Thermal Analysis of Hydrogen Fast-Filling Process

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List Of Nomenclature

Symbol	Description	Symbol	Description
a	Local speed of sound (m/s)	Mt	Turbulent Mach number (–)
Cp	Specific heat at const. pressure (J/kg·K)	p	Absolute static pressure (MPa)
Cv	Specific heat at const. volume (J/kg·K)	r	Radial coordinate (m)
E	Total specific energy (J/kg)	T	Static temperature (K)
Gk	Turbulence kinetic energy generation	t	Flow time (s)
h	Specific enthalpy (kJ/kg)	u	Axial velocity (m/s)
k	Turbulence kinetic energy (m^2/s^2)	v	Radial velocity (m/s)
keff	Effective thermal conductivity (W/m·K)	YM	Compressibility correction (–)
γ	Specific heat ratio Cp/Cv (–)	ρ	Density (kg/m^3)
ε	Turbulence dissipation rate (m^2/s^3)	μ	Dynamic viscosity ($N·s/m^2$)
μJT	Joule–Thomson coefficient (K/MPa)	μt	Turbulent eddy viscosity ($N·s/m^2$)
Z	Compressibility factor (–)	NWP	Nominal Working Pressure
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Abstract

A significant rise in the number of hydrogen-fuelled electric vehicles has created an ongoing need for reliable, safe, and effective refuelling methods. When filling high-pressure Type IV hydrogen storage tanks, the gas temperature increases significantly due to both compression and turbulence during filling. This temperature increase can exceed the maximum safe limit of 358 Kelvin, as defined by dispensing regulations from fuel dispensing companies/standards [21]. Higher temperatures can reduce the cylinder's structural integrity and limit the available volume for charging during a refuelling operation. Therefore, thermal management within the hydrogen storage systems is an essential consideration [50].

In this study, we used Computational Fluid Dynamics to investigate how well hydrogen performs thermally during rapid filling of a cylinder using ANSYS Fluent. The CFD model we created was two-dimensional and axisymmetric, simulating a composite Type IV cylinder. We solved a set of governing equations for the mass, momentum and energy distributions. Using a realisable k-ε turbulence model and real gas properties for hydrogen to represent its heat and gas properties, the analysis was based on established thermodynamic principles [1][11]. The transient simulation gives insight into how the temperature, pressure and flow conditions evolve over time during the filling of the cylinder.

Heat transferred through thermal accumulation and the limited time for convection are why gas temperatures are high and why they occur last in the cylinders. The maximum gas temperature occurs at some point during the first stage when filling occurs and consistently reaches about 390-420 K at the end of the first stage. As heat travels to the cylinder wall, the gas temperature decreases slightly because the transfer time between injection and the wall creates a time lag.

The research highlighted the critical integration of pre-cooling mechanisms into hydrogen refuelling infrastructure during the installation of hydrogen fuel tanks and high-pressure dispensing systems [24]. The research finds that if the refuelling operation lacks a suitable pre-cooling system, the temperature will rise above acceptable levels during fast filling, negatively affecting refuelling efficiency and commercial viability. The research also proposes the creation of a support-oriented B2B ecosystem (business-to-business), which will include chiller-based pre-cooling systems, optimised refuelling protocols, and integration of hydrogen tank manufacturing [50]. Such a support-oriented ecosystem is vital for the safe, cost-effective, and large-scale commercial adoption of hydrogen technologies, particularly in high-volume applications such as heavy-duty transportation.

The results show a high demand for proper pre-cooling practices, including inlet pre-cooling methods and optimum pressure ramp-up technique. In order to mitigate possible temperature increases and provide for safe, efficient hydrogen refilling operations.

1. INTRODUCTION

The global shift to sustainable, low-carbon energy systems has been boosted by rising concerns about climate change, declining availability of fossil fuels, and growing worldwide energy consumption. Hydrogen is one of several forms of energy now believed to be among the best ways to generate energy for the future [29]. It has a relatively high energy density, does not produce any pollutants when burned, and can be used in many different applications. Thus, hydrogen is recognised as a significant contributor to the future energy mix, driven by the commitment of various agencies and governments to reduce greenhouse gas emissions globally [41],[44]. For this reason, building global infrastructure for producing, storing, and transporting hydrogen is crucial as we expand vehicles and technologies powered by it.

Efficient and safe hydrogen storage poses a substantial challenge for developing hydrogen energy systems. Hydrogen has a low volumetric energy density at normal temperature and pressure and thus requires high pressure to achieve practical energy density levels for onboard use [45]. Several methods for storing hydrogen have been developed, but high-pressure composite tanks, particularly Type IV composite tanks, have been widely accepted for their superior performance characteristics. Type IV cylinders are formed with a polymer inner liner generally made of high-density polyethene [HDPE] or polyamide, which is completely encased in a carbon-fibre reinforced polymer (CFRP) wrapping [37]. They provide a light-weight and strong mechanical structure that is resistant to fatigue and corrosion. Therefore, they are ideally suited for automotive applications [31], [35]. The cylinders can store hydrogen at pressures up to 70 MPa. This is critical in providing sufficient driving range for fuel cell-powered automobiles.

Due to the rapid filling of Type IV hydrogen cylinders with Hydrogen gas, the thermal challenges we'll face during this process are considerable. When filling hydrogen cylinders with gas quickly from low to high pressure, the internal temperature in the cylinder will increase rapidly due to thermodynamic and hydraulic conditions. Specifically, the increase in cylinder temperature is primarily due to adiabatic compression, viscous heat generation, and turbulent mixing between the incoming gas jet and the existing gas inside the cylinders [1], [5], [42]. Also, a rapid increase in temperature will produce localised heating at the end of the cylinder because the heat at the end of the cylinder will take considerable time to dissipate. If localised heating occurs within a cylinder due to the rapid temperature increase, it can reduce the mechanical integrity of the cylinder material and result in significant long-term damage to the cylinder [38].

As temperatures rise, there is a risk of safety being compromised with regard to the limits of the hydrogen fuelling protocols [28]. The SAE J2601 protocol specifies that the maximum temperature to be used in hydrogen refuelling is 358 K to guarantee safe operation and avoid degradation of materials [22]. Likewise, guidelines are provided by international standards (ISO 19881) related to the design and operation of high-pressure hydrogen storage systems, which stress the importance of thermal management while refueling [23]. When the temperatures exceed that given in the guidelines, there would be a decreased service life of the composite materials, possible failure of the polymer liner, as well as a substantially greater risk of injury or death.

Many methods of pre-cooling have been put forward and studied as solutions to these problems. One of the most widely investigated methods is pre-cooling of hydrogen prior to entering the storage cylinder. Pre-cooling of hydrogen before it enters the storage cylinder will help mitigate the increase in temperature that occurs from compressing hydrogen after entering the cylinder. Ramping rates during filling process can affect the thermal performance of the system. For example, if a cylinder is filled with hydrogen at the correct ramping rate, it can dramatically decrease the rate at which the temperature increases, thereby improving both safety and efficiency when completing refueling process [2], [3]. There are many other ways to pre-cool a cylinder through various filling methods, such as filling in stages and maintaining pressure at certain times [45]. This allows improved heat transfer and minimized temperature differentials within the cylinder. However, most of these approaches are relatively complex and involve tradeoffs concerning fill times, energy usage and overall complexity of the system.

As hydrogen infrastructure develops from laboratory sizes to more usable locations, technology supporting hydrogen systems will be integrated more. Hydrogen fueling stations need both high-pressure pumps and high-volume storage for precooling because of the large amount of heat produced by rapid filling [25], [46]. Without using precooling, a hydrogen fuelling system’s reliability and longevity are impacted directly. Thus, from a technical perspective, installing a precooling system with chillers is necessary; this system will help facilitate commercial hydrogen fuel use.

In this regard, our studies will model the thermal capacity of hydrogen at ambient conditions in a Type IV composite cylinder. Composite cylinders consist of a combination of carbon fibre composite and an inner liner at a very fast fill rate. The modelling effort will involve computational fluid dynamics methods to better understand how the gas's temperature changes during fill, how the gas's pressure changes during fill, and how the flow acts during fill based on the way the gas is filled. We will primarily focus on identifying where the highest temperatures occur in terms of the gas filling the cylinder and understanding how the cooling strategies employed in refuelling hydrogen-powered vehicles will help to mitigate against thermal penalties to the cylinder [46]. Overall, our modelling will help to alleviate the thermal issues associated with the fast fill process and support improved hydrogen storage technologies that would lead to more widespread use of hydrogen as an "alternative energy carrier."

1.1 Research Objectives

Hydrogen thermal and fluid dynamic behavior during fast filling of a high-pressure Type IV composite cylinder is the main objective. A comprehensive numerical analysis has been conducted due to the complex relation of compression effect, turbidity, and heat transfer. In order to accurately simulate the temperature history, as well as the compliance with safety standards [28]. To investigate the thermal performance of a hydrogen storage system with the help of computational fluid dynamics (CFD) is conducted.

This study's primary aim is to calculate the warm-up of a hydrogen gas tank under high-speed filling conditions. Since the rapid compression of hydrogen gas during filling can lead to a large increase in gas temperature, the fast-filling process can have a temperature above the maximum safe limit specified by hydrogen refueling standards (358 K) [21]. Thus, to understand the safety and reliability of a hydrogen storage system, it is crucial to accurately calculate the transient temperature distribution. The numerical model developed in the current study will provide an accurate representation of hydrogen temperature as it fills, based on time and distance from the filling line.

The goal of the second objective is to understand what happens to hydrogen as a working fluid when heated within a cylinder. Through understanding the mechanism behind increased temperature for hydrogen as well as to locate areas of concentrated increased temperature. Hot spots are significant from both a structural and a safety perspective. The analysis will also include an evaluation of the thermal interactions between the hydrogen and materials of the cylinder. In order to completely understand and characterize the thermal behaviour of the whole vessel system[1],[5].

In the third objective, the study will look to establish how the filling conditions of the tank have an effect on the rate of increase in tank temperature. Through the distribution of thermal energy inside the tank when comparing the inlet pressure profile and mass flow versus time. Also according to the direct correlation, the study will provide information about how operational parameters can be changed during the filling process. It is important to reduce tank temperatures, and also make sure it remain efficient while refuelling [2], [3].

The last objective is to study the effective cooling strategies for hydrogen refueling systems as it concerns thermal management strategies like hydrogen pre-cooling and controlled pressure ramping. The primary objective of this research is to provide data from temperature, pressure, and flow analysis, which will explain the significance of such thermal management strategies. The implementation of thermal management strategies to minimize excessive heat generation and meet safety requirements. Along with their implementation as a means of improving the overall efficiency of the refueling process. It should improve the overall design and optimization of hydrogen storage systems to ensure safer and more reliable storage of hydrogen.

2. LITERATURE REVIEW

Efficient and safe methods for hydrogen storage and refueling have been researched for decades because of the increasing popularity of hydrogen as an environmentally friendly source of energy. There are numerous academic studies that address the issues of hydrogen storage, which include, but are not limited to, the physical properties, thermodynamics of the process, and computational methods used to model and predict the behavior of hydrogen during storage. The research also considers high-pressure tanks employed in fuel cell cars and the measures used to cool down the hydrogen during refueling.

In the evolution of hydrogen storage technology, numerous approaches to storing hydrogen have been developed in order to address the limitations posed by hydrogen's low volumetric energy density. Initial research focused on hydrogen storage through materials-based technologies, including metal hydrides and absorption systems, but recent literature has focused on the benefits of high-pressure gas storage systems, which offer greater feasibility and advanced technology [32], [33]. Of all these storage systems, composite cylinders have become the favored option, specifically type IV cylinders, owing to their lightweight nature and ability to withstand high pressure [31], [35].

One of the major problems highlighted in the literature is related to the thermodynamic properties of hydrogen during fast fueling. High compressibility of hydrogen leads to large variations in temperature. Many experimental and simulated studies have been conducted to determine how adiabatic compression, heat transfer limitations and fluid motion affect the temperature of hydrogen during refuel. Each study produced valuable data on the temperature and pressure variation of hydrogen tanks during refuel. Furthermore, studies show that maintaining sufficient operating conditions is crucial to avoiding heat problems during operation of the tanks [6], [8].

