



Research Article

Characterizing temperature profiles and thermal management in hydrogen storage systems for aerial vehicles

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ABSTRACT

This research concentrates on the problem associated with rapid filling of type III hydrogen cylinders in hydrogen-powered aerial vehicles. Rapid filling leads to certain temperature rises in the cylinder due to adiabatic compression and it is jeopardizing the structural integrity. Existing research mainly focused on the effects of pressure variation and temperature rises on hydrogen cylinders. However, there is limited research on the effects of temperature rises in Type III hydrogen storage cylinders incorporated with PTFE-coated aluminium liners under various temperature and mass flow rates related to aerial application. Based on the previous research gap, a 2D axisymmetric cylinder model was developed in ANSYS R21 for a 5 L, 35 MPa Type III PTFE-coated aluminium liner wrapped in carbon fiber hydrogen cylinder. A model analysed under the real gas behaviours through the Redlich-Kwong equation with various inlet conditions of temperature (283–323 K), filling pressure (5–35 MPa) and mass flow rate (0.01–0.05 kg/s). The simulation outcome indicates the increase in internal gas temperature from 293 K to 417 K and the optimum temperature region near the inlet due to recirculatory heating. At a maximum temperature of 323 K, the internal temperature rises up to 600.2K toward the thermal stability limits of PTFE. Due to the insulating properties of PTFE, it reduces the temperature distribution from the inner layer to the outer layer of the cylinder and ensures temperature containment. This research work indicates that a minimum inlet temperature of 283K, a medium filling pressure of 20 MPa, and a moderate mass flow rate of 0.03 kg/s in 6 seconds provide an enhanced thermal stability of the cylinder. This research emphasizes the significance of controlling inlet parameters, not just pressure and flow rate but also temperature, to enhance the safe and efficient lightweight hydrogen storage cylinder used in UAV applications.

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INTRODUCTION

The global demand for pure and sustainable energy sources has intensified research into hydrogen as a suitable alternative to fossil fuels. Hydrogen fuel properties like compatible production methods, zero carbon emissivity, and richer energy density make it a suitable energy source for transportation purposes in fuel cell-powered automobiles and aerial vehicles [1–4]. Hydrogen's storage possesses significant safety and thermal management challenges for storing hydrogen in high-pressure static and dynamic conditions. High-pressure gaseous storage is the most popular adopted method due to its simple structure and higher gravimetric density. The U.S. Department of Energy (DOE) has focused on volumetric and gravimetric energy densities of 2.7 kWh/L and 3.0 kWh/kg, respectively, for onboard working cylinders [5–6]. To attain these targets, newer hydrogen storage systems depend upon composite high-pressure cylinders and combine lightweight materials with high strength. Type III cylinders contain aluminium liners wrapped with carbon fiber and exhibit a balance of structural stability and weight reduction, making them suitable for aerospace and UAV applications [7–9].

Rapid filling of hydrogen cylinders is a most required process in vehicle refuelling stations during that time. Temperature increases by adiabatic compression, frictional heating, and real gas effects. Rapid filling of cylinders at high pressures (350–700 bar) within a short span of time significantly increases gas temperatures to exceed safe operational limits. To resolve this issue, accurate computational modelling is needed to calculate temperature changes during filling, specifically when multi-layered materials and thermal insulators are involved [10–12]. Demonstrated thermal effects in Type III and IV tanks by considering parameters like inlet pressures, filling times, and design [13–15]. Adoption of multi-material layering, ignorance of real gas behaviour, or influence of coatings like PTFE, which can significantly change heat transfer within the cylinder materials. Many existing models are created for automotive-scale tanks with minute concentration on small-capacity systems adopted in UAVs, where rapid thermal gradients pose a higher cause of limited thermal mass. The studies elaborated that the temperature hike during hydrogen refuelling drastically depends upon parameters like filling rate, inlet temperature, and pressure [16–20].

By considering all thermal challenges, researchers have proposed optimized filling methods focused on attaining higher filling rates and short fuelling durations [21]. In addition to investigating the effect of various liner and wrapping materials on temperature distribution inside hydrogen storage vessels, addressing material selection as a thermal protection technique [22]. A unique temperature-absorbing technique was demonstrated to reduce excessive thermal hikes with an intense concentration on mass flow rate and cylinder design [23].

Research gap

- Previous research mainly concentrated on Type IV hydrogen cylinders with various polymer materials but lagged with modelling of Type III cylinders.
- Research on rapid filling of hydrogen remains unstudied, incorporating a PTFE-coated aluminium Type III hydrogen cylinder.
- The previous work did not concentrate on thermal interactions between multi-layered hydrogen cylinders, especially for smaller-capacity UAV storage applications.
- There is insufficient numerical simulation on the combination of various inlet parameters like filling pressure, inlet temperature, mass flow rate, and time to determine the internal temperature rise and thermal safety of a hydrogen cylinder.
- Lagging of design recommendations by simulation for optimizing filling strategies in smaller capacity, lightweight, and high-performance hydrogen cylinders.

Research Novelty

- This research develops a 2D axisymmetric computational model analysed with real gas effects using the Redlich-Kwong equation of state.
- This study provides a detailed thermal analysis of a Type III PTFE-coated aluminium liner and carbon fiber wrap hydrogen cylinder specially for UAV application.
- The simulation model reveals the thermal insulation and structural safety effects of a PTFE-coated aluminium cylinder under rapid filling.
- This research provides a validated design procedure for thermal stability under rapid filling of hydrogen in a small-scale hydrogen storage cylinder.
- This quantitative research focuses on optimal inlet parameters such as 20 MPa inlet pressure, 0.03 kg/s flow rate, 283 K inlet temperature, and 6 sec filling time to prevent the internal temperature rise.

PROCESS OF HYDROGEN FILLING: A THEORETICAL INVESTIGATION

Mechanisms Contributing to Temperature Rise During Rapid Hydrogen Filling

Rapid filling of hydrogen is accompanied by several phenomena that contribute to temperature rise inside the cylinder. Under certain conditions, hydrogen exhibits a negative Joule-Thomson coefficient, especially at medium-high pressure. This action indicates that while hydrogen expands more quickly, it cools rather than heats up [24–27]. However, this cooling effect is often overshadowed during compression-dominant fast-filling operations. If hydrogen gas is compressed into the cylinder very quickly, with little heat transfer to or from the surrounding, the compression of hydrogen gas is called adiabatic compression. The ideal gas law ($PV = nRT$) dictates that this compression raises the gas's internal energy which in turn raises the temperature [28–32].

Filling into pipelines, valves and narrow passages, hydrogen rapidly interacts with the surfaces of the passages through friction between the molecules, causing further heat to be generated. This frictional heating is particularly important for high pressure fueling systems and is responsible for additional heat rising in the cylinder. Hydrogen gas will also be affected by the surrounding environmental temperature while being refuelled. Further increases in the internal cylinder temperature may be caused by the transfer of additional heat into the gas in hot climates or high ambient temperatures [33]. When the gas is filling rapidly, external work is done on the gas during the compression process, increasing both its internal energy and temperature. This effect, called “heat of compression,” can lead to significant temperature increases in the HSS [34–39].

Impact on Safety and Mitigation Strategies

Together, these mechanisms can cause dramatic increases in temperature, which can cause internal pressures to exceed limits. This rise can cause severe safety concerns such as possible damage to the storage vessel. Also, hotter temps may cause the fuelling parts to be less efficient and less durable.

To reduce these risks, a number of engineering approaches are usually taken:

- Developing a method to more effectively dissipate heat through the use of materials with higher thermal conductivity when building tanks, and
- Pre-heating water prior to its compression, and
- Controlling and optimizing the filling rate, to prevent rapid heat build-up,

Including cooling system into fuelling station or compressor [40–42].

