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MODELING AND SIMULATION OF HYDROGEN PIPELINE NETWORKS FOR SAFE AND EFFICIENT TRANSPORTATION

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ABSTRACT

Hydrogen Pipeline Network Transportation is a convenient means of efficiently conveying large quantities of Hydrogen from the Industrial Producers of Hydrogen to the Industrial Consumers of Hydrogen. The world of men is gradually transitioning into a more Carbon-Neutral Industrial Climate and Hydrogen is increasingly becoming a preferred energy carrier and industrial feedstock for several industries, some of such Industries including The Cement Producing Industry, The Steel Producing Industry and The Transportation Industry. This paper provides a finite solution to Hydrogen Pipeline Network Design and Implementation by first performing Crystallographic Analysis to determine the appropriate material to comprise the components of the Hydrogen Pipeline Transportation Network, and then creating a Robust Mathematical Model for a Hydrogen Pipeline Network which can be used to calculate certain parameters within the network like pressure, velocity and temperature distribution, proposing an appropriate Real-Time Monitoring and Control System for the network, simulating multiple hydrogen pipeline network geometries to investigate the general behavior of Hydrogen when it is subjected to Pipeline Network Transportation and providing general guidelines for Hydrogen Pipeline Transportation Networks. The results proved the theories of Major and Minor Losses in a Pipeline and determined that Austenitic Stainless Steel (ASS) and Fiber Reinforced Polymer (FRP) were the preferred materials to comprise the components of the Transmission and Distribution segments of the network respectively. The overall aim of this paper was achieved.

Keywords: Hydrogen, Pipeline, Pressure, Volume, Fibre-optic, Temperature, Sensor

1 INTRODUCTION

Hydrogen Pipeline Networks are the most efficient and reliable means of transporting large quantities of Hydrogen from its Industrial Producers to its Industrial Consumers because they provide a direct and uninterrupted channel for conveying Hydrogen Gas in large quantities from one location to another incessantly and in a timely manner. Furthermore, the incentive of establishing appropriate Hydrogen Pipeline Transportation Networks to seamlessly transport large quantities of Hydrogen from Industrial Producers of Hydrogen to Industrial Consumers of Hydrogen is becoming increasingly popular on a Global scale because the world of men is transitioning into a more Carbon-Neutral Climate in which Hydrogen is steadily becoming more and more a preferred Energy Carrier for Industrial Processes and Industrial Feedstock for Industrial Products such as the Steel Producing Industry which has the new initiative of replacing Carbon with Hydrogen as a feedstock for Steel Production in an effort to reduce its carbon footprint (FCHEA, 2026), as well as the Cement Producing Industry which has the new initiative to replace the Fossil Fuels it uses in Kilns

with Hydrogen in order to reduce its carbon footprint. The Automobile Industry is an additional example of such Industries that are 'switching' to Hydrogen with the introduction of Hydrogen Fuel Cell Electric Vehicles (EV's). Pipeline transportation of Hydrogen remains the choicest means of transporting Hydrogen Industrially and poses complicated issues which are all addressed in this paper. (Richard & Mordechai, 1978; Julius, 2022; Aasha et al., 2024; Cristello, 2023; Shourideh et al., 2025; Andrzej et al., 2017; Eugene et al., 2022; Qingqing et al., 2025; Campbell & Chigozie, 2025).

2 MATERIALS AND METHODS

2.1 Materials

The research work for this paper was a theoretical research with computer-aided simulation and end-result analysis, and thus utilized no further material than The Computer System with strong internet connection. Autodesk AutoCAD Computer-Aided Design (CAD) Software and SOLIDWORKS Fluid Flow Simulation Software were used for the Simulations.

2.2 Methods

The methodology employed by the research behind this paper was to first perform crystallographic analysis to determine the appropriate material to comprise the components of a Hydrogen Pipeline Network, and thereafter create a Robust Mathematical Model for a Hydrogen Pipeline Network, proposing an appropriate Real-Time Monitoring and Control System for the network. The research also performed simulation, with the aid of ideal fluid flow simulation computer software, of the flow of Hydrogen Gas through multiple pipeline geometries to investigate the general behavior of Hydrogen when it is subjected to pipeline transportation, and finally produced a compact set of guidelines for Hydrogen Pipeline Transportation Networks. (Nkoi & Orike, 2025).

2.2.1 Crystallographic Analysis

The Crystallographic analysis was carried out by ascertaining the atomic properties of Hydrogen -its atomic structure, atomic radius and atomic diameter, and then determining the permeability of Hydrogen in specific materials of acceptable strength which would comprise the components of the Hydrogen Pipeline Network for both the Transmission and Distribution segments of the network.

2.2.2 Mathematical Model

The Mathematical Model was created by applying The Ideal Gas Equation (also called The Ideal Gas Law or The Equation of State) and The Three (3) Transport Equations -The Continuity Equation which applied the law of conservation of mass, The Navier-Stokes Equations which applied the law of conservation of momentum, and The Energy Equation which applied the law of conservation of energy- in cylindrical coordinate notation as it was predetermined that the pipeline network would maintain a circular cross-section throughout its geometry for simplicity sake, as well as considering the fact that most gas pipelines which currently exist today generally maintain a circular cross-section throughout their geometry (Xiaonan W. et al., 2015).

The Continuity Equation in Cylindrical Coordinate Notation: (Felix, 2022).

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(\rho r Ur) + \frac{1}{r}\frac{\partial}{\partial \theta}(\rho U\theta) + \frac{\partial}{\partial z}(\rho Uz) = 0 \quad (1)$$

where Ur, Uθ and Uz are the velocity components in the directions r, θ and z respectively.