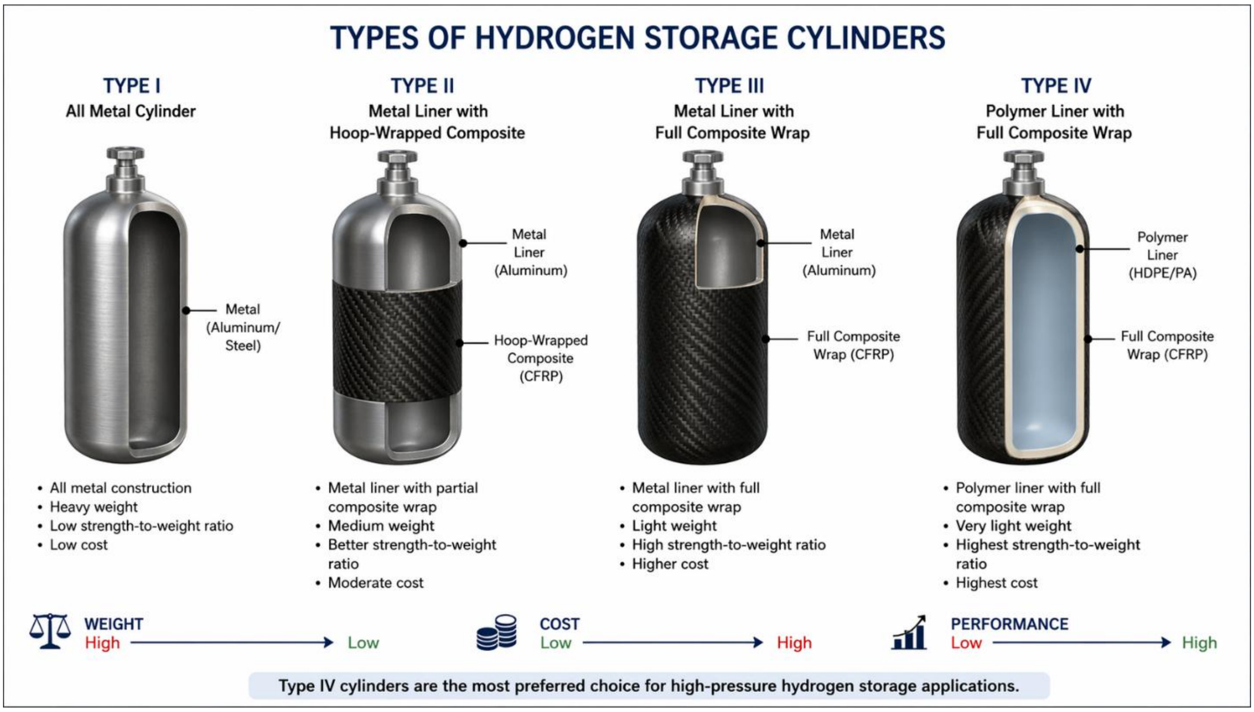
Computational fluid dynamics simulators have been used extensively to model the procedures involved in refueling hydrogen and analyse the related thermodynamic and hydrodynamic properties. In addition to reporting on temperature profile, pressure variation, and flow characteristics of high-pressure tanks, many research papers present results obtained from CFD simulations [1, 2, 4]. To accurately represent the physical phenomena occurring during refueling, these simulations typically account for the thermophysical properties associated with real gases, turbulence, and transient boundary conditions [11,12,13].

Alongside the study on its thermal response, much effort has gone into creating appropriate cooling techniques that will reduce temperature during the rapid fueling process. Among the methods considered are the use of hydrogen pre-cooling, control of pressure ramps, and multistage fueling. The pre-cooling process, in particular, has been found to be among the best ways of minimizing the peak temperature due to its effectiveness in reducing the initial thermal energy of the inflowing hydrogen. This is despite the challenges of using such a method, such as energy use, time, and complexity.

In general, the current state of literature offers an in-depth insight into hydrogen storage tanks and the difficulties that occur during fast refueling of hydrogen fuel cell vehicles. Still, further work needs to be done on combining CFD simulation and the optimal cooling system. The present study expands on the current knowledge of the topic by paying special attention to the influence of different cooling techniques on fast filling processes.

2.1 Hydrogen Storage Types

Hydrogen storage forms one of the essential components of hydrogen energy systems since it directly impacts the efficiency, safety, and feasibility of utilizing hydrogen for transport and stationary purposes. Because of the relatively low energy density of hydrogen at atmospheric temperatures, several methods of hydrogen storage have been invented to obtain realistic values of energy density. In this context, we can distinguish three general methods of hydrogen storage: gas compression, liquid hydrogen, and hydrogen storage materials [32], [33].



Type IV cylinders are the most preferred choice for high-pressure hydrogen storage applications.

Figure 1.Types of Hydrogen Storage Cylinders

The storage of compressed hydrogen gas in the form of compressed gas is a common way to store hydrogen, particularly when used in automotive-related applications. Hydrogen gas is stored under pressure possibly at 35 MPa to 70 MPa in order to create compressed hydrogen gas cylinders, which are then made from various types of materials. Hydrogen gas cylinders have been classified into four different categories (Type I, Type II, Type III and Type IV) based upon the material used to manufacture each individual hydrogen gas cylinder. Hydrogen gas cylinders manufactured with only metal materials are known for being strong and durable. However, Type I cylinders are quite heavy. Composites were used in type II composite cylinders as a partial reinforcement to metallic liners to allow for some weight savings. The entire outside of type III cylinder is made up of a composite wrap completely around a metallic liner. The best type of cylinder is Type IV due to its polymer liner that is completely reinforced with carbon fiber reinforced polymer. It makes it lightweight and also allows it to handle high pressures and be able to resist corrosion [50].

Composite cylinders of Type IV have been chosen by manufacturers of modern hydrogen-powered fuel cell vehicles because of their enhanced properties. In particular, the lack of a metallic liner allows decreasing the weight, which is important from the point of view of increasing efficiency and travel distance. Another advantage of Type IV cylinders is their ability to withstand numerous pressurization and depressurization cycles owing to CFRP being used, which means that the cylinders will not break after several uses [34], [35]. Thus, Type IV cylinders can boast of gas-tightness and sufficient load-bearing capacity.

Unlike compressed-gas storage, which requires storing hydrogen with pressure. Liquid-hydrogen storage requires subjecting the hydrogen to cryogenic very low temperatures (~20K) through the use of liquid-hydrogen storage tanks. While this technology allows for a higher capacity of hydrogen stored, it is also more costly in terms of the energy needed to maintain the cryogenic state as well as the insulation required to prevent the liquid hydrogen from evaporating back into a gaseous state. Therefore, liquid hydrogen storage has limited applications in vehicles.

Hydrogen storage based on materials has also been researched extensively. This kind of hydrogen storage uses either chemical reactions or physical absorption between solid material and hydrogen. There is more volumetric density in material hydrogen storage, and safety is better because the temperature remains lower. However, problems of slow kinetics, expensive process, and difficulties with managing heat have prevented its development to date [32], [33].

In summary, when comparing different hydrogen storage systems, the high-pressure composite tanks, especially the type IV tanks, prove to be the most effective in terms of weight and volume. Nevertheless, the fast filling performance of these tanks is highly dependent on heat transfer, making it necessary to analyze temperature changes in the next sections of this study.

2.2 Fast Filling Thermodynamics

Hydrogen thermodynamics during fast filling have been extensively researched because of their vital role in ensuring safety and efficiency. In fast filling of hydrogen, a low pressure supply is being quickly pressurized into a high pressure tank from the supply within a short period of time. Due to the nature of the filling process, it is non-isothermal and the fill time is very short. The result is a significant rise in the temperature of the gas. The most significant contributor to the increase in temperature during rapid filling of hydrogen is the adiabatic compression. The amount of energy doing work onto the gas increases the internal energy of the gas leading to a large increase in temperature [5], [9].

Several other mechanisms can impact full thermal dynamics within the cylinder, such as viscous dissipation and turbulence mixing. The high velocity jet of hydrogen interacts with surrounding gas through collision leading to complex flow forms that enhance heat transfer across the system [7,8]. As a result, temperature is not uniformly distributed. Generally, temperature rises near the closed end of the cylinder due to reduced convective losses.

Thermodynamically, the process of hydrogen charging requires a complicated interplay of energy input, heat transferred into the cylinder walls, and the nature of gases involved. Since hydrogen deviates from the properties of an ideal gas under pressure, accurate equations of state must be used to determine thermodynamic properties [36]. It is critical to grasp the fundamentals of thermodynamics in order to make proper predictions and manage heat effectively.

2.3 CFD Studies

Using computational fluid dynamics to simulate hydrogen fast-filling has proven effective due to its high accuracy for complex flows and heat transfer processes over spatial and temporal dimensions. Experimental studies typically require significant financial investment and present challenges in obtaining certain metrics. You are able to obtain valuable data from computational fluid dynamics that include hydrogen tank temperature, velocity, pressure, and heat transfer characteristics. [2], [3].

A number of researchers have made use of CFD methods in the study of the thermodynamic properties of hydrogen during the process of refueling. The effect of flow rate and inlet parameters on the rise in temperature was studied by Acosta et al. [2] numerically during the fast filling of Type IV tanks. Melideo et al. [3] also showed the efficiency of various filling methods for temperature control through transient CFD calculations.

CFD flow modelling uses three different equation groups as flow governing equations. The conservation equations of mass, momentum, and energy along with various turbulence models. Such as the realizable k - ε model which gives very good predictions of the turbulent behaviour of jets especially surrounding a cylinder [11], [16] defined the governing equations. The other model being used in this work is a real gas model based on REFPROP data which allows for accurate predictions of hydrogen behaviour under high pressures [36].

Model validation by comparing with experimental data has also been stressed by earlier researchers. Good correlation has been found between the simulation and experimental findings, with the temperature prediction error being generally within the acceptable limit [1, 4]. This confirms that CFD can be effectively used for studying the hydrogen fueling process.

In general, CFD investigations have been useful for comprehending the dynamics of hydrogen filling, allowing one to determine factors influencing the temperature increase and thereby formulating an approach for developing effective methods for cooling.

2.4 Cooling Strategies

Fast hydrogen filling results in a quick temperature change that requires efficient cooling to be employed in order to provide for safe operation. The use of several methods to address thermal challenges in hydrogen fueling has been considered, the main objective being to minimize the maximum temperature value not exceeding 358 K according to [21] [24].

Hydrogen pre-cooling is one of many popular techniques for storing liquid hydrogen. Hydrogen pre-cooling is achieved by lowering the temperature of hydrogen prior to introducing it into a storage tank. Because the hydrogen entering the tank will have less heat when at a lower temperature, this will reduce the overall amount of heat added to the system and therefore reduce the amount of heat produced by the compressor during compression. There are reports that show pre-cooling is very effective in reducing peak temperatures [2][3].

An alternative method is optimizing the rate at which we pressurize when filling. If we pressurize at a gradual pace instead of an instant increase, this should reduce heat generated and give more time for the heat to be released from the material. Research has looked at using multi-stage fill where there are different pressure levels with rest intervals between them.

Apart from these techniques, there have been studies on hybrid approaches, for example, combining the effect of pre-cooling with the appropriate pressure profile to enhance efficiency. The goal of these techniques is to maintain a balance between the time taken to refill the battery, the energy used, and the temperature control process.

Even though many achievements have been made, there are still difficulties involved in developing efficient and cost-effective cooling mechanisms. The main problem is that the current research deals mostly with the use of separate cooling techniques, whereas few studies examine a combination of them. Thus, more research should be done to optimize the cooling technique used.