The root cause of the rising temperature

Zhang RY et.al [43] observed the expression for final temperature during the rapid filling operation.

$$T_2 = \frac{\lambda \mu T_1 (T_1 + \alpha P_1) - \alpha (\lambda P_1 T_1 - P_1 T_1)}{T_1 + \alpha P_1 + \frac{\alpha T_1 P_1 - P_1 T_1}{P_2}} \quad (1)$$

A rise in temperatures and filling rate have an exponentially related. On the other hand, a straight line exists between temperature growth and beginning pressure or temperature. It shows that the entry temperature and the surrounding temperature were equal. Developed an empirical formula using modelling and experimental studies [44] as.

$$T_2 = 1.01 - 1.52e^{-\frac{P_2}{8.44}} (-6.81 \times 0.9^{\dot{m}} + 0.3T_1 - 2.2P_1 + 68 + T_1) \quad (2)$$

Where $\dot{m}$ is the filling rate in g/s, T_1 and T_2 are the entry and exit temperatures of hydrogen in the cylinder in K and P_1 , P_2 are the entry and exit pressures of hydrogen in the cylinder in MPa.

Mathematical examination of rising temperatures

For open systems, the following the first law of thermodynamics [45-46]

$$dU = dH_{in} - dH_{out} + \delta Q - \delta W \quad (3)$$

Where dQ is the heat generated by the system expressed in kJ, dH_{in} and dH_{out} are the enthalpy in entry and exit of the system. The system's work is denoted by dW and kJ.

Formulating above equation with $dH_{out} = 0$ and $dW = 0$ is as follows:

$$dU = dH_{in} + \delta Q \quad (4)$$

The final energy is expressed as

$$U_2 = U_1 + dU \quad (5)$$

Where U_1 and U_2 are initial and final internal energy of cylinder expressed in kJ and the resultant energy is as follows:

$$U_2 = U_1 + dH_{in} + \delta Q \quad (6)$$

The relationship between temperature and the specific internal energy of hydrogen is shown as

$$u = aT - b \quad (7)$$

Where u is specific internal energy in kJ/kg, T is the hydrogen's temperature K.

$$U_1 = m_1(aT_1 - b) \quad (8)$$

$$U_2 = m_2(aT_2 - b) \quad (9)$$

Where m_1 and m_2 are initial and final mass of hydrogen in kilograms. In terms of expression, the final mass is

$$m_2 = m_1 \int \dot{m} dt \quad (10)$$

Where $(\dot{m})$ is mass flow rate in kg/s. An expression for the enthalpy of the system is

$$dH_{in} = h_{in} \int \dot{m} dt \quad (11)$$

Where h_{in} is specific enthalpy of hydrogen at the input temperature expressed in kJ/kg [47].

$$\delta Q = \int q dt \quad (12)$$

Where q is the power in kW, heat transmission to the surrounding. The above equations allow us to express the final temperature as follows:

$$T_2 = \frac{m_1(\alpha T_1 - b) + h_{in} \int \dot{m} dt + \int q dt}{\alpha(m_1 + \int \dot{m} dt)} - \frac{b}{a} \quad (13)$$

Geometrical Framework

The PTFE-coated metal layers and insulating layer make up the liquid hydrogen transit storage device. Carbon fibre and epoxy are combined to create insulation, which is placed between the environment and the metal's exterior. A drawing of the hydrogen transfer tank under design is shown in Figure 1. The PTFE coating thickness is T_3 , and the layer thicknesses are T_1 and T_2 and dimension are listed in Table 1.

CFD Simulations

- A 2D axisymmetric model was developed in ANSYS Fluent for a 35 MPa, 5L Type III hydrogen cylinder to improve computational efficiency and accuracy.
- Buoyancy effects were neglected due to the dominance of high-speed axisymmetric flow.

Key Assumptions

- Inlet valve allows high-pressure gas entry with minimal heat exchange; modelled as a time-dependent pressure boundary.
- The PTFE-coated aluminium liner minimizes heat transfer to the outer carbon fiber wall due to its low thermal conductivity (0.3 W/mK).
- PTFE is assumed to be isotropic, with constant thermal conductivity and specific heat capacity.
- Inlet temperature is considered constant, based on stable pre-filling conditions in experiments.
- Before hydrogen filling, nitrogen is purged, allowing initial hydrogen and wall temperatures to be equal.
- Convective heat transfer at the outer wall is negligible due to PTFE insulation.
- Mechanical deformation of the cylinder is ignored; all solids are treated as rigid bodies.

Governing Equations

Above assumption gives the basics for creating the flow and heat transfer 2D axisymmetric. Below is a description of the governing equations. The equations for mass conservation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial x}(\rho v) \frac{\rho v}{r} = 0 \quad (14)$$

where x represents the horizontal distance, r the radial distance, ρ the gas density, t the filling period, and u the filling linear velocity and v the radial velocity. As the axisymmetric model's momentum transit,

$$\begin{aligned} & \frac{\partial}{\partial t}(\rho u) + \frac{1}{r} \frac{\partial}{\partial x}(r \rho u u) + \frac{1}{r} \frac{\partial}{\partial r}(r \rho u v) \\ &= -\frac{\partial p}{\partial x} + \frac{1}{r} \frac{\partial}{\partial r} \left[r(\mu + \mu_t) \left(2 \frac{\partial u}{\partial x} - \frac{2}{3} (\nabla \cdot \vec{v}) \right) \right] \\ &+ \frac{1}{r} \frac{\partial}{\partial r} \left[r(\mu + \mu_t) \left(2 \frac{\partial u}{\partial r} + \frac{\partial v}{\partial x} \right) \right] \end{aligned} \quad (15)$$

Where p - Absolute pressure, μ -Dynamic viscosity, and μ_t Turbulence viscosity. The energy equation is

$$\begin{aligned} \frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x}(u(\rho E + p)) &= \frac{\partial}{\partial r} \left[k_{\text{eff}} \frac{\partial \tau}{\partial r} + u(\mu + \mu_t) \left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial x} \right) \right. \\ &\quad \left. - \frac{2}{3} u(\mu + \mu_t) \frac{\partial u}{\partial x} \right] \end{aligned} \quad (16)$$

Table 1. Characteristics of the cylinders' structural integrity

Parameter	Dimension	Unit
Type of cylinder	III	
Volume of cylinder	5	L
Working pressure	350	MPa
Internal Diameter of cylinder, D_i	140	mm
Total length of cylinder, L	395	mm
Inlet diameter of cylinder, D_{in}	18	mm
Carbon fibre layer thickness, T_2	4	mm
aluminium liner thickness, T_1	1.5	mm
PTFE coating thickness T_3	0.5	mm
Maximum weight of cylinder	1.85	kg
Application	(UAV hydrogen storage tank) UAVHST	

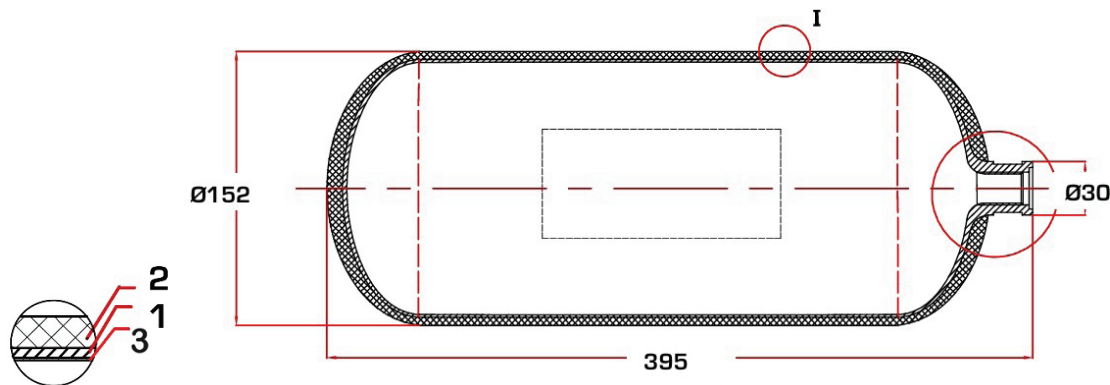


Figure 1. Geometrical structure of type-III hydrogen storage vessel.

where E is: and k_{eff} stands for effective heat conductivity.

$$E = h - \frac{p}{\rho} + \frac{u^2}{2} \quad (17)$$

where the hydrogen's h -specific enthalpy is.