(Ideriah, 2024)

The Navier-Stokes Equation in Cylindrical Coordinate Notation: (Bistafa, 2017; Ideriah, 2017; Ideriah, 2022).

r-component momentum:

$$\rho\frac{DUr}{Dt} = -\frac{\partial p}{\partial r} + \mu\left[\frac{\partial}{\partial r}\left\{\frac{1}{r}\frac{\partial}{\partial r}(rUr)\right\} + \frac{1}{r^2}\frac{\partial^2 Ur}{\partial \theta^2} - \frac{2}{r^2}\frac{\partial U\theta}{\partial \theta} + \frac{\partial^2 Ur}{\partial z^2}\right] + \rho fr \quad (2)$$

θ-component momentum:

$$\rho\frac{DU\theta}{Dt} = -\frac{\partial p}{\partial \theta} + \mu\left[\frac{\partial}{\partial r}\left\{\frac{1}{r}\frac{\partial}{\partial r}(rU\theta)\right\} + \frac{1}{r^2}\frac{\partial^2 U\theta}{\partial \theta^2} + \frac{2}{r^2}\frac{\partial Ur}{\partial \theta} + \frac{\partial^2 U\theta}{\partial z^2}\right] + \rho f\theta \quad (3)$$

z-component momentum:

$$\rho \frac{DUz}{Dt} = -\frac{\partial P}{\partial z} + \mu \left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial Uz}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 Uz}{\partial \theta^2} + \frac{\partial^2 Uz}{\partial z^2}\right] + \rho fz \qquad (4)$$

(Ideriah, 2024)

The Energy Equation in Terms of Temperature in Cylindrical Coordinate Notation: (Marquet, 2024).

$$\rho C_P\left(\frac{\partial T}{\partial t} + U_r\frac{\partial T}{\partial r} + \frac{\partial \theta}{r}\frac{\partial T}{\partial \theta} + U_z\frac{\partial T}{\partial z}\right) = k\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2}\right] + 2\mu\left[\left(\frac{\partial Ur}{\partial r}\right)^2 + \left\{\frac{1}{r}\left(\frac{\partial U\theta}{\partial \theta} + Ur\right)\right\}^2 + \left(\frac{\partial Uz}{\partial z}\right)^2 + \frac{1}{2}\left(\frac{\partial U\theta}{\partial z} + \frac{1}{r}\frac{\partial Uz}{\partial \theta}\right)^2 + \frac{1}{2}\left\{\frac{1}{r}\frac{\partial Ur}{\partial \theta} + r\frac{\partial}{\partial r}\left(\frac{U\theta}{r}\right)\right\}^2 + \frac{1}{2}\left(\frac{\partial Uz}{\partial r} + \frac{\partial Ur}{\partial z}\right)^2 - \frac{1}{3}\left\{\frac{\partial Ur}{\partial r} + \left(\frac{1}{r}\frac{\partial U\theta}{\partial \theta} + Ur\right) + \frac{\partial Uz}{\partial z}\right\}\text{^}2\right] + q''' \qquad (5)$$

(Ideriah, 2024)

The Ideal Gas Equation: (LibreTexts Chemistry, 2013).

$$PV = nRT \qquad (6)$$

where

P is the Pressure of the Gas in Pascals (Pa)
V is the Volume of the Gas in Cubic Meters (m^3)
n is the number of moles of the Gas in Moles (mol)
R is the Universal Gas Constant (R = 8.314 J/mol.K) and
T is the Absolute Temperature of the Gas in Kelvin (K)

2.2.3 Real-Time Monitoring and Control System

The Real-Time Monitoring and Control System was proposed for the Hydrogen Pipeline Transportation Network with the aim of ensuring ease, simplicity, effectiveness and accuracy in monitoring and controlling the network through a computer system. Furthermore, a unique and uncommon leak-detection system was also proposed for the hydrogen pipeline transportation network.

2.2.4 Simulation

Autodesk AutoCAD Computer-Aided Design (CAD) Software was used to create four (4) hydrogen pipeline pipe geometries, shown in Figures 1 and 2 below, and SOLIDWORKS Fluid Flow Simulation Software was thereafter used to perform simulation of Compressed Hydrogen Gas through the respective geometries in order to investigate the general behavior of Hydrogen when it is subjected to Pipeline Network Transportation. (Campbell & Chigozie, 2025; Aasha et al., 2024).

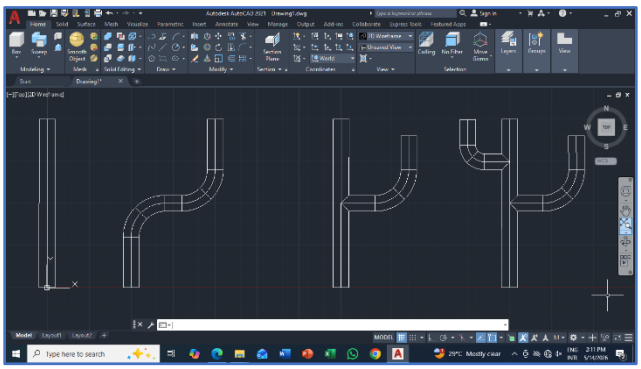


Figure 1: The Four (4) Autodesk AutoCAD Geometries in Wireframe View

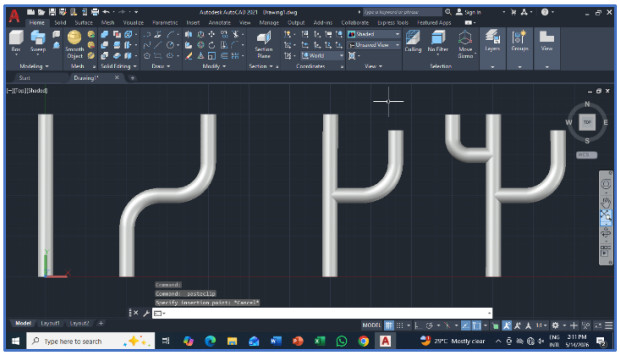


Figure 2: The Four (4) Autodesk AutoCAD Geometries in Shaded View

2.2.5 Guidelines

The Final Guidelines produced for Hydrogen Pipeline Transportation Networks included

- Technical Safety Guidelines
- Technical Efficiency Guidelines
- and Economic Guidelines.

