Numerical simulation in pipes with leakages

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Synopsis

Petroleum and marine technology applications and infrastructures consist of extended pipelines' networks in order to accommodate fluid transfer needs. The pipelines' leaks may occur and lead to high energy and working fluid losses, while most of the times these are related to environmental hazards. Additionally, corrosion problems are reported due to this un-desirable flow rate loss. In this paper the rheological behavior of the crude oil flow inside pipes with one or two leakages is numerically analyzed, studied and solved. Un-uniform and adaptive grids to the location of the leakages are generated in order to cover the specific requirements of the pipe domain, while finite volume methodology is followed for the discretization of the flow equations. The type of the oil has been received to be the Arabian light one, while an approach is developed for its properties. The boundary conditions are the corresponded flow rate – pressure flow conditions for all the exits of the pipe due to the better control of the algorithm that they usually provide. Various test cases have been developed for different Reynolds number values, providing robust and accurate results concerning the velocity and pressure distribution. It seems that high pressure variation is depicted near the location of the leaks, and in this way a clear indication is occur for such phenomenon.

Keywords: Numerical calculation, pipe with leakages, incompressible flow, crude oil flow

1. Introduction

Important and interesting research have been recently developed focus on leak detection. Mathematical modeling or experimental units' development in combination sometimes with electronic automatic control systems circuits (Sun, 1998), are the most popular general ideas which have been presented.
Baghdadi (1998) presents a very good validation of his results with the corresponded experimental ones. However, the analytical

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approach of this field is not so simple and requires a lot of effort in order to provide accurate results for all the possible cases with multiple leaks. That is why the numerical solution of this problem is necessary, useful for the industrial sector and may accomplish many applications in a satisfied rate of response. A very good literature review and analytical presentation of the most popular leak detection techniques is presented effectively by Murvay (2012), who has succeeded to specify and connect the leak's requirements with the LDS technique. Concerning the numerical approach of the leak detection, it worth mentioning the pressure traverse calculation applied by Kam (2010), in order to monitor and detect the leaks at the subsea pipelines, or a stable and robust methodology for monitoring the leaks by Espinosa (2013), with promising results concerning the pressure drop identification.

Various computational approaches have been connected with multiphase flows, like the one of Tavares (2014), where a numerical model is developed using ANSYS with quite good accuracy. This commercial software has been used by some other researchers in order to attempt to monitor the leaks, applying different approaches concerning the grid generation or the boundary conditions application especially at the area of leaks (Araujo, 2014). Some leak detection techniques are developed in the literature with good monitoring results, as the pressure analysis technique which has been developed in Ostapkowicz work (2016) and the thermal monitoring detection, which is presented by Bhuiyan (2016). Most of the approaches are characterized by advantages and disadvantages according to the industrial flow application. However high industrial and chemical engineering interest is developed to the crude oils flows numerical estimation (Santos, 2014), (Georgantopoulou, 2016), where properties' calculation techniques must be explored and the recirculation zones according to the flow rate range have to be localized. The leak study and detection in such flows present high demand by the relating industries and present a challenge in order to manage and create a flexible, accurate and simple scheme, easy to be implemented in various cases by industrial engineers.

1.1 Aim and Objectives

In the present paper the monitoring of incompressible flows inside straight pipes with leaks is studied. It is attempted a numerical simulation and estimation of the aforementioned flow field to be developed, trying to predict the location of each leakage, according to the pressure sudden and unexpected variation. The Navier-Stokes equations are numerically solved along the channel. The crude oil flow is tested under the necessary assumptions for several Reynolds number values, while the estimation of its properties is explored and finally achieved applying the appropriate correlations. The behavior of the crude oil is numerical analyzed and presented under the influence of one leak inside the pipe while the detection of the leaks is achieved. The commercial software ANSYS - Fluent is used for the numerical scheme setting and development, while special treatment is presented concerning the way and the flow rate-pressure type of the boundary conditions application, the appropriate type and size of grid in order to receive high accuracy at the leaks' area with deduction of the computational memory simultaneously.

2. Mathematical modeling and numerical scheme

The numerical procedure, modelling, simulation and estimation of crude oil flows inside straight pipes with one leakage area will be presented. Although the steps that are followed are common for all the numerical techniques as well as ANSYS, a commercial software, will be used for the numerical estimation, special treatment will be applied concerning the type of the grid and the type of boundary conditions, investigating the influence to the accuracy of the results and detection of the leaks.