While analyzing several turbulent models, concluded that the Realizable k model is best suited for the hydrogen rapid filling process and that the TKE dissipation follows an equation [48-50].

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial r}(\rho k u) = \frac{\partial}{\partial r} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial r} \right] + G_K - \rho \epsilon - Y_M \quad (18)$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial r}(\rho \epsilon u) = \frac{\partial}{\partial r} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial r} \right] + \rho C_1 S \epsilon - \rho C_2 \frac{\epsilon^2}{k + \sqrt{v \epsilon}} \quad (19)$$

$$G_K = -\rho \overline{u'v'} \frac{\partial v}{\partial x} \quad (20)$$

Where $-\rho \overline{u'v'}$ -Reynolds stress, u' and v' -fluctuating quantities

$$Y_M = 2\rho \epsilon M_t^2 \quad (21)$$

Where M_t -turbulent Mach number

$$M_t = \sqrt{\frac{k}{a^2}} \quad (22)$$

Where "a" indicates the sound speed. The vicinity at turbulence t is

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon} \quad (23)$$

Table 2 listed properties of materials used in PTFE-coated aluminium wrapped with a carbon fiber cylinder. The low thermal conductivity of PTFE, 0.304 W/m·K, provides insulation for reducing heat transfer to the outer layers. High conductivity of aluminium is 238 W/m·K more heat distribution, while carbon epoxy fiber offers structural strength with reasonable thermal conductivity of 3.72 W/m·K. These layered properties dominate the temperature distribution during rapid filling [51-52].

The Table 3 shows the comparative study in various parameters of different material, used to select the best

Table 2. Properties of material

Layers	Density (kg/m ³)	Specific heat (J/kgK)	Thermal conductivity (W/mK)
Teflon	2200	1.5	0.304
Aluminium	2700	902	238
Carbon epoxy fiber	1513	920	3.72

Table 3. Comparison of various cylinder materials properties

Property	PTFE-Coated Aluminium	Aluminium (Uncoated)	Stainless Steel	Fiber-Reinforced Polymer (FRP)
Thermal Conductivity (W/m K)	0.25–0.3 (Low, better insulation)	200 (Very high, poor insulation)	16 (High, rapid heat transmission)	Low (0.2–1)
Corrosion Resistance	Excellent (PTFE exhibits better protection against hydrogen embrittlement and corrosion)	Good (But liable to corrosion under certain conditions)	Excellent (High corrosion resistance)	Good (Resistant to corrosion but less durable than stainless steel)
Hydrogen Compatibility	Highly compatible (non-reactive with hydrogen)	Highly compatible (But can corrode under certain conditions)	Highly compatible (non-reactive, but higher risk of hydrogen embrittlement)	Moderate (requires special resin for hydrogen compatibility)
Insulation Effectiveness	Superior (Prevents rapid heat transfer, reducing thermal stress)	Poor (Requires additional insulation layers)	Poor (Requires additional insulation)	Moderate (Low thermal conductivity but less effective than PTFE)
Durability (Under High Pressure)	High (Aluminium provides strength, PTFE prevents thermal damage)	Moderate (requires reinforcement for high pressure)	Very High (extremely durable under pressure, but less effective thermally)	Moderate (Good for light applications but requires additional structural support)

Table 4. Comparison of various input parameter

Parameter	Current Study	Zhao et al. [53]	Li et al. [56]	Kim et al. [57]
Filling Pressure (MPa)	5–35	5–35	20–70	20–50
Inlet Temperature (K)	283–323	283–323	283–303	283–303
Mass Flow Rate (kg/s)	0.01–0.05	0.01–0.05	0.02–0.1	0.01–0.1
Filling Time (s)	0.5–12	0.5–12	1–5	1–5

materials based on the performance requirements and operational conditions.

Table 4 shows the initial parameter comparison with existing research work; listed parameters are freeze for conduct the simulation to optimize the hydrogen cylinder. By understanding the different to help to selection of influencing parameters [53–57].

Table 5 indicates the boundary condition for CFD simulation of the rapid hydrogen filling process Initial temperature of the gas and the ambient temperature are established as 293 K, which is considered in the simulation as the temperature is in equilibrium. The conventional heat transfer

Table 5. Simulation boundary conditions

Parameters	Value	Unit
Atmospheric temperature	293	K
the convective coefficient of the air around the cylinder and its outer surface.	10	W/m ² K
Gas inlet pressure	2	MPa
Inlet mass flow rate	0.002	kg/s
Gas initial temperature	293	K
Inlet gas pressure		MPa
Initial gas temperature	293	K

Table 6. comparative study of Type III and IV hydrogen cylinder

Parameter	Type III Cylinder (PTFE-coated Aluminium)	Type IV Cylinder (Carbon Fiber)	Remarks
Material	Aluminium liner with PTFE coating	Composite material	Type III uses a combination of metal and insulation, whereas Type IV is fully composite.
Thermal Conductivity (W/m K)	0.25–0.3 (PTFE), 200 (Aluminium)	5–15 (Carbon Fiber)	Type III has better thermal insulation due to PTFE coating, while Type IV has low conductivity but requires additional thermal management.
Strength	Moderate (Aluminium provides structural integrity)	High (Carbon fiber provides lightweight, high-strength structure)	Type IV offers higher strength and better pressure resistance than Type III.
Weight	Moderate (Aluminium is relatively heavy)	Lightweight (Carbon fiber offers high strength at a lower weight)	Type IV is ideal for applications where lightweight is essential, such as UAVs.
Pressure Resistance	Moderate (Withstand up to 35–70 MPa)	High Designed for high-pressure systems (up to 700 bar)	Type IV is better suited for high-pressure applications compared to Type III.
Temperature Resistance	Can withstand up to 250°C without degradation	200°C–300°C (depends on resin, composites)	Type III has better temperature tolerance in extreme conditions.
Thermal Management	Effective with PTFE for insulation, aluminium dissipates heat	Lower thermal conductivity, insulation strategies may be needed for efficient thermal management	Type III offers better thermal insulation naturally, while Type IV may need additional cooling.
Corrosion Resistance	High (PTFE prevents hydrogen embrittlement, corrosion)	Moderate (Carbon fiber is resistant, but polymer liner may degrade under certain conditions)	Type III has better corrosion resistance due to PTFE, while Type IV needs more attention to resin degradation.
Hydrogen Compatibility	Highly compatible with hydrogen (PTFE and aluminium)	Highly compatible with hydrogen, but composite material may need special treatments	Both cylinders are highly compatible with hydrogen, but Type III has better chemical stability.
Safety Considerations	More prone to thermal deformation, requires effective thermal management	Stronger structural integrity, better resistance to high pressure and thermal stress	Type IV offers greater safety due to its strength, while Type III requires careful thermal management during refuelling.

coefficient of $10 \text{ W/m}^2\text{K}$ is assigned to the outer surface of the cylinder; its influence is minimal due to the insulating PTFE layer. Hydrogen was filled at an inlet pressure of 2 MPa and a mass flow rate of 0.002 kg/s . These conditions reflect realistic refuelling.

Table 6 provides the comparative analysis of Type III and Type IV hydrogen cylinders with several key parameters. This delivers the insights into the operating conditions, material selection and thermal management in hydrogen cylinder.

RESULTS AND DISCUSSION

The thermal and flow behaviour of 5 L and 35 MPa PTFE-coated hydrogen cylinders was simulated during the

rapid filling process, and the outcomes show the characteristics with various inlet pressures, temperatures, and mass flow rates.

The temperature distribution of the hydrogen cylinder at various filling durations of 0.5 s, 1 s, 3 s, 6 s, and 12 s are shown in Figure 2. The peak temperature of gas is attained near the inlet due to recirculatory flow and compression effects. The flow is thermally stable with a high-duration filling process because of significant heat transmission within the flow region and from inside to the surrounding cylinder. But at lower filling times, the temperature is concentrated in a particular region and leads to reduced structural stability of the cylinder.

