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Title:

Optimizing crude oil flow behavior: Impact of pipe elbow design configuration on rheological characteristics

Presented by:

- **Souhila ABAD**
- **Sabrina OTSMANE ELHAOU**

Supervised by:

Dr. Bassam G.N. MUTHANNA

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DEDICATION

First of all, I would like to express my gratitude to Allah the Almighty, who has granted me the health, patience and courage to carry out this work.

To my dear mother, it is impossible to thank you enough for giving me life. No words can express the depth of my gratitude to you. Your presence has always been my source of strength, and without you, I would have achieved nothing. All the education I have received and the character I have developed are the result of your principles and efforts. You have paved the best path for my life. My mother, who finds happiness in my future, has never forgotten me in her prayers. I love you infinitely.

To my dear father, who sacrificed his life for me to become what I am today. I have grown, studied and succeeded thanks to you. You provided me with everything I needed, and it is because of you that I obtained this diploma. I am extremely lucky to have you as a parent.

To my husband for his great patience, I warmly thank him especially for his uninterrupted moral support and his numerous advice throughout my thesis.

To my dear brothers and sister, I wish you a future filled with joy, happiness, success and serenity.

To all my family, my cousins, and my friends, I thank you for your support and prayers for my success.

To all the people who encouraged me throughout my studies and my life, to all those who are dear to me, to all those who love me, and to all those I love, I dedicate this sincere recognition to you.

Abad SOUHILA

DEDICATION

I dedicate this modest work:

to the woman who suffered without letting me suffer, who never said no to my demands and who spared effort to make me happy, my adorable mother FATMA.

To the man who owes me my life, my success and my respect, to the one who has never forgotten me with recognition and gratitude, here I am today presenting to you the joy of the graduation ceremony, thanks to you I am here my dear dad KADER.

To my husband ISHAK who has never stopped encouraging me and supporting me throughout my studies, may cod protect him and give them luck and happiness.

To my lovely son RAKANE.

To my sister FARAH and the whole family, may god give them long and happy life.

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Abstract

Crude oil and natural gas are pivotal to Algeria's economy. Pipelines serve as important tools for safely transporting these fluids. Pipe bends play a central role in piping systems by altering fluid flow, but they are prone to issues such as corrosion and erosion from fluid flow and acceleration. Optimizing elbow designs can improve crude oil flow behavior and prevent damage to internal surfaces. This final project focuses on two primary parameters: varying bending radius and adjusting velocity. Four different geometries based on bending radius were designed and analyzed. Additionally, four different velocity values were examined. The results demonstrate that increasing the bend radius can reduce erosion and enhance fluid flow behavior. Furthermore, decreasing the velocity value reduces wall shear stress, contributing to improved pipeline performance.

Keywords : Crude oil; Pipeline; Bending radius; Velocity; Shear stress.

Resumé

Le pétrole brut et le gaz naturel sont essentiels à l'économie algérienne. Les pipelines sont des outils cruciaux pour transporter ces fluides en toute sécurité. Les coudes de tuyaux jouent un rôle central dans les systèmes de tuyauterie en modifiant l'écoulement des fluides, mais ils sont sujets à des problèmes tels que la corrosion et l'érosion causées par l'écoulement et l'accélération des fluides. Optimiser la conception des coudes peut améliorer le comportement de l'écoulement du pétrole brut sur les surfaces internes et prévenir les dommages à la paroi interne. Ce projet final se concentre sur deux paramètres principaux : la variation du rayon de courbure et l'ajustement de la vitesse. Quatre géométries différentes basées sur le rayon de courbure ont été conçues et analysées. De plus, quatre valeurs de vitesse différentes ont été examinées. Les résultats montrent que l'augmentation du rayon de courbure peut réduire l'érosion et améliorer le comportement de l'écoulement du fluide. En outre, la diminution de la valeur de la vitesse réduit la contrainte de cisaillement sur la paroi, contribuant ainsi à améliorer les performances du pipeline.

Mots-clés : Pétrole brut ; Pipeline ; Rayon de courbure ; Vitesse ; Contrainte de cisaillement.

الملخص

النفط الخام والغاز الطبيعي يشكلان جزءاً أساسياً من الاقتصاد الجزائري. تعتبر أنابيب النقل أدوات رئيسية لنقل هذه السوائل بطريقة آمنة. أكواع الأنابيب تلعب دوراً مركزياً في أنظمة الأنابيب من خلال تغيير تدفق السوائل، ولكنها عرضة للمشاكل مثل التآكل الناتج عن تدفق السوائل وتسارعها. يمكن تحسين تصميم الأكواع لتحسين سلوك تدفق النفط الخام على السطوح الداخلية والوقاية من التلف للجدران الداخلية. يركز هذا المشروع النهائي على معلمتين رئيسيتين: تغيير نصف قطر الانحناء وضبط السرعة. تم تصميم وتحليل أربع هندسيات مختلفة استناداً إلى نصف قطر الانحناء. بالإضافة إلى ذلك، تم فحص أربع قيم مختلفة للسرعة. توضح النتائج أن زيادة نصف قطر الانحناء يمكن أن تقلل من التآكل وتعزز سلوك تدفق السائل. علاوة على ذلك، تقليل قيمة السرعة يقلل من إجهاد القص على الجدار، مما يسهم في تحسين أداء الأنابيب.

الكلمات المفتاحية: النفط الخام؛ الأنابيب؛ نصف قطر الانحناء؛ السرعة؛ الإجهاد القصي

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CHAPTER I : OVERVIEW ON CRUDE OILS USED IN ALGERIA

CHAPTER III: RESULTS AND DISCUSSION

Nomenclature

α: Bending radius.

μ_o: Under saturated oil viscosity.

μ_{od}: Dead viscosity.

D: The pipe diameter.

k: Consistency index.

k-ω: k–omega turbulence model

n: Power law index (dimensionless).

R: Bend radius.

Re: Reynolds number.

v: Velocity.

γ: Shear rate

γ_o: Specific gravity of the oil.

ρ_w: Density of the water.

ρ_{oil}: Density of crude oil.

⍰: Shear stress.

Glossary of abbreviations

ad: adsorption state

Sol: solution state

API: American Petroleum Institute

CFD: Computational fluid dynamics

CO_2 : Carbon dioxide

H_2S : Hydrogen sulphide

O_2 : Oxygen

H_2O : Water

Fe : fer

H_2CO_3 : Carbonic acid

OH : Hydroxyde

H_3O : *i*on hydronium

GENERAL INTRODUCTION

General Introduction

Hydrocarbons play a important role in global energy supply. Their production is a challenge due to its high cost and through a complex service operation including network of pipes. Transportation from production sites to end-users also considers an important challenge to the companies. The increasing daily demand for hydrocarbons, such as natural gas and crude oil, highlights the importance of enhancing supply flow. Efficient production methods, particularly utilizing pipelines, are crucial for meeting this growing demand while ensuring cost-effectiveness and safety.

The oil and gas sectors are the backbone of the Algerian economy. According to the latest report issued by OPEC, Algeria held an estimated 12.2 billion barrels of proved crude oil reserves at the beginning of 2023 [1].

Pipe bends (elbows) are integral components used in these systems to transport petroleum fluids and alter their direction. However, they are prone to issues such as corrosion and erosion, influenced by mechanical, chemical, and environmental factors. Emulsions, complex rheological fluids composed of mixtures like oil with water, inhibitors, or gas, exacerbate corrosion issues. The global hydrocarbons industry spends billions annually addressing corrosion [2]. Researchers worldwide are intensifying efforts to control and mitigate this problem.

This project focuses on Computational Fluid Dynamics (CFD) analysis of pipe bends, taking into account the change of velocity value. This Master's project aims to explore solutions for managing corrosion in pipeline bends. It divided into three chapters with an introduction and conclusion.

- Chapter I discusses the significance of crude oil in Algeria, covering its importance, physical properties, rheological parameters, and mathematical models.
- Chapter II examines the corrosion phenomenon within piping systems, offering a comprehensive literature review on this complex issue. The chapter briefly outlines its processes, influencing factors, and types, and highlights various solutions employed by industrial companies.
- Chapter III presents the results and numerical analysis obtained from studying four different pipe elbow geometries.

CHAPTER I :

OVERVIEW ON CRUDE OILS USED IN ALGERIA

I.1 Introduction

Petroleum, a finite fossil fuel, is essential for global technological and economic growth due to its high energy density and chemical complexity. Despite new discoveries and a global shift towards decarbonization and alternative energy sources, oil remains a critical part of the energy and petrochemical mix until alternatives become sufficiently scalable and cost-competitive. Oil can enter the sea naturally, allowing marine organisms to adapt, but anthropogenic releases from exploration, production, and transport pose environmental risks. Understanding oil sources, quantities, and composition is crucial to minimize environmental impacts. In Algeria, the largest OPEC member in Africa by geographic area, the economy relies heavily on fossil fuels, with 12,200 million barrels of proven crude oil reserves, producing 1,157.1 thousand barrels per day and exporting 642.2 thousand barrels per day. The national oil and gas company, Sonatrach, manages these resources [3].

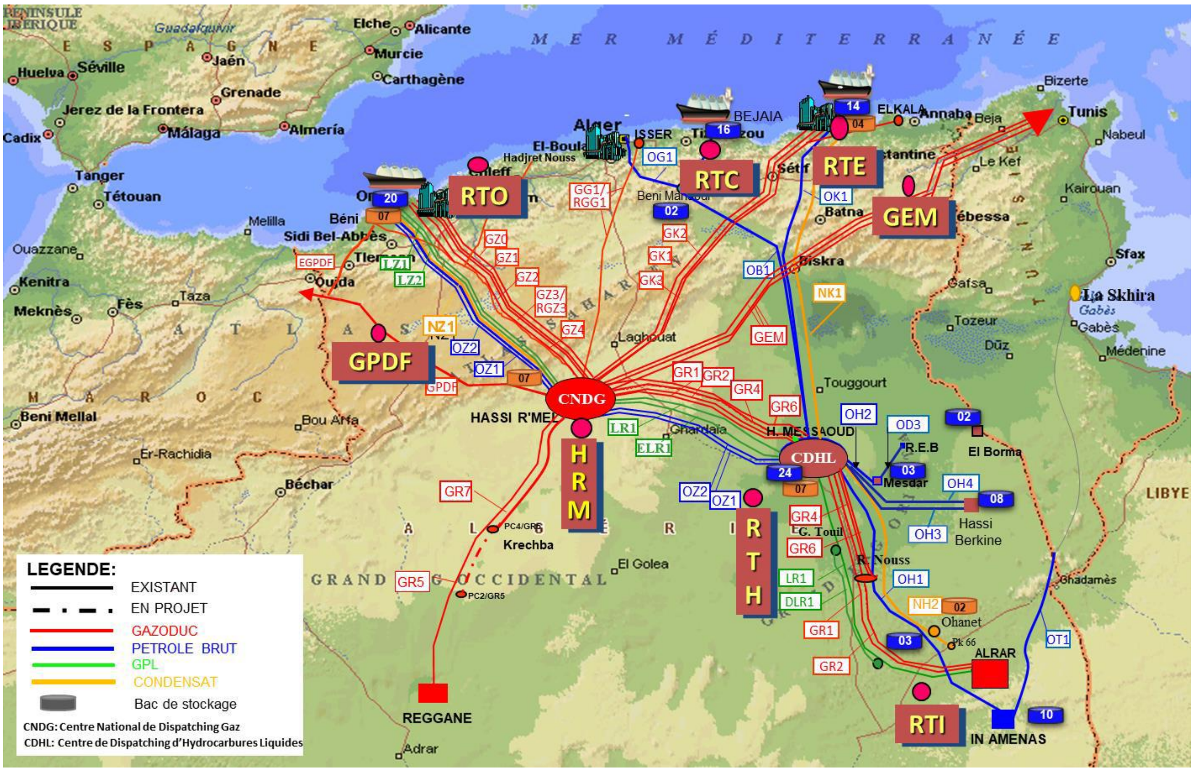


Figure I.1: Current Transport Network Mapping [3].

Table I.1 : Algeria's energy obtained from OPEC website [1].

	Crude oil	Natural gas	Coal	Nuclear	Hydro	Other renewables	Total
Primary energy consumption (quad Btu)	0.8	1.6	0.0	0.0	0.0	0.0	2.3
Primary energy consumption (%)	32%	67%	1%	0%	0%	0%	100%
Primary energy production (quad Btu)	2.8	3.8	0.0	0.0	0.0	0.0	6.7
Primary energy production (%)	42%	58%	0%	0%	0%	0%	100%

I.2 Types of crude oil

Oil investors are concerned about the quality and location of crude oil because prices are influenced by geopolitical factors, natural events, and organizational influences. Crude oil is classified into six categories based on sulfur content and density as shown in Table I.2 and Figure I.2 [4,5].