2.1 Physical domain geometry description

As the main aim of this paper is the study of the crude oil flow inside pipes with leakages, a straight pipe has been chosen as the physical domain containing no other particular characteristics. The dimensional characteristics of the pipe and the physical domain is depicted in Figure 1.

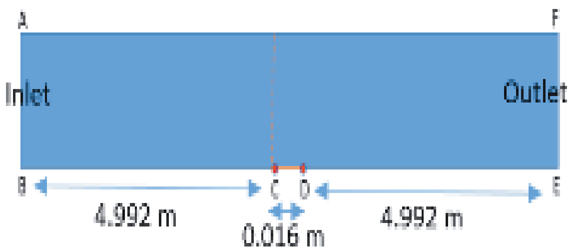


Figure 1: 2D Domain geometry description of the pipe with one (1) leak. (C, D)

The length of the pipe has been chosen in order to ensure that the flow will be fully developed after the leak's position, while the diameter of the pipe has been proposed by oil & gas companies as this was the most popular pipe size that they use before the refinery process for the crude oil transfer. It is known the length of the pipe has influence to the pressure distribution along it. However, as this flow application is mainly for crude oil pipelines, long pipe has been chosen (Espinosa, 2013). The problem can be set – up as dimensionless (D=1) and in this way all the extracted results can be modified according to the pipe diameter, although the length effect will be investigated in future research where flow estimation will be developed for short pipes as well.

The discharge ratio is important also for this type of study as it characterizes the relationship of the pipe and leakage flow. This is defined as per below:

$$Qr = \frac{Q_L}{Q_{in}} \quad (1)$$

where Qr is the flow ratio, Q_L the flow rate at each leakage and Q_{in} the flow rate at the inlet of the pipe. In this way we can test our numerical model for various ratios and explore mainly the influence to the pressure distribution along the pipe. If the above conditions remain the same, this ratio can be modified according to the diameter of the leakage or the number of leaks.

2.2 Grid type and generation

As the main problem is just the numerical simulation of flows inside straight pipes, Cartesian grids seems to be the first and simple choice for these cases. However after the first approach, huge number of computational cells is needed in order to achieve the desired accuracy at the leaks are due to the very low values of the aspect ratio $d_{p/}l$, where d_p is the diameter of the pipe and l the length of the main pipe. Due to this reason an adaptive grid approach is demanded and this cannot be achieved by the use of uniform Cartesian grids. The proposed mesh is a non-uniform one, presenting adaptation only at the positions of the leaks inside the pipe (Fig. 2). The aspect ratio plays a significant role to the final compilation of the flow model, where convergence difficulties are appeared at the final flow estimation stage.

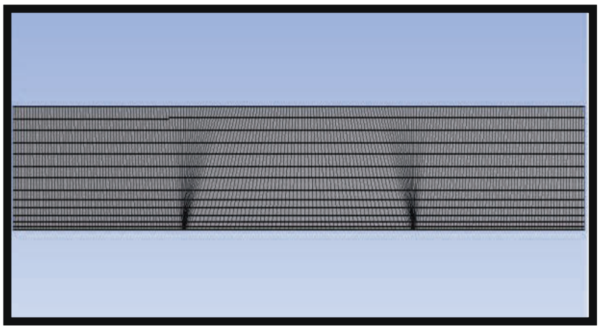


Figure 2: The adaptive non-uniform grid for the pipe with 2 leaks

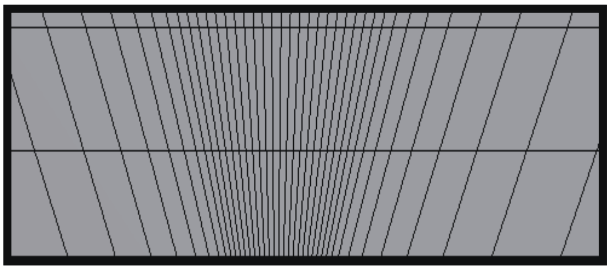


Figure 3: The meshing at the leakage location.