3. Physical Model and Assumptions

3.1 Cylinder Geometry

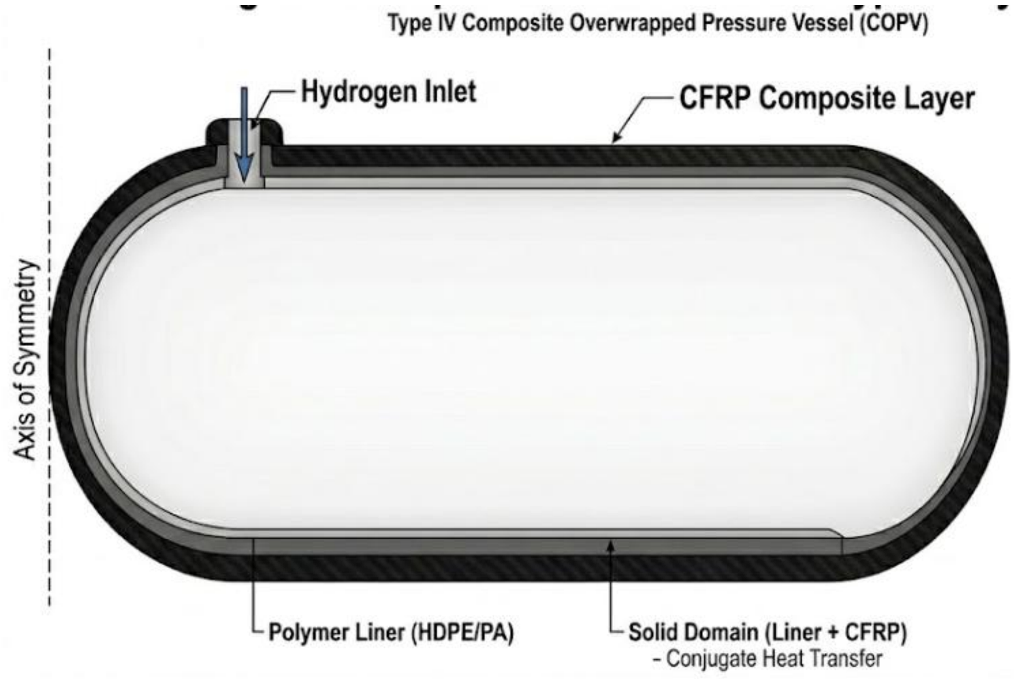


Figure 2.Simplified 2D Model of the Type IV Cylinder

This research will evaluate the temperature and flow properties of a high pressure (Type IV) hydrogen storage vessel when rapidly filled. The geometry was chosen specifically to match the configuration of existing hydrogen storage vessels used in fuel cell vehicles, which usually have maximum filling pressures of 70 MPa to provide sufficient range and performance [31], [35]. The shape used to build an extremely high-pressure storage tank includes a long cylinder in the middle and two-half had the same shape with respective hemispherical top or bottom caps on both ends. This type of configuration will minimize stress concentration which allows for more distributed mechanical loads to be applied in a uniform manner throughout the entire vessel during under maximum operating pressure.

The volume of the interior of the cylinder has a major effect on how the temperature of the fluid changes as it fills up. Since larger volumes will have greater amounts of gas in addition to lower efficiencies when it comes to dissipating heat. Due to this relationship between the volume of gas and the temperature of gas will create increased temperatures at the upper region of the cylinder than it would within a smaller volume cylinder. Therefore, it is important to define the geometry of the cylinder prior to performing a simulation on it, so that the results from the simulations may be accurate. The inlet will be at one end of the cylinder, and is normally done using a nozzle or valve assembly which the higher-pressure hydrogen enters into the cylinder. As the hydrogen enters into the cylinder it produces a high-velocity jet that interacts with the hydrogen that was originally stored in the cylinder causing the flow patterns and temperature of the fluid inside of the cylinder to be highly complex.

In order to effectively simulate the physical processes while still having enough computational resources to do the simulation, a 2D Axisymmetric model will be used. The cylindrical symmetry of the geometry allows for a reduction of the 3D problem to a 2D domain without a large loss in accuracy since 3D cylindrical relationships have been reduced to 2D cylindrical relationships via the axisymmetric assumption. One such example of this modeling approach being useful in CFD simulations is that they will lead to substantial reductions in computational time and resource requirements while still providing excellent simulation results for important flow and thermal phenomena (e.g., axial and radial directions). Additionally, the model allows for the flow and temperature gradients within the cylinder to be analyzed in great detail in both the axial and radial directions.

Two significant areas are used for measuring the computation. One is the fluid domain, where the hydrogen gas exists within the cylinder. The other is the solid domain, which comprises both the liner and composite material that constitute the cylinder. It is thought that a distinction between these two domains will be necessary to account for the conjugated heat transfer occurring as a result of heating during compression and subsequently transferring heat from the hydrogen gas to the external solid medium. Therefore, it is critical for both domains to be involved in order to have an adequate calculation of temperature variations, as the walls act as a sink absorbing and redistributing generated heat. Proper representation of both domains would allow high accuracy when analyzing both fluid dynamics and heat transfer.

3.2 Materials of Construction

The current study considered a type IV hydrogen tank consisting of a polymer inner tank and an external composite layer. Lines and composites have different roles in constructing the lines; therefore, both are needed for ensuring safety and efficiency. For instance, the polymer liner, which is always constructed from HDPE or PA, acts as a gas barrier preventing hydrogen from leaking out of the tank. Since hydrogen molecules are so small, gas leakage mustn't occur. The role of the liner is very crucial as it acts as a barrier for containing all of the hydrogen gas inside the tank [34, 35].

Table 1.Simplified 2D Model of the Type IV Cylinder

Material	**Density (kg/m³)**	**Specific Heat (J/kg·K)**	**Thermal Conductivity (W/m·K)**
Hydrogen (Gas)	Variable (Real Gas)	~14,300	~0.180
Polymer Liner	950	1900	0.40
CFRP (Composite)	1600	800	0.50

The thermophysical properties of the materials used in the simulation play a critical role in determining the heat transfer characteristics during the hydrogen filling process. Type IV cylinder construction involves a polymer liner and an outer CFRP shell, both having lower thermal conductivity than metals. Thermal conductivity is an important factor affecting the rate at which heat is lost from the compressed hydrogen gas. The properties of the materials used in this research work are shown in Table 2. Properties of hydrogen are considered real gas and were taken from the REFPROP database to obtain accurate results under high pressure [36].

A Type IV hydrogen storage vessel has been used in the current study, which is composed of two important material constituents. These include the polymer liner tube along with the carbon fiber reinforced polymer composite external casing. Both these materials play an individual part in providing stability and safety for storage purposes. The first role, i.e., that of the polymer inner tube, which is usually made up of HDPE and polyamide, is to ensure gas tightness as it acts as a barrier against the leakage of the gas. The fact that the hydrogen molecule is very tiny makes it extremely necessary to attain gas-tightness [34], [35].

However, the mechanical performance of the polymer liner is relatively low, and it cannot withstand higher internal pressure values either. However, the structural performance of the cylinder can be achieved using the carbon fiber reinforced plastic layer that encloses the polymer liner. Carbon fiber reinforced plastics have been widely used in high-pressure conditions owing to its exceptional strength-to-weight ratio and fatigue resistance [39], [40]. Thus, using carbon fiber reinforced plastic in hydrogen tanks would be appropriate since both properties are essential in hydrogen tanks.

Regarding the topic of thermodynamics, the thermophysical characteristics of the liner and CFRP coating will play a significant role in the process of heat exchange. The main characteristic of the liner, which is made of a polymer material, is that it has low thermal conductivity; therefore, heat cannot escape from the gas and get into any part of the system easily. It results in the temporary entrapment of heat in the gas, which causes high temperatures when fast refilling occurs. In addition, it should be noted that the CFRP coating also has low thermal conductivity compared with that of metals [15].

Apart from thermal conductivity, several other material properties like density, specific heat, and thermal diffusivity influence the heat transfer phenomena as well. A combination of all of these properties defines the rate at which heat can be absorbed by the cylinder walls and subsequently transferred within the walls due to the heating effects of compression. It is important to have knowledge about the thermal behavior of these materials since that will enable us to analyze the efficiency of the cooling system.

3.3 Modeling Assumptions

For the feasibility of simulating hydrogen fast filling along with maintaining a sufficient level of accuracy, some assumptions have been taken into account in this analysis. The assumptions taken for the purpose are quite common in CFD analysis for hydrogen tanks and are made in view of the physical nature of the problem as well as the aims of the analysis [1], [4]. Even though these assumptions make it easier from a computational point of view, they have been selected in order to capture physical effects accurately.

In this case, the primary assumptions to be made include symmetry of the fluid flow within the cylinder because it becomes possible to consider only a two-dimensional problem. This assumption may be made due to the fact that because of the symmetry of the system itself, there should be symmetry with regard to the flow profile and temperature profile along the centerline of the system.

Secondly, hydrogen is considered to be a **compressible real gas**, and the thermodynamic properties of hydrogen are simulated by using proper equations of state to simulate the high-pressure conditions. At pressures ranging up to 70 MPa, there is a very large departure from the ideal gas law, hence necessitating the need to include the real gas effect [36]. However, for convenience, some material properties, such as thermal conductivity and heat capacity, are assumed to have constant values [7].

The other significant assumption is that of the neglect of the effect of **buoyancy forces**. Due to the quick-filling nature of the flow, jet inflow and convective effects are much greater than the effects of natural convection, such that buoyancy forces can be considered insignificant compared to forced convection.

Another assumption of the model is that there will be no change in the structure of the cylinder while filling. Despite the high internal pressure, the cylinder is built to endure such stress without undergoing any structural changes. This assumption helps keep the dimensions static in the calculations.

In addition, the **radiative mode of heat transfer is disregarded**, with the only considerations being the conduction and convection modes. The reasoning for this lies in the fact that the temperature differences are not so large that radiative heat transfer does not come into play in any significant way.

Lastly, the temperature of the inlet hydrogen flow is supposed to be uniform and constant in each simulation case. Such a supposition makes it easier to analyze the changes in temperature under various conditions. As far as the initial conditions inside the engine cylinder, they are assumed to be uniformly distributed as far as temperature and pressure are concerned.

These assumptions make it possible to create an effective model that describes the physics of the hydrogen fast filling process. Although some small-scale phenomena are not taken into account, the model gives accurate results concerning the distribution of temperatures, gas flow, and heat transfer mechanisms in the Type IV hydrogen storage tank [1].

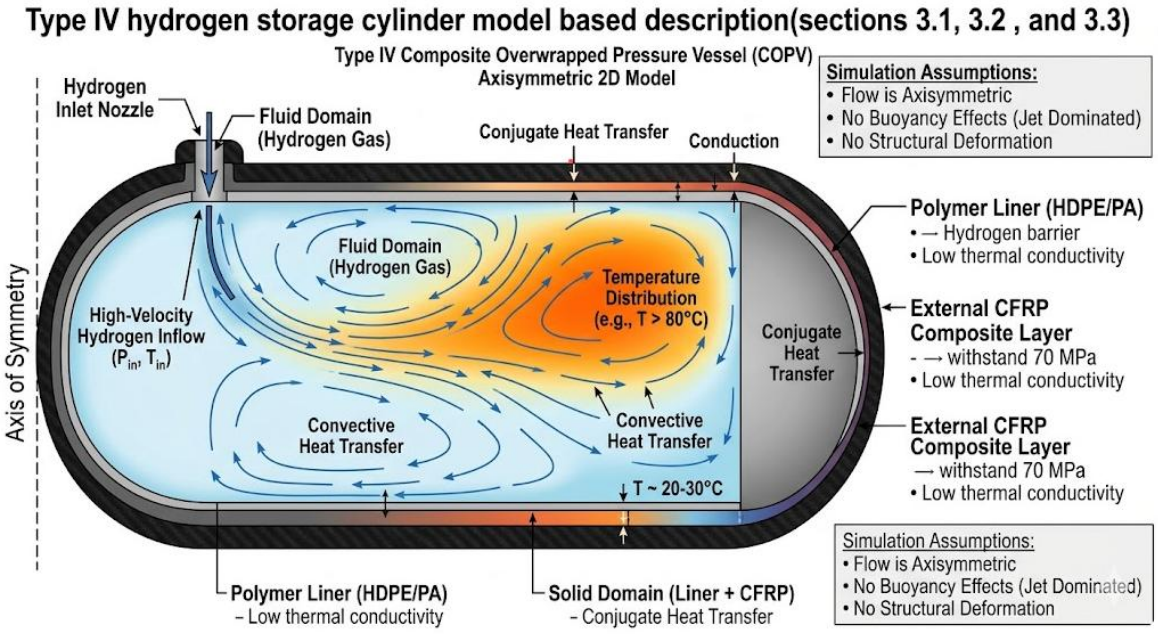


Figure 3.Type IV Hydrogen Storage Cylinder Model Based Description (Sections 3.1 , 3.2, 3.3)

4. MATHEMATICAL MODELLING

Refueling the Type IV high-pressure hydrogen tank at a fast rate is a technically challenging task. During this process, the hydrogen flows into the tank at very high pressure, leading to several physical phenomena. Compressible flow, turbulence, pressure variations, and heat exchange between the fluid and the tank surface happen at once. The process takes place very quickly, causing an increase in temperature. This rise in temperature needs to be taken into account.

