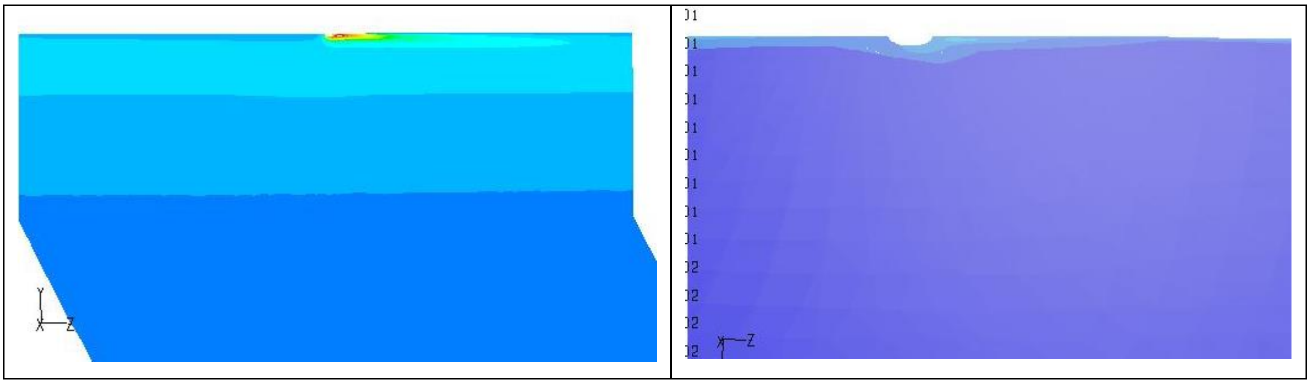


Figure 3.2.5 a and b – Flow disturbance ***for two helix angles*** *: 15 deg (left) and 60 deg (right). Iso surfaces of turbulent kinetic energy ranging from 0.35 (red) to 0.001 m2/s2 (blue). Pipe length: 1 period, pipe dia: 0.61 m, weld type: "M1; M2", roughness:15 µm. Reynolds number: 7.8E6*

As it can be expected, when the **weld height** increases the turbulent kinetic energy (therefore the pressure losses) increases too (figure 3.2.4). The volume representing the largest values of the turbulent kinetic energy is considerably greater in the case of the largest weld height (L1). In addition, perturbations are transmitted more intensively in the central core in the case of the largest weld height as it can be seen by the change in colour in the central core. Note that the same colour scaling is used for the two figures.

As it can also be expected, when the **helix angle** increases the turbulent kinetic energy (therefore the pressure losses) reduces (figure 3.2.5). The volume representing the largest values of the turbulent kinetic energy is considerably greater in the case of the smallest helix angle (15 deg). In addition, perturbations are transmitted more intensively in the case of the smallest helix angle as it can be seen by the change in colour in the central core. Note that the same colour scaling is used for the two figures.

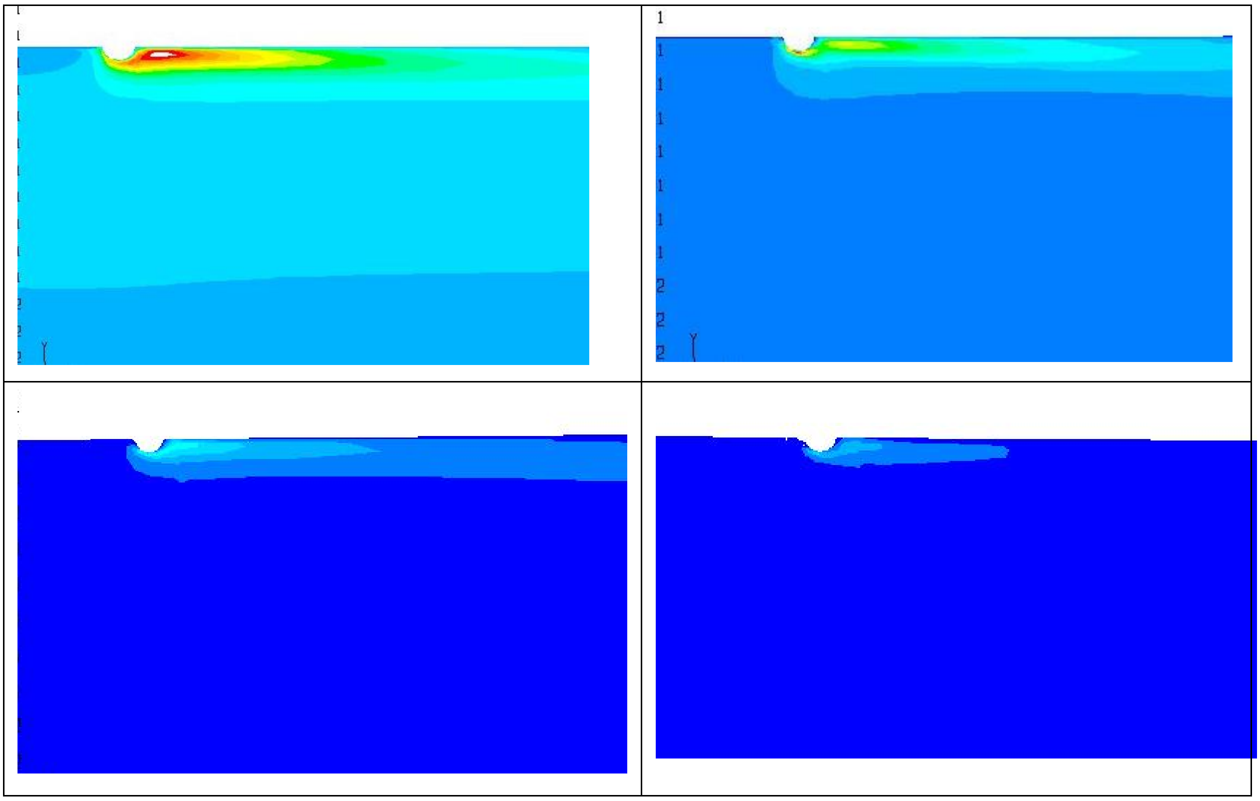


Figure 3.2.6 a, b, c and d – Flow disturbance ***for four pipe diameters****: 610, 813, 1067, 1321 mm (upper left to lower right). Iso surfaces of turbulent kinetic energy ranging from 0.35 (red) to 0.001 m2/s2 (blue). Pipe section: 1 period, weld type "M1; M2", helix angle: 15 deg; roughness: 15 µm; Reynolds number: 7.8E6*