Table I.2 : Types of crude oil [4].

Type		Description
Heavy	Sweet	- Heavy oils are utilized in the production of industrial products such as asphalt and plastics.
	Sour	
Medium	Sweet	- Medium oils have sulfur content that falls somewhere between heavy and light.
	Sour	
Light	Sweet	- Light oils in Fuels - Used in diesel, gasoline, aviation fuel due to less processing - Sour crude requires more refining and incurs higher costs.
	Sour	

Figure I.2: Types of crude oil:heavy vs light, sweet vs sour [5].

I.3 Classification of fluids

Fluids are commonly classified into two types: Newtonian and non-Newtonian.

- **Newtonian Fluids:** For Newtonian fluids, the shear stress is proportional to the shear rate, with viscosity being a constant that depends on temperature and pressure, not on the flow boundary conditions. This means their dynamic viscosity remains constant regardless of the shear rate.

- **Non-Newtonian Fluids:** Non-Newtonian fluids exhibit more complex behavior and are modeled differently based on their rheological properties. There are two types of non-Newtonian fluids:

  1) **Without yield stress:** Includes dilatant fluids (n > 1) and pseudoplastic fluids (n < 1).

  2) **With yield stress:** Includes ideal fluids (Bingham plastics, n = 1) and non-ideal fluids (Herschel-Bulkley, n < 1).

Table I.3: Classification of fluids.

Type of fluid		Equation	Condition
Newtonian		$\tau = k\,\gamma$	$n = 1$
Non-Newtonian	Dilatant	$\tau = k\,\gamma^n$	$\tau_0 = 0$, $n > 1$
	Pesudoplastic	$\tau = k\,\gamma^n$	$\tau_0 = 0$, $n < 1$
	Bingham plastic	$\tau = \tau_0 + k\,\gamma^n$	$\tau_0 \neq 0$, $n = 1$
	H-B	$\tau = \tau_0 + k\,\gamma^n$	$\tau_0 \neq 0$, $n < 1$

I.4 Physical properties of crude oil

I.4.1 Crude oil gravity

Crude oil density is the mass of a unit volume of crude oil at a specific pressure and temperature. Specific gravity is the ratio of oil density to water density, measured at 15.5 °C and atmospheric pressure.

$$\gamma_0 = \frac{\rho_{oil}}{\rho_{water}} \tag{I.1}$$

Where $\gamma_0,\ \rho_{oil}, and\ \rho_{water}$ are specific gravity of the oil, density of the crude oil (kg/m^3), and density of the water (kg/m^3) respectively.

The density and specific gravity are widely used in the petroleum industry where API gravity is the preferred scale. API gravity is precisely related to specific gravity by the following expression:

$$API = \frac{141.5}{\gamma_0} - 131.5 \tag{II.2}$$

The API gravities of crude oils usually range from 47° API for the lighter crude oils to 10° API for the heavier asphaltic crude oils as indicated in Figure I.3.

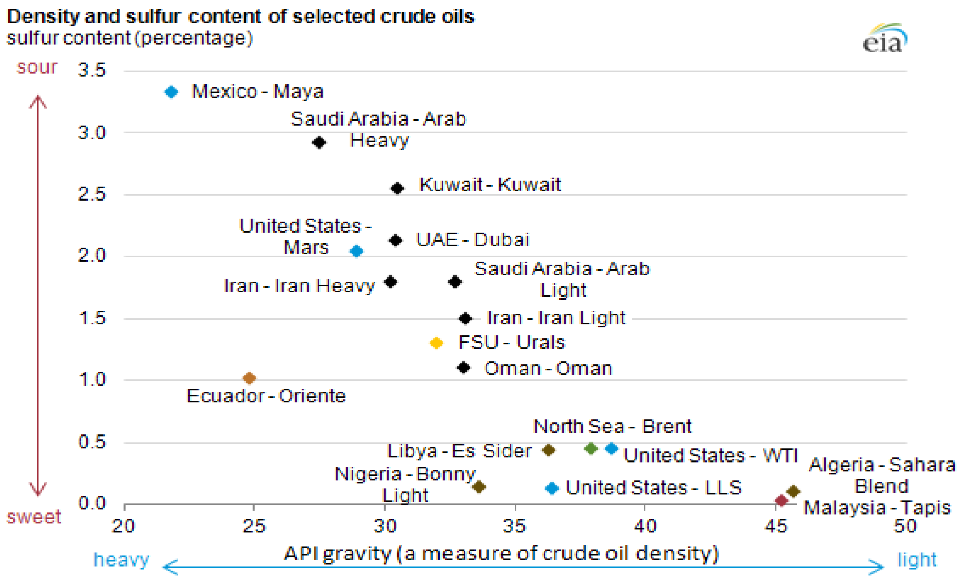


Figure I.3: Crude oils have different quality characteristics [6].

Algeria's oil resources produce high-grade, light, sweet crude oil with very low sulfur content. The primary crude oil grade in the nation is Sahara blend, a mixture derived from fields in the Hassi Messaoud region.

I.4.2 Crude oil viscosity

Crude oil viscosity is an important property that affects oil flow through porous media and pipes. It represents the internal resistance of the fluid to flow and is one of the most challenging oil properties to calculate accurately. Viscosity is influenced by temperature, pressure, oil gravity, gas gravity, gas solubility, and crude oil composition. Crude oil viscosity can be classified into three categories based on pressure:

1) **Dead oil viscosity**: This is the viscosity of crude oil with no gas in solution, measured at atmospheric pressure and system temperature.
2) **Saturated oil viscosity**: This is the viscosity of crude oil at any pressure less than or equal to the bubble-point pressure.
3) **Undersaturated oil viscosity**: This is the viscosity of crude oil at a pressure above the bubble-point and reservoir temperature.

I.5 Oil and petroleum products

Oil and petroleum products are essential for transportation, heating, road construction, electricity generation, and chemical production. Crude oil undergoes refining processes to break it down into various components, which are then selectively reconfigured into different products. These complex industrial facilities involve three fundamental steps as shown in Table I.4. These steps are important in the refining process, ensuring the production of diverse and useful petroleum-based products.

Table I.4: Refining processes.

Separation	• Pipeline crude oil through hot furnaces. • Discharge liquids and vapors into distillation units. • Atmospheric distillation unties in all refineries. • Vacuum distillation units in complex refineries.
Conversion	• Distillation converts heavy fractions into lighter, higher-value products like gasoline. • Fractions are transformed into intermediate components, eventually becoming finished products. • Cracking is the most common conversion method, using heat, pressure, catalysts, and sometimes hydrogen.

Treatment	• Combines various streams from processing units. • Octane level vapor pressure ratings determine blend.

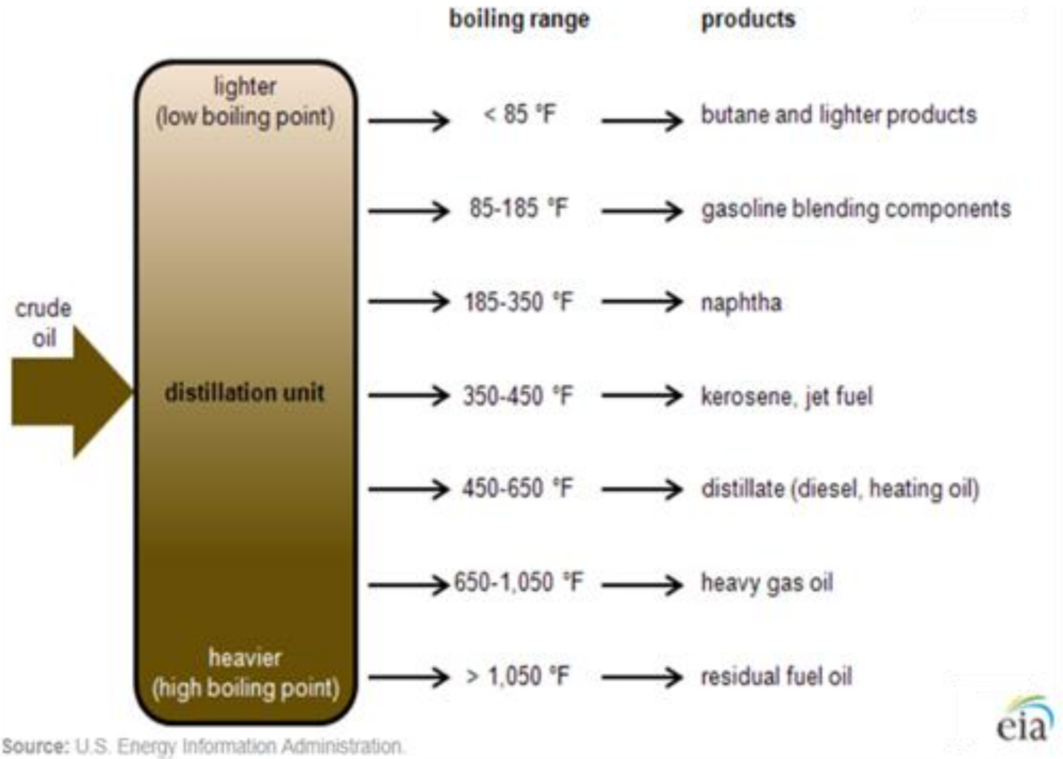


Figure I.4: Crude oil distillation unit and products [6].

I.6 Crude oil flow behavior

The transition from laminar to turbulent flow in crude oil is influenced by factors such as the geometry of the pipeline, surface roughness, flow velocity, and the inherent properties of the crude oil. Osborne Reynolds conducted seminal experiments in the 1880s to investigate this behavior. In the context of flow in a circular pipe, the behavior can be categorized as follows:

- For $Re \leq 2300$, the flow is laminar.
- For $2300 \leq Re \leq 4000$, the flow is transitional.
- For $Re \geq 4000$, the flow is turbulent.

Where Re represents the Reynolds number, which characterizes the fluid flow based on the balance between inertial and viscous forces within the pipe. It is specifically formulated for internal flow in a circular pipe as:

$$Re = \frac{\rho v D}{\mu} \quad \textbf{(I.3)}$$

Where v, D, and μ are velocity (m/s), diameter (m), and viscosity of the fluid (mPa.s), respectively.

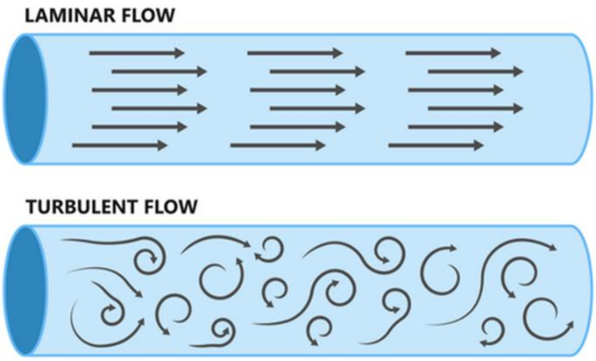


Figure I.5: Laminar flow vs turbulent flow in flow measurement.

Figure I.6 illustrates the velocity profile of crude oil in the internal surface of pipe elbow. These results conducted by Wang et al. [7]. They analysed three turbulent models to study multiphase flow in pipe elbows with sand particles and fluid attack.

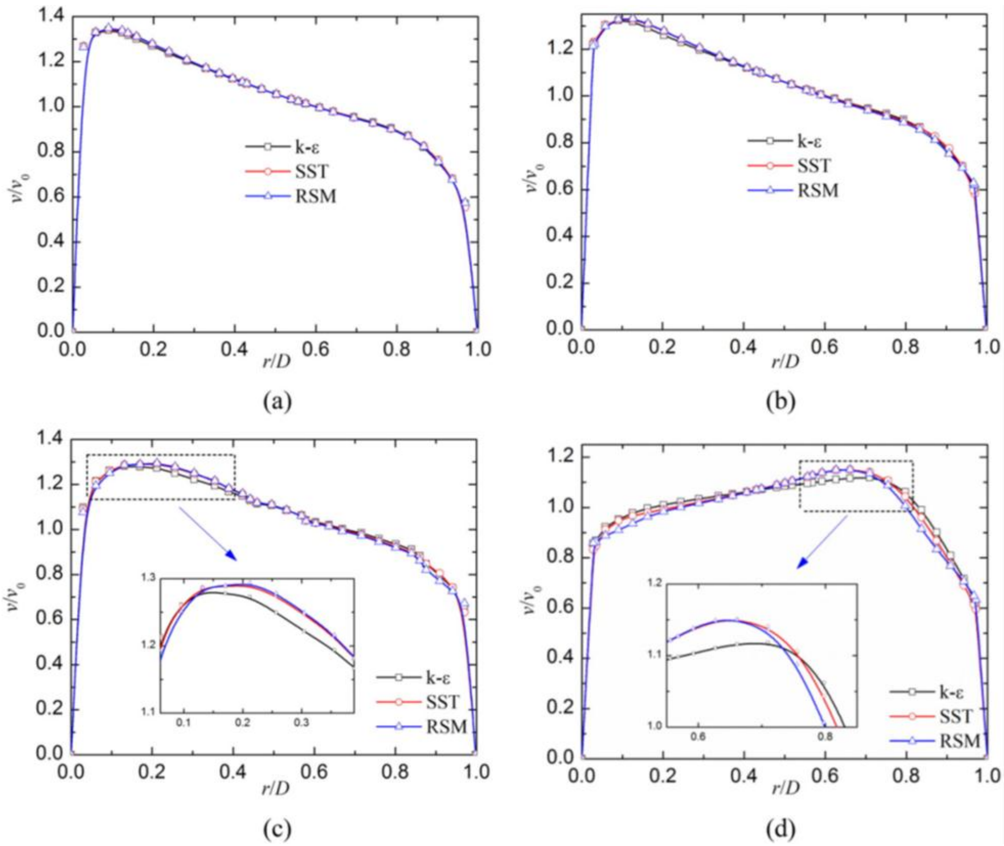


Figure I.6: Velocity profiles in a cross-section perpendicular to the elbow axis at (a) 30°, (b) 45°, (c) 60° and (d) 90° [7].