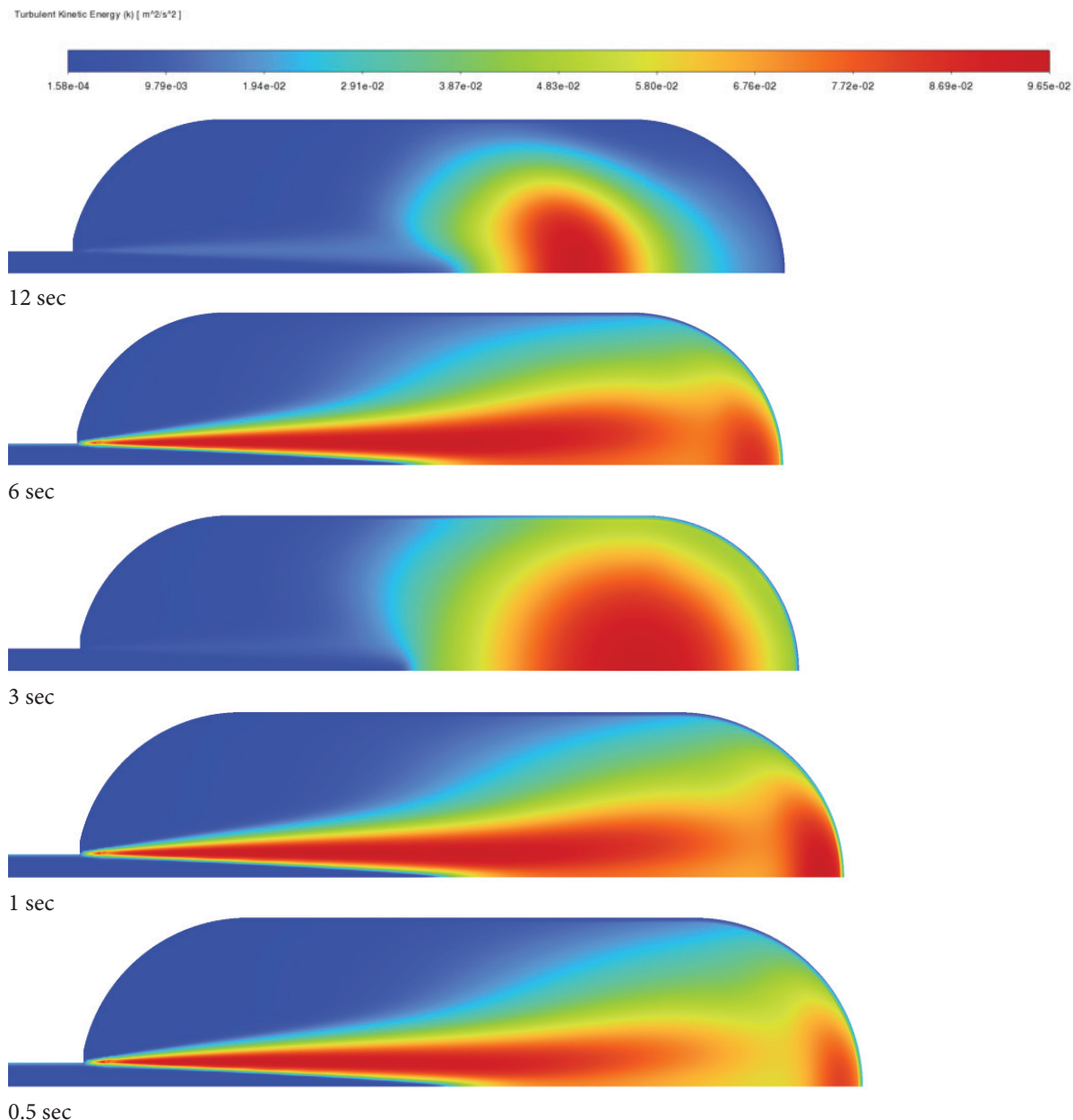


Figure 2. Temperature distribution of inner vessel in various filling time.

The Figure 3 shows the temperature distribution throughout the length of the cylinder with different initial gas temperatures of 283 K, 303 K, and 313 K in the fast-filling process. The simulation outcomes indicate that the internal gas temperature is raised with increasing initial gas temperature, specifically towards the inlet region, due to adiabatic compression and recirculatory flow. At a lower gas temperature, 283 K has less impact on internal gas temperature rises due to high temperature distribution; on the other side, at 313 K, accelerating the recirculatory flow with high pressure leads to increased thermal stress on the PTFE layer.

The internal gas temperature profile within the Type III hydrogen cylinder in the rapid filling process with

different inlet temperatures is shown in the Figure 4. The high-pressure rapid filling process creates optimum recirculatory flow causes for accumulation of high-temperature gas at the inlet zone. During the rapid filling process, most of the thermally affected zone occurs at the central axis of the cylinder, so emphasize the potential precooling strategy to enhance the thermal stability of the cylinder. Figure 5 shows the profile of turbulent kinetic energy distribution throughout the length of the cylinder. The highest TKE is attained at maximum inlet gas temperature due to adiabatic compression and recirculatory flow within the system. The localized heat occurs near the inlet zone due to low recirculation of gas, accelerating the thermal load on the PTFE layer.

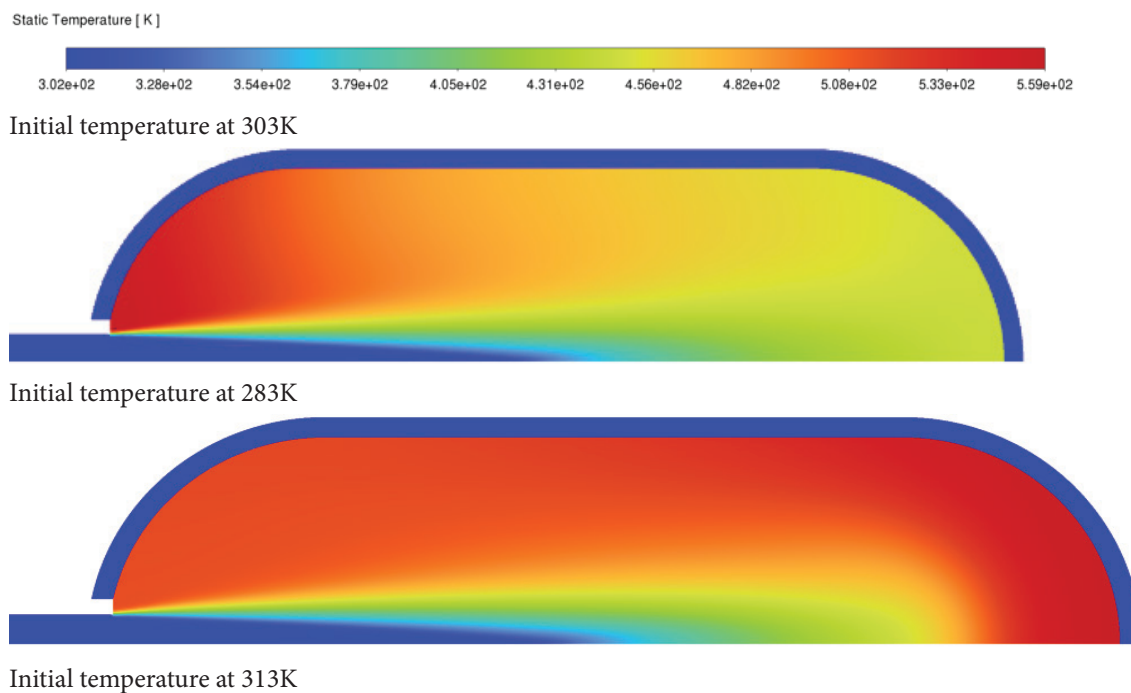


Figure 3. Temperature distribution of inner vessel in various hydrogen entry temperature.