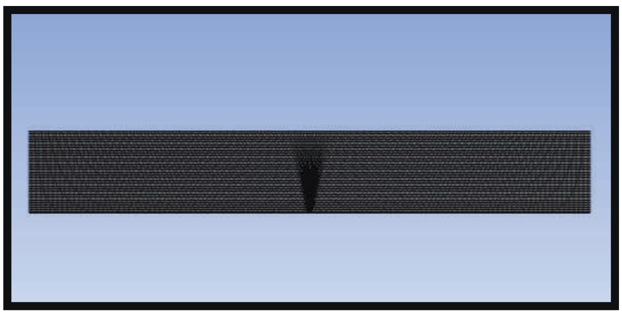


Figure 4: Mesh for the pipe with one leak

2.3 Flow rate – pressure boundary conditions

The initial and boundary conditions in every numerical simulation and estimation problem are fundamental for the accuracy of the results. Usually there are two main options for the boundary conditions setting in similar cases, the flow rate – pressure conditions and the pressure – pressure conditions (Espinosa, 2013). In this paper we have chosen to apply the flow rate – pressure conditions, believing that the numerical results will be more stable and robust when only in one bound of the domain we set the value of the pressure and we calculate the velocity (Georgantopoulou, 2017). The boundary conditions for this case are presented in Table 1 according to the physical domain geometry description (Figure 1).

Physical domain boundaries	Boundary conditions
Inlet, [AB]	$u = u_0, \frac{\partial p}{\partial x} = 0$
Outlet, [FE]	$\frac{\partial u}{\partial x} = 0, p = p_{ref}$
Wall conditions, [AF], [BE]	$u = 0, \frac{\partial p}{\partial y} = 0$
Leakage, [CD]	$\frac{\partial u}{\partial y} = 0, p = p_{ref}$

Table 1: Boundary Conditions

The flow has been chosen to be laminar in order to test the model in terms of accuracy and convergence time, with other similar simulations from the literature. The above symbols are: u, the velocity of the flow, p the pressure and *x,y* the Cartesian coordinates of the physical domain.

2.4 Crude oil properties

Crude oil is a naturally occurring, unrefined petroleum product composed of hydrocarbon deposits and other organic materials. Crude oil can be refined to produce usable products such as gasoline, diesel and various forms of petrochemicals. It is a nonrenewable resource, also known as a fossil fuel, which means that it can't be replaced naturally at the rate we consume it and is therefore a limited resource (Georgantopoulou, 2016).

The crude oil API gravity can be determined by the equation:

$$API\ Gravity = \frac{141.5}{Specific\ Gravity} - 131.5 \quad (2)$$

The American Petroleum Institute "API" has classified the different types of crude oil, the degree for measuring and classifying the crude oil is "API" which has its own formula. In order to classify the type of crude oil, the viscosity and "API" degree are important parameters although their specific calculation varies according to the methodology. Crude oil Properties

The crude oil type depends on the geographical source, the chemical consistency and its composition is not stable. There are various research approaches for the crude oil properties estimation based on empirical methods (Elsarkawi, 1999), (Minero, 2014) and (Alomair, 2014). In our case, we are mainly interested in studying the behavior of the crude oil in GCC and mainly in Bahrain. The crude oil type in this region is light and the API value of the Saudi Arabia – Arabian light according to the Energy Information Administration is 34.2 while according to Alomair (2014), the API value must be between 20 to 48 for Middle east crude oil. Choosing the Elsharkawy – Alikhan (1999) methodology in order to calculate the viscosity, we apply the following formulas:

μ= 〖antilog〗 _10 (x)-1 (3)

x= 〖antilog〗 _10 (y) (4)

y=2.1694-0.02525API-0.68875 〖log〗 _10 (T) (5)

where the dynamic viscosity can be predicted according to the operating constant temperature T. More extended analysis regarding the aforementioned area can be retrieved by the Georgantopoulou' s work (2016).