3 RESULTS AND DISCUSSION

3.1 Crystallographic Analysis

The Hydrogen Atom was ascertained to have a single proton in its nucleus and a single electron in the adjacent electron shell from the proton in its nucleus, having an atomic radius of 0.53 Angstrom Units (Å) and an atomic diameter of 1.06 Å.

3.1.1 Transmission Segment

The Transmission Segment of the Hydrogen Pipeline Transportation Network is the segment of the network that will be responsible for transporting Gaseous Hydrogen at very high pressures over very long distances. The conventional material that is preferred for the transmission segment of a gas pipeline like a Natural Gas Pipeline is Carbon Steel because it has a very high mechanical strength, capable of withstanding the inevitable operational stresses which will invariably be incurred on the transmission segment of the network, but is however highly susceptible to Hydrogen Embrittlement. For this reason, Austenitic Stainless Steel (ASS), which is a corrosion-resistant metal alloy of high mechanical strength featuring a face-centered cubic (FCC) crystal structure created by adding nickel or nitrogen to Carbon Steel, was placed under crystallographic analysis to ascertain its resistance to the permeability of Hydrogen. (Ayodele, 2025; Weijie et al., 2023; Peter, 2005; Khaing & Yin, 2025).

Figure 3 is the Crystal Lattice Structure of Austenitic Stainless Steel (ASS). It is a Face Centered Cubic (FCC) Structure with lattice constant of 3.59 to 3.61 Angstrom Units (Å) and atomic packing factor of 0.74 (74%), giving it a very high density. The Outer-edge to outer-edge distance between the atoms in an Austenitic Stainless Steel (ASS) Crystal Lattice is approximately 1.06 Å (this value is obtained by taking the total length of the cube edge in the unit cell, 3.6 Å, and subtracting the combined diameters of the two corners atoms, 2.54 Å), which is the exact atomic diameter of a Hydrogen Atom.

This implies that the Hydrogen Atom will be simply incapable of penetrating into the Crystal Lattice Structure of the Austenitic Stainless Steel (ASS), making the Austenitic Stainless Steel (ASS) perfectly impervious to Hydrogen Embrittlement. Furthermore, Austenitic Stainless Steel has an exceedingly high mechanical strength with average yield strength of 255 Megapascals (MPa) and average tensile strength of 600 Megapascals (MPa), which is more than sufficient to withstand the internal pressures from the Hydrogen as the internal pressure exerted on a Hydrogen Pipeline typically ranges from 3 Megapascals (MPa) to 10 Megapascals (MPa) in high-capacity long-distance transmission networks.

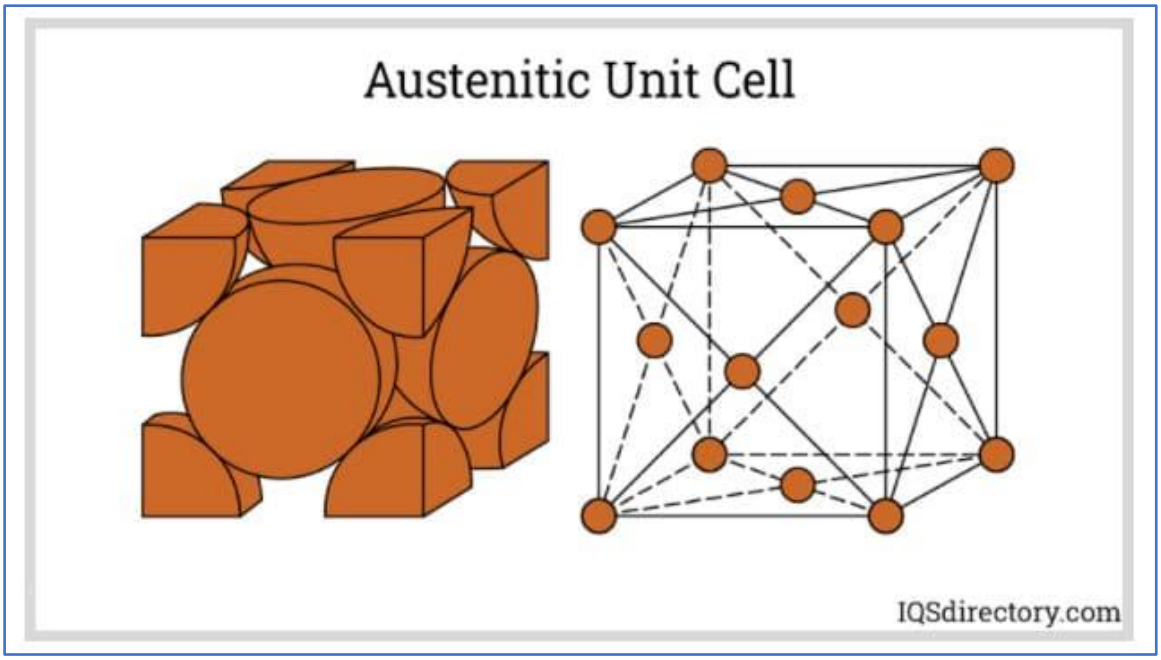


Figure 3: Crystal Lattice Structure of Austenitic Stainless Steel (ASS)

3.1.2 Distribution Segment

The Distribution Segment of the Hydrogen Pipeline Transportation Network is the segment of the network that will be responsible for transporting Gaseous Hydrogen at much lower pressures over much shorter distances. According to The United States Department of Energy (2026), Fiber-Reinforced Polymer (FRP) is a good choice of material to comprise the components of the distribution segment of a Hydrogen Pipeline Transportation Network because of its resistance to Hydrogen Embrittlement and its great strength-to-weight ratio, and was therefore placed by the research behind this paper under crystallographic analysis to ascertain its resistance to the permeability of Hydrogen and its applicability as the appropriate material to comprise the components of the distribution segment of the Hydrogen Pipeline Transportation Network.