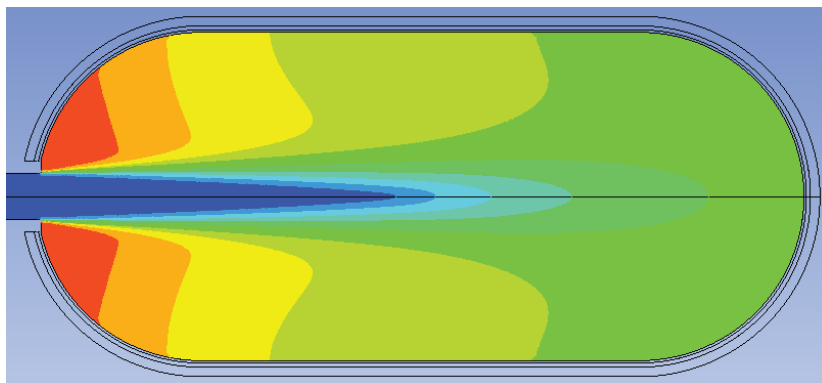


Figure 4. Hydrogen gas interior temperature profile.

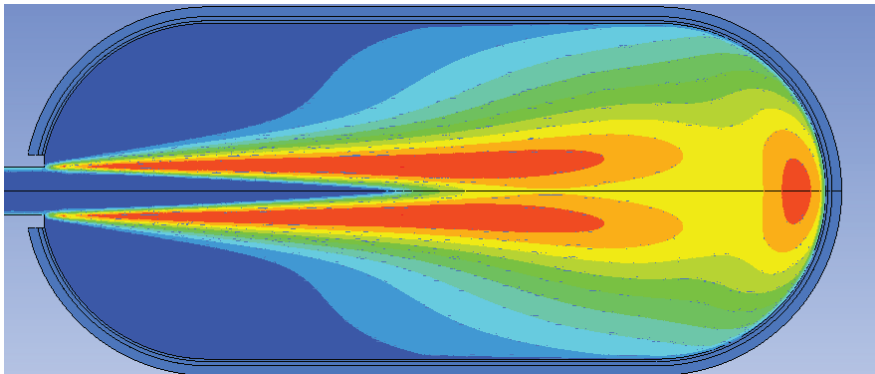


Figure 5. Hydrogen gas interior turbulent kinetic energy profile.

Effects of Filling Timing

The Figure 6 depicts that the variation of static temperature throughout the axis length of the cylinder with different filling times is 0.5 s, 1 s, 3 s, 6 s, and 12 s. Initially the all-static temperature curves are uniform and maintain a temperature of about 298K up to 0.15m, and further follow steep temperature rises along the axis of the cylinder, indicating that the hydrogen gas under the compression leads to rapid heating due to adiabatic effects beyond 0.15m from the inlet. The temperature magnitude is increased with increasing filling time, as at 0.5 s the maximum temperature is above 360 K, and at 12 s it exceeds 480 K. This progressive rise indicates that the greater thermal accumulation within the cylinder at optimum filling duration, even at lower pressure rises. The temperature rises are mainly located between the inlet region of 0.15–0.25 m beyond the taper, indicating the limited thermal stress in the downstream.

The overall thermal analysis of 5L and 35 MPa type III hydrogen cylinders in rapid filling with various filling durations is shown in the Figure 7. The maximum final

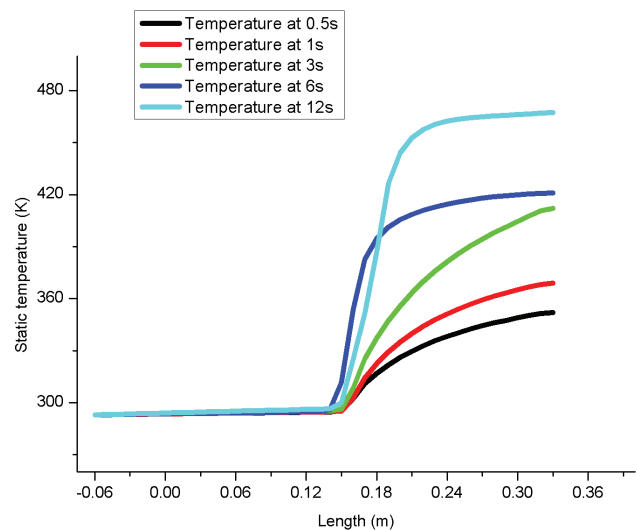


Figure 6. Variation of static temperature along the cylinder length.

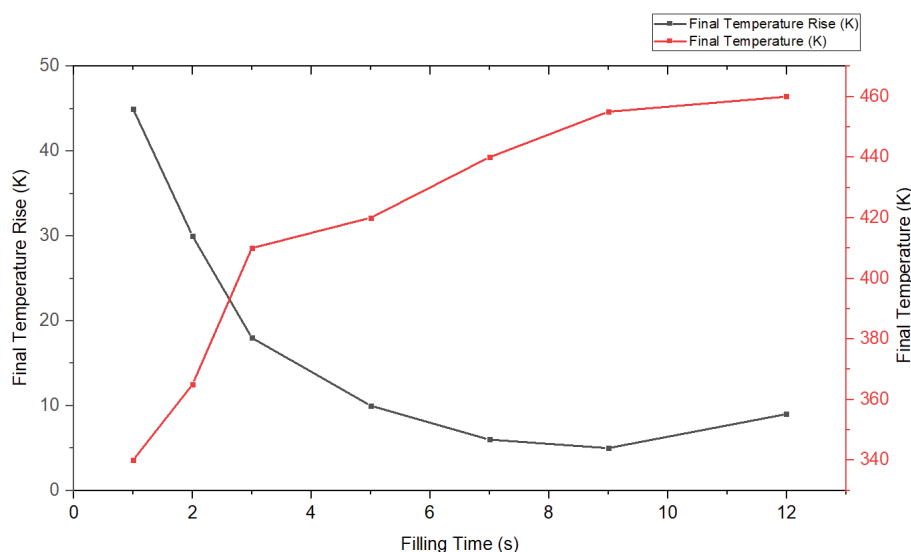


Figure 7. Variation of final temperature with different filling time.

temperature rise (ΔT) of about 40K is attained at a short filling duration of 0.5 to 1 second sharply. The sudden temperature rise occurs due to adiabatic compression of hydrogen gas in the rapid filling process, causing a reduction in heat transfer with surroundings. At filling times of 6 to 9 seconds, the heat conduction rate is significantly increased due to low temperature rises in multi-layered wall cylinders. As well as, the temperature rise does not continue beyond 10 seconds due to the concentration of thermal energy near the inlet. The final temperature variation shows as monotonic rises with filling time from 340 K to over 450 K up to 12 seconds filling time. The trend demonstrates that initial gas temperature and filling rate should be optimized to reduce the temperature rise (ΔT) and reduce the concentration of thermal load; otherwise, the integrity of the PTFE-coated hydrogen cylinder is reduced due to exceeding the thermal limits.

The Figure 8 reveals that the maximum TKE is attained at 0.25 m from the inlet; the rapid filling of hydrogen causes

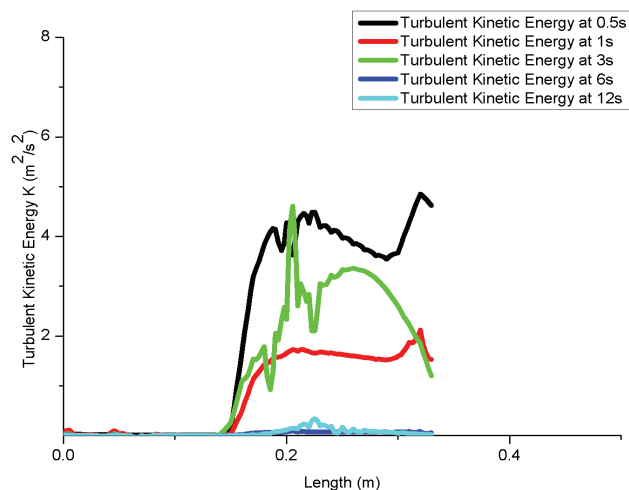


Figure 8. Turbulent kinetic energy variation along the cylinder length.