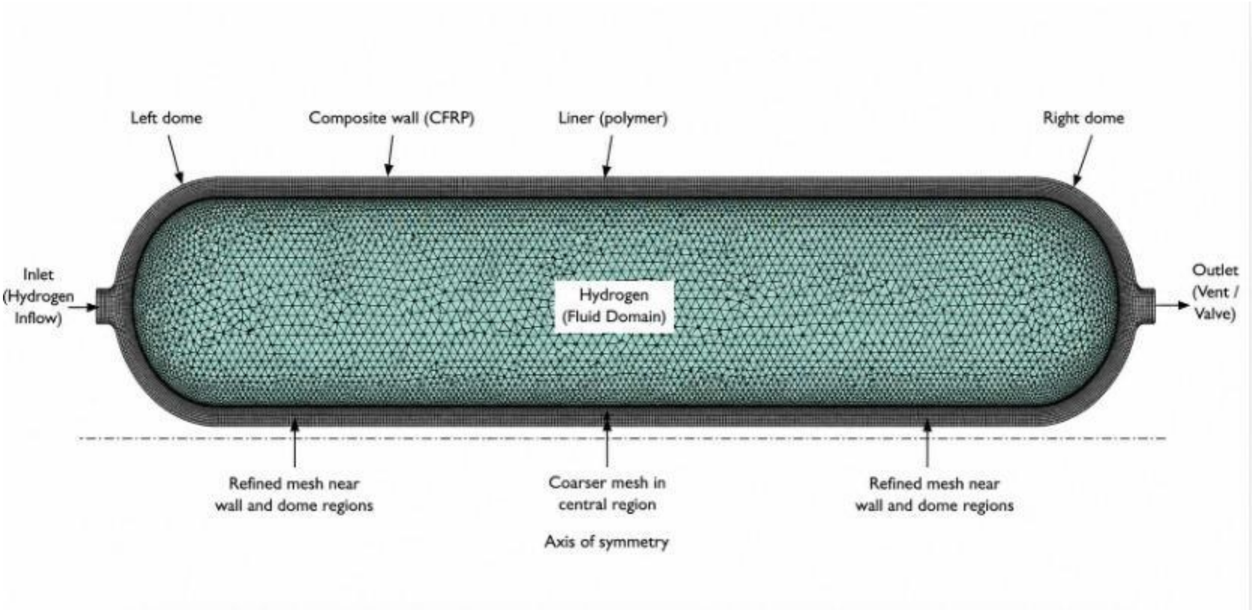


Figure 4.Mesh Image

To study this process, a transient computational fluid dynamics (CFD) approach is used. The model is built on the basic conservation laws of mass, momentum, and energy, which are solved together across the domain. These equations are non-linear and closely linked because properties such as density, pressure, and temperature change during the filling process. Turbulence models are also included to represent the irregular flow, especially near the inlet where the gas enters. Since hydrogen behaves differently at high pressures, real gas models are used to describe its properties more accurately [11], [13].

A transient computational fluid dynamics (CFD) method is applied for the analysis of the problem under consideration. The model is developed using fundamental conservation equations for mass, momentum, and energy. The system of non-linearly coupled equations will be solved simultaneously throughout the domain of interest. These relationships are non-linear and highly coupled due to the variation in physical quantities, like density, pressure, and temperature during the filling process. Furthermore, turbulence models have been incorporated to account for turbulent flow, particularly in regions close to the inlet. For hydrogen flow, real gas models have been utilized[11], [13].

By linking these specific real-gas thermodynamic models with rigorous turbulence tracking and foundational conservation equations, this comprehensive CFD framework grants us a highly detailed, dynamic visualisation of the internal gas flow, pressure surges, and localised temperature spikes[7]. With this kind of detailed foresight, engineers can actually dial in the high-pressure fill process. It lets them control the dangerous heat spikes and make sure the whole system stays safe for the long haul.

4.1 Governing Equations

The fundamental conservation equations of fluid mechanics govern the hydrogen fast filling process [14]. To include time-based changes in flow behaviour, these equations are solved in a transient compressible framework.

Continuity Equation for Mass Conservation

The principle of mass conservation in a compressible fluid is given by:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \tag{4.1}$$

This is what will ensure that the mass within the control volume is always conserved. With the high rates of filling occurring, there is a lot of variation of the hydrogen density owing to a rise in pressure and temperature [19]. For this reason, accurate solutions for the continuity equation are necessary to know the accumulation and distribution of mass within the cylinder [18].

Navier–Stokes Momentum Equation

The conservation of momentum of a compressible Newtonian fluid is formulated using the Navier–Stokes equation, as follows:

$$\rho\left(\frac{\partial\vec{v}}{\partial t}+\vec{v}\cdot\nabla\vec{v}\right)=-\nabla p+\nabla\cdot[\mu(\nabla\vec{v}+(\nabla\vec{v})^T)] \qquad (4.2)$$

The Navier-Stokes equation describes hydrogen dynamics by considering pressure, viscous effects, and momentum. Blowing gas out of the nozzle generates huge variations in speed and turbulence, thereby making the internal flows turbulent. This jet, upon impact with the entrapped gas, results in the generation of whirlpools and turbulence, leading to heat dispersion [49].

Energy Equation

The conservation of energy equation accounts for heat transfer, compression work, and viscous dissipation:

$$\frac{\partial(\rho E)}{\partial t}+\nabla\cdot(\vec{v}(\rho E+p))=\nabla\cdot(k\nabla T)+\Phi \qquad (4.3)$$

This equation plays a central role in predicting the temperature rise during fast filling. The term involving pressure work represents the effect of compression, which is the primary cause of temperature increase. The conduction term accounts for heat transfer to the cylinder walls, while the viscous dissipation term represents energy conversion due to fluid friction.

Equation for the conservation of energy can be used to describe the following phenomena: heat transfer, compression work, and viscous dissipation:

$$\frac{\partial(\rho E)}{\partial t}+\nabla\cdot(\vec{v}(\rho E+p))=\nabla\cdot(k\nabla T)+\Phi \qquad (4.3)$$

It is of great importance for the estimation of temperature rise during rapid filling. Pressure work term is responsible for the compression process, which is considered to be the main source of temperature increase. Heat transfer is associated with the conduction term, whereas viscous dissipation reflects energy transformation due to fluid friction [20].

Total Energy Definition

$$E=h-\frac{p}{\rho}+\frac{v^2}{2} \qquad (4.4)$$

It describes the energy contained in the fluid as the sum of the internal energy, pressure energy, and kinetic energy. It is fundamental for the interconnection between thermodynamic parameters and the flow phenomena.

Heat Conduction in Solid Domain

Heat transfer in the cylinder wall composed of liner and CFRP layer will be controlled by the equation:

$$\rho_s c_p\frac{\partial T}{\partial t}=k_s\nabla^2 T \qquad (4.5)$$

It shows the process of heat conduction in solids. The heat produced in the gas goes to the cylinder wall as a thermal shield. The capacity of the cylinder wall to absorb and release heat plays a crucial role in the overall temperature distribution in the cylinder.

4.2 Turbulence Model – Realisable k–ε Model

When high-velocity gas blasts into the cylinder during a fast fill, the internal flow instantly becomes violently turbulent. Since this completely chaotic mixing dictates exactly how heat and physical momentum spread throughout the tank, you absolutely need a rock-solid turbulence model to build a simulation that actually reflects real-world conditions.

In this case, the realizability-based k–ε turbulence model would be the most suitable. The model is uniquely suited for dealing with complex phenomena such as jet injection at high speeds, vortex formation, and extreme deformation rates [16], [17]. The inclusion of two additional differential equations, namely one for the energy (k) and the other for its dissipation rate (ε), provides an extremely accurate description of the turbulent flow.

Turbulent Kinetic Energy Equation

$$\frac{\partial(\rho k)}{\partial t}+\nabla\cdot(\rho k\vec{v})=\nabla\cdot(\alpha_k\nabla k)+G_k-\rho\varepsilon \qquad (4.2.1)$$

The above equation shows the generation and transfer of the energy of the turbulence. The G_k term is the source term for turbulence generation due to velocity gradient effects that are more pronounced in the inlet jet area.

Dissipation Rate Equation

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \nabla \cdot (\rho\varepsilon\vec{v}) = \nabla \cdot (\alpha_\varepsilon \nabla\varepsilon) + C_1\frac{\varepsilon}{k}G_k - C_2\rho\frac{\varepsilon^2}{k} \qquad (4.2.2)$$

The above equation shows the generation and transfer of the energy of the turbulence. The G_k term is the source term for turbulence generation due to velocity gradient effects that are more pronounced in the inlet jet area.

Turbulent Viscosity

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \qquad (4.2.3)$$

Turbulent viscosity is a measure of how turbulence increases momentum transport. It plays a key role in modelling mixing and diffusion processes inside the cylinder.

4.3 Real Gas Equation (Hydrogen Properties)

High-pressure hydrogen shows substantial deviations from the characteristics of an ideal gas; hence, the application of real gas theory becomes inevitable. In this study, hydrogen properties are accessed using the REFPROP data table developed by the National Institute of Standards and Technology [36].

Real Gas Equation of State

$$p = Z\rho RT \qquad (4.3.1)$$

Density Relation

$$\rho = \frac{p}{ZRT} \qquad (4.3.2)$$

Enthalpy Relation

$$h = h(T,p) \qquad (4.3.3)$$

Speed of Sound

$$a = \sqrt{\gamma RT} \qquad (4.3.4)$$

The incorporation of the characteristics of a real gas becomes very important when accurate thermodynamic predictions are needed during rapid filling. Hydrogen compressibility plays a crucial role in the determination of density and temperature changes at a maximum pressure of 70 MPa. Direct input of the REFPROP database to the simulation makes sure that the mathematical equations are firmly rooted in reality.

5. ANSYS Fluent Setup

The simulation uses a **pressure-based transient solver** in ANSYS Fluent since it can deal with big density changes in gases like hydrogen. As filling happens quickly, the gas compresses fast, and pressure, temperature, and density all move together. Therefore, the solver is configured to include **energy equation coupling**, allowing simultaneous solution of momentum and thermal fields. This coupling is essential for accurately capturing the temperature rise associated with compression heating and turbulent mixing.

For enhancing the accuracy of calculations, the **second-order upwind approach** is used to discretize the spatial derivatives. The numerical diffusion in such approach becomes small, making it possible to more precisely resolve rapid variations in velocity, pressure, and temperature fields, particularly close to the region of the inlet jet where variations are rapid. When using time discretization, a relatively small time step must be chosen to take into account the transient character of the process. Since at the initial stages of filling, the process is rather sensitive, as pressure rapidly increases, resulting in a rapid increase in temperature.

The **SIMPLE** algorithm is employed for pressure-velocity coupling, guaranteeing convergence of the equations at each time step [12] and [13]. Moreover, under-relaxation parameters are properly selected to ensure the stability of the calculations. The **realizable k-ε turbulence model** is switched on to account for the influence of turbulence, which becomes important owing to the large speed of hydrogen inflow into the cylinder. The realizable k-ε turbulence model gives better predictions of jet flows, recirculation zones, and mixing processes than standard turbulence models [16].

In addition, actual gas properties of hydrogen have been taken into account by making use of data provided by the REFPROP package [36]. The significance lies in the fact that hydrogen deviates significantly from the characteristics of an ideal gas even when pressures range between 1 and 70 MPa. It is important to take into consideration real gas properties while running CFD calculations because otherwise, the results would not be realistic enough [10].

Mesh Generation

Prior to conducting the simulation, the domain needed to be discretized such that the solver would have a “vision” of what is occurring within the cylinder. The meshing process greatly affects the outcome of the simulation results. In this instance, the use of **a structured mes**h was adopted for the axisymmetric model in two dimensions, providing better organization and stability in terms of convergence compared to the unstructured mesh. One benefit of using structured mesh is that it allows one to easily determine areas of high and low density.

Not every part of the cylinder needs the same level of detail. For example, **the inlet region** is quite active. Hydrogen enters at high speed, forming a jet and mixing with the gas already inside. Because of this, that area was given a much finer mesh to properly capture the sharp changes in velocity and temperature. The same idea applies near the walls. Heat transfer between the gas and the cylinder surface happens here, so the mesh was tightened in this region to follow those variations more closely.

The streamlines in other parts of the model will be less turbulent. In the core part, a larger grid mesh was employed to cut down on the costs of computation but at the same time ensuring that some degree of accuracy is maintained. This is more of an equilibrium state than a rigid rule. To avoid having the outcome being influenced by the choice of mesh size, several grids were considered. Once additional refinements had no effect on temperature/pressure calculations, then the selected grid was used.