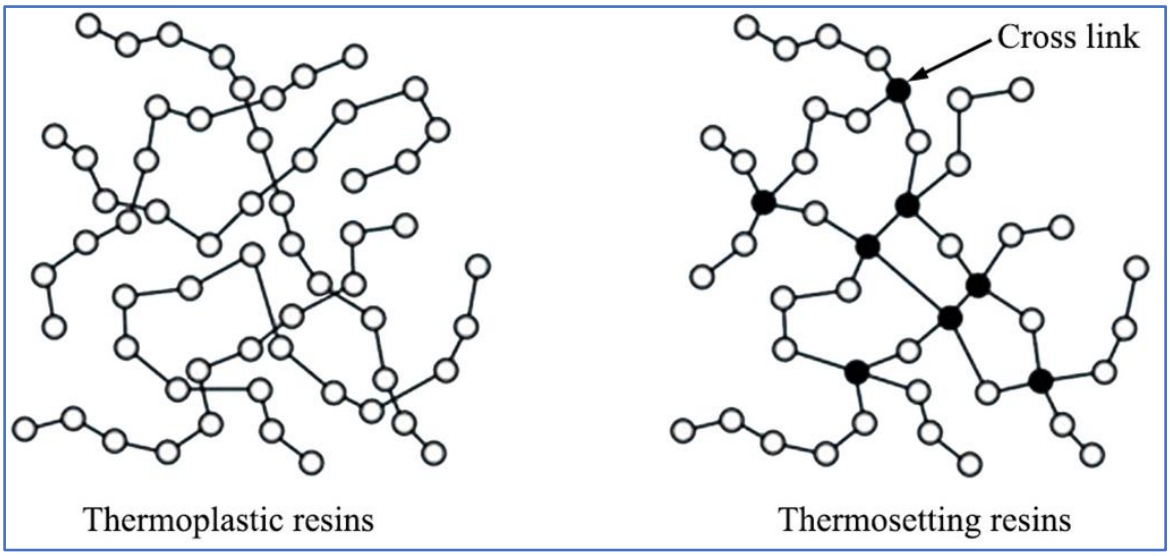


Figure 4: Amorphous Atomic Structure of Fiber Reinforced Polymer (FRP)

Figure 4 is the atomic structure of Carbon Fiber Reinforced Polymer (CFRP). It is an amorphous atomic structure which has an average distance between the nuclei of adjacent atoms of 1 Å, making it perfectly impervious to Hydrogen Embrittlement. Furthermore, Carbon Fiber Reinforced Polymer (CFRP) has a Tensile Strength of 480 to 1,600 Megapascals (MPa), making it very capable of withstanding the inevitable operational stresses (internal fluid pressure and external load pressure) which will be invariably incurred on the distribution network and is thus the appropriate material to comprise the components of the distribution segment of the Hydrogen Pipeline Transportation Network. (Girmay, 2025).

3.2 Mathematical Model

As briefly mentioned in section 2.2.2, the research behind this paper produced The Mathematical Model for a Hydrogen Pipeline Transportation Network by applying The Ideal Gas Equation and The Three (3) Transport Equations in Cylindrical Coordinate Notation. Following The "Physics" of The Flow (The physical characteristics of the flow of Hydrogen within the Hydrogen Pipeline Transportation Network),

3.2.1 Physics of The Flow

The Flow is Transient (Unsteady and Non-Uniform) because changes occur within the flow with time such as density and velocity of Hydrogen. Thus, $\partial/\partial t \neq 0$

The Flow is Compressible because the density of Hydrogen changes along the Hydrogen Pipeline Network. Thus, $\rho \neq$ Constant

The Flow is of Non-Uniform Viscosity because the viscosity of hydrogen changes with density and pressure, and the density and pressure of hydrogen change along the Hydrogen Pipeline Network. Thus, $\mu \neq$ Constant

The Flow is Fully Developed in the axial direction. Thus, $U_r = U_\theta = 0$, $U_z \neq 0$,

3.2.2 Applying The Continuity Equation

The Continuity Equation in Equation (1) from section 2.2.2 and below

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(\rho r Ur) + \frac{1}{r}\frac{\partial}{\partial \theta}(\rho U\theta) + \frac{\partial}{\partial z}(\rho Uz) = 0 \quad (1)$$

where Ur, Uθ and Uz are the velocity components in the directions r, θ and z respectively.

(Ideriah, 2024)

Was reduced to Equation Eight (8) below

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z}(\rho Uz) = 0 \quad (8)$$

which accurately describes the density distribution along the flow with respect to velocity.