CHAPTER II :

OVERVIEW ON PIPELINE CORROSION

II.1 Introduction

Generally, the corrosion issue is defined as the physicochemical interaction between two different structural solids due to the contact. In our case study, the contact between internal surface of pipeline and fluid flow is the main factor may cause to the corrosion phenomenon. Therefore, the results of this problem can change the properties of steel and often a functional degradation of the pipeline itself. In other cases, the corrosion can be happened due to the interaction between external environment and external surface of piping system. In this chapter, general information and overview on the causes of corrosion phenomenon are discussed. In addition, some of mechanical and chemical elements that may responsible for this issue are expressed.

II.2 Corrosion problems in petroleum metallic structures

Corrosion occurs in the piping system due to different factors. It is considered as a natural operation which is difficult to eliminate it completely. Its reaction may turns the steel into different form of chemical compounds such as; oxide, hydroxide, or sulfide. This change in the material structure may cause to the progressive destruction or degradation.

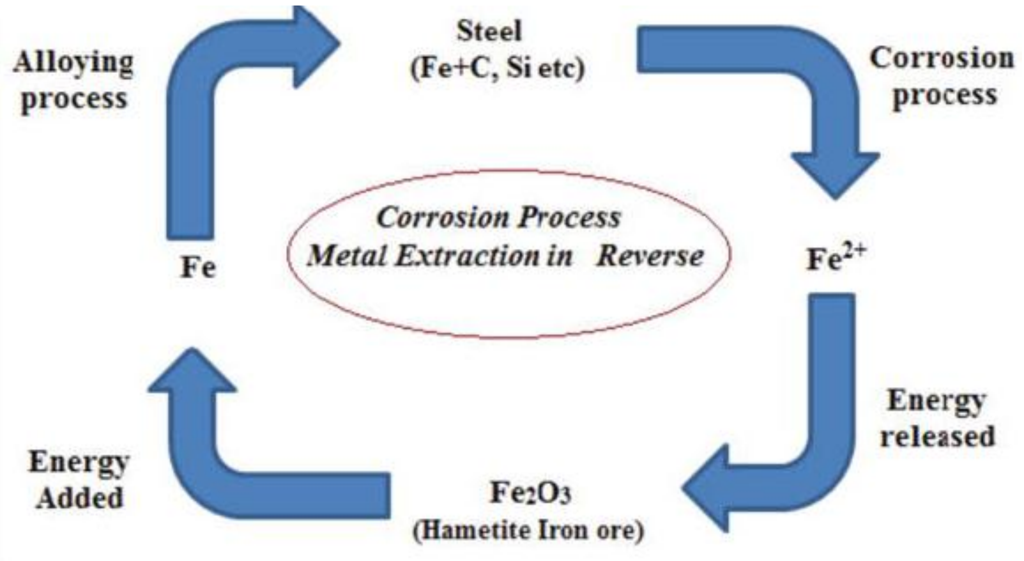


Figure II.1: Refining corrosion cycle process [8].

In the petroleum industries, the corrosion problem is always in presence especially in the refinery process. Figure II.1 shows the cycle process of corrosion in the metal reaction. Due to the oxidation results of corrosion process, solid structure losses the energy which cause the degradation and may stop its operation service

[8].

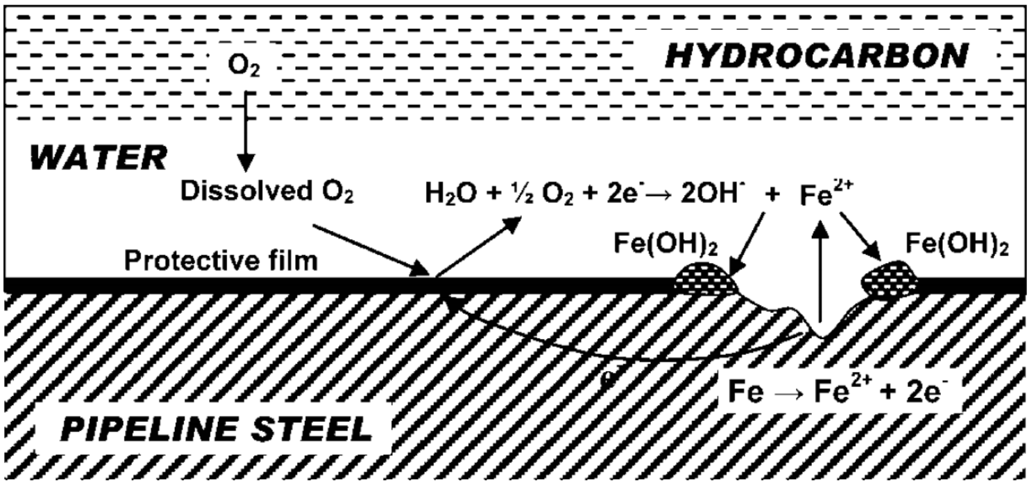


Figure II.2: An example of steel corrosion process [9].

The interaction between metal surface and fluid flow can cause to the oxidation which degrades the wall thickness as shown in Figure II.2. This process may expressed as the following reactions:

At cathode: $O_{2(g)} + 4H^{+}_{(aq)} + 4e^{-} \rightarrow 2H_2O_{(l)}$ **(II.1)**

at anode: $Fe_{(s)} \rightarrow Fe^{2+}_{(aq)} + 2e^{-}$ **(II.2)**

overall: $2Fe_{(s)} + O_{2(g)} + 4H^{+}_{(aq)} \rightarrow 2Fe^{2+}_{(aq)} + 2H_2O_{(l)}$ **(II.3)**

II.3 Different types of corrosion

Pipelines can be exposed to the corrosion issue as any other steels or metals. The corrosion is presented in different types which make the dangerous differs from type to other one. There are many different types of corrosion issue as follow:

- Generalized corrosion (uniform corrosion)
- Localized corrosion
- Galvanic corrosion
- Crevice corrosion
- Pitting corrosion

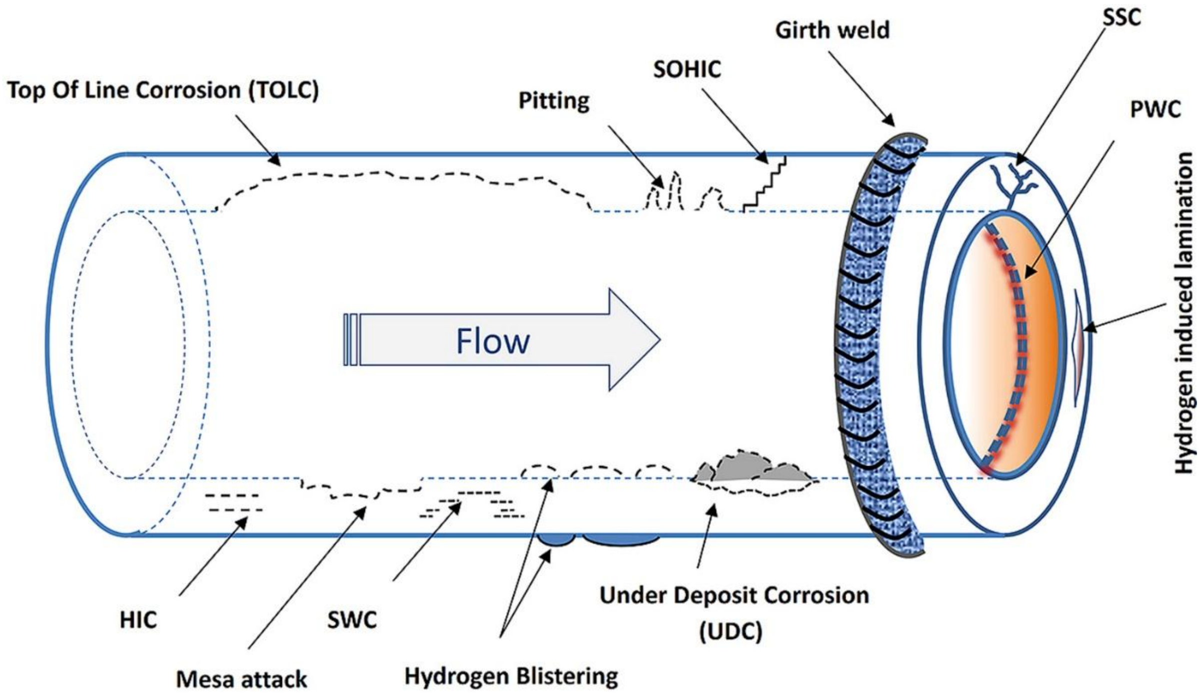


Figure II.3: Various types of corrosion forms in a pipeline [10].

II.4 Erosion and Corrosion

Erosion is a type of corrosion that occurs in pipelines due to the attack of flowing fluid on the wall surface or by small solid particles. This process causes the degradation of pipe wall thickness. Additionally, elbow steels are the components of piping systems most susceptible to erosion due to their curvature. Figures II.4 shows the degradation of wall thickness for 90° pipe elbow.

Ilman et al. [9] investigated an accident involving an offshore pipeline elbow. After 27 years of service, the pipeline steel failed. The primary cause of the failure was identified as internal corrosion on the underside of an API 5L X52 steel elbow, as shown in Figure II.5. The research demonstrated that the teardrop-shaped pits and grooves was caused by oxidation and the presence of water.

Another incident involving a pipe elbow in geothermal production was studied by Kusmono et al. [11]. As seen in Figure II.6, the failure occurred at the bottom elbow of the piping system. The erosion and corrosion processes in the elbow pipe are attributed to the presence of steam, water, and solid particles [11].

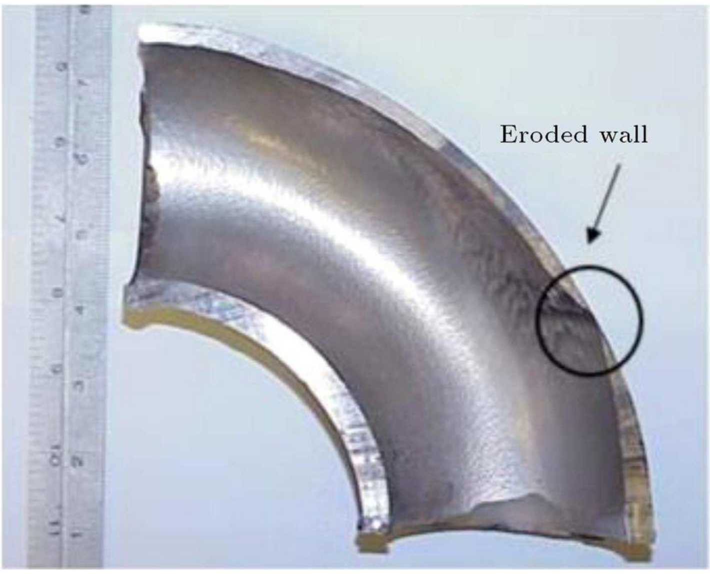


Figure II.4: Erosion corrosion for pipe elbow 90° [12].

Figure II.5: The location internal corrosion on subsea pipe elbow [9].

