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Simulation of Hydrogen Gas Transportation through Pipeline Manifold Systems in Gas Gathering Facilities using CFD Software

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ABSTRACT

This paper presents a computational fluid dynamics (CFD) study on the simulation of hydrogen gas transportation through a pipeline manifold system using SimFlow. The project aims to evaluate the flow characteristics of hydrogen gas, focusing on velocity and pressure profiles to identify potential inefficiencies and areas for optimization. Using a simulated 3D model of a pipeline manifold, the study analyzes the behavior of hydrogen flow through varying pipeline geometries and cross-sections. Key findings include high-velocity regions reaching 2.3 m/s near the pipeline exit and low-velocity zones around 0.59 m/s near the inlet branches. Pressure variations were also observed, with high-pressure zones up to 4.3 MPa at the inlets and low-pressure regions dropping to -1.4 MPa near the outlet, indicating significant pressure loss along the pipeline. These variations contribute to turbulence, recirculation, and potential material stress. Convergence of the simulation was achieved after 388 iterations, indicating numerical stability in the solution. This study provides valuable insights into optimizing hydrogen transport infrastructure, ensuring safe and efficient delivery in pipeline systems.

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1. INTRODUCTION

The global energy landscape is undergoing a significant transformation as nations confront the challenges posed by climate change, air pollution, and energy security. Central to this shift is the adoption of clean energy solutions, with hydrogen emerging as a pivotal player in decarbonizing transportation, industry, and power generation. Hydrogen's high energy density, versatility, and ability to produce zero carbon emissions when utilized as a fuel position as a promising pathway toward a sustainable energy future. However, despite its vast potential, the deployment of hydrogen as a major energy carrier faces several challenges, particularly in the efficient and safe transportation of hydrogen gas from production sites to end users.

The unique properties of hydrogen, such as low molecular weight, high diffusivity, and susceptibility to embrittlement, create engineering and safety challenges in pipeline infrastructure design. Ensuring minimal leakage, stable flow dynamics, and resistance to corrosion and mechanical stresses is essential for maintaining the integrity of hydrogen transportation networks over time [1]. Hydrogen is also prone to leakage, which can significantly undermine its environmental benefits. Studies indicate that hydrogen leaks can contribute to greenhouse gas warming effects that are more severe than previously understood [2].

To address these challenges, advanced Computational Fluid Dynamics (CFD) simulations are essential tools for optimizing pipeline designs, predicting performance under various conditions, and identifying potential bottlenecks or instabilities in flow [3]. This study focuses on utilizing CFD software, specifically SimFlow, to simulate hydrogen gas transportation through complex pipeline manifold systems. SimFlow offers robust capabilities for analyzing fluid flow behavior, pressure distributions, and turbulence characteristics within pipelines under various operating conditions [4].

The relevance of this research extends beyond academic inquiry; it is directly tied to real-world applications in regions with untapped potential for hydrogen development. Nigeria possesses the largest natural gas reserves in Africa and has a growing interest in utilizing its gas infrastructure for hydrogen production and distribution [5]. Developing effective transportation systems tailored for hydrogen can help reduce environmental harm from flaring while positioning Nigeria as a leader in clean energy innovation [6].

This manuscript aims to contribute valuable insights for policymakers, engineers, and industry stakeholders by enhancing the understanding of hydrogen transportation dynamics through advanced modeling techniques. This study seeks to pave the way for more widespread adoption of hydrogen as a clean energy carrier by addressing critical technical in hydrogen transportation [7].

1.1. Physical Properties of Hydrogen Relevant to Pipeline Transport

Hydrogen possesses unique physical characteristics that significantly affect its behavior during pipeline transport. These properties include low density, high diffusivity, and extensive flammability limits. A thorough understanding of these attributes is essential for conducting accurate computational fluid dynamics (CFD) simulations.

Hydrogen has a density of 0.08988 kg m^3 at standard temperature and pressure (STP), which is approximately one-fourteenth that of air. Due to this low density, hydrogen experiences high velocity for a given volumetric flow rate (Q) (1).

$$Q = A \cdot v \tag{1}$$

In (1), Q represents the volumetric flow rate (m^3/s), A denotes the cross-sectional area (m^2), and v indicates the velocity (m/s). The low density also leads to a reduced mass flow rate ($\dot{m} = \rho \cdot Q$), necessitating larger diameters or higher pressures to achieve energy-dense flow conditions.

The molecular diffusivity (D) of hydrogen in air or other gases is considerably higher than that of most industrial gases, as described by the relationship (2).

$$D \propto \frac{1}{\sqrt{M}} \tag{2}$$

In (2), M represents the molar mass of the gas. For hydrogen, this results in a diffusivity of approximately $6.3\times10^{-5} m^2/s$ in air at STP, which facilitates permeation through materials and raises leakage risks.