3.2.3 Applying The Navier-Stokes Equations

The Navier-Stokes Equations in Equations (2), (3) and (4) from section 2.2.2 and below

r-component momentum:

$$\rho\frac{DUr}{Dt} = -\frac{\partial p}{\partial r} + \mu\left[\frac{\partial}{\partial r}\left\{\frac{1}{r}\frac{\partial}{\partial r}(rUr)\right\} + \frac{1}{r^2}\frac{\partial^2 Ur}{\partial \theta^2} - \frac{2}{r^2}\frac{\partial U\theta}{\partial \theta} + \frac{\partial^2 Ur}{\partial z^2}\right] + \rho fr \quad (2)$$

θ-component momentum:

$$\rho\frac{DU\theta}{Dt} = -\frac{\partial p}{\partial \theta} + \mu\left[\frac{\partial}{\partial r}\left\{\frac{1}{r}\frac{\partial}{\partial r}(rU\theta)\right\} + \frac{1}{r^2}\frac{\partial^2 U\theta}{\partial \theta^2} + \frac{2}{r^2}\frac{\partial Ur}{\partial \theta} + \frac{\partial^2 U\theta}{\partial z^2}\right] + \rho f\theta \quad (3)$$

z-component momentum:

$$\rho\frac{DUz}{Dt} = -\frac{\partial P}{\partial z} + \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial Uz}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 Uz}{\partial \theta^2} + \frac{\partial^2 Uz}{\partial z^2}\right] + \rho fz \quad (4)$$

(Ideriah, 2024)

Were reduced to Equations (12), (13) and (14) below

r-component momentum:

$$\frac{\partial p}{\partial r} = 0 \quad (12)$$

θ-component momentum:

$$\frac{\partial p}{\partial \theta} = 0 \qquad (13)$$

z-component momentum:

$$\rho \frac{DUz}{Dt} = -\frac{\partial P}{\partial z} + \mu \left[\frac{\partial^2 Uz}{\partial z^2}\right] \qquad (14)$$

Equation (14) above accurately describes the pressure and velocity distribution along the flow.

3.2.4 Applying The Energy Equation

The Energy Equation in Equation (5) from section 2.2.2 and below

$$\rho C_P\left(\frac{\partial T}{\partial t} + U_r\frac{\partial T}{\partial r} + \frac{\partial \theta}{r}\frac{\partial T}{\partial \theta} + U_z\frac{\partial T}{\partial z}\right) = k\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2}\right] + 2\mu\left[\left(\frac{\partial Ur}{\partial r}\right)^2 + \left\{\frac{1}{r}\left(\frac{\partial U\theta}{\partial \theta} + Ur\right)\right\}^2 + \left(\frac{\partial Uz}{\partial z}\right)^2 + {}^1\!/_2\left(\frac{\partial U\theta}{\partial z} + \frac{1}{r}\frac{\partial Uz}{\partial \theta}\right)^2 + {}^1\!/_2\left\{\frac{1}{r}\frac{\partial Ur}{\partial \theta} + r\frac{\partial}{\partial r}\left(\frac{U\theta}{r}\right)\right\}^2 + {}^1\!/_2\left(\frac{\partial Uz}{\partial r} + \frac{\partial Ur}{\partial z}\right)^2 - \frac{1}{3}\left\{\frac{\partial Ur}{\partial r} + \left(\frac{1}{r}\frac{\partial U\theta}{\partial \theta} + Ur\right) + \frac{\partial Uz}{\partial z}\right\}\text{^}2\right] + q''' \qquad (5)$$

(Ideriah, 2024)

Was reduced to Equation (16) below

$$\rho C_P\left(\frac{\partial T}{\partial t} + U_z\frac{\partial T}{\partial z}\right) = k\left[\frac{\partial^2 T}{\partial z^2}\right] + 2\mu\left[\left(\frac{\partial Uz}{\partial z}\right)^2 - \frac{1}{3}\left\{\frac{\partial Uz}{\partial z}\right\}^2\right] + q''' \qquad (16)$$

Which accurately describes the temperature and velocity distribution along the flow.

3.2.5 Final Interpolations

After a complex series of mathematical interpolations, Equations (8), (12), (13), (14) and (16) produced Equations (31), (24) and (42) below, Equation (31) representing the Pressure Distribution along the flow, Equation (24) representing the Velocity Distribution along the flow and Equation (42) representing the Temperature distribution along the flow,

$$\mathbf{P_z = P_0 - \rho z\frac{DUz}{Dt}} \qquad \mathbf{(31)}$$

where Pz is the pressure of the flow at location z along the flow aft of the compression station.

z is the location along the flow aft of the compression station.

P_0 is the pressure of the flow just aft of the compression station.

$$\boldsymbol{Uz = Uz_0 - \rho\left(\frac{\partial \rho}{\partial t}\right)z} \qquad \mathbf{(24)}$$

where Uz is the velocity of the flow at location z along the flow aft of the compression station.

z is the location along the flow aft of the compression station.

Uz_0 is the velocity of the flow just aft of the compression station.

$$\mathbf{Tz = T_0 + \frac{\rho C p z^2}{2k}\left(\frac{DT}{Dt}\right) - \frac{q''' z^2}{2k}} \qquad \mathbf{(42)}$$

where Tz is the temperature of the flow at location z along the flow aft of the compression station.

z is the location along the flow aft of the compression station.

T_0 is the temperature of the flow just aft of the compression station.

3.2.6 Applying The Ideal Gas Equation

And Finally, The Ideal Gas Equation from Equation (6) from section 2.2.2 and below

$$PV = nRT \quad (6)$$

where

P is the Pressure of the Gas in Pascals (Pa)

V is the Volume of the Gas in Cubic Meters (m^3)

n is the number of moles of the Gas in Moles (mol)

R is the Universal Gas Constant (R = 8.314 J/mol.K) and

T is the Absolute Temperature of the Gas in Kelvin (K)

Was applied to Equations (31) and (42) which produced equation (46) below, which is The Equation that accurately describes the empirical relationship between the pressure, volume and temperature along the flow,

$$\mathbf{(P_0 - \rho z \frac{DUz}{Dt})V = nR(T_0 + \frac{\rho C p z^2}{2k}(\frac{DT}{Dt}) - \frac{q''' z^2}{2k})} \quad \mathbf{(46)}$$

where n is the number of moles of the gas in the flow.