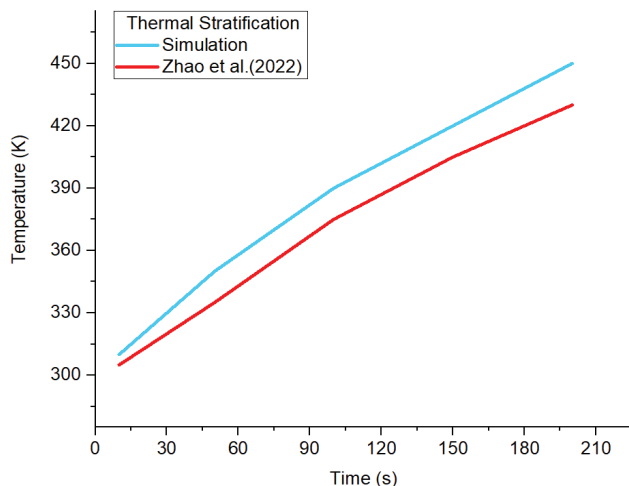


Figure 9. Thermal stratification of hydrogen cylinder.

the intense flow disturbances and turbulence. TKE attains a maximum of $6.5 \text{ m}^2/\text{s}^2$ at 0.5 sec filling time, indicating a violent flow behaviour at the initial stage. On the other side, TKE decreases with increasing filling time, such as $1 \text{ m}^2/\text{s}^2$ at 6 seconds and $0.3 \text{ m}^2/\text{s}^2$ at 12 seconds, indicating the lower filling rate reduces the TKE and exhibits more stable flow. From the inlet upstream (0–0.18 m) and downstream (beyond 0.30 m) region. TKE remains close to zero, indicating the minimum turbulence. The presence of transient eddies and pressure waves during rapid filling induces the turbulent stress and leads to material degradation.

The internal temperature variation of the hydrogen cylinder during the rapid filling process is shown in the Figure 9. The simulation thermal stratification curve is closely aligned with Zhao et al. [53], To demonstrate the trustworthiness of the designed model. This temperature gradually increased as the time progressed, which means that the system became thermally stratified. Contrary to this, Zhao et al. [53], suggest that the temperature increases with time and that the temperature is lower than the simulated temperature. This can be explained by the differences between the initial, boundary and other assumptions used in the models. The graph shows that both Zhao et al. [53] and the simulation show a similar trend predict similar temperature trends during the thermal stratification process.

Effects of Initial Pressure

The Figure 10 represents a temperature distribution along the cylinder axis with different inlet pressures of 50 bar, 100 bar, 200 bar, and 350 bar. The sudden temperature rise occurs at 0.18 m and 0.22 m from the inlet due to strong turbulent effects and adiabatic compression. This localized thermal fluctuation occurs because high-inlet velocity of gas leads to a reduction in the heat transfer rate to the surroundings. The maximum gas temperature increases from 360 to 415 K with a corresponding inlet pressure of 50 to

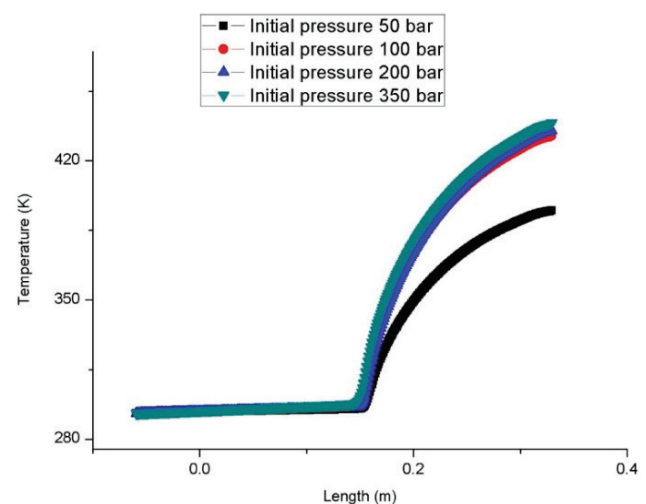


Figure 10. Variation of temperature along the cylinder length with different filling pressure.

Table 7. Initial parameters for various entry pressure of hydrogen gas

Initial pressure (Mpa)	Filling Temperature (K)	Filling rate (Kg/m ³)	Time step (sec)	Filling time (sec)
5	293	0.02	0.1	10
10	293	0.02	0.1	10
20	293	0.02	0.1	10
35	293	0.02	0.1	10

350 bar, reflecting more aggressive adiabatic compression with optimum inlet pressure. The outcome shows higher inlet pressure filling produces a uniform thermal distribution along the length; in other cases, thermal concentration occurs towards an inlet region, leading to thermal instability in the PTFE layer, and these effects are prevented by pressure ramping or pre-cooling strategies.

Table 7 presents the simulation setup for various hydrogen gas inlet pressure (5–35 MPa) effects on internal gas temperature rise. The input parameters of hydrogen gas filling are maintained at a filling temperature of 293 K and a 10-second filling time with a constant filling rate.

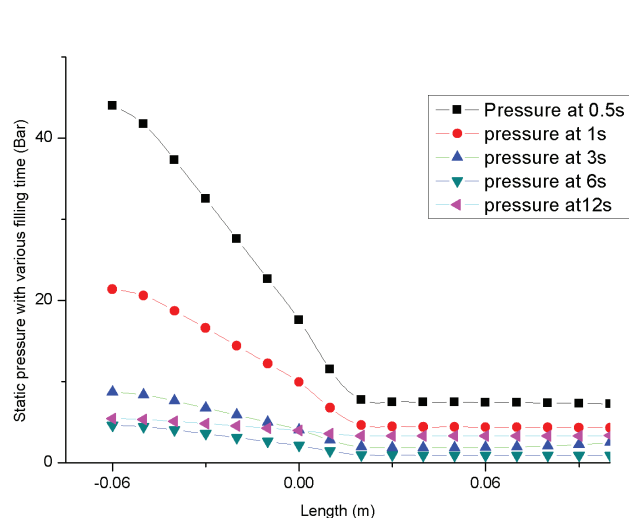
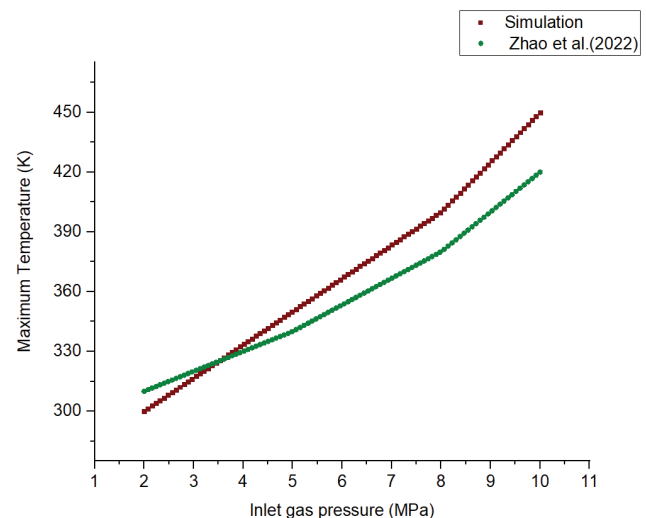
The Figure 11 shows the static pressure distribution throughout the length of the cylinder at various filling times: 0.5 s, 1 s, 3 s, 6 s, and 12 s. The plot elaborates the highest static pressure in the inlet and gradually drops toward the center and stabilizes downstream. At 0.5 s, the static pressure research was about 45 bars towards the inlet and then stabilized due to adiabatic compression and pressure shock during ultra-fast filling. As the filling time increases, the pressure profile becomes more uniform and less extreme. This behaviour reflects smoother pressure gradients and minimizing the mechanical stress on the cylinder walls. Additionally, the convergence of the pressure curves at the center and downstream sections indicates a steady-state

behaviour that develops more clearly with extended filling durations.

The comparison of simulation maximum temperature and Zhao et al. [53] outcome with different inlet pressure is shown in Figure 12. Both plot line trends indicate that as high inlet pressure increases, internal gas temperature rises during the rapid filling process. However, the simulation outcome enhances the internal temperature rises compared with Zhao et al. [53]. due to different modelling assumptions, boundary conditions, and material properties used for simulation. Overall, the trend line indicates the strong correlation between the existing and simulation data, confirming the accuracy of the model used in the simulation.