5.1 Boundary Conditions

Boundary conditions play a big role in CFD accuracy. Incorrect conditions lead to unrealistic results. **Time-dependent Boundary Conditions** improve accuracy by replicating real refueling behavior.

Inlet Pressure Boundary Condition (Figure 5)

The inlet of the hydrogen cylinder is defined as a **pressure inlet boundary**, where the pressure varies as a function of time according to the refueling protocol.

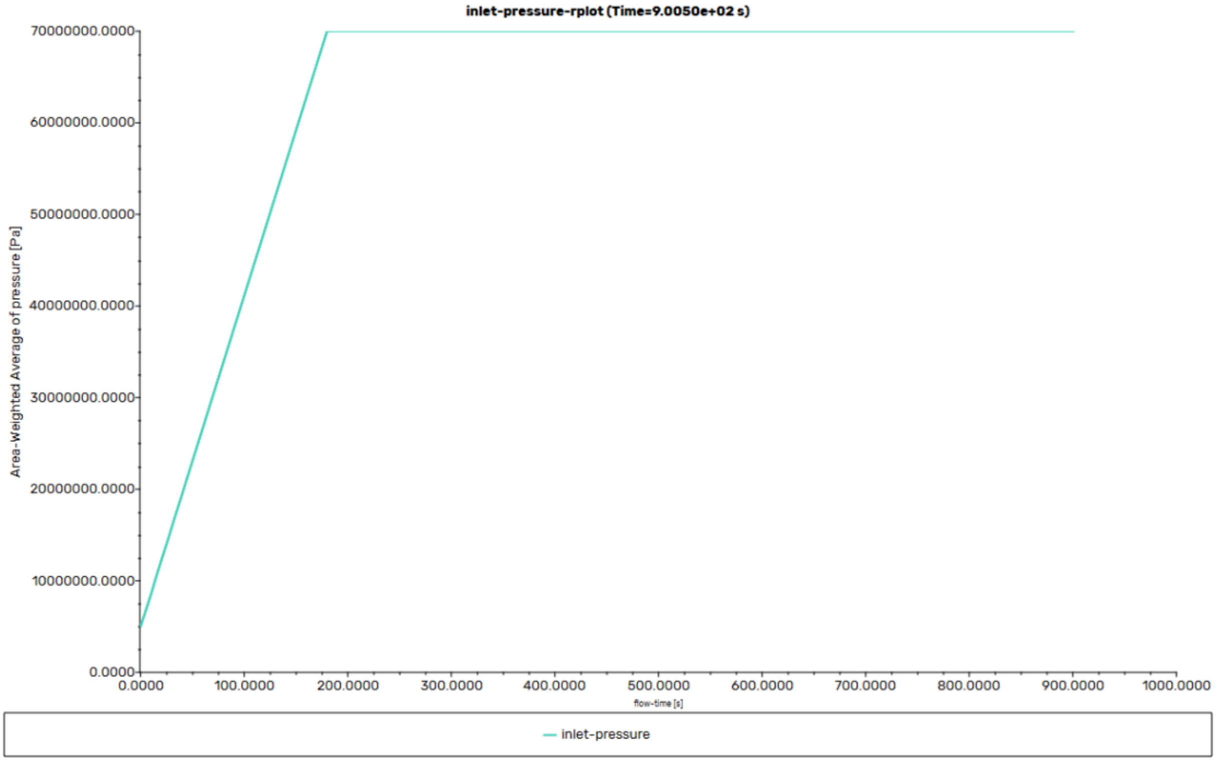


Figure 5.Inlet Pressure vs Time

This diagram represents the **pressure ramping profile** during the filling process. In the beginning, the inlet pressure shoots up as hydrogen starts entering the cylinder. This sharp pressure difference drives a fast flow of gas inside. As the process continues, the pressure rise is gradually regulated through a ramping strategy to limit excessive temperature increase.

How you ramp up the pressure really matters [30]. A sudden increase can heat the gas quickly and push temperatures higher. But a slower, controlled rise gives the system time to release some of that heat to the walls. That's why the pressure profile has to strike a balance between filling quickly and keeping things safe.

Mathematically, the inlet pressure is expressed as a time-dependent function:

$$p_{in}(t) = f(t) \qquad (5.1.1)$$

where f(t) represents the pressure variation based on the refueling protocol, such as SAE J2601 [21]. The use of such realistic pressure profiles ensures that the simulation captures the actual dynamics of hydrogen refueling.

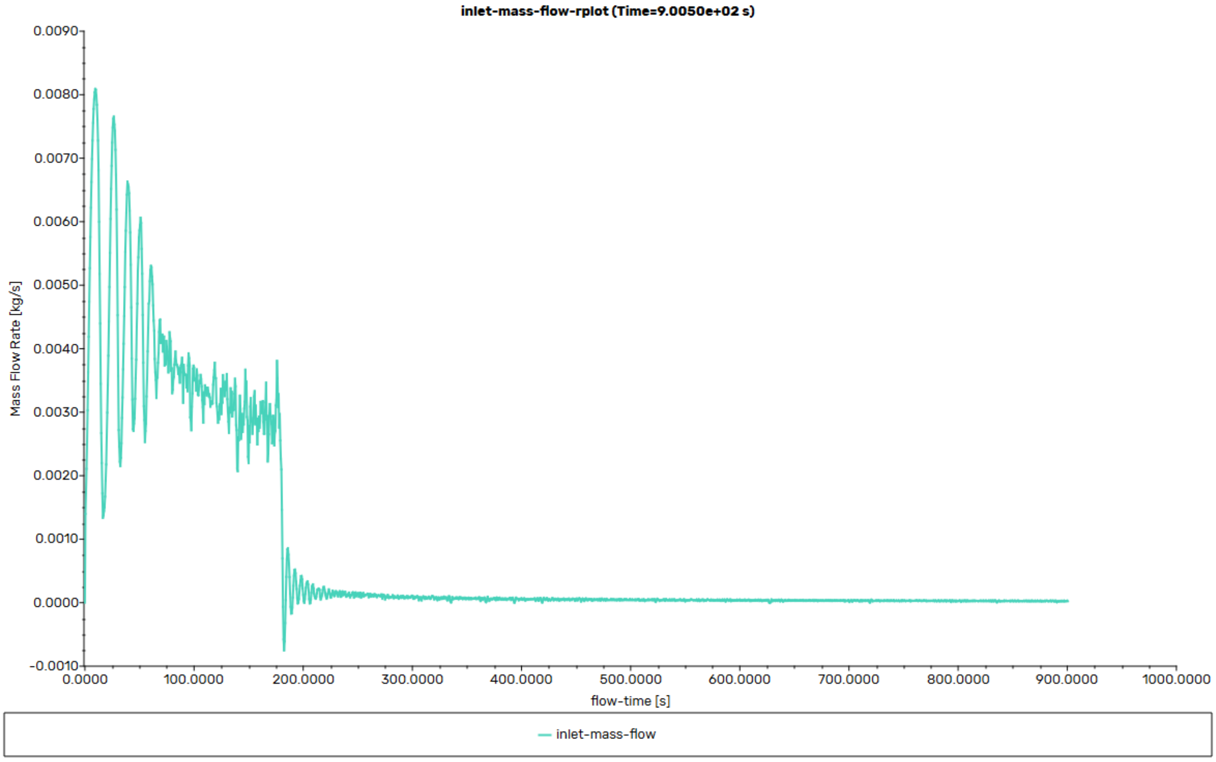


Figure 6.Mass Flow Rate vs Time

One can compare the filling process to the air filling up a place. During the initial stage of filling, the pressure within the cylinder is quite different from the pressure within the pipeline, meaning the hydrogen flows very fast. This is where the flow rate is very high. As the cylinder starts getting filled with hydrogen, the pressure within the cylinder does not remain low anymore since it starts increasing steadily. This implies that the gap between the pressure of the supply system and the pressure within the cylinder gets smaller. The result is a **reduction in flow rate.**

The mass flow rate can be demonstrated as:

$$m^{\cdot} = \rho A v \qquad (5.1.2)$$

where $m^{\cdot}$ is the mass flow rate, ρ is the density, A is the cross-sectional area, and v is the velocity. It basically shows that flow depends on both what the fluid is like and how it's moving.

How much hydrogen enters mainly comes down to a few simple things—the gas density, how big the opening is, and how fast the gas is moving.

This changing flow also affects what happens inside the tank. Early on, the strong inflow creates more disturbance and can raise the temperature faster. Later, as the flow calms down, everything inside starts to settle as well.

Wall Boundary Condition

At the cylinder surface, the gas is treated as if it sticks to the wall, leaving the hydrogen at that **boundary motionless**, while the layers just above it gradually begin to flow. This helps show how the speed of the gas changes from the wall toward the inner region.

The wall also interacts with the gas in terms of heat. When hydrogen enters and gets compressed, it warms up. Some of that heat doesn't stay in the gas—it moves into the cylinder wall. The material of the tank absorbs part of this energy, which slightly reduces the gas temperature as time passes. Including this exchange results in a more realistic representation of temperature behavior inside the cylinder.

Initial Conditions

The first assumption relies on the cylinder's stability, containing hydrogen uniformly in it; therefore, it will have one pressure and temperature level throughout the entire domain of computation. It became possible because of its simplicity and the absence of additional problems in this situation. Nevertheless, **initial conditions** become crucial because the change of pressure and rise in temperature will be proportional to them. Hence, the initial conditions were set close to normal operating conditions.

In order to achieve numerical stability, the initial condition is clearly stated before the transient simulation starts. The clear initial condition makes it easier for the solver to converge during the early stages of the computation. This makes it less likely for non-physical oscillations to occur during the early stage of the filling process. This guarantees that the early transient solution is physically sound and not dictated by numerical issues.

Importance of This Methodology.
The CFD approach employed in this research offers an extensive method for investigating the phenomenon of hydrogen refilling at high speed [10]. With the use of correct solving parameters, a properly created mesh and reasonable boundary conditions, the CFD model can depict the changes in temperature, pressure, and flow rather accurately.
With the addition of the time-dependent mass flow and pressure rates (see Figures 5 and 6), it becomes much closer to reality, which will make further investigations into the limits of safety from overheating and the creation of optimal cooling techniques much easier.
It also allows detailed observation of transient effects that occur during different stages of filling.
The coupling between pressure, temperature, and density is captured more effectively under these conditions. As a result, the model provides better insight into rapid compression heating inside the cylinder. The framework can also be extended to evaluate different operating scenarios and inlet conditions. Overall, it ensures a consistent and physics-based approach to hydrogen fast filling analysis.
This will also provide an opportunity to observe transient behavior that occurs at various phases of the filling process.The relationship among pressure, temperature, and density will be modeled more efficiently under these circumstances. The model will thus be able to predict the heat generation that occurs in the cylinder due to rapid compression more accurately. The model can even be adapted for use in other situations to analyze different scenarios.

6. RESULT

Handling the thermal loads during a rapid hydrogen fill is easily one of the most frustrating bottlenecks in fueling infrastructure design. You are forcing high-pressure gas into a restricted volume in three to five minutes, creating a highly chaotic internal environment. Pressures spike almost instantly, and the internal flow fields turn completely turbulent.

6.1 Temperature Distribution Inside Cylinder

Pulling contour plots directly from the simulation gives us a clear look inside the cylinder as the fill progresses. **Figures 7,8 and 9** break down the thermal field over time.