The effect of the **pipe diameter** was analysed at a constant Reynolds number (7.8E6). When the pipe diameter increases, the turbulent kinetic energy (therefore the pressure losses) reduces (figure 3.2.6). For an increasing diameter, the change in turbulent kinetic energy can be seen as well near the wall as in the central core.

It has to be pointed out that to perform a study at a constant Reynolds number, either the density or the velocity has to be reduced (here the velocity) when the diameter is increased. A slightly different result would have been obtained by maintaining constant the Reynolds number - pipe diameter ratio.

3.3. Velocity profiles

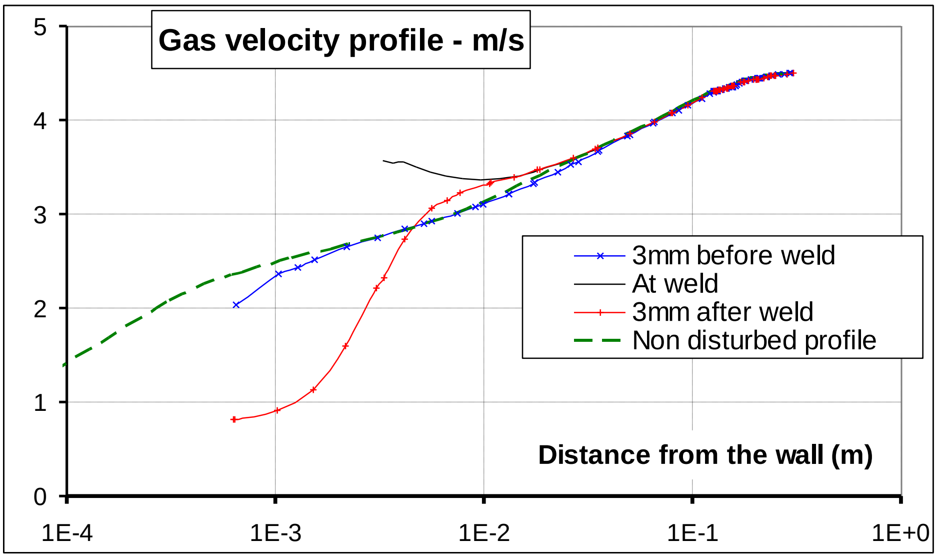


Figure 3.3: Profiles of the axial velocity: Non disturbed profile (straight wall - reference profile), before, at and after the weld. "M1; M2" weld. 7.8E6 Reynolds nb.

Comparing to the reference **velocity profile** (undisturbed profile - straight pipe), the velocity at 3mm upstream of the weld is slightly slowed down up to a distance from the wall of 2/3 the weld height. Above that distance, there is no change in the velocity profile. Approaching the weld, the velocity profile is progressively disturbed.

At the weld surface, the gas velocity is exactly nil (no slip condition). However, at 3/10 of a mm from the weld, the velocity has already reached 3.5 m/s that is almost 1 m/s above the reference velocity. The weld effect (in terms of velocity) is felt up to 30 mm from the pipe wall.

The velocity profile at 3 mm downstream of the weld is highly disturbed, since at 1 mm from the wall the actual velocity is only 30 % of the reference velocity. Above 4.5 mm, the actual velocity exceeds the reference velocity by approximately 10%. As at the weld location, the weld effect is felt up to 30 mm from the pipe wall.

3.4. Flow rotation along the pipe axis

The main flow is entrained in direction of the pipe axis as a result of the action of the pressure gradient. However, the flow displacement is also determined by the wall characteristics (its surface geometry: roughness and larger scale deformations). In the case of a spirally welded pipe, the weld tends to drag the main flow in its direction. Obviously, there is a sliding effect downstream of the weld due to the large axial distance separating two rows of a spiral weld.

This rotation can be classified as a solid vortex as, except very near to the wall where velocity values approach zero (all velocity components), in the transverse direction, velocity values are proportional to the radial distance to the pipe axis. In other words, the angular velocity is constant in the flow core (figure 3.4.1.b).

The rotation of the main flow results by an increase in the flow displacement along the pipe wall and therefore by an increase in friction losses. It is therefore important to analyse this flow motion for a better understanding of the extra pressure losses induced by a spiral weld.