Hydrogen's compressibility factor (Z) deviates from ideal gas behavior at elevated pressures, particularly above 20MPa [8]. The Peng-Robinson equation of state (EOS) is frequently applied to characterize its pressure-volume-temperature (PVT) behavior (3):

$$P = \frac{RT}{v-b} - \frac{a}{v^2-2bv- \ ^2} \tag{3}$$

In (3), a and b are gas-specific constants, R is the universal gas constant (8.314 J mol^{-1} K^{-1}), T represents temperature (K), and v indicates molar volume (m^3/mol).

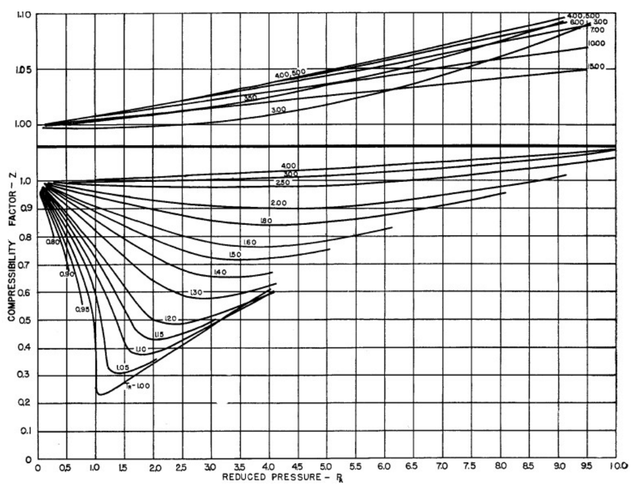

Figure 1: Hydrogen Compressibility Chart - Low Pressure Range [9].

Figure 1 represents the variation of the compressibility factor (Z) of hydrogen at lower pressures. At low reduced pressures (P_R < 20), the behavior of hydrogen is closer to that of an ideal gas, as Z remains near 1.0 for most temperature conditions. However, at very low temperatures and moderate pressures, Z drops below 1.0, indicating that intermolecular attractions dominate, leading to a higher density than predicted by the ideal gas law. This deviation suggests that hydrogen experiences significant real gas effects even at moderate pressures when the temperature is low.

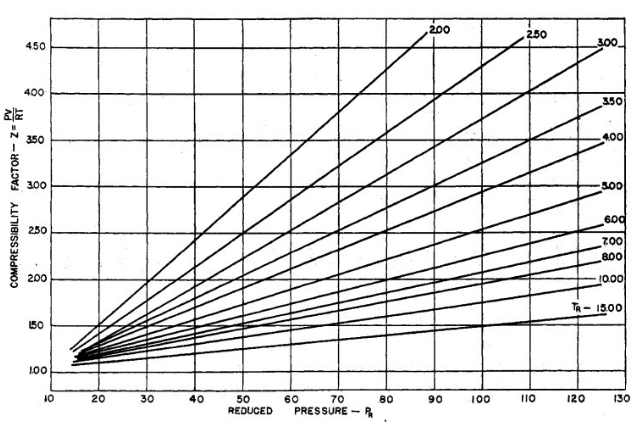

Figure 2: Hydrogen Compressibility Chart - High Pressure Range [10].

Figure 2 shows the compressibility factor for hydrogen at higher reduced pressures (P_R > 20). At these pressures, Z increases significantly, moving well above 1.0, indicating the dominance of repulsive intermolecular forces. This behavior is typical of gases at high pressures, where the volume occupied by gas molecules and their interactions become significant. The trend suggests that hydrogen's deviation from ideal gas behavior becomes more pronounced beyond 20 MPa, requiring real gas corrections for accurate density and flow calculations in pipeline and storage applications

1.2. Challenges in Hydrogen Pipeline Infrastructure

1. Material Compatibility: Hydrogen embrittlement presents a significant challenge as molecular hydrogen dissociates into atomic hydrogen under high pressures, diffusing into steel and causing micro-cracks. This phenomenon can be quantified using Fick's diffusion equation [11].

$$\frac{\partial C}{\partial t} = D\nabla^2 \tag{4}$$

In (4), C signifies the concentration of hydrogen in the material (mol/m^3), D denotes the diffusion coefficient (m^2/s) and t represents time (s).
Selecting appropriate pipeline materials necessitates balancing strength, ductility, and resistance to hydrogen embrittlement, often requiring specialized alloys and coatings.

2. Pressure Drop and Energy Efficiency: Due to its low density, transporting hydrogen necessitates careful consideration of pressure drops along pipelines, which can be modeled using the Darcy-Weisbach equation [12].

$$\Delta P = f \cdot \frac{L}{D} . \frac{\rho v^2}{2} \tag{5}$$

ΔP indicates pressure drop (Pa), f is the friction factor, L represents pipeline length (m), D denotes pipeline diameter (m), ρ signifies hydrogen density (kg/m^3), and v indicates velocity (m/s).