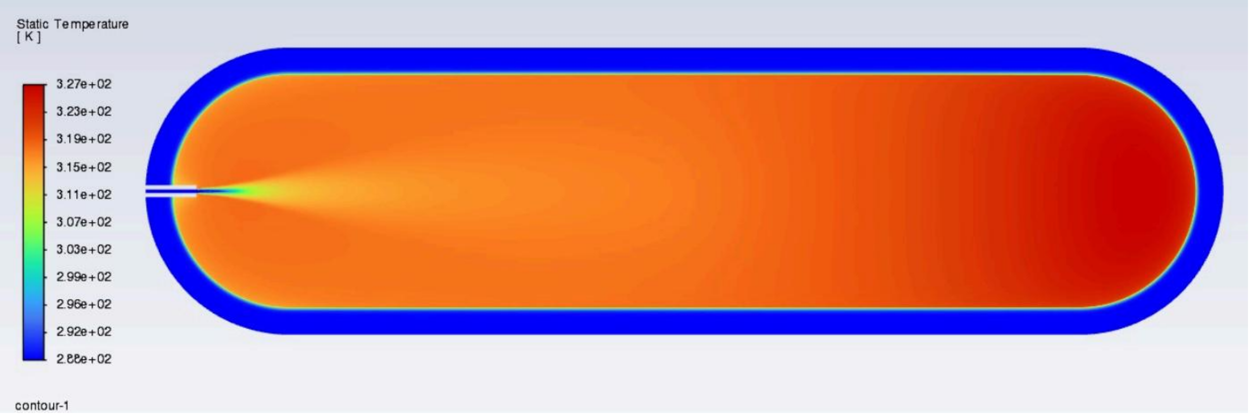


Figure 7

Engineers usually refer to this as the jet cooling effect. The physics behind it are straightforward. The supply gas enters the tank at a much lower temperature than the resident gas already undergoing compression. Furthermore, the extreme velocity of the incoming jet forces massive turbulence into the surrounding fluid.

Formation of Axial Temperature Gradients

Further into the fill cycle, a steep temperature gradient emerges along the length of the cylinder. **Figure 8** shows this transition clearly, moving from a relatively cool front end near the valve to a severely heated rear dome.

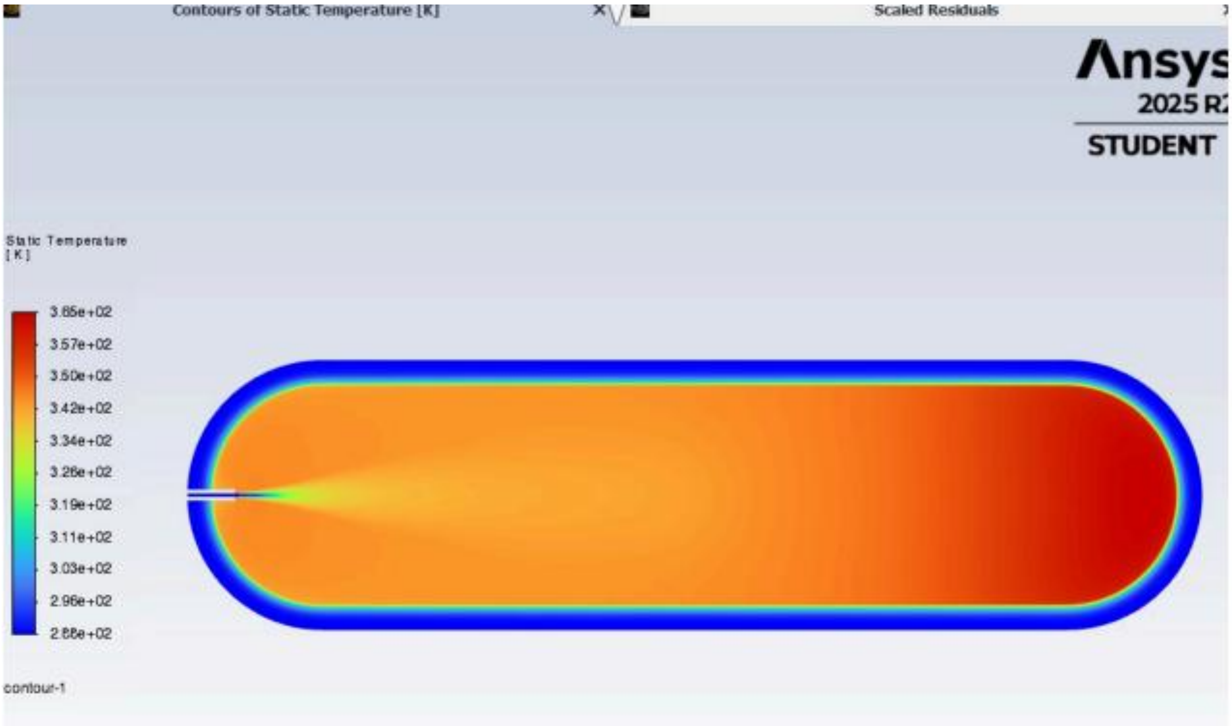


Figure 8

Three distinct factors drive this gradient. First, adiabatic compression naturally forces temperatures up as the pressure builds, requiring no external heat input whatsoever. Without that aggressive, high-speed mixing seen near the valve, the fresh gas only manages to cool the front section. The gas trapped in the back just sits there and cooks.

Hotspot Formation at the Rear Dome

Figure 9 exposes the most critical thermal failure point in the whole system: a massive, highly concentrated **hotspot pinned right against the rear dome**.

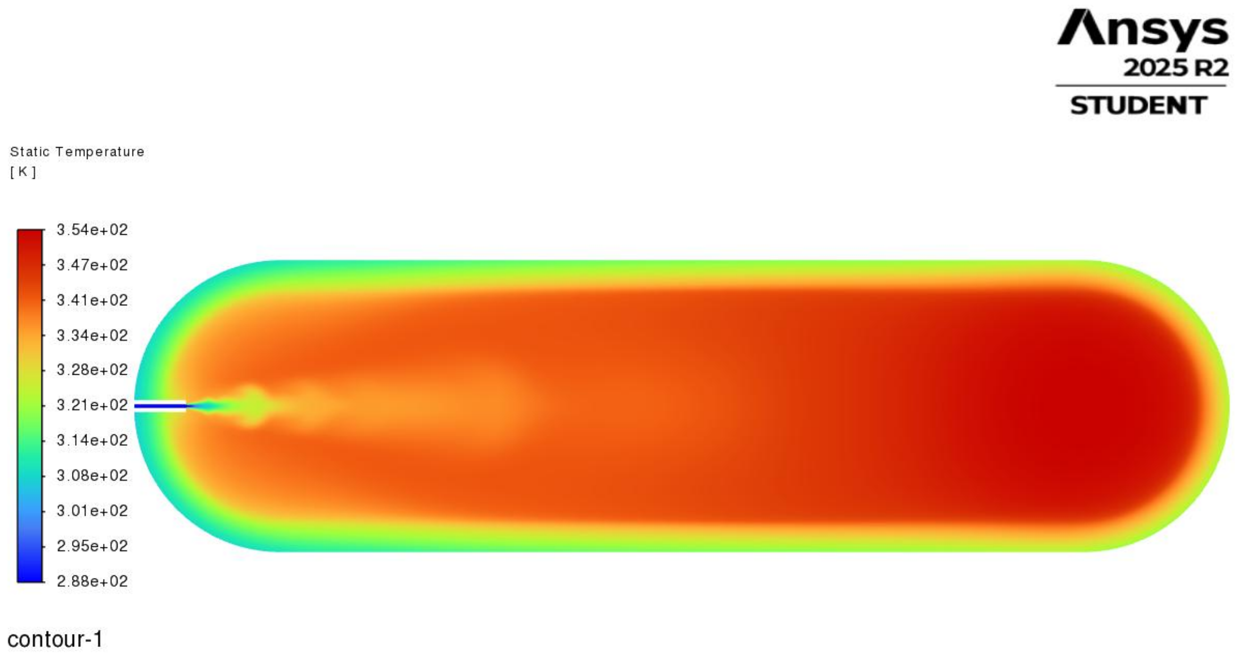


Figure 9

This hotspot ultimately dictates how the entire station operates because repeatedly pushing temperatures past the strict 358 K (85°C) safety limit [22] will warp and crack the Type IV cylinder's polymer liner until the tank structurally fails.

6.2 Temperature Evolution of Hydrogen Gas

Tracking the exact temperature shifts of hydrogen during a quick fill dictates how safe the storage tank actually is. You can track exactly how this heat climbs by checking **Figure 10 (Maximum Gas Temperature)** alongside **Figure 11 (Hydrogen Temperature Variation)**. Both of these charts map out the real-time temperature jump step by step.

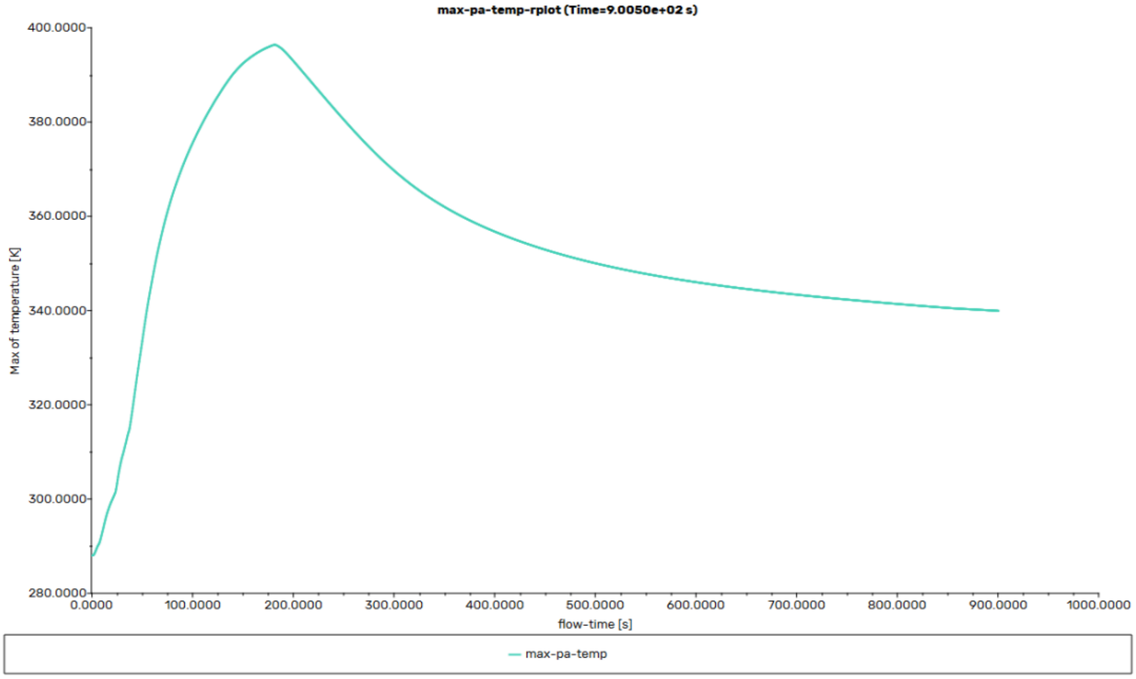


Figure 10.Maximum Gas Temperature

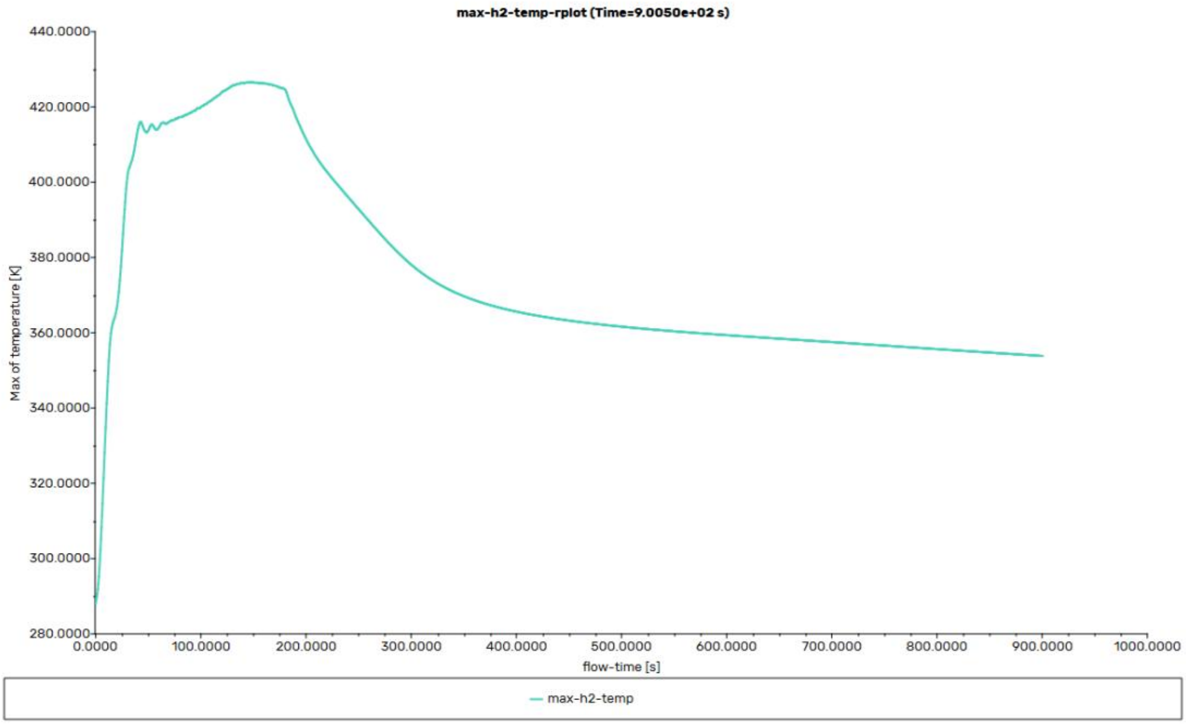


Figure 11.Hydrogen Temperature Variation

Initial Rapid Temperature Rise

The second you start filling the tank, **the internal temperature shoots straight up**. You can clearly see this sudden heat spike kicking off both Figure 10 and Figure 11.