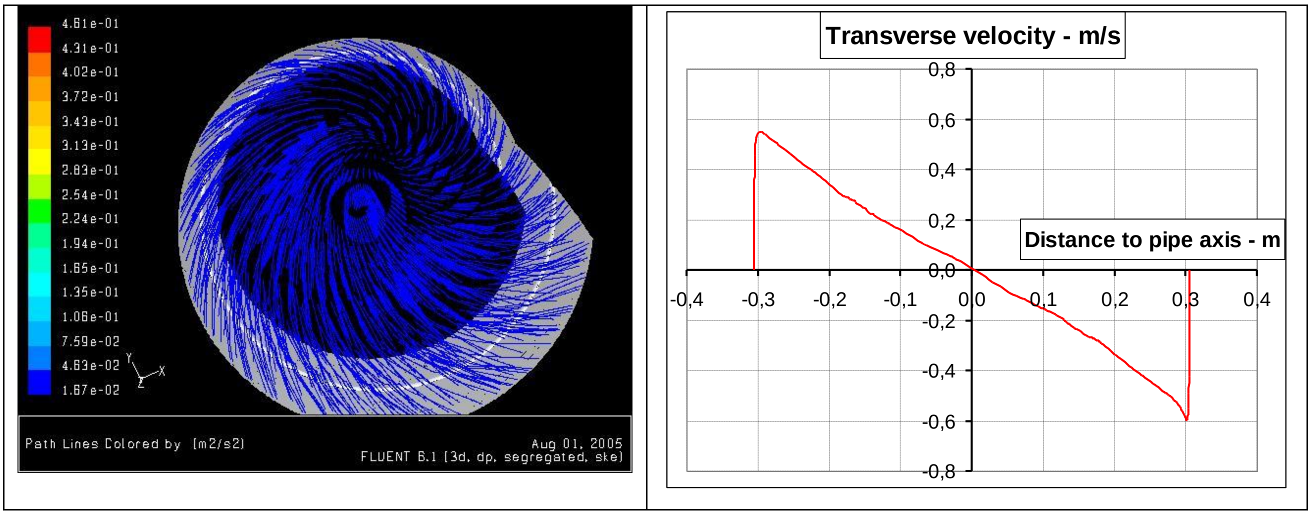


Figure 3.4.1 a - (left): Flow rotation around a pipe axis. Pipe characteristics: 610 mm diameter, 15 deg helix angle, "L1;L2" weld type, 1.8E7 Reynolds number, 50 µm wall roughness. Figure 3.4.1 b - (right): Transverse velocity versus radial position.

3.4.1. Effect of the pipe Reynolds number

The calculation was performed in the case of a 610 mm pipe diameter, with a helix angle of 15 degrees a gas velocity of 4 m/s and a gas density ranging from 37 to 477 kg/m3 simulating Reynolds number ranging from 7.8E6 to 100E6. It can be seen from figures 3.4.2 that the speed of rotation increases as the gas density (Reynolds number) is increased.

3.4.2. Effect of the pipe wall roughness

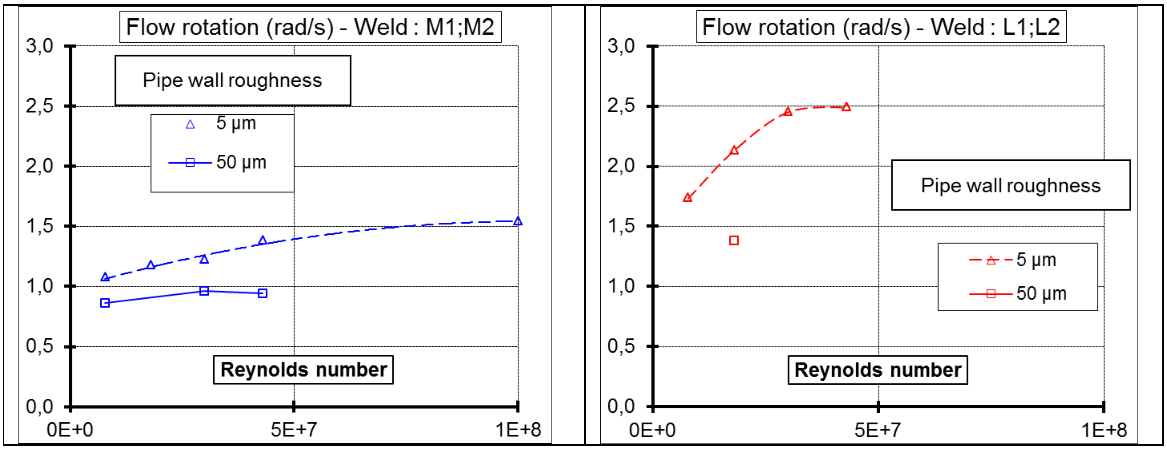


Figure 3.4.2 a - (left): Speed of rotation of the flow around the pipe axis versus Reynolds number and for two values of wall roughness. Pipe characteristics: 610 mm diameter, "M1;M2" weld type and 15 deg helix angle. Figure 3.4.2 b - (right): as above but for a "L1;L2" weld type

The calculation was performed under the conditions of paragraph 3.4.1 for two conditions of wall roughness: 5 and 50 microns.

In all cases, an increase in the pipe wall roughness tends to reduce the flow rotation. This may be explained by considering that the rotation (transversal velocity) induced by the weld is more rapidly damped by a rough wall than a smooth one.

3.4.3. Effect of the weld height

The calculation was performed under the conditions of paragraph 3.4.1 for two weld types: "M1;M2" and L1;L2.

The speed of rotation increases as the weld height is increased, a larger weld height being more efficient than a small one to guide the flow along the weld structure.

In the case of a "M1;M2" weld type, a speed of rotation of 1.5 rad/s is reached at the largest Reynolds number (1E8) while for a "L1;L2" weld type a speed of rotation of 2.5 rad/s is reached at a lower Reynolds number (4E6). Above these values, the speed of rotation seems to have reached an asymptotic value.

These two values of speed of rotation are rather small compared to the speed of rotation which could be reached if the flow was following exactly the weld direction (case, for instance, of a pipe wall containing only juxtaposed parallel welds). Considering an axial velocity of 4 m/s, a helix angle of 15 degrees and a pipe diameter of 0.61 m, the maximum achievable speed of rotation would be of the order of 50 rad/s that is approximately 20 times the value reached by the largest weld height.

In the case of a "L1;L2" weld type, a speed of rotation of 2.5 rad/s corresponds to an angle of rotation of approximately 11 degrees. This indicates that over a time interval of one second, the displacement in the transversal direction is of 0.7 m compared to a displacement in the axial direction of 4 m.

3.4.4. Effect of the helix angle

The rotating motion reduces significantly as the helix angle is increased. From an average of 1.2 rad/s with a helix angle of 15 degrees, it is approximately 6 times smaller with a helix angle of 60 degrees.