R is the ideal gas constant.

V is the volume of the gas in the flow.

3.3 Real-Time Monitoring and Control System

As briefly mentioned in section 2.2.3, The Real-Time Monitoring and Control System was proposed for the Hydrogen Pipeline Transportation Network with the aim of ensuring ease, simplicity, effectiveness and accuracy in monitoring and controlling the network through a computer system, and a unique and uncommon leak-detection system was also proposed for the hydrogen pipeline transportation network.

3.3.1 Fiber Optic Sensor System

A Real-Time Monitoring and Control System is made up of the following Three (3) Segments:

The Monitoring (or Sensing) Segment in which sensors measure variables like temperature, pressure, flowrate, voltage, etc. , such as pressure reading in a gas pipeline.

The Processing (or Decision-Making) Segment in which a computer analyses data in real time, compares actual values with desired values (set points) and then initiates corrective measures for control.

The Control (or Action) Segment in which the Computer automatically adjusts actuators (valves, motors, pumps, etc.) to keep the system stable.

A Real-Time Monitoring and Control System is very important for the Hydrogen Pipeline Network because it will minimize the Human effort needed and will ensure that any sudden failure or glitch in the Network is immediately detected and remedied, and any fault in the network is recognized as soon as possible.

A Fiber-optic sensor system was chosen for the Monitoring (or Sensing) Segment Network because of the following Seven (7) major advantages:

- A Single Fiber-Optic Cable can provide All Sensory Data required for monitoring the entire Hydrogen Pipeline Network
- Fiber-Optic Sensor Systems are Highly Accurate and Reliable
- Fiber-Optic Sensors perform very well in harsh, corrosive and high-electromagnetic interference (EMI) environments
- The Fiber-Optic Cable does not use Electrical Power and requires no downhole electronics and is thus safe as it cannot introduce a spark along the Hydrogen Pipeline Network
- The complexity of the Real-Time Monitoring and Control System for the Hydrogen Pipeline Network is minimized by the Fiber-Optic Sensor System

- Fiber-Optic Sensor Systems are immune to Electromagnetic Interference
- The Fiber-Optic Sensor System will maintain a neat and tidy appeal.

A Fiber-Optic Sensor Systems Works by sending light through a Laser down a fiber-optic cable. Physical changes like heat, strain, or vibration alter the light intensity, phase, wavelength or scattering. Thereafter, an Interrogator Box at the surface analyzes the back-scattered or reflected light and a specialized software converts the light changes into Temperature, Pressure, Acoustic or Other Readings. (Fatimah & Zuhdi, 2024).

The Unique and Uncommon Internal Leak Detection System which was proposed for the Hydrogen Pipeline Transportation Network is called A 'Smart Hydrogen Pipeline Pigging (SHyPP)' System. The SHyPP System will utilize a special pig which will be used to clean the inside of the hydrogen pipeline of debris, and will have an internal sensor which will utilize a combination of optic sensing and advanced imaging to detect holes or leaks along the pipeline. The two (2) major advantages of the SHyPP System are:

- It not only serves as a Leak-Detection System but also an Internal Cleaning System for the Hydrogen Pipeline Transportation Network
- It utilizes highly reliable technology for Leak-Detection including Optic Sensing and Advanced Imaging Technologies

3.4 Simulations

As briefly mentioned in section 2.2.4, Autodesk AutoCAD Computer-Aided Design (CAD) Software was used to create the four (4) hydrogen pipeline pipe geometries which were shown in Figures 2.1 and 2.2, and SOLIDWORKS Fluid Flow Simulation Software was thereafter used to perform simulation of Compressed Hydrogen Gas through the respective geometries in order to investigate the general behavior of Hydrogen when it is subjected to Pipeline Network Transportation.

The Four (4) Sub-Geometries shown above in section 2.2.4 in Figures 2.1 and 2.2, named G1, G2, G3 and G4 respectively, are designed to investigate the general behavior of Hydrogen when it is subjected to Hydrogen Pipeline Transportation. G1 (or Sub-Geometry 1) is a straight pipe, G2 (or Sub-Geometry 2) is a curved pipe with a total end-to-end displacement of the exact same as G1, with a greater total curved length than G1's total straight length. G3 (or Sub-Geometry 3) is an exact copy of G1, but includes a side outlet curved pipe, and finally, G4 (or Sub-Geometry 4) is an exact copy of G3, but includes an additional side outlet curved pipe.