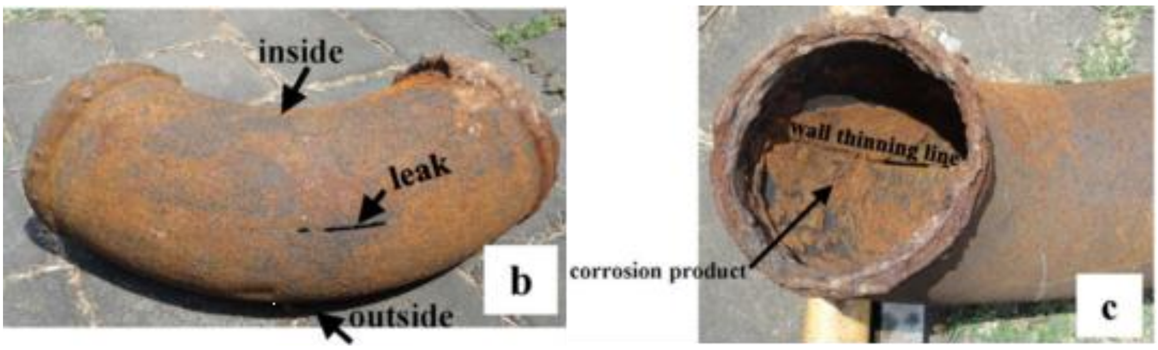


Figure II.6 : A view of failure location location and wall loss on pipe elbow, (a) external crack and, (b) internal wall loss [11].

II.4.1 Sweet corrosion (*CO_2*)

In the oil transportation, CO_2 and O_2 often are considered a responsible factor for corrosion problems due to activity of carbonic acid (H_2CO_3) with pipeline of low carbon steel. It is called as a sweet corrosion which happens in the absence of hydrogen sulfide (H_2S) or other compounds of sulfide. The most known reaction of sweet corrosion is the mixture of carbon dioxide (CO_2) with water (H_2O) which results the carbonic acid (H_2CO_3) as the following reactions:

$$CO_{2(sol)} \rightarrow CO_{2(ad)} \quad \textbf{(II.4)}$$

$$CO_{2(ad)} + H_2O \rightarrow H_2CO_{3(ad)} \quad \textbf{(II.5)}$$

$$O_2 + 2H_2O + 4e^- \rightarrow OH^- \quad \textbf{(II.6)}$$

$$H_2CO_{3(ad)} + H_2O \rightarrow H_3O^+ + HCO_3^- \quad \textbf{(II.7)}$$

$$HCO_3^- + H_2O \rightarrow H_3O^+ + CO_3^{2-} \quad \textbf{(II.8)}$$

$$H_3O^+ + e^- \rightarrow H_{(ad)} + H_2O \quad \textbf{(II.9)}$$

$$H_{(ad)} + H_{(ad)} = H_2 \quad \textbf{(II.10)}$$

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2 \quad \textbf{(II.11)}$$

where the subscript (sol) and (ad) refer to the solution state and adsorption state, respectively.

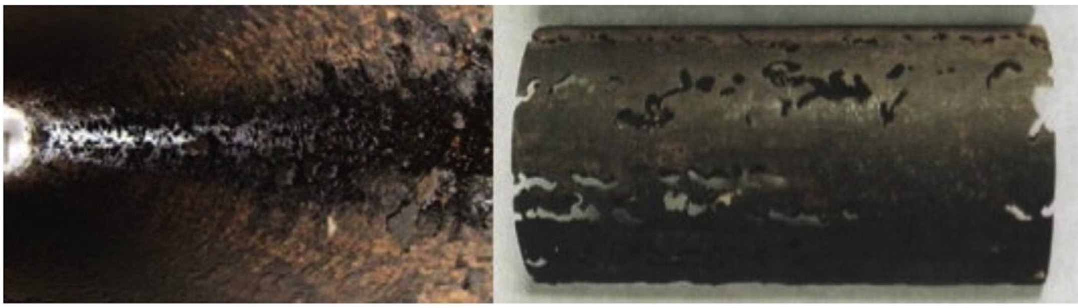


Figure II.7: Visual observation for corroded pipe of L485 steel due to CO_2 environment corrosive [13].

II.4.2 Sour corrosion (*H_2S*)

Sulfur (S) is also a serious element which is a responsible for pipeline corrosion. It is usually in presence with crude oil compositions. As shown in the following reaction (II.12-

II.15), sulfur (*S*) and hydrogen sulphide (H_2S) have an influence for initial cracks and create defects on the internal surface of pipeline wall.

$$RSH + H_2 \rightarrow RH + H_2S \qquad \textbf{(II.12)}$$

$$Fe + H_2S \rightarrow FeS + H_2 \qquad \textbf{(II.13)}$$

$$Fe(RCOO)_2 + H_2S \rightarrow FeS + 2RCOOH \qquad \textbf{(II.14)}$$

$$FeCl_2 + H_2S \rightarrow FeS + 2HCl \qquad \textbf{(II.15)}$$

II.5 Aspects of Corrosion

In addition to the degradation and deterioration causes due to the corrosion issue, there are different aspects can be occurred:

- Impermeability;
- Reducing of mechanical properties;
- Absence of assessment integrity;
- Change of physical properties;
- Damage to humans;
- Environmental Pollution;
- Damage to equipment and economical wastage;
- Stopping product components and operating services.

II.6 Corrosion protection methods

Most businesses have been maintaining, repairing, and welding for decades. The most popular techniques for preventing corrosion in the hydrocarbons field relied on controlling boundary conditions, pressure, temperature, the origin of the hydrocarbons (including whether undesired components are present), and the type of materials used in piping systems [14]. The following are the methods that are frequently employed in the field of hydrocarbon protection:

- Corrosion protection by different layers of coatings.
- Corrosion protection by natural and industrial inhibitors.
- Using the Composite materials at the critical zones.
- Using the welding operation for the ordinary materials

As a result, these methods lengthen the material lifetime of piping systems. To elucidate the prevalent solutions anti-corrosion, Figure II.8 illustrates the majority of corrosion-resistant piping system protection methods, accounting for both chemical and physical.

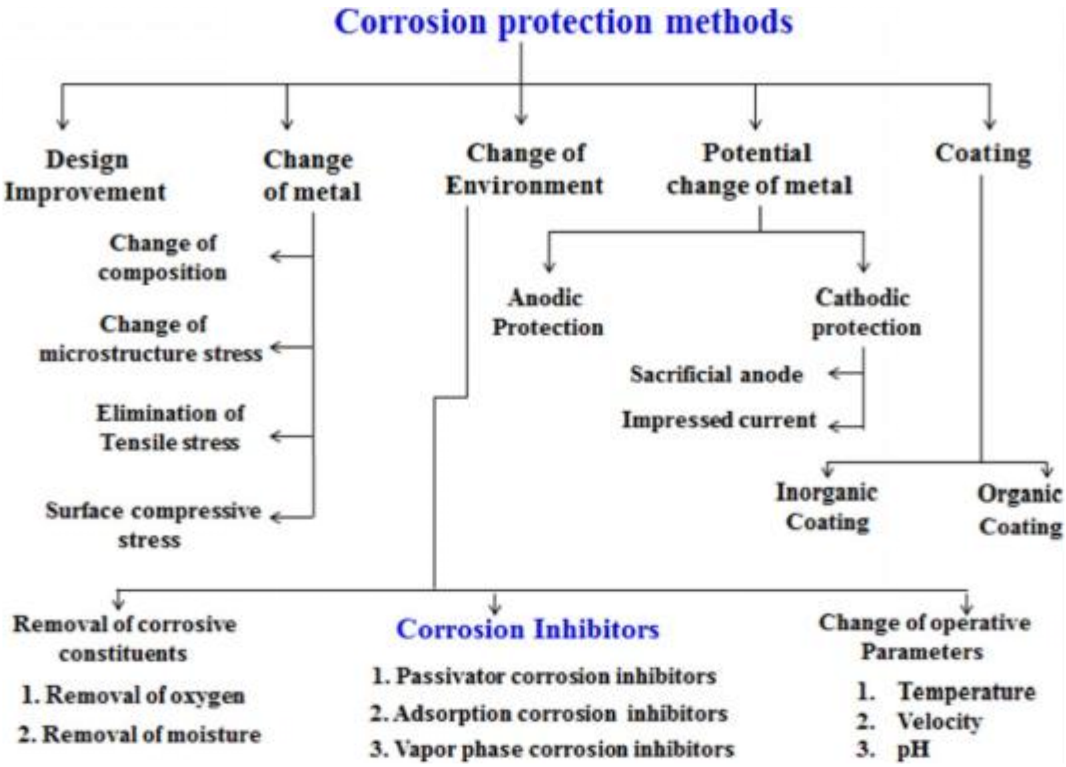


Figure II.8: Protection methods of corroded piping system [15].

CHAPTER III :

RESULTS AND DISCUSSION

III.1 Introduction

The design of piping systems plays a crucial role in optimizing the flow behavior of crude oil by influencing its rheological and chemical characteristics. A well-designed pipeline ensures efficient and reliable transport, minimizes energy consumption, and prevents operational issues such as flow interruptions, deposit formation, and corrosion.

The interaction between crude oil and elbow pipes commonly creates erosion and/or corrosion phenomena. The aim of this chapter is to show the influence of design on crude oil flow behavior with changes in velocity. The numerical study was performed using k-ω turbulent flow modeling and the process of CFD steps is shown in Figure III.1. Four different elbow pipes were designed with varying bend radii (1.5D, 2D, 2.5D, and 3D).

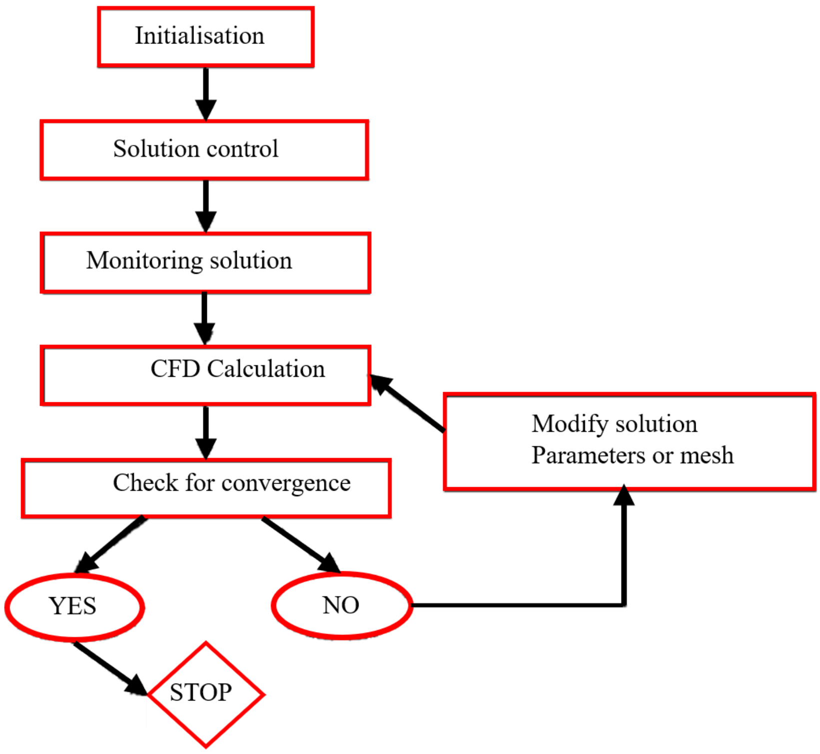


Figure III.1: Organizational chart for simulation steps.

III.2 Design, boundary conditions and mesh

In the designed elbows, the parameters of the geometrical model (Figure III.2 (a)) and boundary conditions (Figure III.2 (b)) are as follows:

- Diameter (D) = 0.5 m
- Horizontal and vertical length (L_h and L_v) = 1D = 0.5 m
- Bend radius (R_i) = 1.5D, 2D, 2.5D, and 3D

- α: the measured angle of the elbow

The fluid flow direction is from down to up, as shown in Figure III.2 (b) (inlet and outlet). In general, meshing is performed to compute solutions of partial differential equations and to ensure the convergence of results, taking into account the number of elements and the partitioning of the cell space. The quadrilateral mesh (Figure III.2 (c)) is the appropriate type for two-dimensional analysis to achieve precise solutions. In the current analysis, a quadrilateral mesh is considered a structured grid (higher quality), which enhances solution precision. The mesh was refined until the shear stress was stabilized as shown in Table III.1.