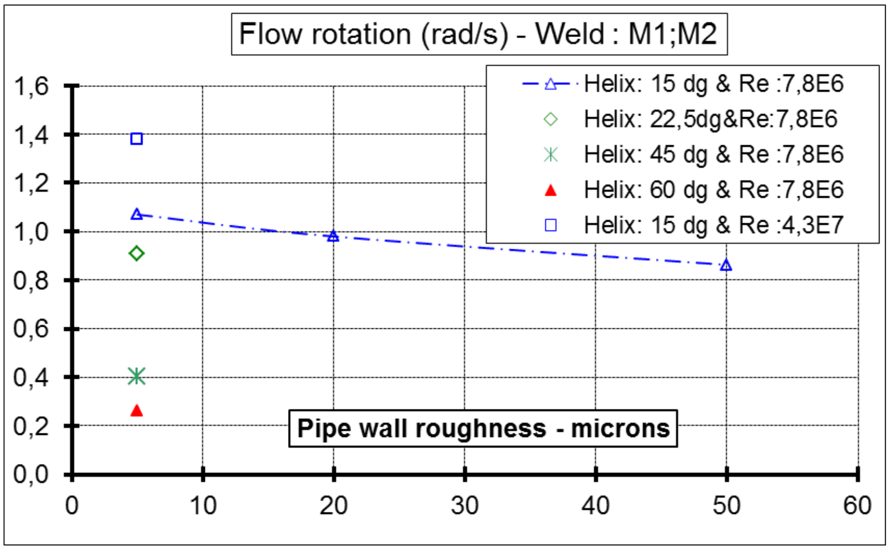


Figure 3.4.3 - Speed of rotation of the flow around the pipe axis versus the pipe wall roughness for several helix angles. Pipe characteristics: 610 mm diameter and "M1;M2" weld type.

3.4.5. Effect of the pipe diameter

The speed of rotation was analysed for several pipe diameters ranging from 24 inch (610 mm) to 42 inch (1321 mm). This was performed at:

- a constant Reynolds number (7.8E6). In that instance, for a gas density of 37.2 kg/m3 and a viscosity of 1.17E-5, the Re number is kept constant by reducing the gas velocity from 4 to 1.85 m/s when the diameter is increased from 610 to 1321 mm.
- a constant viscous layer thickness. This is obtained for given gas density, velocity and viscosity (see equation below) by keeping the Reynolds number proportional to the pipe diameter.

Calculation of the viscous layer thickness: $e_{vis} = 5 \frac{D}{\text{Re}} \sqrt{\frac{8}{f}} = 5 \frac{\mu}{V\rho} \sqrt{\frac{8}{f}}$

For a constant Reynolds number, the rotating motion is considerably reduced by increasing the diameter. This occurs for two reasons: the gas velocity (and therefore, the local Reynolds number) is reduced proportionally to the reciprocal of the diameter and the axial distance between two rows of a spiral weld is increased proportionally to the diameter.

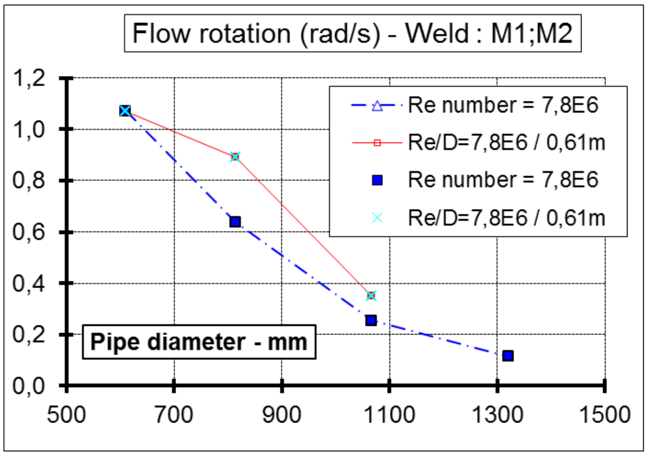


Figure 3.4.4 - Speed of rotation of the flow around the pipe axis versus the pipe diameter for several pipe Reynolds numbers. Pipe characteristics: 610 mm diameter, "M1;M2" weld and 15 degrees helix angle.

For a constant viscous layer thickness, the rotating motion is reduced but not as much as in the previous case as only the axial distance between two rows of a spiral weld is increased in this second case.

4. Pressure losses

4.1. Pressure loss of a spiral weld in a specific case

The pressure loss due to a spiral weld is calculated, in the following paragraphs, relatively to a straight pipe (no weld) as below:

$$DP_{weld\_rel} = 100\left(\frac{DP_{with\quad weld}}{DP_{without\quad weld}} - 1\right) \text{ (relative pressure loss in percent)}$$

In the following paragraphs, a spiral weld is designated by two parameters *(h;w)* where *h* designates the weld height and *w* the weld width.

A 610 mm diameter pipe operating at a Reynolds number of 30 million is a relatively common case of production. Similarly, a weld with a height of M2 (Average industrial value) is also currently met into the industry. Under these conditions and with a 15 degree helix angle of the spiral weld, the total pressure loss of a spirally welded pipe is 179 % those of a straight pipe. In other words, a spiral weld generates an extra pressure loss of 79 % relatively to a straight pipe.

This pressure loss is, under similar conditions of pipe operation and weld characteristics, 20 times bigger than the loss produced by a junction weld. This may be explained by several considerations:

- on the basis of the same pipe length, the total helix length is considerably longer than the one of a junction weld. It increases as the helix angle is reduced. Also, locally, it is as disturbing to the flow as a junction weld when the helix angle is small (main flow almost perpendicular to the spiral weld). For instance, in the case of a 15 degree helix angle, the length of one helix row being approximately 0.5 m, in a 12 m long pipe, there are approximately 24 helix rows.

- in a spirally welded pipe, the core flow rotates slightly in the weld direction tending to increase the friction surface. The rotating speed is increased and therefore the friction losses are increased as the helix angle is reduced.