2.5 Governing Equations

As our numerical case is for incompressible, steady, laminar and viscous flows the Navier-Stokes equations in combination with the continuity one are solved. These can be seen below:

- The continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(rw)}{\partial y} + \frac{\partial(rv)}{\partial z} = 0 \quad (6)$$

- The X- momentum equation:
- $$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re}\left(\frac{\partial \tau_{\chi\chi}}{\partial \chi} + \frac{\partial \tau_{\chi y}}{\partial y} + \frac{\partial \tau_{\chi z}}{\partial z}\right) \quad (7)$$
- $The\ Y - \ momentum$
- $$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{Re}\left(\frac{\partial \tau_{\chi y}}{\partial \chi} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}\right) \quad (8)$$
- The Z-momentum
- $$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{Re}\left(\frac{\partial \tau_{\chi z}}{\partial \chi} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}\right) \quad (9)$$

where ρ the density, u,v and w the velocity components, p the pressure, x,y and z the Cartesian coordinates and τ the stresses.

In the below test cases, we assume that the flow is steady, viscid and incompressible. The corresponded crude-oil fluid is considered as Newtonian with constant chemical properties and no variation occurs in temperature during the flow (Araujo, 2014). The current case will be tested for low Reynolds numbers.

3. Results

The leakages influence to the velocity and pressure distribution to a straight pipe is going to be simulated, estimated and presented. The main reason of those outcomes is not only to localize the disturbance of the flow but also to provide certain information about the potential leakages to a piping system. This can be achieved because of the certain disturbance of the flow pressure, due to potential leakages and can produce a leakage prediction model. Several cases studies have been developed for three different values of the discharge ratio as well as Re number. The study will be developed for one along the pipe while it can be easily expended for more leaks as well. Important information and results are presented regarding the numerical model stability as well as the pressure distribution along the pipes, especially close to the leakages.

3.1 Incompressible pipe flow – 1 leakage

The flow inside a pipe with one leakage is numerical simulated and estimated. The flow is steady, laminar and incompressible. The liquid has been received to be crude oil, Arabian light type. The geometry description is presented to the Figure 5, while the specific dimensions of the physical domain can be found in Figure 1 as well. The crude oil flow has been numerically estimated for various low Re number values, (Table 2) and useful results have been produced regarding the velocity (Figure 6 and 7) and pressure distribution along the pipe as well as the behavior of the flow around or close the leakage area. As it can be seen in the below table_, the inlet velocity values are quite low as the flow has been received as laminar.

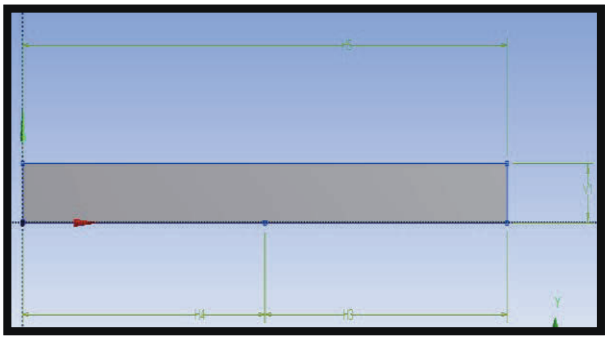


Figure 5: Geometry description of the pipe domain with one leakage area.

Reynolds number	Velocity (m/s)
100	3.045×10^{-3}
500	0.0152
750	0.0228
1000	0.0304
1500	0.04567

Table 2: Re number and inlet velocities

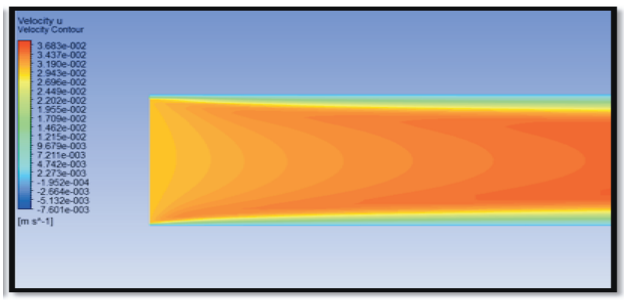


Figure 6: Velocity contour at the inlet of the pipe. Crude oil flow, Re=100.