3. Safety Concerns: Hydrogen's extensive flammability range (4−75% by volume in air) and low ignition energy (approximately 0.02 mJ) [13] significantly elevate explosion risks. Effective leak detection is critical and can be modeled using CFD simulations of plume dispersal based on the Navier-Stokes equations and Fick's law for mass transport:

$$\frac{\partial C}{\partial t} + \nabla \cdot (Cv) = \nabla \cdot (D\nabla C) \tag{6}$$

In (6), v is the flow velocity field (m/s).

CFD modeling of hydrogen transportation must incorporate these physical properties and challenges to ensure an accurate representation of flow dynamics, material interactions, and safety risks. SimFlow enables this through advanced turbulence models, multiphase solvers, and custom material libraries, facilitating comprehensive simulations of hydrogen transport within complex pipeline manifold systems.

1.3. Previous Studies Utilizing CFD for Flow Simulation

Computational Fluid Dynamics (CFD) is a numerical tool for analyzing fluid flow in intricate systems, such as pipelines used for the transportation of hydrogen. Engineers can forecast flow behavior, pressure distributions, and possible leakage spots by using CFD to solve the governing equations of fluid motion [14]. These predictions are helpful for maintaining efficiency and safety in flow systems. CFD makes it possible to analyze flow parameters like pressure and velocity in detail.

Numerous studies have used CFD to simulate similar flow in pipeline systems. A study by Cao et al utilized CFD simulations to investigate mean velocity, head loss coefficient and discharge coefficient in water pipelines [15]. In 2024, Xu et al [16] used CFD to examine the diffusion and leakage properties of natural gas pipelines to carry hydrogen. By simulating how factors like pressure, leak size, and wind speed affect the hazardous diffusion range, the study showed that, in comparison to pure natural gas, hydrogen mixing marginally expands the diffusion range. CFD has been used to simulate the dispersion of hydrogen fuel gas in enclosed spaces, showing its behavior under varying release conditions. Parameters like concentration distribution, flammability, and ventilation effects were analyzed, providing information for mitigating explosion risks [17]. Giannissi and Venetsanos used CFD to model liquid hydrogen dispersion in an open environment, addressing critical safety hazards like fire and asphyxiation [18]. It compares Homogeneous (HEM) and Non-Homogeneous Equilibrium Models (NHEM), demonstrating the improved accuracy of NHEM in accounting for slip effects in the non-vapor phase.

1.4. Pipeline Manifold Systems in Gas Gathering Facilities

In gas gathering facilities, pipeline manifold systems connect and direct gas flows from various inlet sources to a central processing unit or outlet point. They ensure efficient handling of pressure, flow distribution, and separation of gas from liquids or other impurities. Manifolds are also key to operational flexibility, allowing maintenance or isolation of specific pipelines without interrupting the entire system. Proper design is critical for managing high-pressure and multiphase flows while minimizing energy losses and ensuring safe, efficient operations.

Figure 3: Pipeline Manifold.

Figure 3 shows a pipeline manifold in a at the Kwale Gas Gathering (KGG) facility in Delta State, Nigeria, with three inlet lines and a single outlet, which is the basis of the 3D model designed for this research. The manifold serves as a central hub for managing gas flow efficiently.

While numerous studies have utilized CFD to analyze hydrogen flow, many focus on simple pipeline configurations rather than complex manifold systems. The interactions between multiple branches and varying flow rates in manifold systems present unique challenges that are often overlooked in existing literature. This study aims to provide in-depth analysis of flow distribution, pressure drops, and turbulence in hydrogen manifold systems.

1.5 Statement of Problem:

Transporting hydrogen through pipeline systems in gas gathering facilities involves unique challenges due to its low density, high diffusivity, and vulnerability to material degradation under high-pressure conditions. Despite the increasing role of hydrogen in energy systems, there is a lack of in-depth simulations that explore hydrogen flow behavior within pipeline manifolds, especially concerning issues like pressure drop, turbulence, and flow velocity. These factors can contribute to operational inefficiencies and safety concerns, such as material stress, leakage, and uneven flow distribution, particularly at junctions or pipeline exits. To address these issues, more precise simulations are needed to enhance the design and safety of hydrogen transportation infrastructure.

1.6 Aim of the study:

This study aims to utilize Computational Fluid Dynamics (CFD) software to simulate hydrogen gas flow through pipeline manifold systems in gas gathering facilities. The goal is to pinpoint areas with high turbulence and pressure losses and ultimately provide guidance on optimizing manifold designs for more efficient and safer hydrogen transport.