4.2. Effect of the Reynolds number

4.2.1. Pipe wall - Low roughness case

As the Reynolds number is increased, the flow disturbance near the weld increases, particularly downstream the weld (figures 3.2.1 to 3.2.3). At this location, the highly turbulent flow anneals a large part of the drag reduction provided by a smooth wall. In the case of:

- a “M1;M2” weld type, the relative pressure loss of the weld is 67 % at a Reynolds number of 7.8E6, increasing to 90 % at a Re nb of 4.3E7 up to 155 % at a Re nb of 1E8 (figure 4.1.a).
- a “L1;L2” weld type , the relative pressure loss of the weld is considerably bigger due to the larger weld height. It is of 160 % at a Reynolds number of 7.8E6, increasing up to 207 % at a Re nb of 4.3E7 (figure 4.1.b).

4.2.2. Pipe wall - High roughness case

As mentioned above, as the Reynolds number is increased, the flow disturbance near the weld increases, particularly downstream of the weld. However, despite this large disturbance, it does not cause relatively as much disturbance for a rough wall than it does for a smooth wall. In the case of:

- a “M1;M2” weld type , the relative pressure loss of the weld is 42 % at a Reynolds number of 7.8E6, reducing to 34 % at a Re nb of 4.3E7.
- a “L1;L2” weld type , the relative pressure loss of the weld is 107 % at a Reynolds number of 7.8E6, reducing to 80 % at a Re nb of 4.3E7.

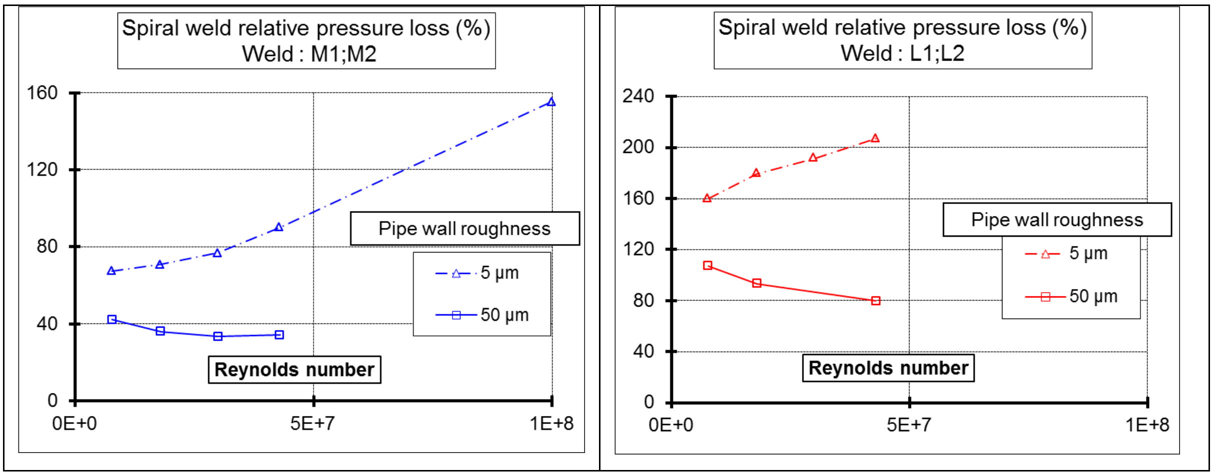


Figure 4.1 a - (left): Relative pressure loss of a spiral weld in a 610 mm dia pipe, 15 deg helix angle and “M1;M2” weld type versus Reynolds number for two values of pipe wall roughness. Figure 4.1 b - (right): as above but for a “L1;L2” weld type

4.3. Effect of the pipe wall roughness

The combined effect of the pipe wall roughness and the pipe Reynolds number may be seen on figures 4.2.a and b, respectively, for two weld types, "M1;M2" and "L1;L2", showing similar trends at high and low Reynolds numbers between the two weld types.

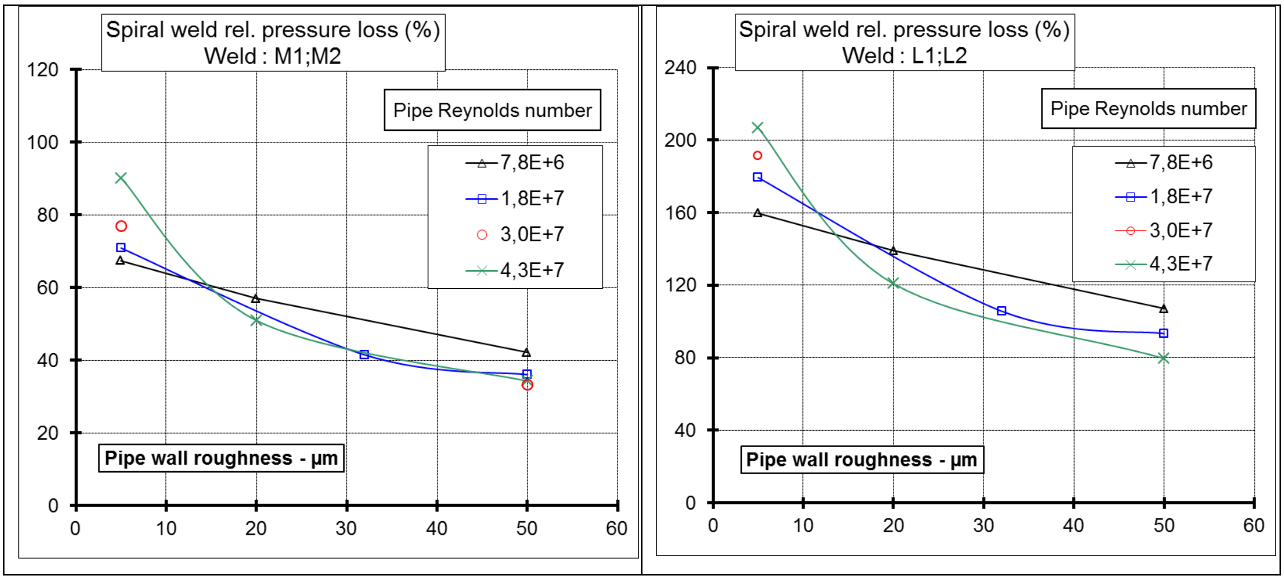


Figure 4.2 a - (left): Relative pressure loss of a spiral weld in a 610 mm dia pipe, 15 deg helix angle and "M1;M2" weld type versus the pipe wall roughness for several Reynolds number values. Figure 4.2 b - (right): as above but for a "L1;L2" weld type