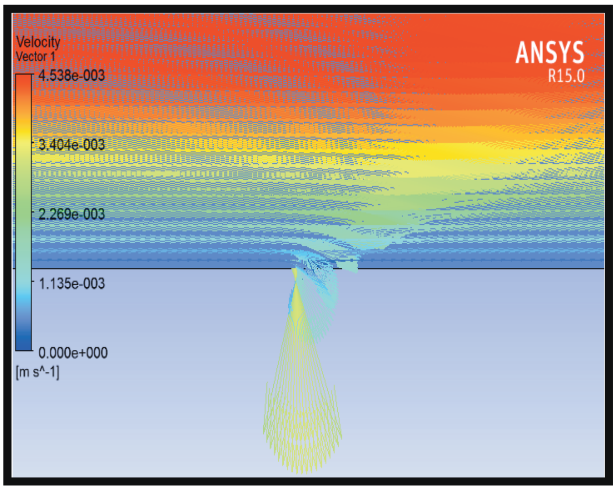


Figure 7: Velocity vectors along the crude oil flow field. Re=100.

In order to study the influence of the pipe leakage and determine a way of inspection the pressure distribution along the flow field is presented.

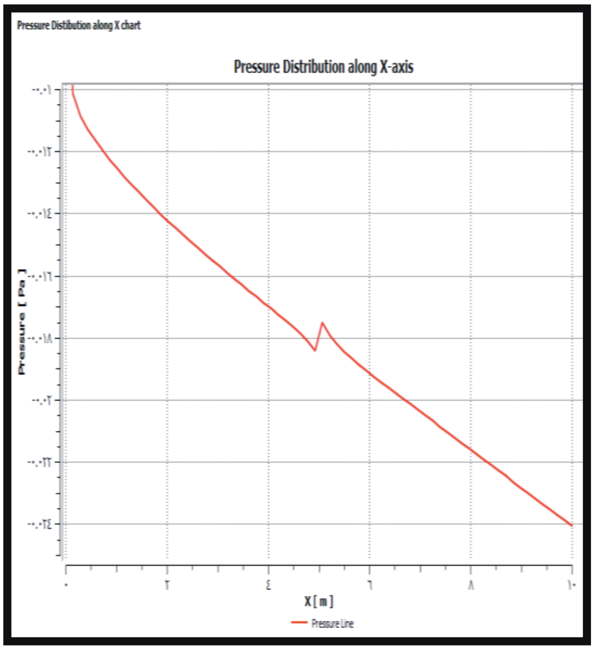


Figure 8: Pressure drop along the pipe, discharge ratio is equal to Re=100.

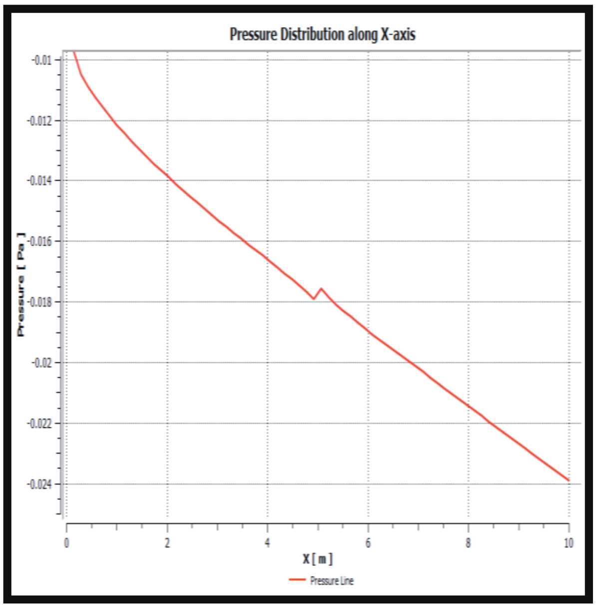
It is identified that it the leakage area an abnormal sudden pressure difference is developed and it is clearly stated that in that area leakage takes place.

In the Table 3 the various values of the mass flow rate as well as the inlet velocity are presented for different discharge ratios and Reynolds number values. According to the mass flow rate values, it is clearly identified the leakage mass flow rate. In our case the discharge ratio varies according to the leak diameter. However, the boundary conditions and the flow solver scheme remain the same.