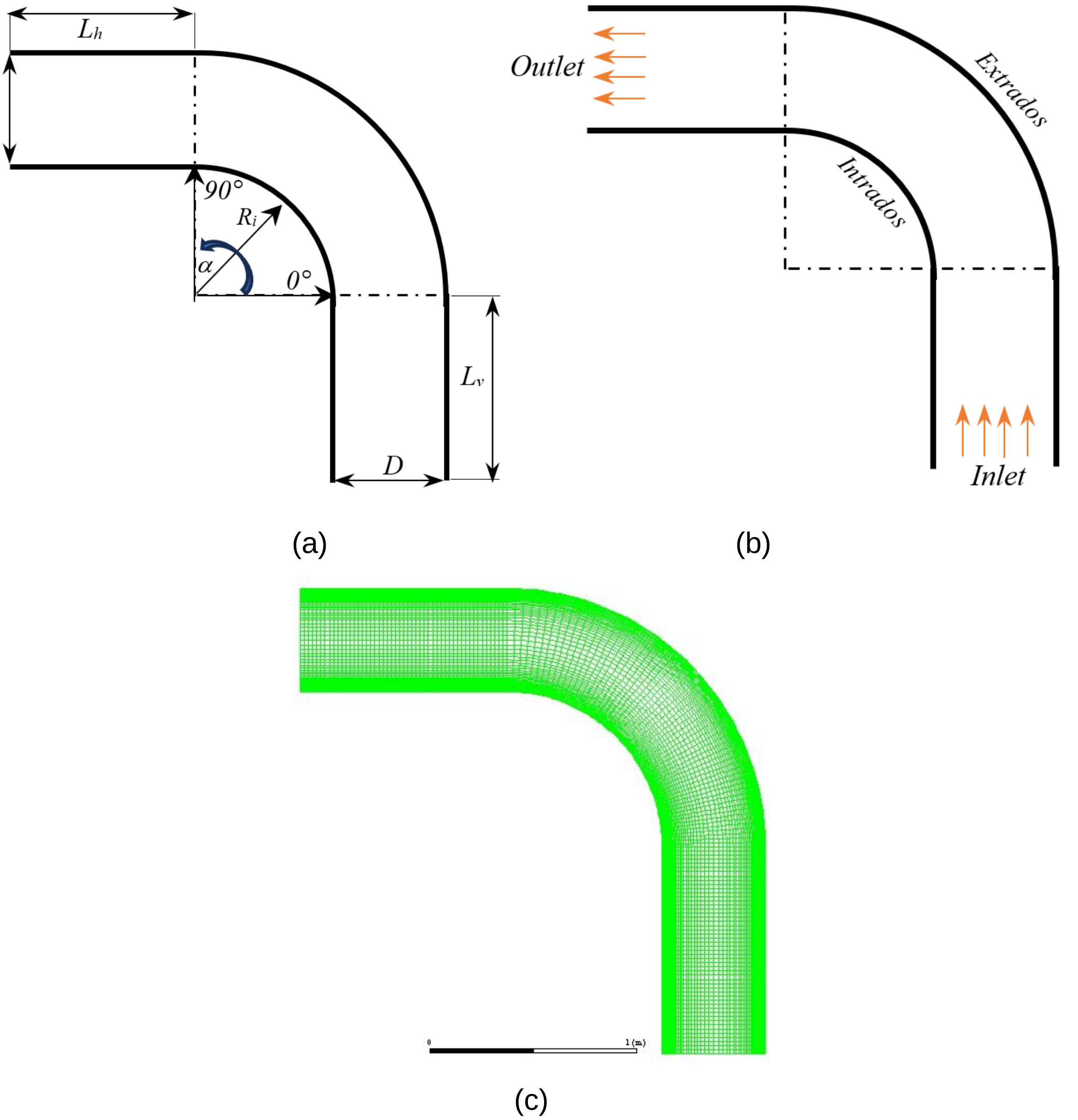


Figure III.2: (a) Dimensions of design, (b) boundary conditions, and (c) mesh

Table III.1: Study of mesh convergence.

Nmbr of elements	Shear stress, τ (Pa)
1600	0.306106
3200	0.366058
4800	0.39056
6400	0.399935
8000	0.40461
9600	0.40068
11200	0.41849
12800	0.45574
14400	0.48107
16000	0.49235
17600	0.4976387
19200	0.4934606

The rheological data of crude oil were obtained by Meriem-Benziane et al. [16]. Figure III.3 illustrates the non-Newtonian fluid behavior described by the Bingham model, which is formulated as follows:

$$\tau = \tau_0 + k\,\gamma^n \qquad \textbf{(III.1)}$$

where τ is the shear stress in (Pa), τ_0 is the yield stress in (Pa), γ is the shear rate in (s^{-1}), and K is the consistency index in (Pa.s). For Bingham model, n is equal to 1.

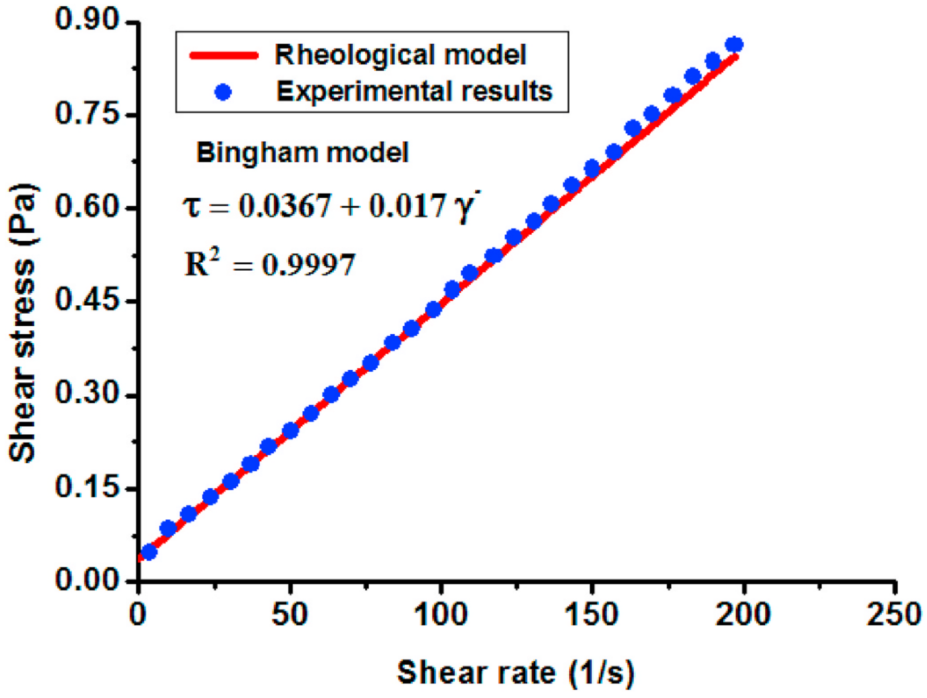
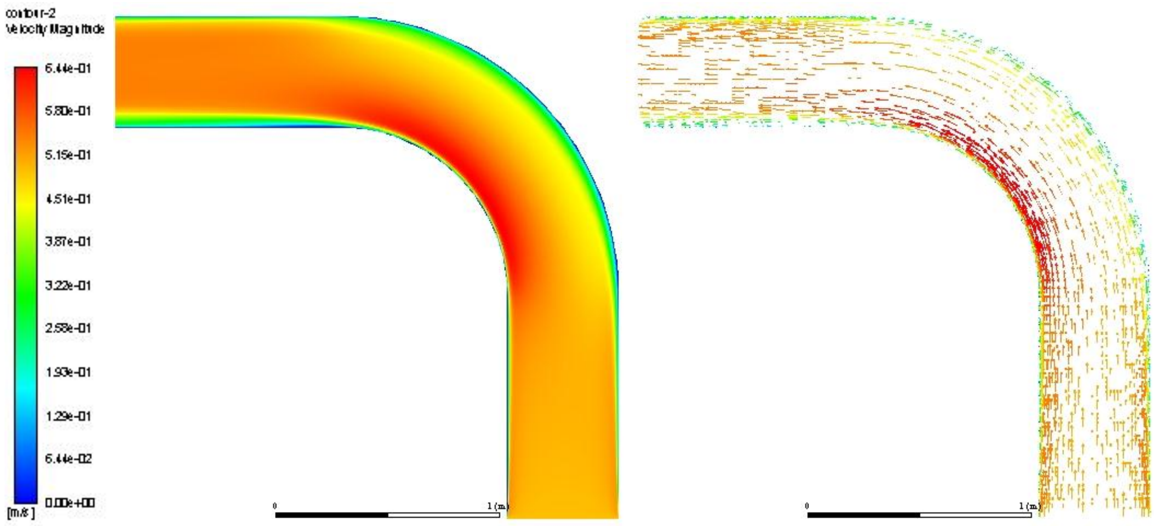


Figure III.3: Rheological model of crude oil behavior [16].

III.3 Results and discussion

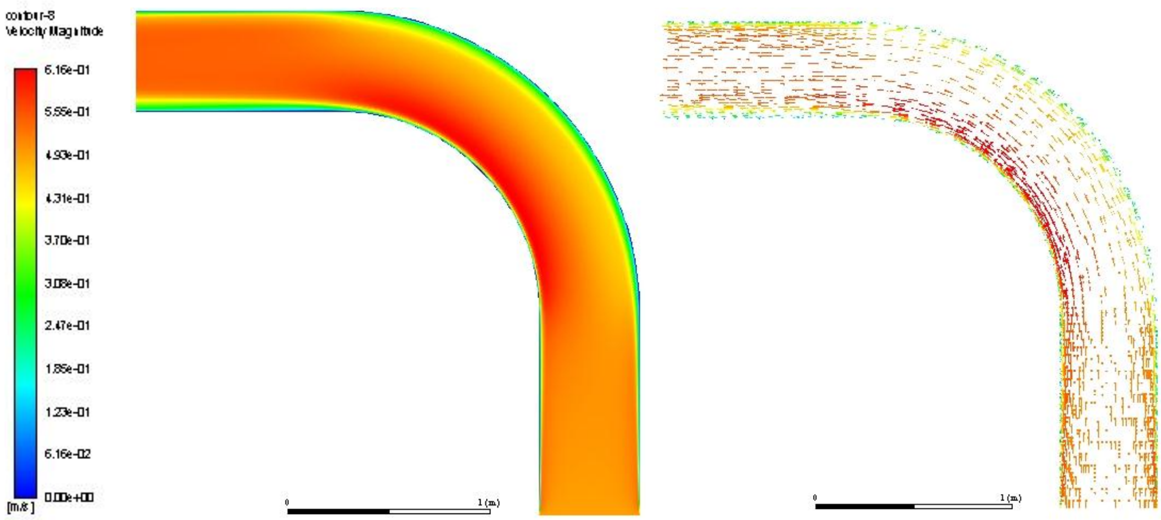
In this numerical analysis, we are going to show crude oil flow in the internal surface of pipe elbows according to the velocity profiles. The velocity profile is used to describe the motion of flow fluid behavior according to governing equations (Continuity and Navier Stokes equations). The velocity distributions were taken at different positions (angle 0°, angle 45°, and angle 90°) in elbow geometries (1.5D, 2D, 2.5 D, and 3D) using CDF software.

a) Velocity v=0.5 m/s



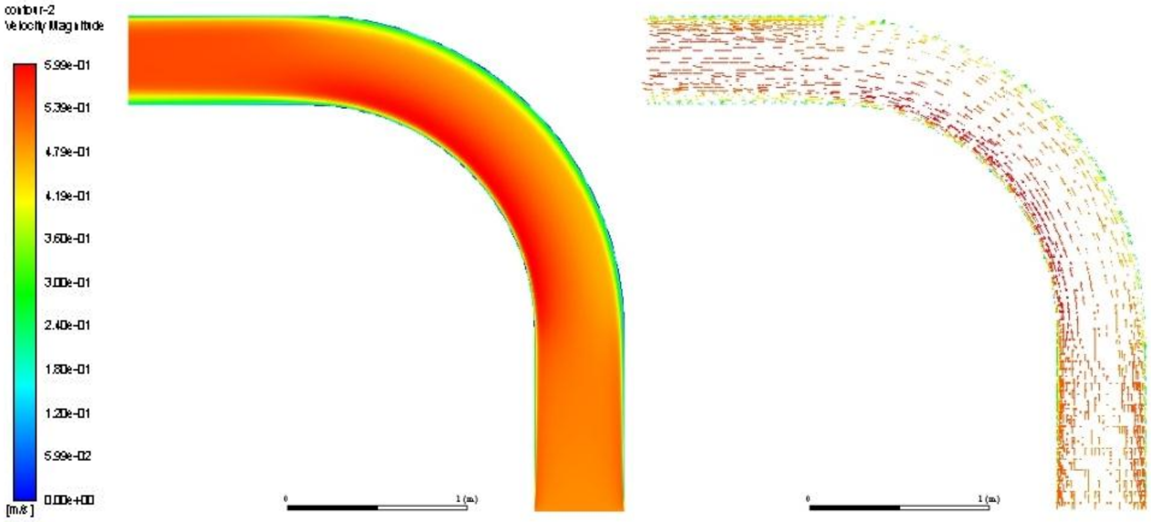
(a) (b)

Figure III.4: Impact of flow on elbow design 1.5D at v=0.5 m/s, (a) contour, (b) vectors.