In a general manner, the relative pressure loss of the weld decreases as the wall roughness is increased considering that the disturbance of the flow near the weld is less penalizing in the case of a rough wall than in the case of a smooth wall. However, the relative effects are significantly different at low and high Reynolds numbers.

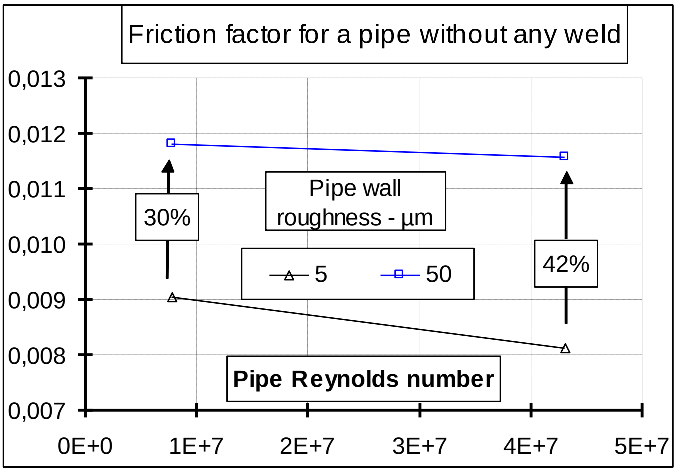


Figure 4.3 – Variation of the friction factor of a straight pipe (no weld) from low to high wall roughness versus the Reynolds number.

At a high Reynolds number, the friction factor, therefore the pressure loss, is more sensitive to the roughness than at a low Reynolds number. Therefore for a "L1;L2" weld type and a large Reynolds number :

- *in a low roughness case*, the presence of a weld is very penalising (207 % at a Re nb of 4.3E7 for only 160 % at a Re nb of 7.8E6) due to the very large pressure loss reduction provided by the smooth wall without a weld.

- *in a high roughness case*, the pressure loss provided by the wall roughness being considerably larger, the presence of a weld is comparatively less penalising (80 % at a Re nb of 4.3E7 but 107 % at a Re nb of 7.8E6).

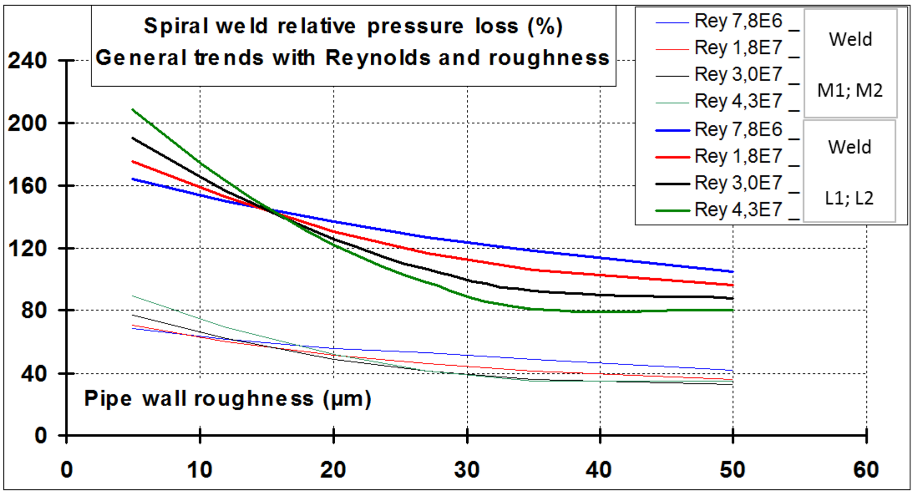


Figure 4.4 – Prediction of the relative pressure loss due to spiral welds following extension (root mean square) of CFD calculations. Results presented for two weld dimensions.

4.4. Effect of the weld dimensions

4.4.1. Weld width

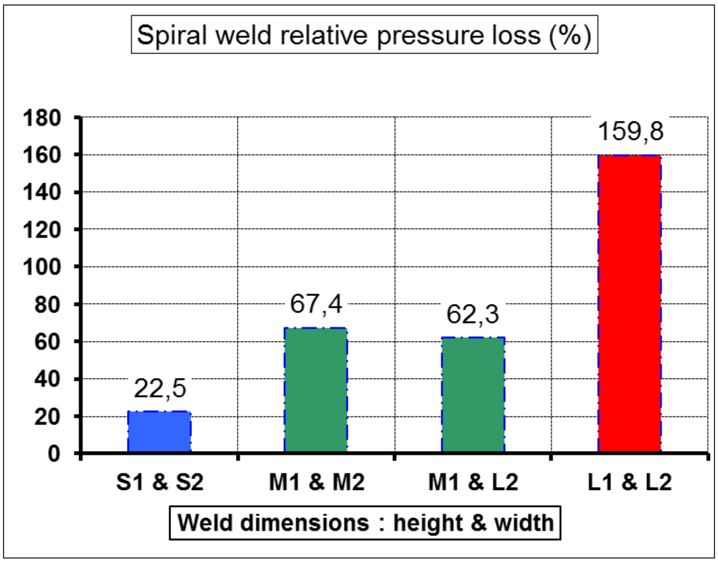


Figure 4.5.a – Relative pressure loss for several weld types. Flow conditions: 610 mm dia. pipe, 7.8 E 6 Reynolds number and 15 deg helix angle.