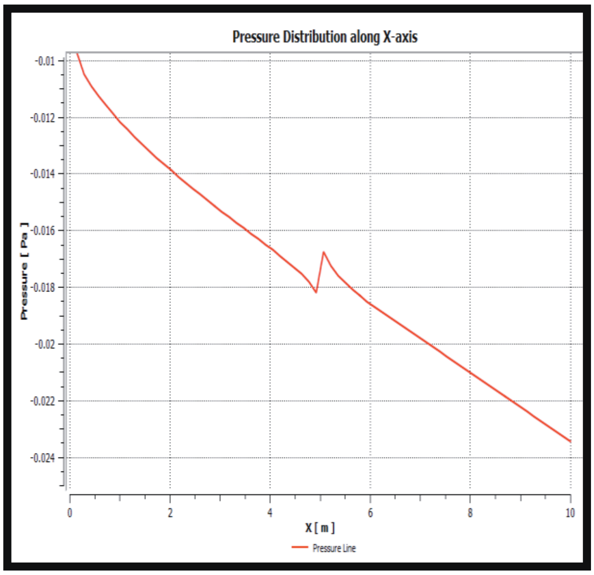
1 Leakage				
Disch. ratio	**Re**	**Mass flow rates (Kg/s)**		**Maximum Velocity (m/s)**
		Inlet	Outlet	
0.01	100	2.00009	1.98009	
	750	14.9760	14.8263	
	1500	29.9981	29.6981	
0.02	100	2.00009	1.96009	
	750	14.9760	14.6765	
	1500	29.9981	29.3981	
0.03	100	2.00009	1.94009	
	750	14.976	14.5268	
	1500	29.9981	29.1158	

Table 3: Mass flow rate for various discharge and Reynolds number values. 1 leak area along the pipe

The leaks' influence at Re number equal to 100 is detected, although is quite low due to the low flow rate value.



(a)

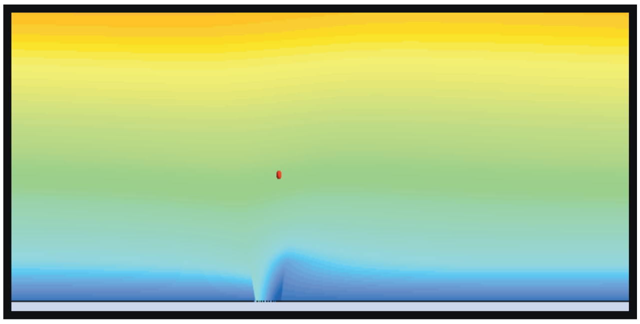


(b)

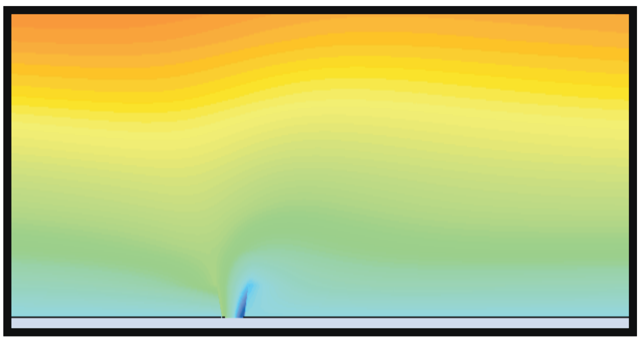
Figure 9 (a) and (b): Pressure distribution along the pipe with 1 leakage area. Re=100 and discharge ratio 0.01 (a) and 0.03 (b).

In the figure 9a and 9b, the pressure distribution and contours are presented along the pipe for two different values of the discharge ratio. It is obvious that if the discharge ratio is higher, which means that the leak diameter is larger, the pressure difference is higher as well

The velocity contours for Re=1500 and discharge ratio equal to 0.01 and Re=750 and discharge ratio equals to 0.01 are presented at the figure 10. Although the distribution and disturbance along the velocity field has been visualized as it was expected, it is difficult to be used for leakage detection. However, it is expected that in higher flow rates the velocity differences will be higher as well but still the pressure model will provide better leakage inspection accuracy and potential ability of analysis.