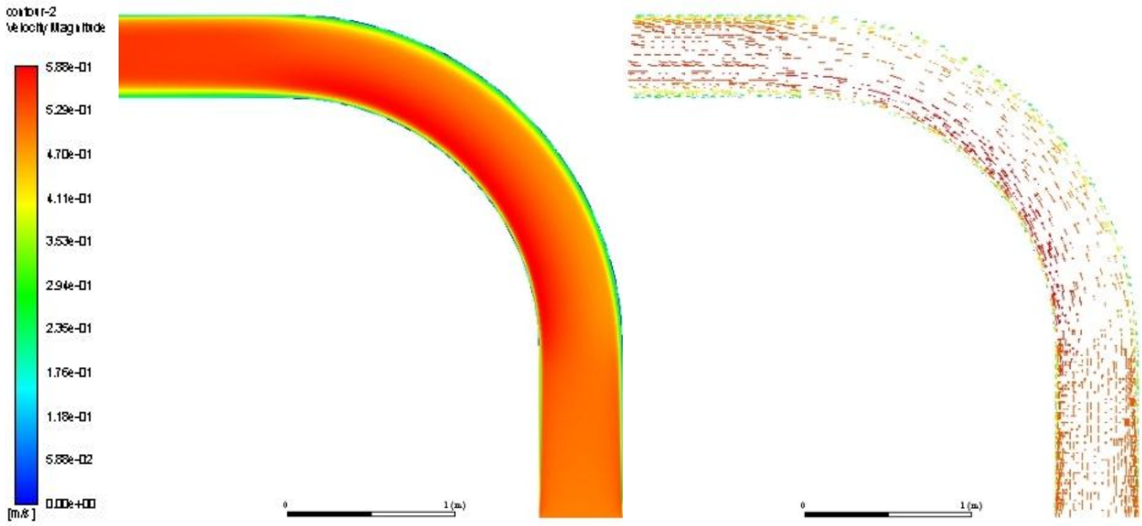
(a) (b)

Figure III.5: Impact of flow on elbow design 2D at v=0.5 m/s, (a) contour, (b) vectors.



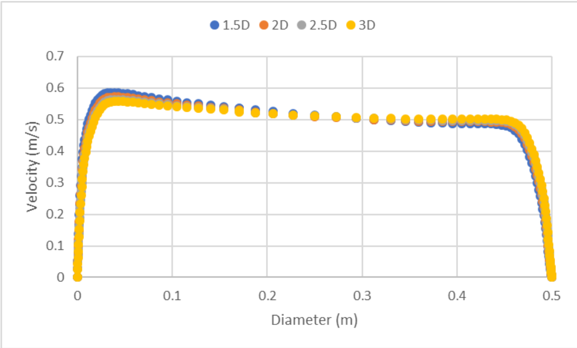
(a) (b)

Figure III.6: Impact of flow on elbow design 2.5D at v=0.5 m/s, (a) contour, (b) vectors.

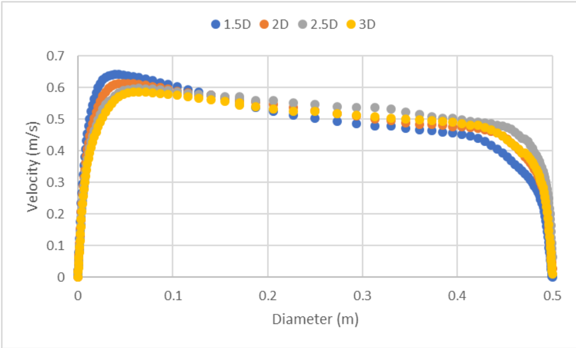


(a) (b)

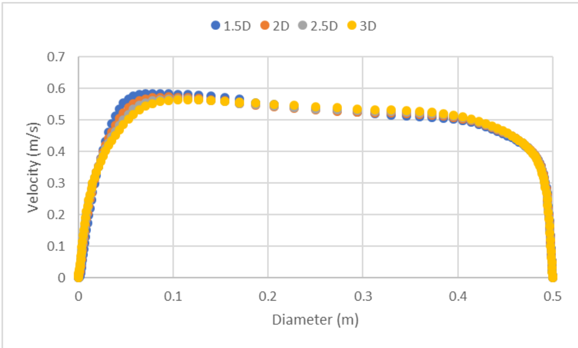
Figure III.7: Impact of flow on elbow design 3D at v=0.5 m/s, (a) contour, (b) vectors.



(a)



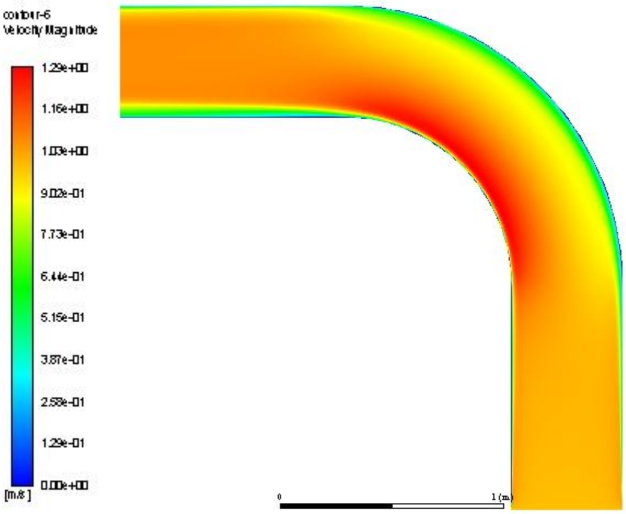
(b)



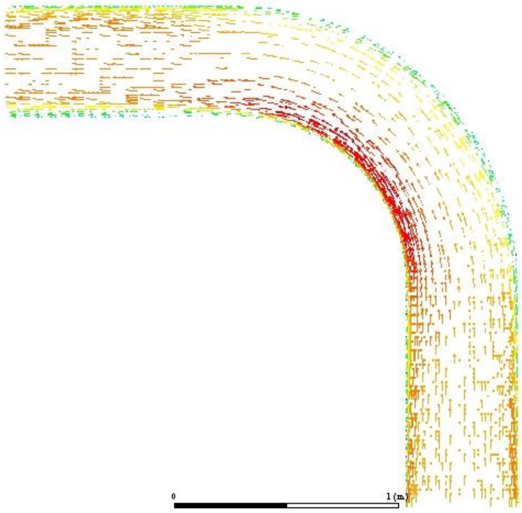
(c)

Figure III.8: Velocity profile vs. diameter at v = 0.5 m/s (a) Angle 0°, (b) Angle 45°, (c) Angle 90°.

b) Velocity v=1 m/s

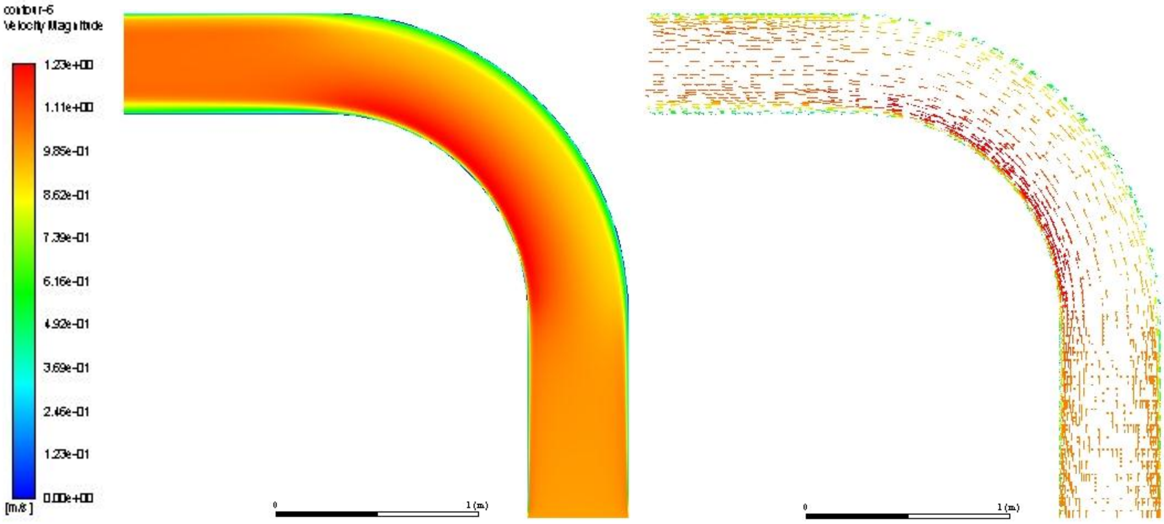


(a)



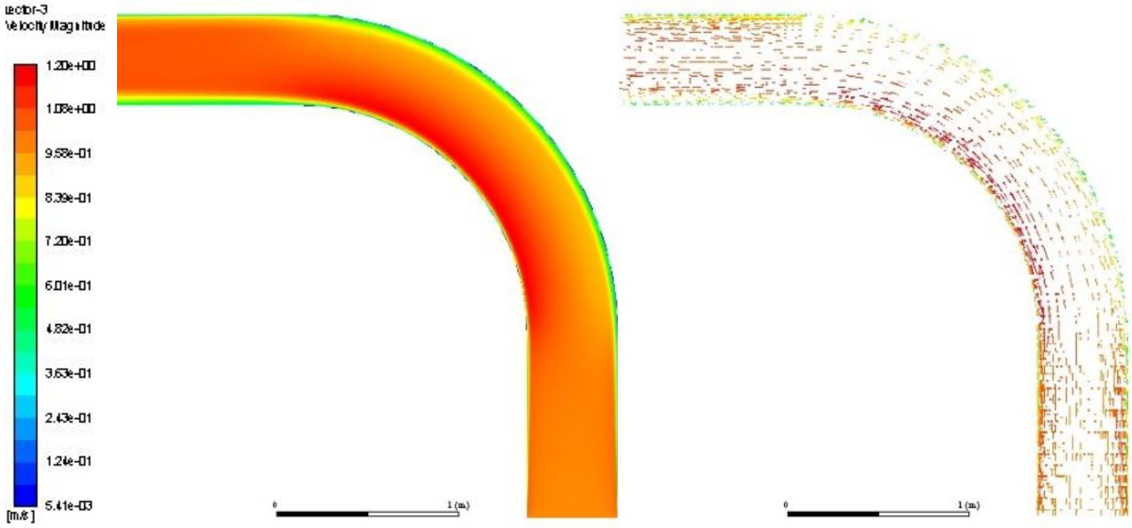
(b)

Figure III.9: Impact of flow on elbow design 1.5D at v=1 m/s, (a) contour, (b) vectors.



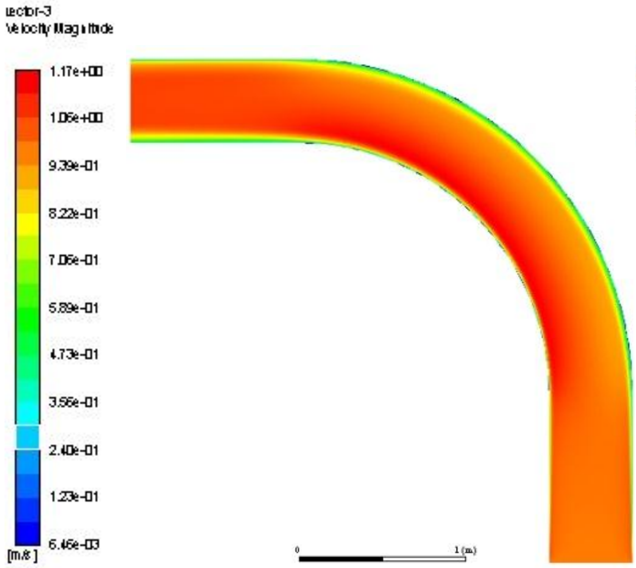
(a) (b)

Figure III.10: Impact of flow on elbow design 2D at v=1 m/s, (a) contour, (b) vectors.

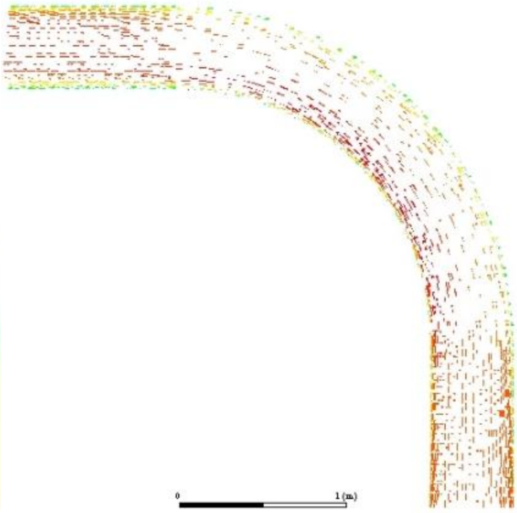


(a) (b)

Figure III.11: Impact of flow on elbow design 2.5D at v=1 m/s, (a) contour, (b) vectors.