Effect of Initial Temperature

Figure 13 shows the effects of initial temperature on the internal temperature rise of a hydrogen Type III cylinder in a rapid filling process. The initial temperature from 283 to 323 K and corresponding internal temperature rise is 416 to 525 K. The plot curve indicates the strong correlation in the initial gas temperature in terms of final gas temperature. The linear temperature rises up to 310 K, and beyond that point, temperature nonlinear acceleration occurs due to enhanced internal energy and less heat dissipation. This

**Figure 11.** Variation of static pressure throughout length of the cylinder.**Figure 12.** Maximum temperature variation with different gas inlet pressure.

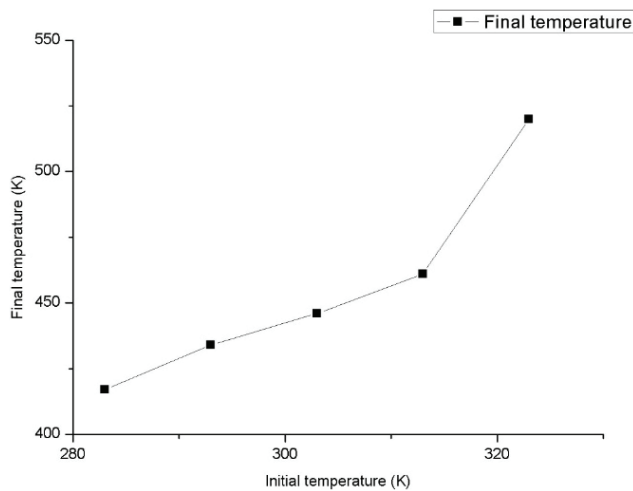


Figure 13. Variation of final gas temperature with different inlet gas temperature.

behaviour clearly shows the contribution of adiabatic compression and limited cooling in the rapid filling process. The results underscore the importance of controlling inlet gas temperature, as elevated pre-fill conditions can lead to critical thermal loads that may exceed the material limits of the PTFE liner and composite structure. Therefore, implementing pre-cooling strategies or thermal regulation protocols is essential to ensure structural safety and prolong cylinder life in high-pressure hydrogen storage systems [54-55].

Axial static pressure variation along with different inlet gas temperatures of 283 K, 303 K, and 313 K is shown in the Figure 14. All three curves show a U-shaped profile with maximum pressure attained at both ends of the cylinder and minimum static pressure attained at the center zone. Near the inlet region, the pressure attains up to 2.8 bar and gradually tapers towards the center to 0.5 bar and again rises towards the end of the cylinder. This behaviour is expected because pressure is primarily governed by the imposed boundary conditions and filling dynamics. Energy distribution and gas density are primarily influenced by temperature, while bulk flow resistance is not. The shape is regular in all cases suggesting that the flow is steady, symmetric and that the effects of the thermals on the pressure gradients are relatively small. Overall, these findings suggest that thermal control has a limited effect on pressure distribution in such a hydrogen system but is necessary to control material constraints and thermal stresses during the fast-filling process.

The final temperature as a function of initial temperature is compared between simulation and Zhao et al. [53] as shown in the Figure 15. The plot indicates the significant rise in the final temperature with increasing initial temperature, especially higher in higher magnitude. In contrast, Zhao et al. [53] saw a general trend of increasing final temperature as the initial temperature increased. The

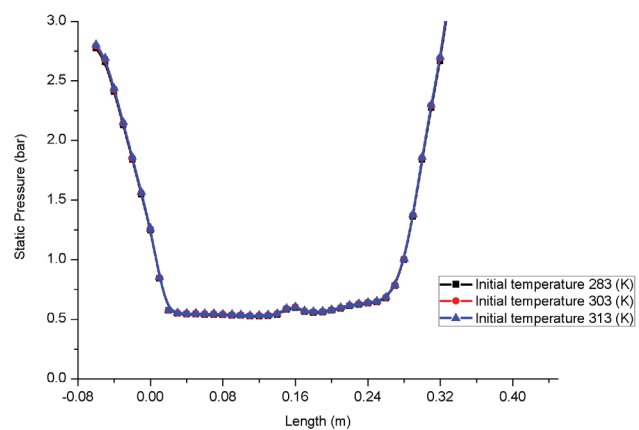


Figure 14. Static pressure variation with different inlet gas temperature.

simulation curve has the higher magnitude due to different boundary conditions, such as the mass flow rate, filling rate, and thermodynamic models. The comparison shows a better trend, though the simulation results suggest a more significant thermal response compared to Zhao et al. [53].

Effects of Filling Rate

The Figure 16 demonstrates variation of temperature along the cylinder length with different filling rates of 0.01 kg/s, 0.015 kg/s, 0.03 kg/s, and 0.05 kg/s. All curves remain uniform until 0.12 m from the inlet, but the optimum peak occurs between 0.2 and 0.25 m due to adiabatic compression in the high-pressure inlet. The maximum gas temperature is increased from 360 K to 425 K, corresponding to a filling rate of 0.01 to 0.05 kg/s. After 0.25 m, thermal stress is concentrated at the inlet and creates material fatigue by heating cycles.

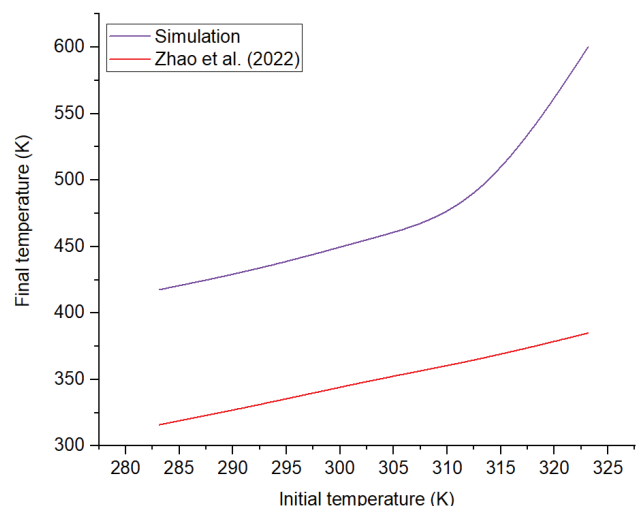


Figure 15. Variation of temperature in UAV cylinder.

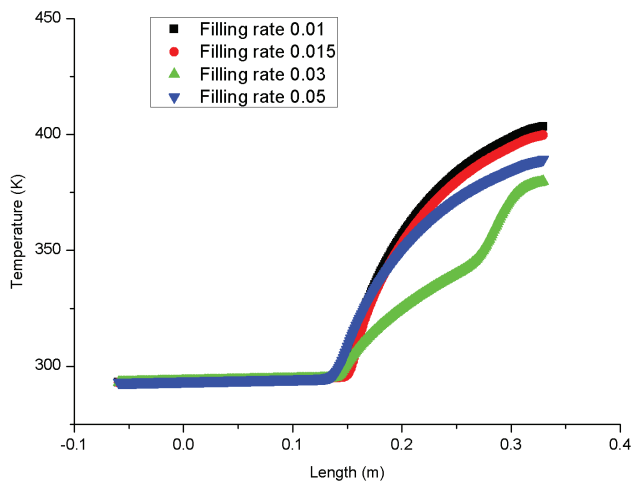


Figure 16. Variation of temperature with different filling rate.

The TKE distribution along the axial span of the cylinder with different filling rates of 0.01 kg/s, 0.015 kg/s, 0.03 kg/s, and 0.05 kg/s are shown in the Figure 17. The maximum intensity of TKE is formed at a higher filling rate in the region of 0.18 to 0.25 m near the inlet. The notable flow instability and energy dissipation are attained at a filling rate of 0.05 kg/s, and the peak occurs above $0.12 \text{ m}^2/\text{s}^2$. On the other hand, the lower TKE is attained at a minimum filling rate, such as 0.01 kg/s, and remains below $0.03 \text{ m}^2/\text{s}^2$. The plot shows that the turbulence intensity not only increases with filling rate but also becomes more spatially extended along the axial direction as the flow rate rises. The outcome emphasizes that controlling the turbulence and its effects, such as accumulation of heat, structural stress, and mixing performance in hydrogen cylinders.