(a)



(b)

Figure10 a and b: Pressure contours close to the leak. (a) Re=1500 and discharge ratio 0.01 (b)Re=750 and discharge ratio 0.03

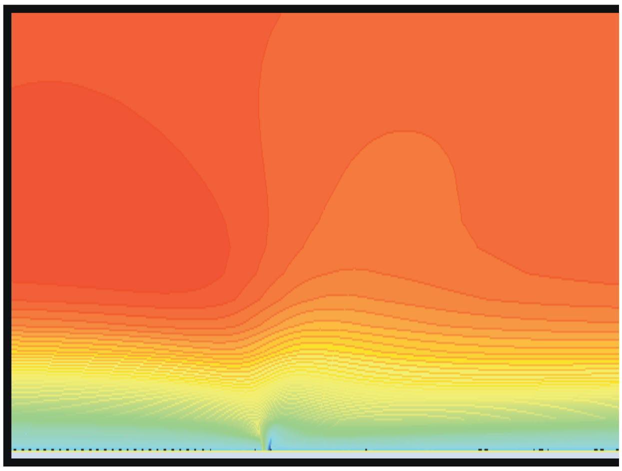


Figure 11: Velocity contour close to the leakage area. Re=1500 and discharge ratio equals to 0.03.

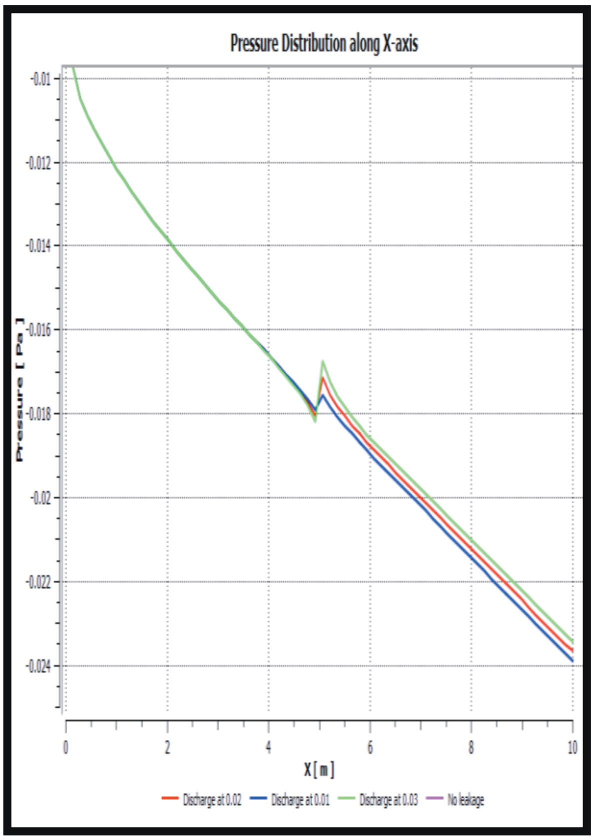


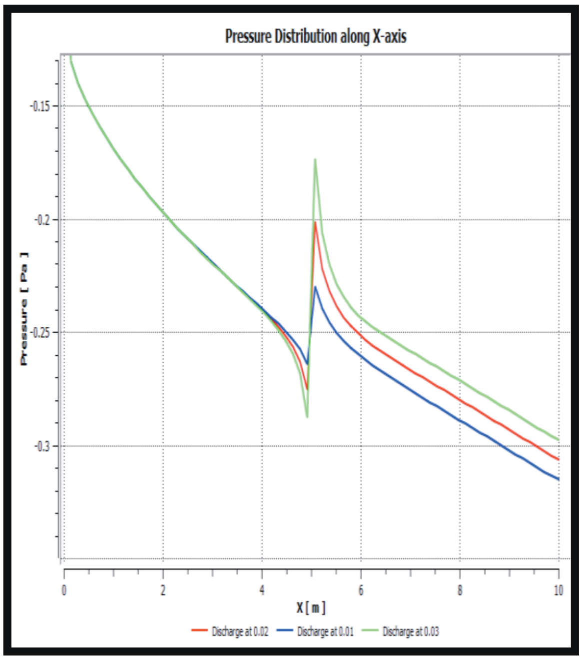
Figure 12: The pressure distribution along the pipe for different discharge rates for Reynolds number 100

In order to study the discharge ratio influence to the crude oil flow, the above figure 12 has been generated where the pressure drop is depicted for three different discharge ratio values. It seems that the higher the discharge ratio the higher the pressure disturbance as it was expected (Espinosa, 2013). The same conclusion is retrieved from the figure 13 where similar results are presented for Re=750 and Re=1500.