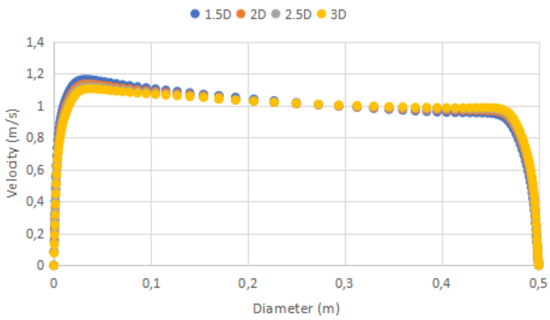


(a)

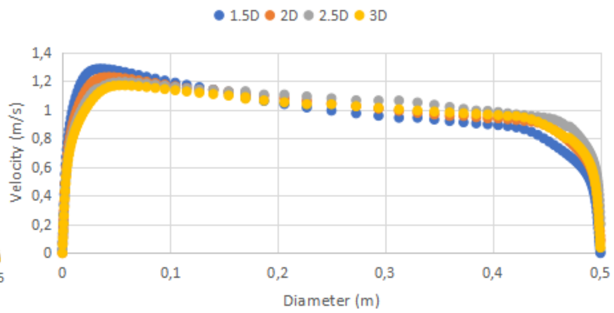


(b)

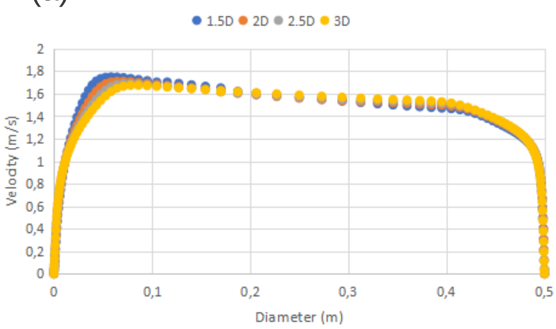
Figure III.12: Impact of flow on elbow design 3D at v=1 m/s, (a) contour, (b) vectors.



(a)



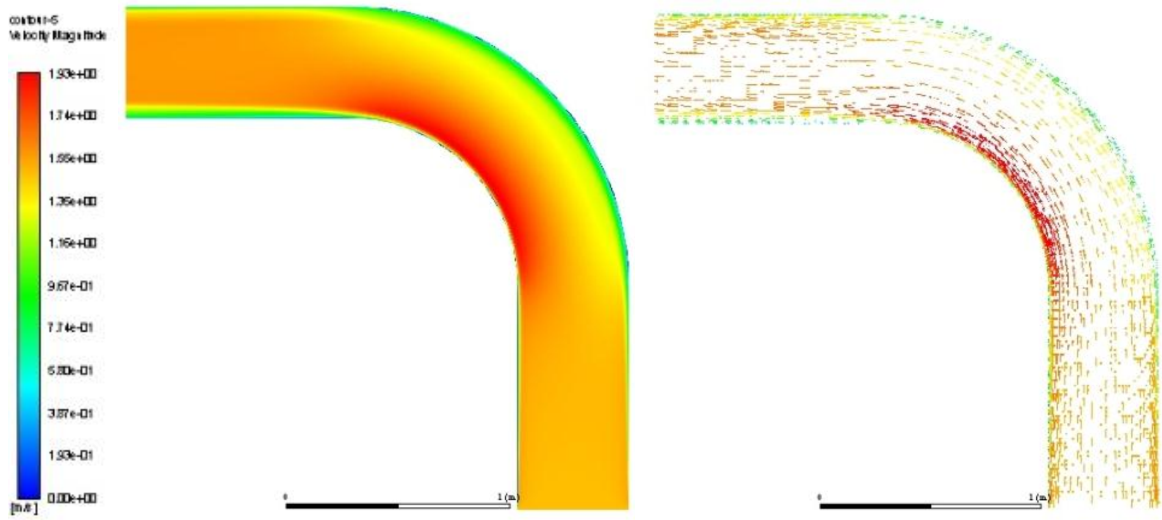
(b)



(c)

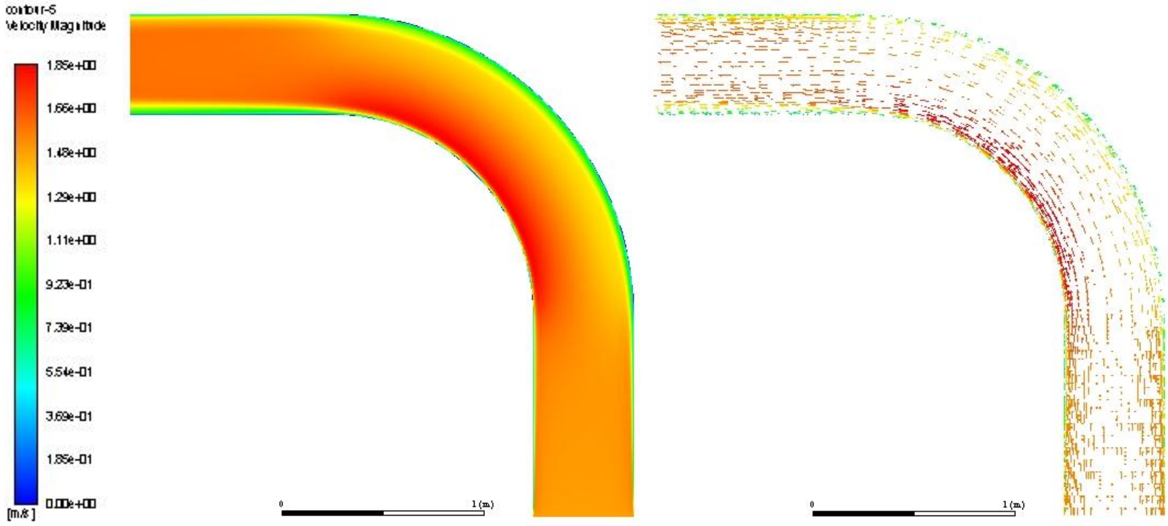
Figure III.13: Velocity profile vs. diameter at v = 1 m/s (a) Angle 0°, (b) Angle 45°, (c) Angle 90°.

c) Velocity v=1.5 m/s



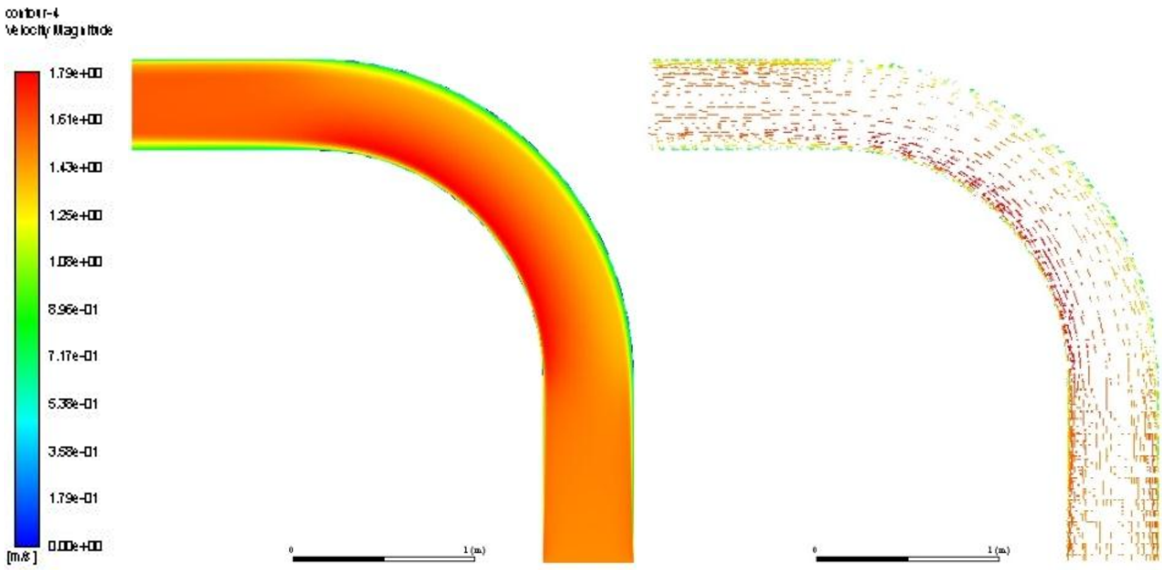
(a) (b)

Figure III.14: Impact of flow on elbow design 1.5D at v=1.5 m/s, (a) contour, (b) vectors.



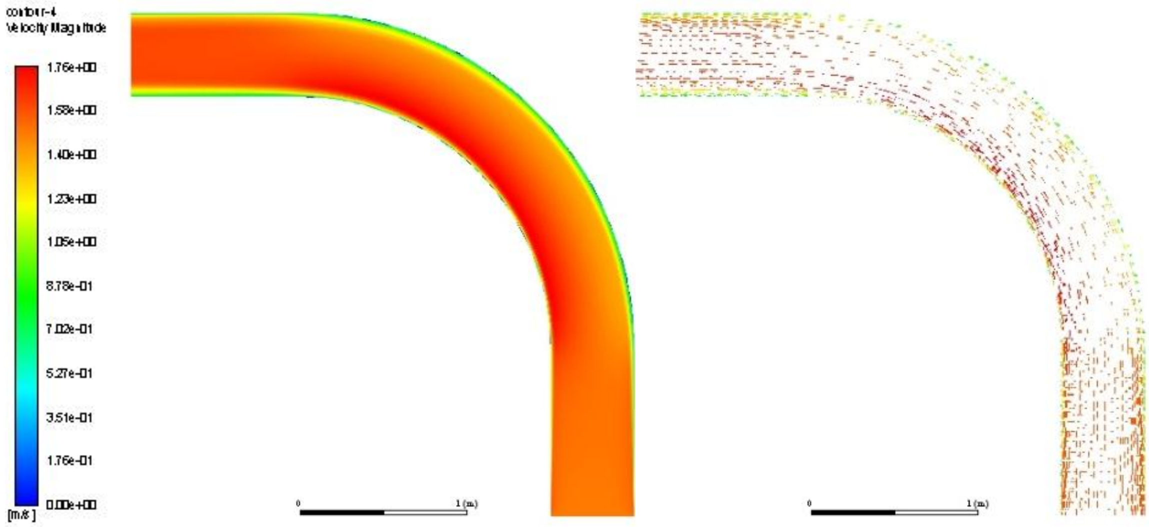
(a) (b)

Figure III.15: Impact of flow on elbow design 2D at v=1.5 m/s, (a) contour, (b) vectors.



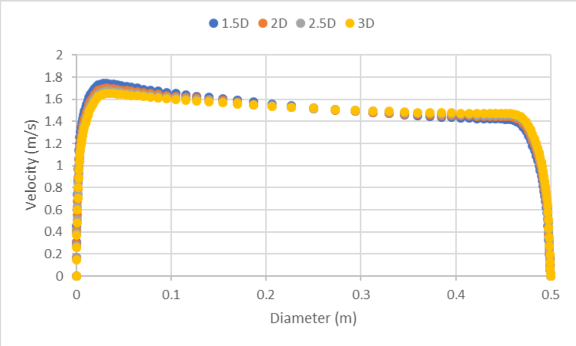
(a) (b)

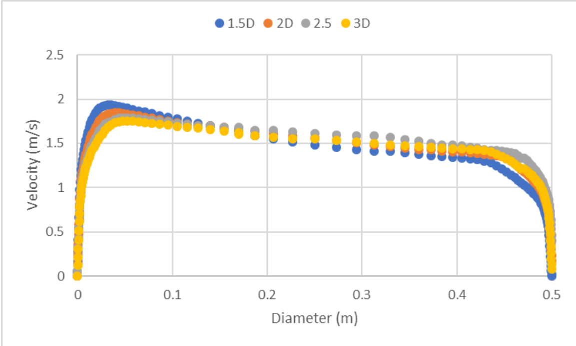
Figure III.16: Impact of flow on elbow design 2.5D at v=1.5 m/s, (a) contour, (b) vectors.



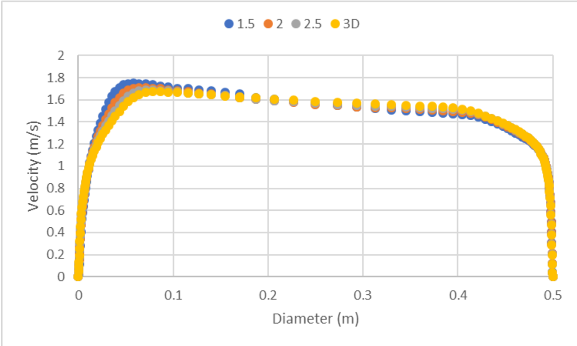
(a) (b)

Figure III.17: Impact of flow on elbow design 3D at v=1.5 m/s, (a) contour, (b) vectors.