2. EXPERIMENTAL METHODOLOGY OF RESEARCH

2.1. SimFlow Software Overview

SimFlow is a robust Computational Fluid Dynamics (CFD) software that offers a highly accessible platform for simulating fluid flow, heat transfer, and related physical processes. Built on the OpenFOAM engine, a widely recognized open-source CFD toolkit, SimFlow combines the flexibility and power of OpenFOAM with a user-friendly interface. This integration makes SimFlow an ideal choice for both academic research and industrial applications, providing accurate and efficient simulations for a wide range of fluid dynamics problems, including multiphase and compressible flow scenarios. SimFlow simplifies simulation setup, mesh editing, and visualization. It supports various solvers for laminar, turbulent, and multiphase flows. The software also includes a library of material properties and thermophysical models, facilitating accurate simulations of hydrogen and other fluids, making it ideal for pipeline flow simulations. It is also completely free to download, making it a great choice for research purposes.

2.2. Manifold Infrastructure Design and Mesh Generation

The simulation begins by establishing a new project case in SimFlow, where the project directory and the initial simulation parameters are specified. The manifold infrastructure is then designed on the SimFlow Geometry panel. First, Cartesian coordinates of the origin and axes of each inlet cylindrical pipe as well as their dimensions are input. The dimensions are in meters, and for this study a scale model of a manifold with three inlet pipelines on the x-axis and one inlet line on the y-axis as well as an outlet point on the y-axis, all in a three-dimensional environment, was created.

To create a single unit for analysis, all pipelines are selected and the tool “Unite Geometries” is used to merge them together. The resulting manifold geometry for this study is shown below.
In figure 4, the manifold infrastructure is shown. It was designed on SimFlow software and is saved as a .stl file.

Face groups were then defined. By defining face groups, the inlet points, outlet points, and boundary walls were specified. Meshing was then done in CFD to discretize the computational domain into smaller elements, enabling numerical solutions of fluid flow equations by approximating them across the grid points. To mesh the created geometry, the Hex Meshing panel was selected, and the settings ‘Mesh Geometry’ and ‘Create Boundary Layer Mesh’ were enabled. The discrete divisions were then specified as 25, 200, 60, on the x-, y- and z- axes respectively. This was to ensure enough finite elements for a comprehensive analysis, while taking CPU power into account.

Figure 5 displays the meshing of the manifold 3D model. The discrete divisions are specified as 25x200x60, allowing for proper finite element analysis.

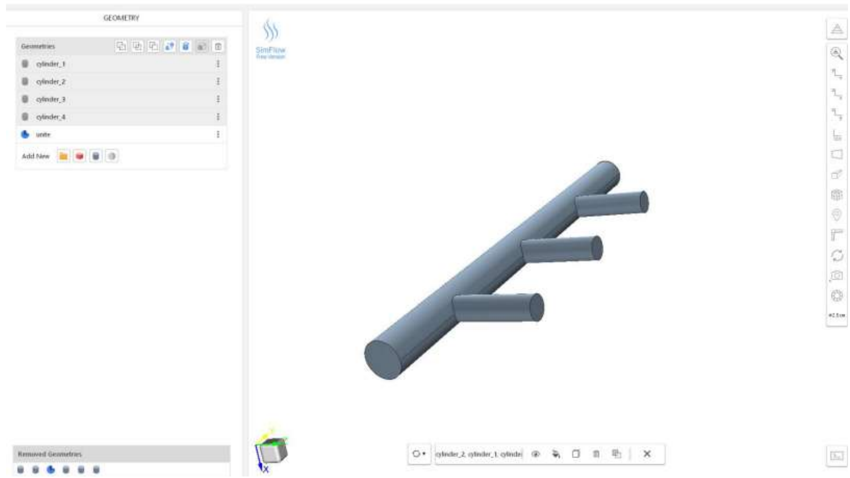

Figure 4: Manifold Infrastructure.

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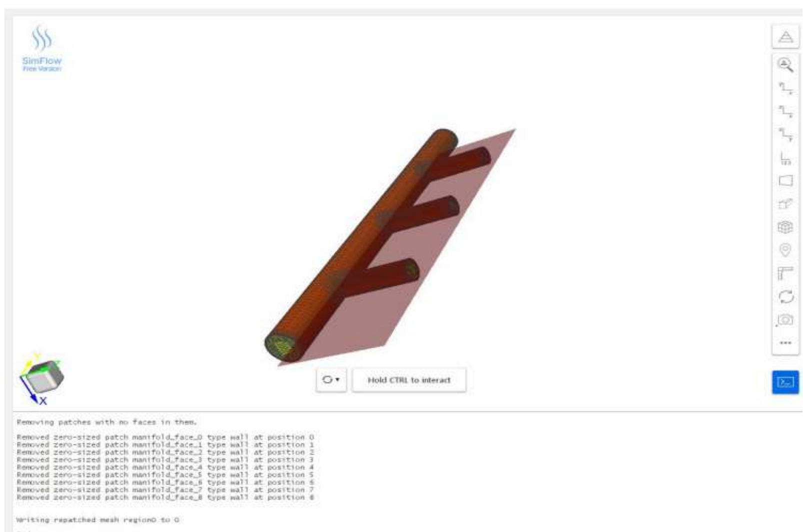