To figure out exactly how much the temperature is going to jump, you just look at the standard thermodynamic math for compressible gases:

$$T \propto p^{\frac{\gamma-1}{\gamma}} \qquad (6.2.1)$$

6.3 Solid Wall Heat Transfer

Figuring out how heat bleeds off the hydrogen and into the actual tank wall tells you if the system will survive a fast fill. **Figure 12 (CFRP Temperature Variation)** maps this exact physical response out, tracking just how much heat the structural wrap actually soaks up while you pump the cylinder full.

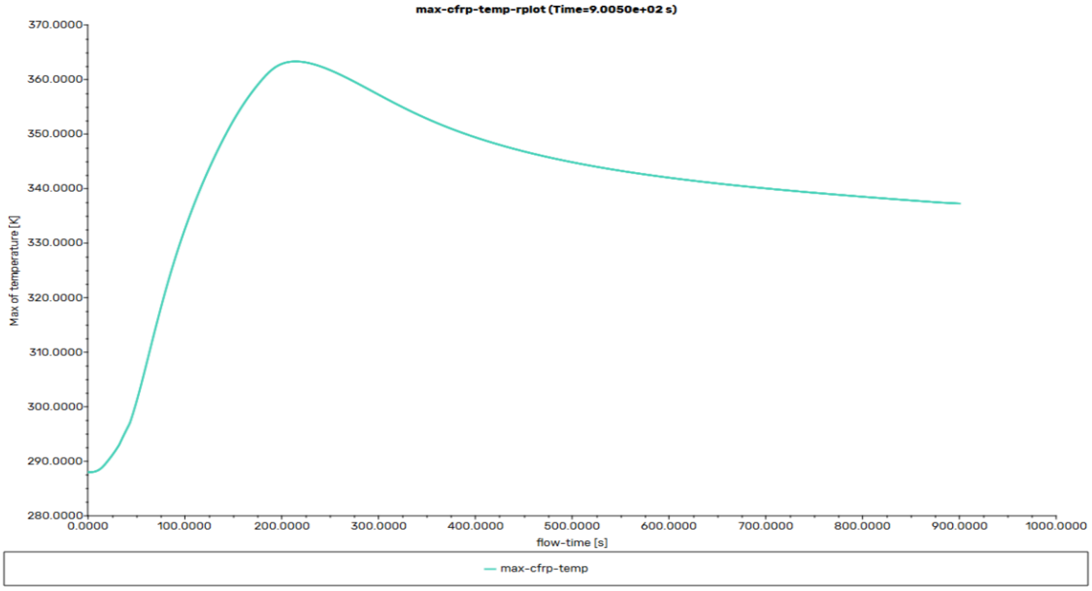


Figure 12.CFRP Temperature Variation

Delayed Heating Response of the Solid Wall

Looking at **Figure 12**, the carbon fiber shell heats up much slower than the trapped hydrogen.
Plastic liners and CFRP composites are notoriously bad conductors [15], [39]. An old metal tank would dump that heat straight through to the outside.

6.4 Average Temperature Behavior

Checking the average temperature gives you the big picture of how the entire storage system reacts to a fast fill. **Figure 13** tracks exactly how this average internal temperature shifts as the clock runs.

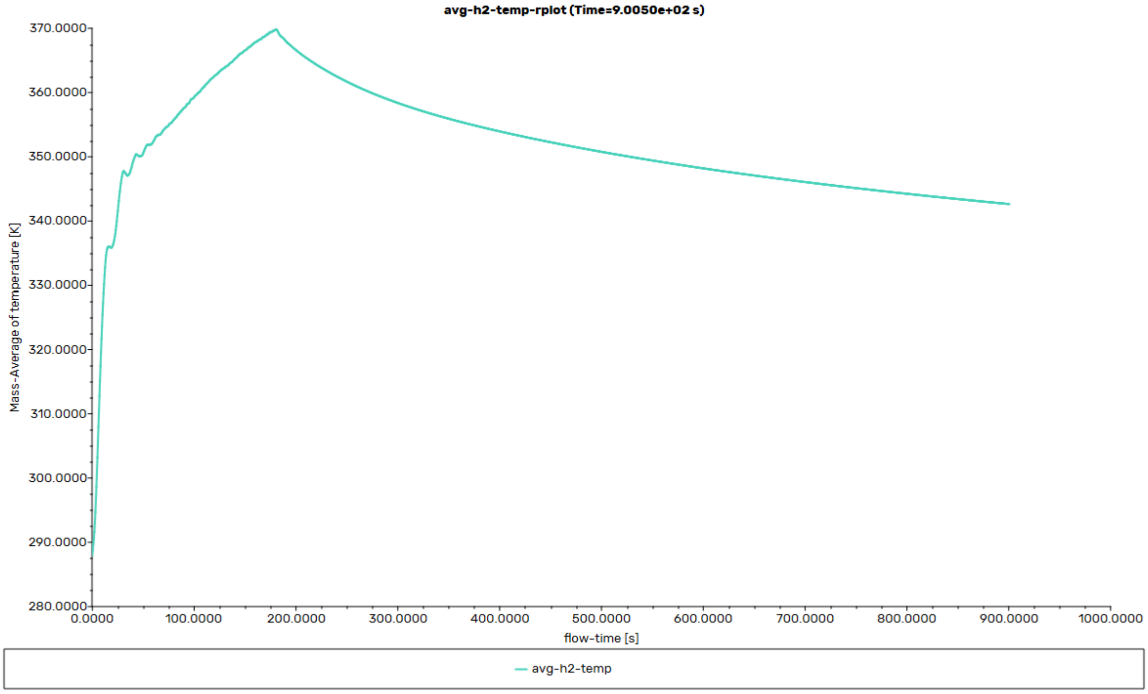


Figure 13

7. DISCUSSION

In this study, the thermal properties of hydrogen during fast filling in a type IV storage tank are examined in detail. As a result, it can be stated that all effects of fluid compressibility, heat exchange processes, and fueling conditions are interrelated and significantly influence the increase in temperature.

7.1 Interpretation of Thermal Behaviour

The adiabatic compression process is the major cause of the sharp temperature increase at the beginning of the filling process. The sharp rise in gas temperature shown in Diagrams 4 and 5 indicates that the start-up stage of the filling process is quite hot. This is true because, according to other works [1], [5], the temperature increase is associated with a rapid increase in gas pressure.

Moreover, the spatial temperature distribution shows an uneven distribution. There is a low-temperature zone near the pipe inlet, whereas a high-temperature zone forms at the pipe end. In this particular scenario, the presence of a hot spot near the closed end can be attributed to slowed flow, reduced turbulence, and poor convective heat transfer.

Moreover, the study of heat transfer through the solid walls reveals that the use of CFRP as a construction material provides a passive heat-dissipation system that absorbs a portion of the heat generated during compression. Nevertheless, due to the poor thermal conductivity of the composites, heat dissipation is relatively slow. Therefore, it can be concluded that passive heat dissipation is insufficient for temperature control.

7.2 Implications for Hydrogen Refuelling Systems

One of the important aspects discussed in the previous sections has significant implications for the design of hydrogen refuelling systems. According to Figure 5, the temperature is significantly influenced by the pressure-increase profile; thus, a rapid pressure increase results in greater compressional heating. At the same time, a gradual increase helps to regulate temperatures.

A similar effect is observed regarding the variation in mass flow rate (Figure 6). A high flow rate at the start of the process increases mixing and turbulence. This necessitates careful regulation of the ratio between filling speed and temperature control during refuelling.

From an engineering standpoint, the results support the need for integrated refuelling strategies that combine pressure control, flow regulation, and thermal management [47]. This aligns with modern hydrogen refuelling protocols such as SAE J2601, which emphasise temperature limits and controlled filling conditions [21].

High flow rates at the beginning of the process promote better mixing and turbulence. This implies that a higher level of control of the balance between the rate of filling and temperature management is required during refuelling. Based on the engineering approach, the study's outcomes suggest the importance of using integrated fueling techniques that account for pressure, flow rate, and temperature control. It agrees with the current standards of hydrogen fuelling processes, SAE J2601 [21].

7.3 Role of Pre-Cooling and Thermal Management

The first practical implication from this research is the validity of pre-cooling procedures when refuelling with hydrogen. Given that most of the temperature increase occurs due to compression, reducing the inlet temperature of hydrogen could noticeably lower the peak temperature reached during the process [47], [48].

Based on these results, if no pre-cooling is applied, there is a risk that the safety limit will be reached or exceeded, since even with a relatively rapid filling procedure, it approaches 358 K quite closely. Thus, pre-cooling cannot be considered merely an option but rather an essential component.

Beyond conventional pre-cooling, the results also indicate opportunities for advanced thermal management, such as improved heat transfer pathways or hybrid cooling approaches. However, such solutions must be carefully designed to account for the material limitations of CFRP-based structures.

7.4 Possibilities for Optimisation of Refuelling Procedure

The combination of pressure and temperature values obtained in this research makes a solid base for further optimisation of the refuelling procedure [27]. Instead of automatically feeding fuel into the pipes, it is possible to set up feedback-based control loops to achieve real-world behaviour from the system.

For example:

- Throttling the initial pressure surge stops the internal tank heat from spiking early.
- Shifting the mass flow speed mid-cycle constantly stabilises the thermodynamic load.
- Wiring the live sensor data directly to the intake valves creates an automated safety net.

Running the pumps, this way means you stop relying so heavily on massive external chillers to survive the thermal limits. Pushing these dynamic adjustments to the main control board sets the strict mechanical groundwork for fully algorithmic, machine-driven refuelling stations.

7.5 Limitations of the Present Study

These structural calculations operate within strict boundaries. The software mapped a flat 2D slice instead of tracking the true 3D fluid dynamics. Treating the tank as a perfect cylinder saves processing power, but it completely ignores isolated turbulence spikes inside the physical chamber.

Table 2.SAE J2601 compliance assessment: peak temperatures from ANSYS Fluent simulation

Parameter	**Peak Temp. (K)**	**Time of Peak (s)**	**SAE J2601 Limit (K)**	**Violation (ΔK)**
Max. H_2 temperature	425	≈ 175–180	358	+67 K (FAIL)
Mass-avg. H_2 temperature	368	≈ 170–180	358	+10 K (FAIL)
PA6 liner max. temperature	396	≈ 190	358*	+38 K (FAIL)
CFRP max. temperature	363	≈ 220–250	358*	+5 K (WARN)

We also locked the solid tank materials in place and stripped out all outside weather variables. Only the hydrogen gas properties mutated during the run. Finally, we did not verify these numbers through stress testing of actual physical hardware. We simply cross-checked the final match against older published data to confirm the baseline physics.

7.6 Future Research Directions

These baseline calculations expose several immediate physical engineering problems that require direct testing:

- Intake Temperature Adjustments: Tracking exactly how much a colder gas feed drops the maximum internal heat limit.
- Live Hardware Throttling: Building active pressure curves that mutate automatically when the sensors detect a heat spike.
- Virtual Clone Deployment: Wiring live station data into continuous fluid dynamic software to spot structural failure before it happens.
- Full Grid Integration: Connecting the isolated tank software directly to the external chiller arrays to map the entire thermodynamic loop.
- Physical Stress Testing: Pumping actual gas into real hardware on a test stand to prove these mathematical predictions hold up under strain.