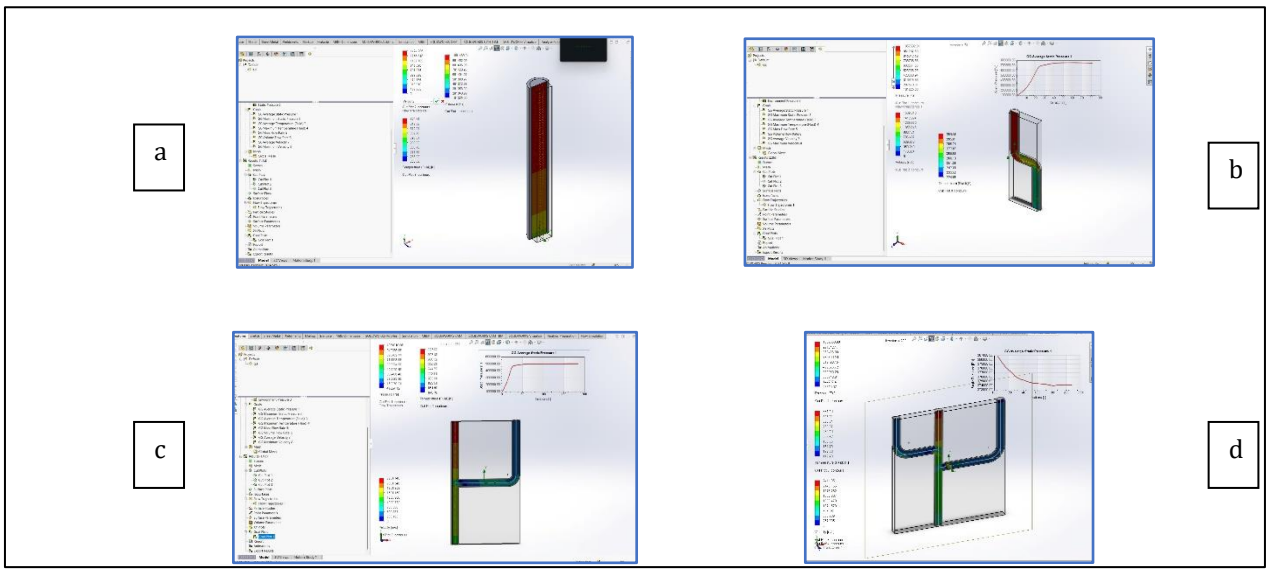


Figure 5: The Pictorial Results of The Four (4) SOLIDWORKS Simulations of the respective four (4) AutoCAD Geometries, G1, G2, G3 and G4

For the simulations, each geometry (G1 to G4) was given One (1) inlet as the top central opening of the respective geometry, with as many outlets as there were other openings for the respective geometry. That is to say, G1 had One (1) Inlet and One (1) Outlet, G2 had One (1) Inlet and One (1) Outlet, G3 had One (1) Inlet and Two (2) Outlets and G4 had One (1) Inlet and Three (3) Outlets. Each Inlet received 1 Megapascal (1MPa) influx of Compressed Hydrogen Gas and showed the behavior of the Hydrogen Gas as it flowed through the respective geometry.

Figures 5a, 5b, 5c and 5d above respectively show the pictorial results of the respective four (4) SOLIDWORKS Simulations of the respective four (4) AutoCAD Geometries, G1, G2, G3 and G4. The results were used to plot the graphs in Figures 6, 7 and 8 below:

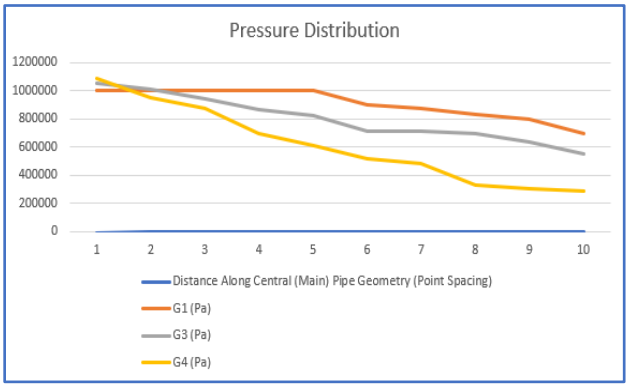


Figure 6: Plot of Pressure Distributions within the Major Central Pipes of G1, G3 and G4

From Figure 6, the major central pipe of G1 experienced a steady pressure drop with the least pressure gradient, the major central pipe of G3 also experienced a steady pressure drop but with the intermediate pressure gradient, and the major central pipe of G4 likewise experienced a steady pressure drop but with the greatest pressure gradient. This result proved that there is a general tendency for pressure to drop along the flow within the pipe, and that with more side outlets in pipe were greater pressure drops produced. The tendency for pressure to drop along the flow is as a result of Major Energy Losses (Losses in the flow energy due to friction between the Hydrogen Gas and the internal walls of the pipe) due to Loss of Pressure Energy by the Hydrogen Gas. (Bai & Bai, 2010; World Iron Steel, 2021).

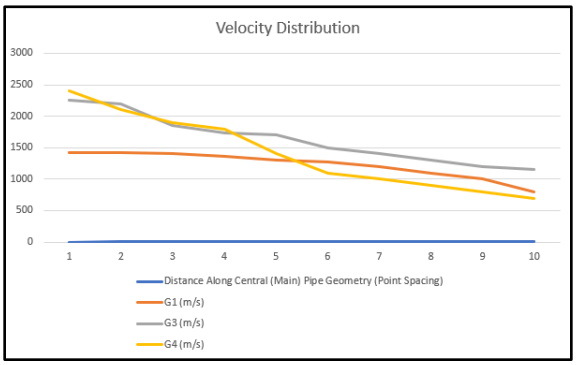


Figure 7: Plot of Velocity Distributions within the Major Central Pipes of G1, G3 and G4

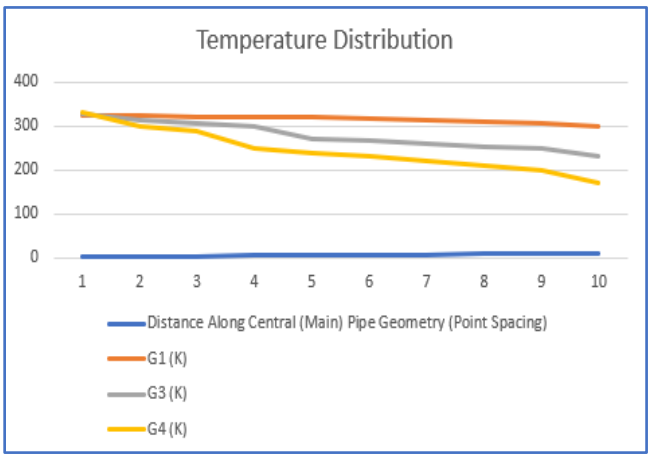


Figure 8: Plot of Temperature Distributions within the Major Central Pipes of G1, G3 and G4

From Figure 7 above, the major central pipe of G1 experienced a steady velocity drop with the least velocity gradient, the major central pipe of G3 also experienced a steady velocity drop but with the intermediate velocity gradient, and the major central pipe of G4 likewise experienced a steady velocity drop but with the greatest velocity gradient. This result proved that there is a general tendency for velocity to drop along the flow within the pipe, and that with more side outlets in pipe were greater velocity drops produced. The tendency for velocity to drop along the flow is as a result of Major Energy Losses (Losses in the flow energy due to friction between the Hydrogen Gas and the internal walls of the pipe) due to Loss of Kinetic Energy by the Hydrogen Gas.