Figure 5: Meshed Geometry (Face Groups In Green)

2.2. Solver Selection, Turbulence Modeling and Simulation Execution

The simpleFoam solver in OpenFOAM and SimFlow is a steady-state solver for incompressible, turbulent flow. It uses the SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm to iteratively solve the Navier-Stokes equations, making it suitable for modeling steady fluid flows in a wide range of engineering applications. Hydrogen gas flow is compressible, and for this study, a steady state approach was used.

Figure 6 shows the solver models available on SimFlow, which can be filtered based on experimental needs of either steady-state or transient time, or compressible or incompressible flow.

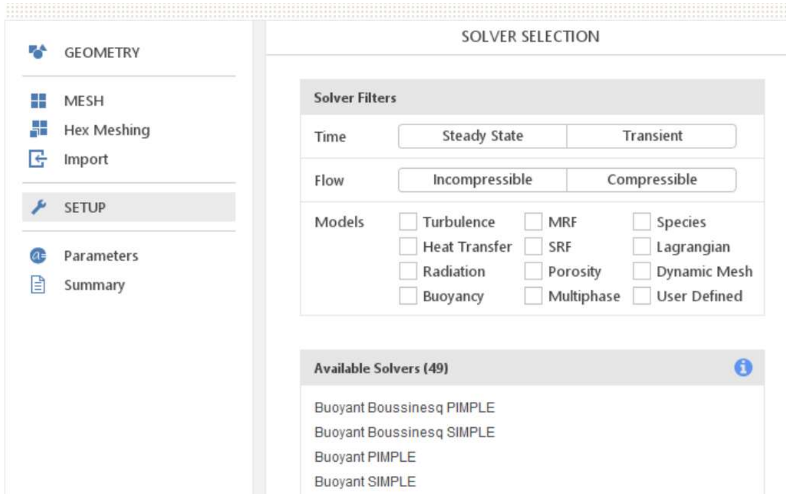

Figure 6: Solver Selection on SimFlow.

Turbulence modeling is done to predict and account for the effects of chaotic and fluctuating fluid motions in simulations, enabling accurate analysis of flow behavior in complex systems. The Reynolds-Averaged Navier-Stokes (RANS) approach is chosen for its computational efficiency in predicting steady-state turbulence behavior over the entire domain. The RANS equation can be written as (7).

$$\frac{\partial(\rho U_i)}{\partial t}+\frac{\partial(\rho U_i U_j)}{\partial x_i} = -\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)-\overline{\rho u_i' u_j'}\right] \tag{7}$$

In (7), U = mean flow velocity, u'= velocity fluctuations due to turbulence, μ= molecular viscosity $\rho u_i' u_j'$= Reynolds Stress term [19].

The k-ω Shear Stress Transport (SST) model combines the strengths of the k-ω model near walls and the k-ε model in free-stream regions. It is well-suited for handling flow separation and boundary layer phenomena, and as such it is ideal for this study's focus on regions of recirculation and turbulence within manifold systems [20].

The relation between dissipation rate (ϵ) and specific dissipation rate (ω) is given by (8).

$$\epsilon = C_\mu k\omega \tag{8}$$

In (8), C_μ= 0.09.

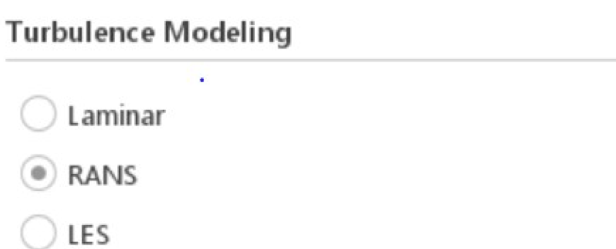

Figure 7: Turbulence Model Selection.

In Figure 7, turbulence modeling options include Laminar, suitable for low Reynolds number flows with smooth motion; RANS (Reynolds-Averaged Navier-Stokes), which time-averages turbulence for computational efficiency (e.g., k-ε, k-ω models); and LES (Large Eddy Simulation), which resolves large turbulent structures for higher accuracy but at a greater computational cost.

Hydrogen was then selected as fluid material.