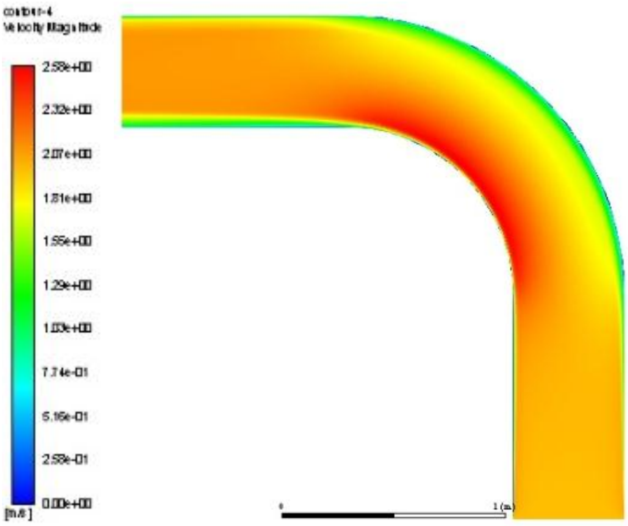
(a) (b)

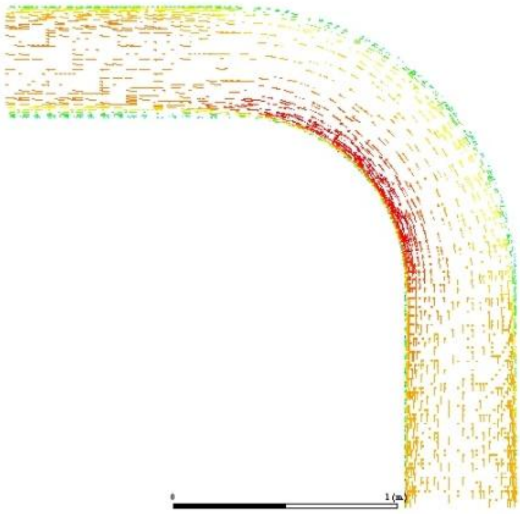


(c)

Figure III.18: Velocity profile vs. diameter at v = 1.5 m/s (a) Angle 0°, (b) Angle 45°, (c) Angle 90°.

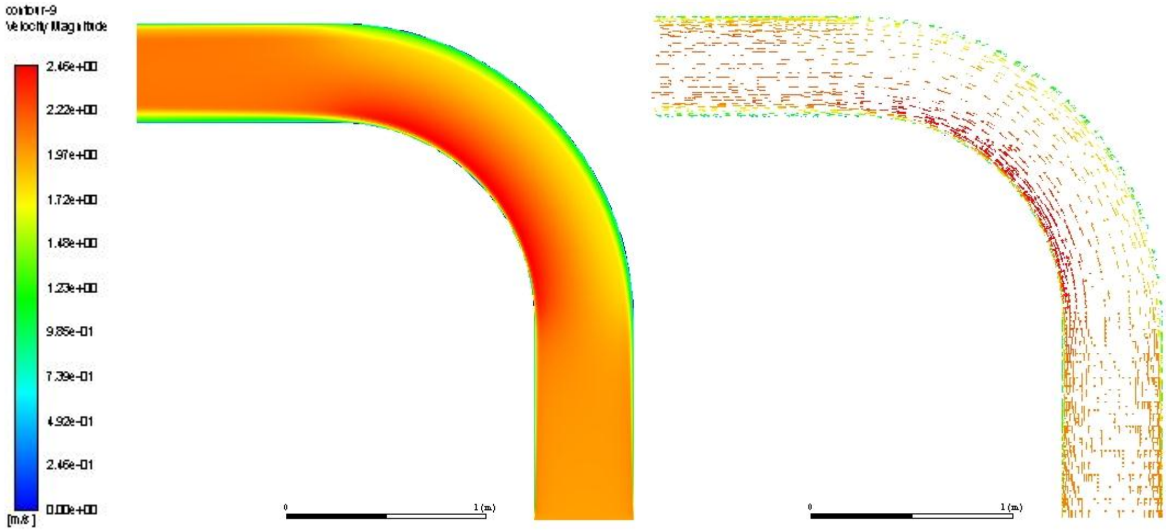
d) Velocity v=2 m/s





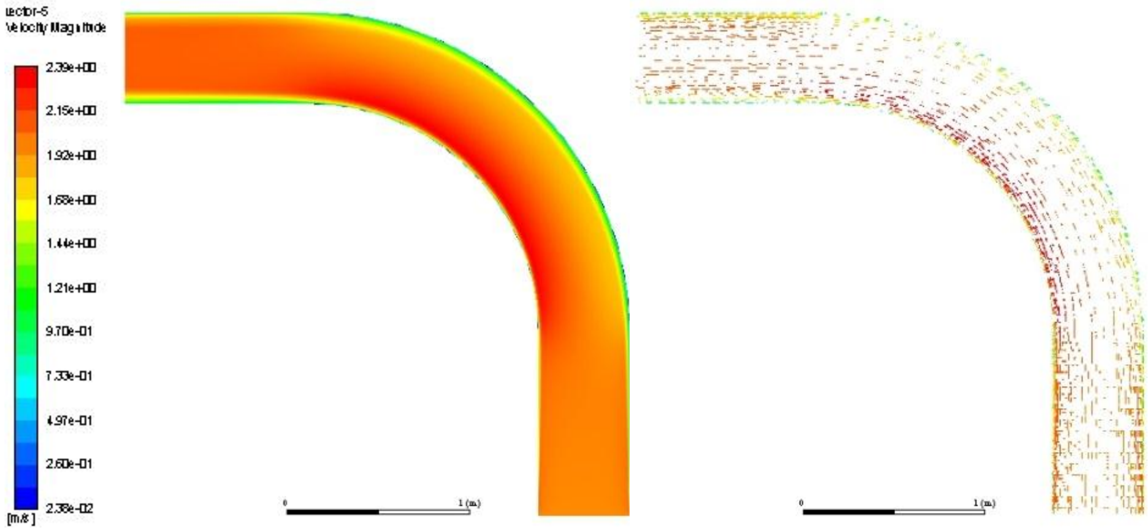
(a) (b)

Figure III.19: Impact of flow on elbow design 1.5D at v=2 m/s, (a) contour, (b) vectors.



(a) (b)

Figure III.20: Impact of flow on elbow design 2D at v=2 m/s, (a) contour, (b) vectors.



(a) (b)

Figure III.21: Impact of flow on elbow design 2.5D at v=2 m/s, (a) contour, (b) vectors.

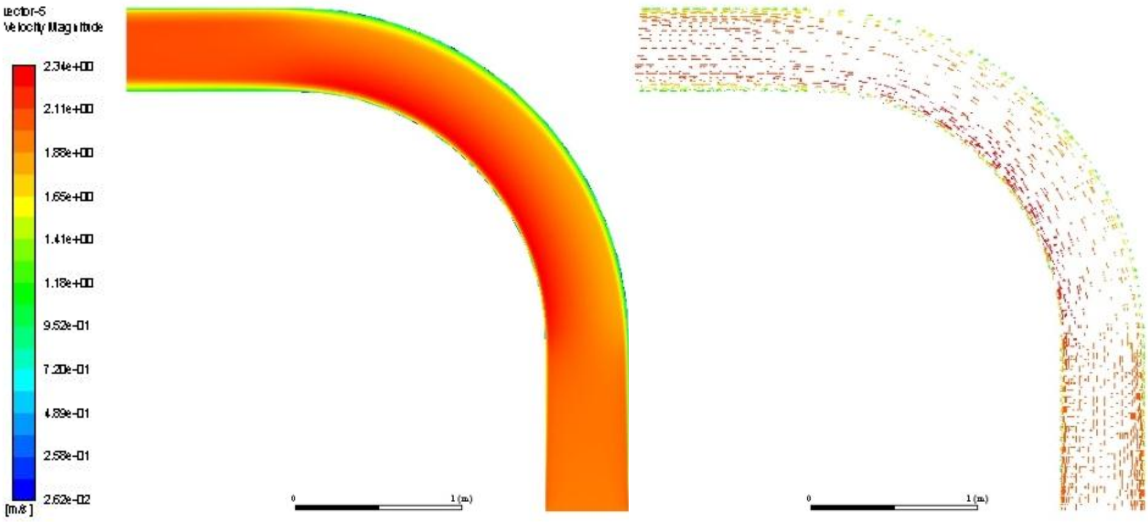
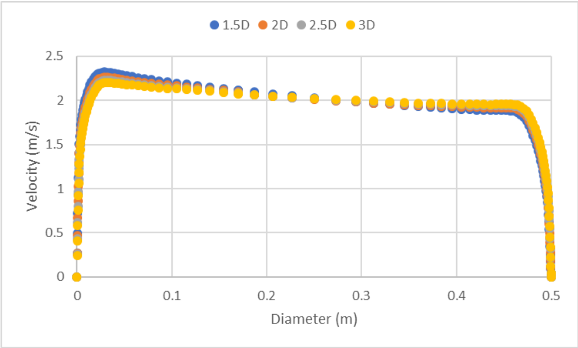
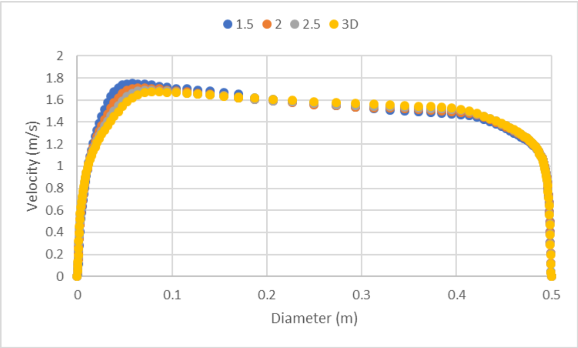


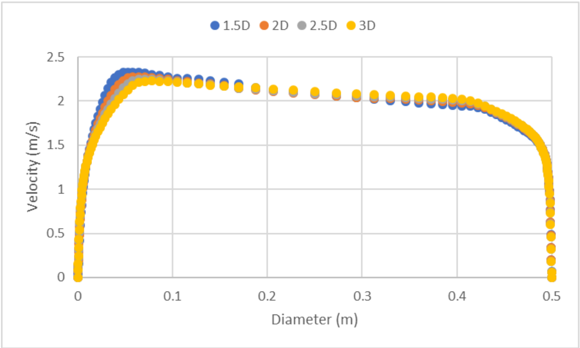
Figure III.22: Impact of flow on elbow design 3D at v=2 m/s, (a) contour, (b) vectors.



(a)



(b)



(c)

Figure III.23: Velocity profile vs. diameter at v = 2 m/s (a) Angle 0°, (b) Angle 45°, (c) Angle 90°.

Table III.2 : Maximum shear stress

Vitess	Maximum shear stress, τ (Pa)			
	1.5D	**2D**	**2.5D**	**3D**
V=0.5	0.008435	0.008435181	0.008435171	0.008435165
V=1	0.02331102	0.2331098	0.02331096	0.02331094
V=1.5	0.04228811	0.04228804	0.042288	0.04228797
V=2	0.06451498	0.06451481	0.06451469	0.06451461

As we observe in the figures (III.4 – III.23), the distribution of velocity magnitude in the internal surface of pipe elbow with different bend radii and change of velocity value. It is clear that the flow behavior is moved from inlet to the outlet. The flow of crude oil is high at the extrados section. The obtained results show that the increase of bend radius decrease the friction between fluid and extrados section. Furthermore, the increase of velocity has a serious influence on the corrosion and erosion on pipe elbow due to its attack in the internal surface.

The rheological behavior of crude oil flowing through an elbow is significantly influenced by its interaction with the intrados wall. The stress forces result in adherence to the intrados wall due to the high viscosity of the crude oil. The velocity profiles are nearly symmetrical around the center, exhibiting an almost parabolic shape. Table III.2 indicated that shear stress increases with the increasing of velocity vale. It is observed that the shear stress is still almost the same for four designs.

GENERAL CONCLUSIONS AND PERSPECTIVES

GENERAL CONCLUSIONS AND PERSPECTIVES

This final project focused on investigating the impact of elbow design on crude oil flow behavior. Computational Fluid Dynamics (CFD) analysis was conducted on four different elbow designs at varying velocities using the k-w turbulent model.

The velocity profiles were analyzed at three angles: 0°, 45°, and 90°. It was observed that the crude oil flow is most influenced at the 45° angle of the elbow. Increasing the bending radius was found to mitigate this effect.

Furthermore, the results indicated that reducing the flow velocity decreases the maximum shear stress, thereby enhancing the effectiveness and extending the lifetime of the pipe elbow. The obtained results of velocity profiles show that the increase of bend radius decrease the friction between fluid and extrados section. Furthermore, the increase of velocity has a serious influence on the corrosion and erosion on pipe elbow due to its attack in the internal surface.

For future studies, we recommend expanding this project to include the consideration of chemical reactions involved in sweet and sour corrosion phenomena.

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