From Figure 8, the major central pipe of G1 experienced a steady temperature drop with the least temperature gradient, the major central pipe of G3 also experienced a steady temperature drop but with the intermediate temperature gradient, and the major central pipe of G4 likewise experienced a steady temperature drop but with the greatest temperature gradient. This result proved that there is a general tendency for temperature to drop along the flow within the pipe, and that with more side outlets in pipe were greater temperature drops produced. The tendency for temperature to drop along the flow is as a result of Major Energy Losses (Losses in the flow energy due to friction between the Hydrogen Gas and the internal walls of the pipe) due to Loss of Internal Energy by the Hydrogen Gas.

Furthermore, Figures 3.4, 3.5 and 3.6 above collectively showed a direct correlation between Pressure, Volume and Temperature along the flow, which reemphasized The Ideal Gas Law and The Ideal Gas Equation wherein Pressure and Temperature are defined having a direct proportionality, described in Section 2.2.2.

3.5 Results of The Produced Guidelines and Discussion

As briefly mentioned in section 2.2.5, The Final Guidelines produced for Hydrogen Pipeline Transportation Networks included

- Technical Safety Guidelines
- Technical Efficiency Guidelines
- and Economic Guidelines.

3.6 Technical Safety Guidelines

The technical safety guidelines for Hydrogen Pipeline Networks listed below ensure that the Hydrogen Pipeline Network will not cause harm to any person, asset or the environment.

- The Materials used for the components of the Hydrogen Pipeline Network must possess the minimum required Mechanical Strength to overcome the inevitable operational stresses (Internal Fluid Pressure and External Load Pressure).
- Pipe Joints along the pipeline, like fasteners or threaded joints, must create perfectly air-tight seals when joining the pipes to unsure the absence of leaks or holes along the pipeline, and must be made of hydrogen-embrittlement-resistant material.
- Hydrogen Pipeline Network must be safe from Lightning which can burst the Pipeline and cause an explosion.
- Hydrogen Pipeline Network must be safe from Overheating or Freezing to ensure the Hydrogen Gas remains in a safe pipeline transportation temperature, and to avoid damage to pipeline components or thermal expansion.
- Hydrogen Pipeline Network must be safe from Human or Animal Activities.
- Hydrogen Pipeline Network must incorporate PRV's or PSV's at strategic locations.

3.6.1 Technical Efficiency Guidelines

The technical efficiency guidelines for Hydrogen Pipeline Networks listed below ensure that the Hydrogen Pipeline Network will function and perform at the highest level.

- Hydrogen-Embrittlement-Resistant Material must be used for regions of the pipeline which will have direct contact with Hydrogen.
- The Pipeline should incorporate as few bends as possible in order to minimize Minor Energy Losses (or Minor Losses)

3.6.2 Economic Guidelines

The economic guidelines for Hydrogen Pipeline Networks listed below ensure that the Hydrogen Pipeline Network is as cost-effective as possible.

- Transmission Pipelines should be made of more expensive, stronger Austenitic Stainless Steel (ASS) Material.
- Distribution Pipelines should be made of less expensive, weaker Fiber-Reinforced Polymer (FRP) Material.

4 CONCLUSION

The Crystallographic Analysis successfully determined that Austenitic Stainless Steel (ASS) is the choicest material to comprise the components of the transmission segment, whereas Fiber Reinforced Polymer (FRP) is the choicest material to comprise the components of the distribution segment of the Hydrogen Pipeline Transportation Network.

A Robust Mathematical Model was successfully created for a Hydrogen Pipeline.

Transportation Network by applying The Ideal Gas Equation and The Three (3) Transport Equations in Cylindrical Coordinates, which follows the conventional methodology which is employed by modern mathematicians and engineers in modeling fluid flow (Tamrakar & Ramachandran, 2018).

Fiber Optic Sensor System was determined as the best to make up the Monitoring (or Sensing) segment of the Real-Time Monitoring and Control System for a Hydrogen Pipeline Transportation Network. Furthermore, The Smart Hydrogen Pipeline Pigging (SHyPP) System was successfully proposed as an advantageous leak-detection mechanism for a Hydrogen Pipeline Transportation Network.

The Simulations successfully demonstrated the general behavior of Hydrogen when it is subjected to Pipeline Transportation and proved the theory of major and minor losses in a pipeline, which are obeyed perfectly by HydrogenA finite system of Guidelines was successfully created for Hydrogen Pipeline Transportation Networks.

Recommendations

The topics of Hydrogen Production and Specialized Hydrogen Compression Technology, which are affiliated with the aim of this paper -to provide a finite solution to hydrogen pipeline network transportation- were not covered in this paper because they were out of its scope, and are thus recommended for further reading (Andrzej et al., 2017; Eugene et al., 2022)

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Author Contribution

Oparadike F. E: Writing the original draft, methodology, investigations, conceptualization. Le-ol A. K: Investigations, final analysis. Gokpa W. O: Reviewing and editing

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