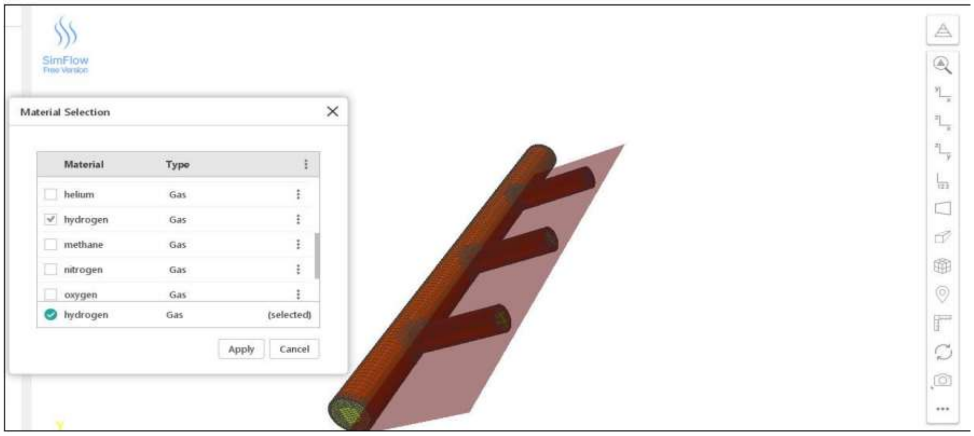

Figure 8: Hydrogen Selection

In the Material Selection tab as shown in Figure 8, various fluids are available for selection, such as helium, hydrogen, methane, divided according to Gas type or Liquid type. In specifying inlet and outlet boundary conditions, a reference velocity of 0.8 m/s, obtained from anectodal observation, was used. The inlets, outlet and body characteristics of the wall were set as Velocity Inlet, Pressure Outlet and Wall, respectively.

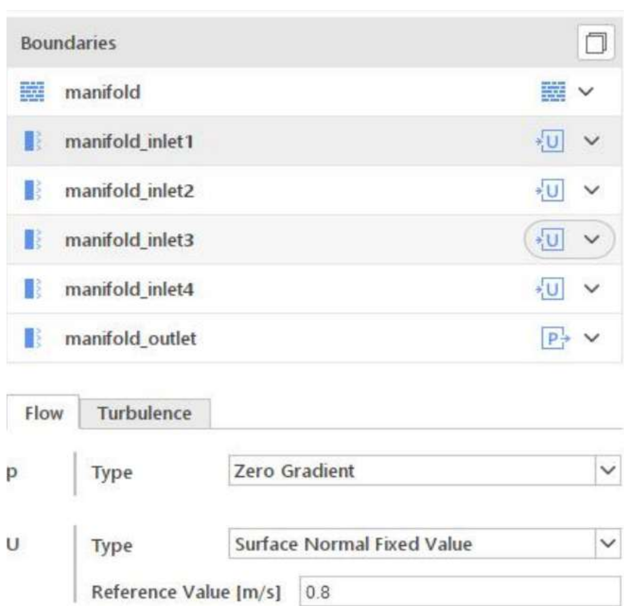

Figure 9: Boundary Conditions.

Boundary conditions (Figure 9) include specifying the manifold body as an impermeable 'wall' and specifying the velocity of the inlets as 0.8m/s. The outlet is specified as a pressure outlet as the velocity at that point is expected from the simulation results.

Simulation execution begins with a process called sampling. In computational fluid dynamics experiments, sampling is done to view the results observed during simulation on a section plane. For this research, the sampled fields were p and U, to obtain a pressure profile and velocity profile of flow. The simulation calculations involve solving the Navier-Stokes equations iteratively until a converged solution is obtained.

3. RESULTS AND DISCUSSION

The velocity profile of hydrogen gas flow in Figure 10 through the pipeline manifold reveals significant variations ranging from approximately 0.59 m/s (low-velocity zones, shown in blue) to 2.3 m/s (high-velocity zones, shown in red). Low-velocity regions are observed near the base of each inlet branch, where momentum decreases as hydrogen is diverted. High-velocity regions downstream the branches, reaching up to 2.3 m/s, indicate flow acceleration due to reduced cross-sectional flow area. Recirculation zones near the branches are evident from localized velocity gradients, while near the outlet, the velocity increases significantly, approaching the maximum value of 2.3 m/s, likely due to cumulative flow acceleration and reduced resistance.

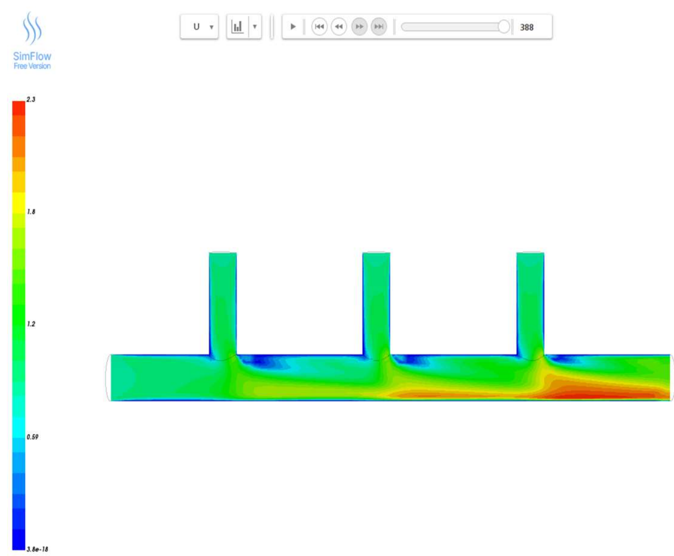

Figure 10. Velocity Profile of Flow.