The pressure loss of a spiral weld has been studied for two very different values of the weld width (M2 and L2 mm) and for the same weld height (M1 mm). It may be seen from figure 4.5.a that despite the relatively large variation of the weld width, this parameter has little effect on the relative pressure loss of the weld.

The calculation indicates that when the weld width is increased the pressure loss is slightly reduced. This may be explained by considering that a sharper obstacle (small width) tends generally to provide a larger flow disturbance.

The calculation results corresponding to the above two weld widths have been used to estimate the effect of the weld width / length ratio in the 2.33 – 6.67 range.

4.4.2. Weld height

Contrary to the weld length, the weld height is a first order parameter for predicting the pressure loss at a spiral weld (figure 4.5.a).

The relative pressure losses of weld "L1;L2" have been compared to the relative pressure losses of weld "M1;M2" in dividing the values of weld "L1;L2" by the corresponding ones for weld "M1;M2" (at same pipe wall roughness and at same Reynolds number).

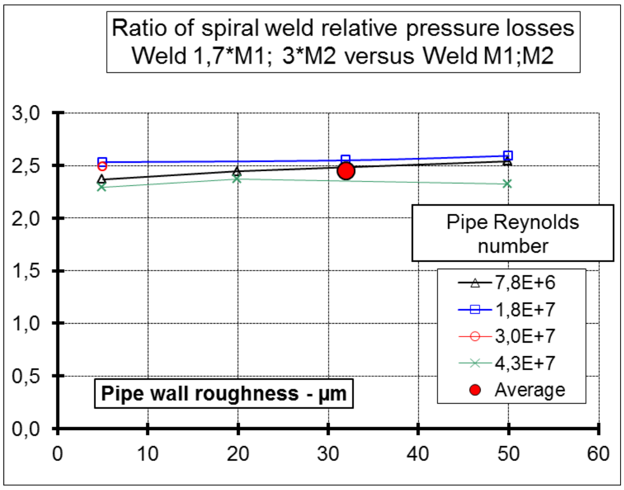


*Figure 4.6 – Ratio of relative pressure loss for weld 1.7 M1;3*M2 by relative pres. loss for weld "M1;M2" versus pipe wall roughness for several values of Reynolds number.*

Results are presented on figure 4.6 showing that the corresponding values are translated by a ratio of approximately 2.45 (average value). This ratio is slightly smaller at the largest Reynolds number (2.3) and slightly larger at the smallest Reynolds number (2.6).

At this stage, it may be concluded that all relative pressure loss values corresponding to spiral welds "M1;M2" and "1.7 M1;3*M2" may be predicted from each other by multiplying or dividing them by a coefficient of 2.45 based on the same condition of Reynolds number and pipe wall roughness.

4.4.3. Generalisation of pressure losses

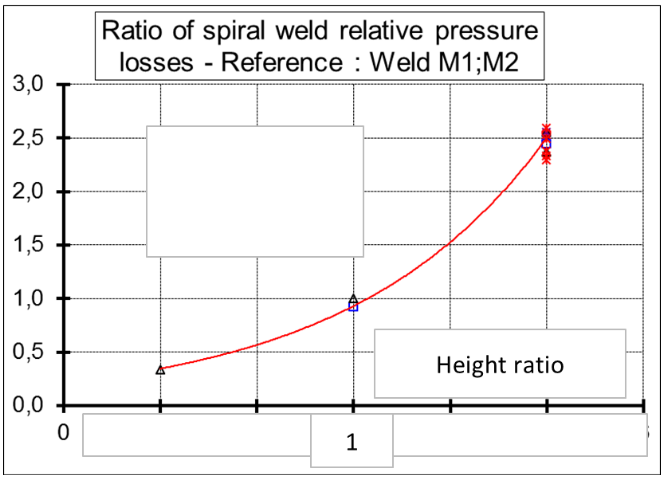


Figure 4.7 – Ratio of relative pressure losses for several weld height ratios- Relative pressure loss reference provided by weld "M1;M2"

Ratio values obtained from relative pressure losses of welds “S1;S2” to “L1;L2” have been plotted on figure 4.7 taking the weld “M1;M2” as a reference. These values are represented versus the weld height ratio.

4.5. Effect of the helix angle

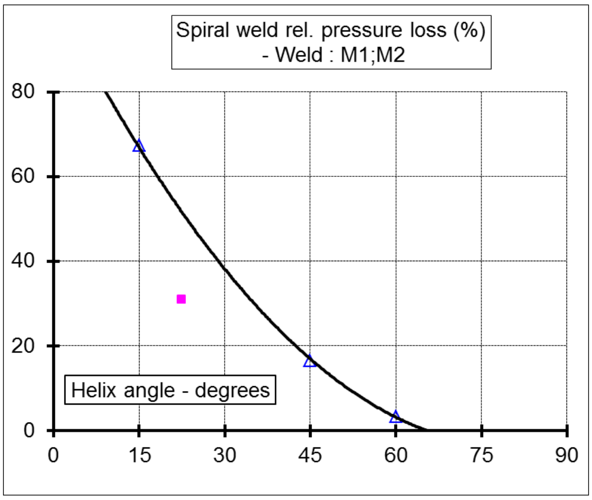
The calculation of the relative pressure loss caused by a spiral weld has been performed for three helix angles: 15, 45 and 60 degrees and for the following pipe and flow conditions, diameter: 610 mm, weld type: “M1;M2”, wall roughness: 5 µm and at a Reynolds number of 7.8E6.

Considering that for helix angles of 0 and 90 degrees the relative pressure loss due to the weld is, respectively, extremely large and nil, the trend of the pressure loss versus the helix angle is as represented on figure 4.8.