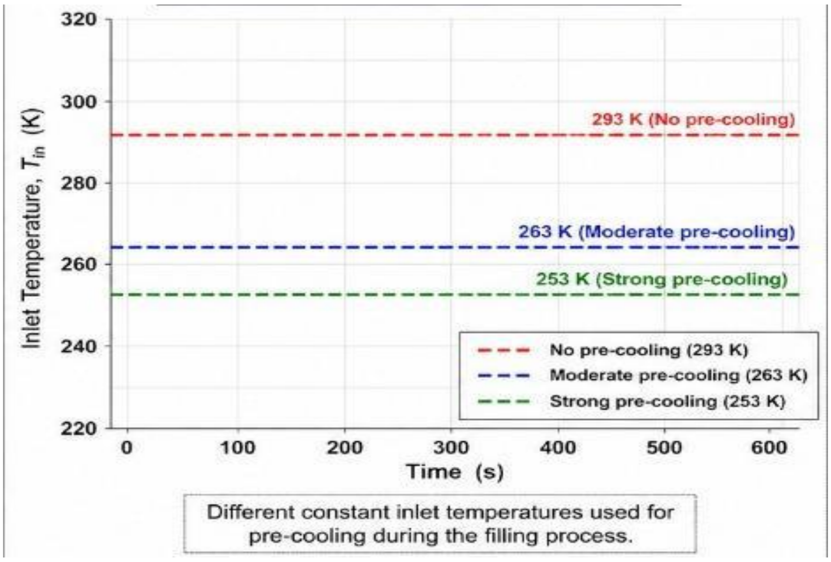
Pushing these specific upgrades will physically stabilise the hardware and drop the operating costs enough to make commercial stations profitable.

The calculations show that survival during the fast-fill procedure entails dealing with enormous pressure surges, violent turbulence of the filling substance, and the heat generated simultaneously. It is impossible to simply fill up your vehicle's tank with fuel. Ensuring that the Type IV composite tank does not fail due to temperature involves mechanical, cooling, and speed adjustments.

8. Pre-Cooling and B2B Hydrogen Infrastructure Systems

8.1 Architecture of the Hydrogen Fuelling System

For practical application, hydrogen energy systems require an effectively integrated fuelling infrastructure that encompasses storage, compression, delivery, and cooling. At a traditional hydrogen refuelling station, hydrogen is stored in high-pressure tanks and then fed to the dispenser via compressors or pumps. During fast refuelling, hydrogen is transported from the station's storage tanks to the vehicle's Type IV cylinder via a fast-fuelling hose.
This process is characterized by high pressure and turbulence, which leads to an increase in temperature in the storage chamber, as observed in present-day CFD simulations. Without a cooling system, the gas temperature exceeds the maximum threshold of 358 K (85°C) inside the storage tank.



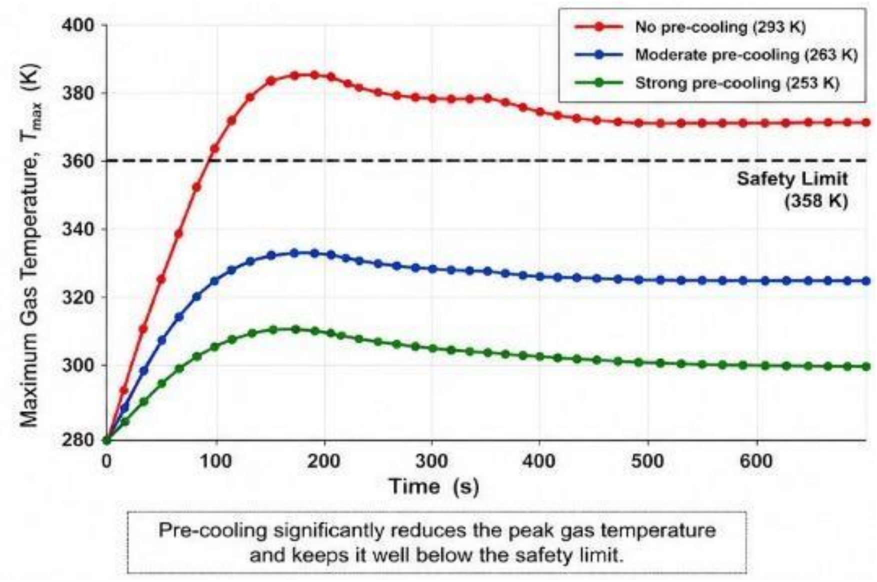
Different constant inlet temperatures used for pre-cooling during the filling process.

Figure 14.Inlet Temperature Vs Time

Different constant inlet temperatures represent no, moderate, and strong pre-cooling conditions applied during the filling process.
Consequently, a pre-cooling system is implemented as part of the refuelling system. Such cooling systems operate upstream of the dispenser to lower the hydrogen's temperature before it enters the vehicle.

8.2 Chiller-Based Pre-Cooling System

The pre-cooling of hydrogen is usually carried out using industrial chillers that operate on the vapour-compression refrigeration cycle. This process allows hydrogen to be cooled below ambient temperature, usually to −20°C to −40°C.
The implementation of the chiller system has been aimed at mitigating the temperature rise associated with high-speed hydrogen filling. According to the simulations, the temperature may reach 420 K during the first hydrogen filling. Lowering the input temperature will help reduce the system's total energy.



Pre-cooling significantly reduces the peak gas temperature and keeps it well below the safety limit.

Figure 15.Maximum Gas Temperature vs Time

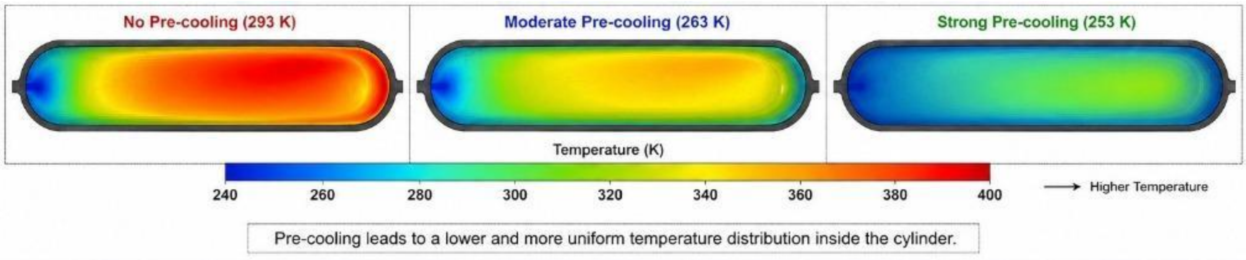
Pre-cooling significantly reduces peak gas temperature, ensuring it remains below the safety limit during fast filling.

In addition to offering an elevated safety level, another advantage of pre-cooling is that it allows the system to have a high rate of mass flow without exceeding the maximum capacity imposed by temperature levels. Nonetheless, because of the fact that chillers use energy, then it becomes vital to operate the system effectively.

8.3 Role of Pre-Cooling in Commercial Adoption

Hydrogen's usage as an alternative fuel in vehicles depends largely on the efficiency of refuelling stations [25] [26]. The major problem here is connected to the issue of heat increase during rapid refuelling.

For example, the application of hydrogen fuel cells in the field of heavy-duty transport, such as trucks and freight transportation, is quite crucial due to the reason that hydrogen has a high energy density and can be applied even to cover long distances. However, what is also necessary in this case is rapid refuelling of hydrogen, and without a good cooling system, the temperature rises above normal, which means slower fill rates [26].



Pre-cooling leads to a lower and more uniform temperature distribution inside the cylinder.

Figure 16.State of Charge (SOC) vs Time

Lower inlet temperatures result in reduced hotspot intensity and a more uniform temperature distribution inside the cylinder.

It is bound to create inefficiencies in the system's functioning. It can be seen that pre-cooling is no longer considered an additional requirement but a requisite to ensure that hydrogen fueling becomes quick and efficient. Pre-cooling would play an important role in making hydrogen viable commercially.

8.4 Manufacturing of Hydrogen Tanks and Thermal Issues

The efficiency of hydrogen storage technologies is highly correlated with the quality of Type IV composite pressure vessels. These tanks consist of a polymer liner and a carbon fibre reinforced polymer (CFRP) shell and are known for their exceptional strength-to-weight ratio, making them a popular choice for contemporary hydrogen-powered vehicles.

However, from a thermal point of view, these materials can pose some problems. First of all, both the polymer liner and the CFRP exhibit very low thermal conductivity. Therefore, it becomes very problematic for heat to escape from the system because fast refuelling occurs, causing heat to build up inside the tank.

This thermal limitation underscores the need to address the problem in tank production. Moreover, considering cooling prior to heating and heat transfer during production could make production more efficient and effective.

8.5 Commercial Support Networks

Rolling out functional hydrogen infrastructure demands a highly integrated commercial supply chain connecting the raw fuel producers directly with tank builders and local station operators. Constructing this massive ecosystem requires seamless coordination between the hardware manufacturers and the actual end users operating the pumps out on the ground.

Local station managers rarely possess the deep technical background required to handle extreme thermodynamic challenges on their own. To bypass this massive skill gap, heavy equipment suppliers deliver the industrial chillers and the complex thermal management software as a completely outsourced commercial package. Offloading these specific mechanical duties allows standard retail locations to safely dispense high-pressure hydrogen without needing to hire dedicated engineering teams.

A proper external service agreement tackles several heavy physical requirements at once to keep the station running smoothly. Contracted technicians physically bolt the massive refrigeration units straight into the existing station plumbing while embedding complex sensor arrays directly into the dispensing hardware. These external control grids constantly monitor the live heat spikes and dynamic pressure changes occurring during every single customer fill cycle. The commercial contracts also enforce rigorous physical maintenance schedules to prevent the chilling loops from breaking down under heavy commercial stress. Utilising the live feedback from the sensors allows the external software to automatically throttle the pump speeds, actively lowering the thermal strain on the storage tanks while keeping the lines moving.

Handing the complex temperature control over to third-party specialists strips away the daily operational friction for the site owner. Relying on identical cooling blueprints allows energy companies to scale up aggressively by installing the same stabilised hardware footprint across dozens of different regional markets simultaneously [43].

8.6 Market Expansion Roadblocks

Setting up a hydrogen grid in a country like India hits immediate physical and financial walls. The baseline weather is extreme. Operating capital is heavily restricted. You are starting with zero existing supply chains. The high ambient temperature is always contributing to the increase in the base thermal load. This will require the cooling equipment to operate more effectively during each dispensing cycle, necessitating the employment of high-capacity chillers at all times. The budgetary constraints in the region, however, compel businesses to utilize standard cooling systems.

Merging basic tank production with standard refrigeration setups and outsourced maintenance contracts creates a functional physical network. Dropping cheap, repeatable hardware templates onto the grid bypasses the initial financial restrictions. This strict, mechanical approach physically forces the regional hydrogen market to scale up.

9. CONCLUSION

In this research we used computational fluid dynamics to analyse the thermal characteristics of hydrogen during the rapid filling of a type-IV composite cylinder (a lightweight design typically constructed from a non-combustible material such as plastic), such as how much the gas will actually heat up due to the rapid compression as well as the turbulence that occurs while being mixed into the container. The results indicated that there was substantial heating of the hydrogen gas – with peak temperatures approaching 420 K (approx. 146 °C) reached at or about the moment of maximum compression. This indicates that there must be careful consideration of thermal management in hydrogen storage systems due to the high levels of heat, as the maximum allowable gas temperature for storage is 358 K (85 °C).

The thermal map shows that there are considerable fluctuations in temperature throughout the cylinder, with some localized hot spots occurring, particularly in the region of the back dome. The poor conductivity of the polymer liner and composite material makes it difficult for heat to be transferred by conduction alone to keep the temperature within acceptable limits.

The research highlights that to meet the previously mentioned challenges, it is important to implement pre-cooling methods as part of the hydrogen refuelling system. Using chiller-based systems reduces the temperature of hydrogen entering the compressors, resulting in lower peak temperatures during compression and, therefore, safer, more efficient refuelling. It will also help by optimising pressure ramping and flow conditions to improve the system's overall thermal control.

The research supports the creation of a full hydrogen renewable energy supply system, including all required equipment, to ensure the consistent and reliable supply of hydrogen from large-scale systems and to build a B2B ecosystem. This includes cooling system equipment, monitoring, and maintenance service.

Temperature control systems have become extremely important in determining how safe, effective and economically viable hydrogen storage and refuelling systems will be. Future research should include improvements to cooling systems, new smart monitoring techniques, and more effective refuelling methods to not only enhance system performance but also drive the mass adoption of hydrogen as a viable alternative energy carrier.

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