The pressure profile of hydrogen gas flows through the pipeline manifold in Figure 11 ranges from approximately -1.4 MPa (low-pressure zones shown in blue) to 4.3 MPa (high-pressure zones, shown in red). High-pressure regions are mostly found at the inlets (branches), where hydrogen enters the main pipe, with the pressure gradually decreasing along the flow direction due to energy dissipation. Low-pressure zones are observed near the outlet, which shows the pressure drop as the flow exits the system. Transition regions between the branches display pressure gradients, as a result of mixing and flow interaction.

The variables represented in Figure 12 are: k (turbulence kinetic energy, light blue), ω (specific turbulence dissipation rate, yellow), p (pressure, black), Ux (x-velocity, dark blue), Uy (y-velocity, red), and Uz (z-velocity, green). The residuals vs. iterations graph provides insights into the convergence behavior of the CFD simulation, showing the reduction in errors across different solution variables as the iterations progress. By iteration 388, all residuals reach acceptable thresholds, confirming a well-converged solution.

In CFD, convergence refers to the process where the solution stabilizes as the simulation iterates through successive steps, with the residuals (errors in the governing equations) reducing to sufficiently small values. Convergence ensures that the solution satisfies the governing equations (here, Navier-Stokes equations) to a high degree of precision. Without convergence, the results may not reflect the true physical phenomena and could lead to incorrect predictions of flow, pressure, temperature, or other variables.

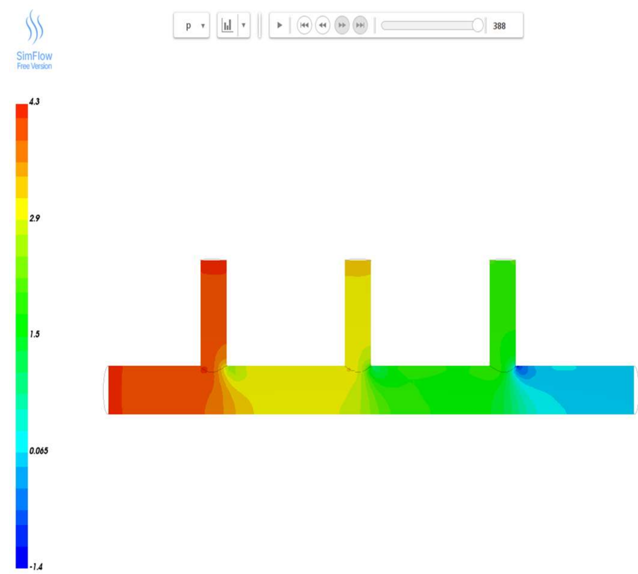

Figure 11. Pressure Profile of Flow.

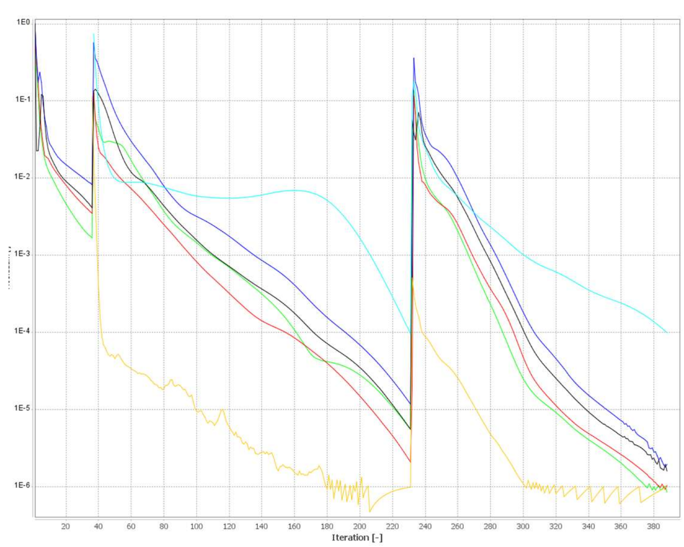

Figure 12. Residual Convergence for Hydrogen Flow in Pipeline Manifold.