In the first extreme case (very small helix angle), the obstacle is almost perpendicular to the main flow and the weld covers almost entirely the pipe wall. In that instance, the losses are maximum tending towards extremely large values. In an extreme theoretical case, when the angle is exactly zero, there would not be any gap between the weld rows and therefore no energy dissipation (some sort of smooth surface in that extreme condition). However, this very extreme case is not of any interest to the present study.

In the second extreme case (90 degrees), the weld is in direction of the main flow therefore it does not constitute any more an obstacle to the flow.

For the smallest studied helix angle (15 degrees), the relative pressure loss is of 67 %. Above 15 degrees, the variation of the relative pressure loss is relatively linear with the helix angle until 45 degrees. Above 45 degrees, the relative pressure loss becomes relatively small tending asymptotically towards zero.



Figures 4.8 – Relative pressure loss versus the helix angle in degrees. Flow conditions: 610 mm dia. pipe, pipe wall roughness = 5µm, 7.8 E 6 Reynolds number and “M1;M2” weld type

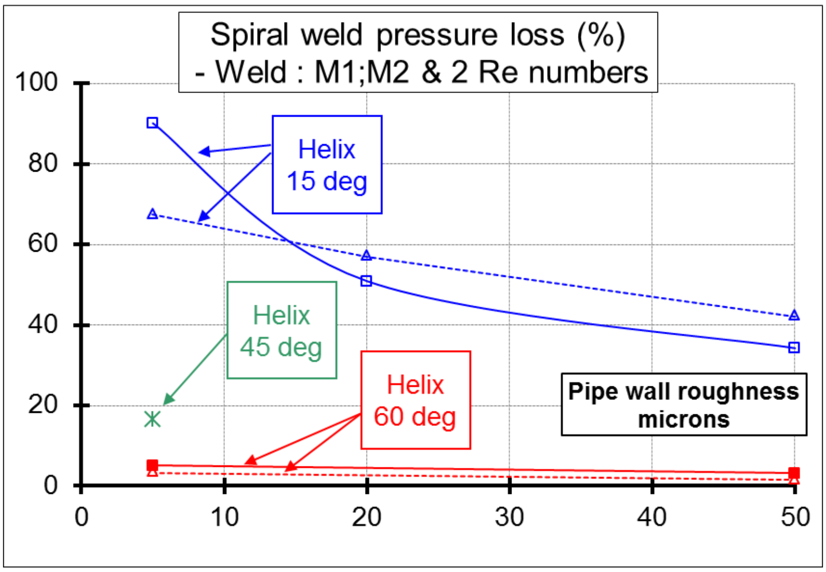


Figure 4.9 – Relative pressure loss versus pipe wall roughness for several helix angle and pipe Reynolds number conditions. Flow conditions: 610 mm dia. pipe and "M1;M2" weld

The variation of the relative pressure loss versus the pipe wall roughness is represented on figure 4.9 for several values of the helix angle and of the Reynolds number.

4.6. Effect of the pipe diameter

The calculation has been performed for four diameters: 610, 813, 1067 and 1321 mm representing pipe diameters in inches of 24, 32, 42 and 52 inches (nominal values). The effect of the pipe diameter was analysed in the case of a pipe wall roughness of 5µm, a weld type of "M1;M2" and a helix angle of 15 degrees.

The effect was analysed first by considering the same Reynolds number for all pipe diameters. This means that for constant gas viscosity (absolute) and density, the gas velocity varies with the reciprocal of the pipe diameter.

Pipe diameter-mm	610	813	1067	1321
Gas velocity-m/s	4.00	3.02	2.30	1.85
Reynolds number, viscosity and density	7.8 E 6, 1.17 E -5 Pa.s and 37.2 kg/m3			
Vis. layer thickness	12 µm	16 µm	21 µm	26 µm

The variation of the relative pressure loss versus the pipe diameter is represented on figure 4.10 showing a maximum for the relative pressure when the pipe diameter is of the order of 750 mm. This may be explained in the following manner:

- from 750 mm, as the pipe diameter is increased, the axial distance between two welds is increased proportionally providing a relatively longer distance between two welds without flow disturbance. As a consequence, the pressure loss due to the weld tends relatively to reduce over a constant pipe length.
- from 750 mm, as the pipe diameter is reduced, the axial distance between two welds is reduced proportionally. However, considering the total axial length *Ld* corresponding to the flow disturbance upstream and downstream the weld and the axial length *Lw* separating two rows of a spiral weld, when *Lw* becomes smaller than *Ld*, there is not

enough length for a full development of flow disturbances each side of the weld. Therefore, the relative pressure loss of the weld tends to reduce.

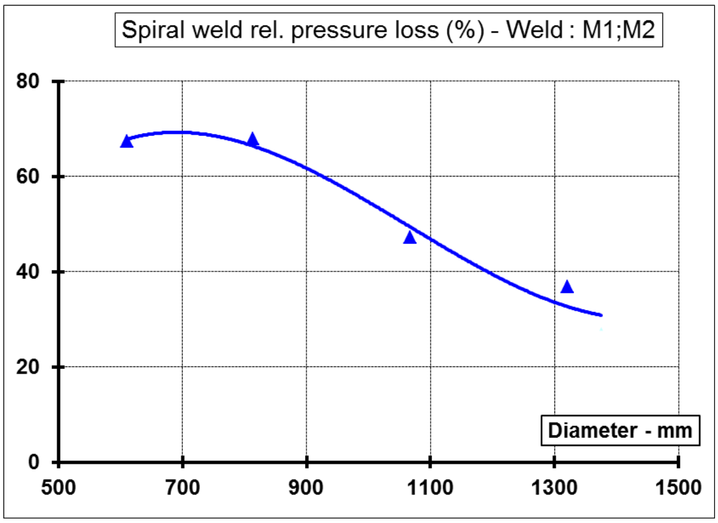


Figure 4.10 – Relative pressure loss versus the pipe diameter in the case of a constant pipe Reynolds number. Flow and pipe conditions: 5 µm wall roughness, M1;M2 weld type and 15 degree helix angle.