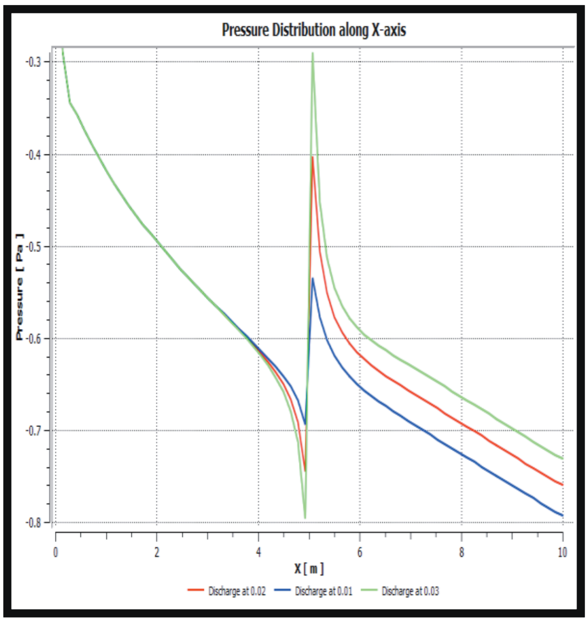
All the aforementioned pressure drop – distribution figures have been produced close to the leakage area in terms of the vertical coordinate as well in order to identify the major impact within the flow. However, although the major flow disturbance occurs close to the leak area, the crude oil flow is influenced across the diameter of the pipe direction as well. In the figure 14 the pressure distribution along the pipe at the mid of the pipe dimeter is presented where the disturbance of the flow is visualized.

However, the pressure “jump” can even more easily depicted in the pressure gradient contours. As it can be seen at the Figure 13, the pressure receives high values close to the leak position.

Figure 13: Pressure gradient contour where the pressure variation is visualized. Re=100.



(a)



(b)

Figure 13 (a) and (b): Pressure distribution along the pipe for the same Reynolds number 750 at different discharge rates equal to 0.01, 0.02 and 0.03. (a) Re=750 and (b) Re=1500

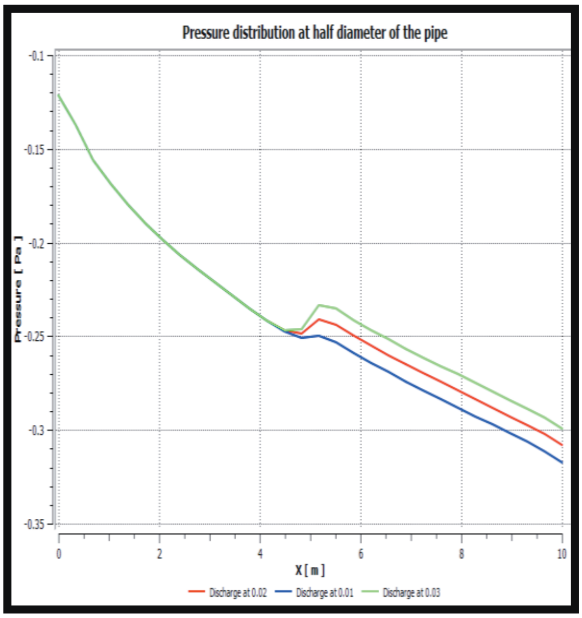


Figure 14: The pressure at half the diameter of the pipe for the same Reynolds number (750) but at different discharge rates

4. Conclusions

The crude oil flow has been studied along straight pipes in order to investigate the leak influence and disturbance in the flow along the pipe. Flow rate-pressure boundary conditions have been applied while an adaptive mesh has been generated in order to avoid the huge computation memory and accelerate the fluid solver convergence. Numerical results have been presented for low Reynolds numbers in order to test the numerical scheme. It is depicted that in the leakage area sudden pressure change is appeared in all cases in a similar manner which is a clear evidence of this flow phenomenon. The discharge ratio plays important role in the pressure variation and it depends on the leak and pipe diameter. The highest discharge ratio the highest pressure variation within the leak area. The same conclusion refers to higher Reynolds numbers as well. In general, the leak detection is more difficult to be achieved when the discharge ratio receives low values. However, if the pressure differences ranges receive an accurate range, the leak will be detected even if the discharge ratio is low. The crude oil properties have been calculated based on a proposed model but its behavior has been studied under certain assumptions at the moment for low Reynolds numbers values. The influence of the length of the pipe, the distance from the inlet and more number of leakages will be studied and presented in a future research paper.

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