3.1. Discussion on Results

i. The role of gas-gathering facilities in Nigeria's blue hydrogen production plans

In natural gas processing, gas gathering facilities enable the collection and transportation of natural gas from multiple production sites and processing plants to distribution networks. In gas gathering facilities natural gas is consolidated from various inlet metering lines, where pressure is managed, impurities are removed, and it is ensured that the product meets pipeline specifications before it is transported to downstream facilities.

A notable example of these facilities in action is the Kwale Gas Gathering (KGG) facility in Nigeria, commissioned by Nedogas Development Company Limited—a joint venture between Xenergi Limited and the Nigerian Content Development Monitoring Board (NCDMB)—in partnership with the Nigerian Gas Company (NGC). Located near Kwale in Delta State, the KGG facility is designed to handle up to 300 million standard cubic feet per day (MMscfd) of natural gas. It gathers gas from multiple fields within Nigeria's OML56 oil province, compresses and processes it, and injects it into the OB3 gas trunk line [21]. This facility serves to curb gas flaring by making the gas available for industrial and residential electricity generation, and as further feedstock for petrochemical manufacturers [22]. In the mid-2020s, the current momentum in the energy industry is swinging towards decarbonization. Blue hydrogen, which is produced through steam methane reforming (SMR) and coupled with carbon capture and storage (CCS), represents a prominent transitional energy source [23]. With the wealth of experience in gas handling Nigeria has had over the past three decades, it is anticipated that infrastructure that mirrors natural gas systems will be used in blue hydrogen distribution and integration. Similar gas gathering facilities would collect hydrogen produced from SMR plants, manage its unique properties and distribute it efficiently. Globally, large-scale plans to develop hydrogen plants are picking up steam, such as the ExxonMobil blue hydrogen plant at Baytown, Texas, which aims to generate up to 1 billion cubic ft of hydrogen per day [24]. Nigeria has the opportunity and resources to be at the forefront of this movement, a movement which efficient gas transportation will play a key role.

Within gas gathering facilities, manifolds function to consolidate gas from multiple inlet lines and direct it towards main transport lines. When considering hydrogen gas transportation, manifold design must account for the low density and high diffusivity of hydrogen, which results in increased turbulence and pressure variations. This study provides experimental evidence of non-uniform velocity distributions within hydrogen manifolds, localized velocity peaks near inlets and regions where recirculation is observed. As such, inlet configurations must be optimized to minimize turbulence and ensure uniform flow. Furthermore, significant pressure drops observed from the inlets to the outlet suggest that precise pressure management is needed. Pressure management will prevent inefficiencies that will arise from this observation. Convergence of residuals in these simulations confirm that the numerical models are reliable, and that their application in hydrogen manifold design will not result in erroneous configurations. From the observations drawn from this study, optimization of hydrogen manifold design and by extension gas gathering facility design can be achieved. If Nigeria is to capitalize on its vast resources and fast-track its transition to greener and cleaner energy sources, blue hydrogen is a critical piece of that ever-expanding mosaic.

ii. Suggested Manifold Design Upgrades from Simulation Results

Perhaps the most important design upgrade that can be inferred from this study is the inclusion of pressure-balancing mechanisms. The simulation shows notable pressure drops along the manifold cross-section, and adjustable pressure control valves (PCVs) and flow regulators at the inlet points will guarantee consistent outlet pressures and minimize pressure differentials. A manifold with smoother internal surfaces could significantly reduce pressure losses, which will result from the low diffusivity of hydrogen gas. Adjusting the configuration of the manifold inlets can also ensure better flow transitions. A fabrication consideration would be to use diffuser-shaped inlets, to achieve a more uniform hydrogen distribution across the manifold.

The study also identified the formation of recirculation zones near inlets, which can create inefficiencies and localized pressure losses. To counter this, internal baffles or flow guides could be installed to streamline the flow and eliminate recirculation. Turbulence management features can also mitigate the high turbulence observed near the inlets. Honeycomb flow straighteners are amazing at conditioning flow and reducing vortices.

4. CONCLUSIONS AND RECOMMENDATIONS

The study emphasized the critical role of gas gathering facilities, such as the Kwale Gas Gathering Facility in Nigeria, in enabling efficient natural gas distribution. This infrastructure serves as a blueprint for future blue hydrogen facilities, which will adopt a similar distribution framework to support the energy transition. CFD simulations successfully characterized the flow behavior of hydrogen within a pipeline manifold, revealing issues such as turbulence, pressure drops, and non-uniform velocity profiles. The velocity profile showed variations between 0.59 m/s (low-velocity zones) and 2.3 m/s (high-velocity zones), while pressure variations ranged from -1.4 MPa to 4.3 MPa. These fluctuations highlight the need for improved pipeline design to minimize inefficiencies.

Specific design recommendations, including tapered inlets, pressure-balancing mechanisms, and turbulence management structures, were proposed to address the challenges identified, improving overall hydrogen transport efficiency.

DECLARATIONS

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