The comparison of temperature variation with different filling rate simulations and Zhao et al. [53] is shown in Figure 18. The plot indicates that temperature increases

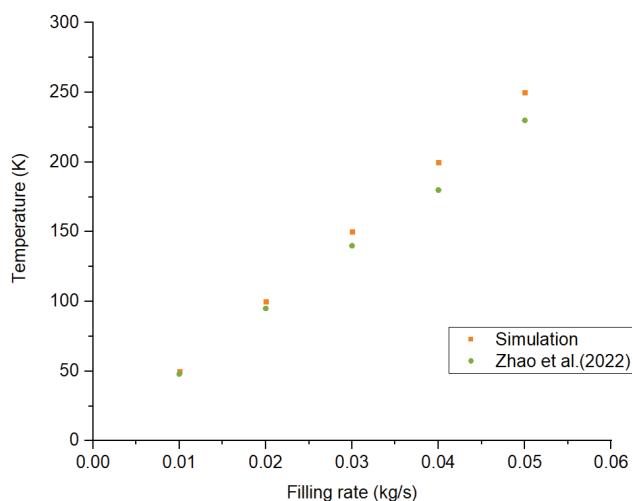


Figure 18. Variation of temperature with different flow rate.

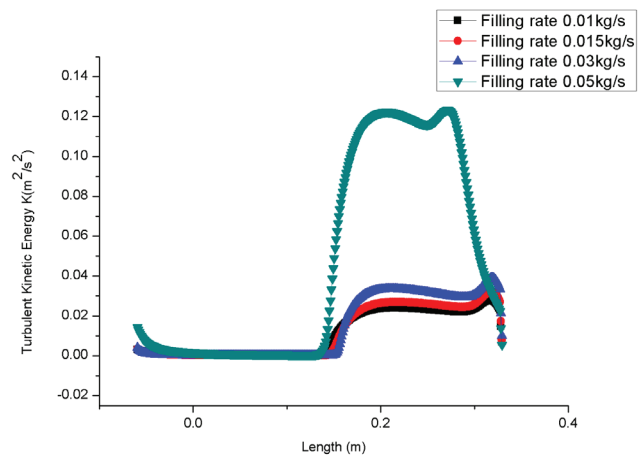


Figure 17. Variation of turbulent kinetic energy with different filling rate.

with increasing filling rate in both the simulation and the Zhao et al. [53] study. Higher filling rates significantly raise the compressional heat due to rapid filling gas compression. Both simulation and Zhao et al. [53] follow similar progressions, yielding slightly higher temperatures at high filling rates. The comparison plot indicates the simulation curve closely aligned with existing outcomes shows the reliability of the designed model. The slight difference indicates the different boundary condition.

Effect of Velocity Variation

The variation of hydrogen gas velocity magnitude along the axis of the Type III storage cylinder at different filling rates, such as 0.01 kg/s, 0.015 kg/s, 0.03 kg/s, and 0.05 kg/s, is shown in the Figure 19. This profile reflects the hydrogen behaviours inside the cylinder with various filling rates. At

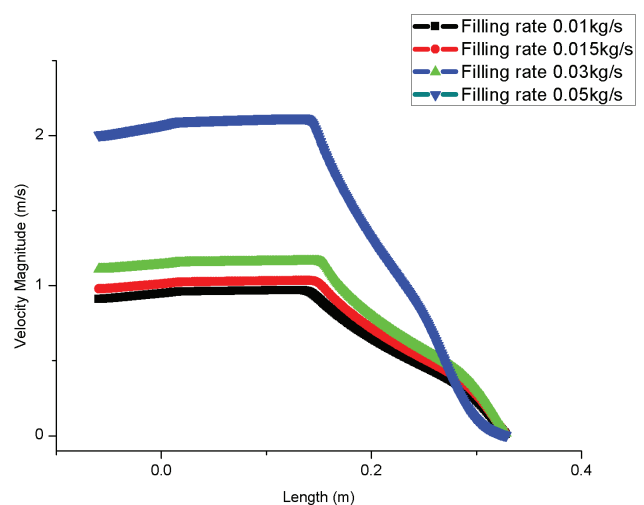


Figure 19. Variation of velocity magnitude with different filling rates.

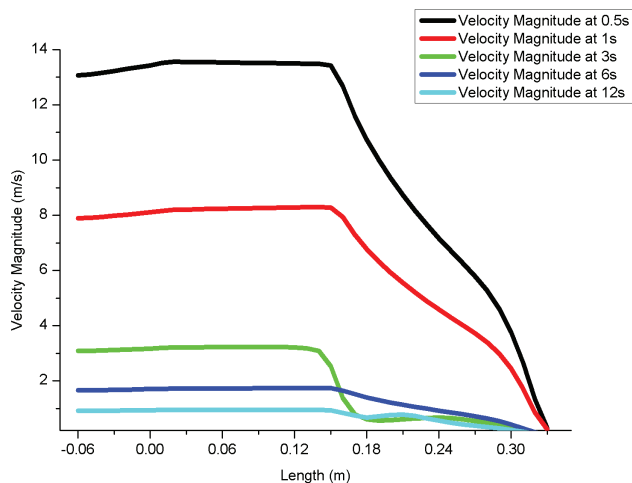


Figure 20. Variation of velocity magnitude with different filling time.

a lower filling rate of 0.01 kg/s, the gas maintains a more uniform velocity of 0.9 m/s up to 0.18 m from the inlet. Further, the velocity is increased with respect to the filling rate, with 0.05 kg/s exhibiting a maximum velocity near 2 m/s. The velocity is decreased beyond 0.2 m from the inlet due to energy dissipation, pressure recovery, and increasing flow resistance. Particularly, filling rates at 0.03 and 0.05 kg/s show a steep fall in velocity due to turbulence and wall interaction.

The velocity magnitude distribution along the axis of the cylinder with different filling durations, such as 0.5 s, 1 s, 3 s, 6 s, and 12 s, is shown in the Figure 20. The trend confirms that the optimum velocity of 13.5 m/s is attained at 0.5 s filling duration up to 0.18 m from the inlet; further, the velocity tapered to zero due to strong deceleration. As increasing filling time gradually decreases the maximum velocity to 8 m/s at 1 s, 3 m/s at 3 s, and below 1.5 m/s at 12 s. The spatial profile also indicates that maximum velocities are withstood over an entire span during rapid filling; in other cases, low-speed filling keeps the flow more stable and evenly distributed. These outcomes indicate that rapid filling causes the more aggressive and localized jet penetration, but lower-speed filling exhibits the gradual diffusion and smoother flow transitions.

CONCLUSION

This research work presents an overall numerical analysis of the thermal, flow and structural performance under rapid filling of hydrogen gas into a 5-liter, 35 MPa Type III storage system. This study explores how the various inlet parameters, such as filling time (0.5–12 s), mass flow rate (0.01–0.05 kg/s), initial temperature (283–313 K), and filling pressure (50–350 bar), influence the hydrogen behaviour with various flow conditions.

1. The simulation outcome reveals that the high-temperature region formed towards the inlet let (0.18–0.25 m) due to adiabatic compression and localized flow recirculation of hydrogen. The non-linear maximum internal temperature rise is localized in the region from 298 K to 480 K at 12-second filling time. However, the filling time of 0.5 seconds provides a lowered internal temperature rise but exhibits high-pressure waves, which, which leads to the dual risks of rapid heating and flow shock.
2. The static pressure distribution is closely associated with the rate of filling; at a 0.5-second filling duration, an internal gas pressure reaches a maximum value of 45 bar, and at a 3–12-second filling duration, gas pressure is uniformly distributed around 5–7 bar. Rapid inflow of hydrogen leads to transient over pressurization. This behaviour reveals that the initiation gas temperature is very low, and it is increased gradually by the pressure spikes.
3. Further analysed the behaviour of velocity magnitude and turbulent kinetic energy (TKE) on flow uniformity and structural integrity. The velocity peaks at 13.5 m/s at 0.5 seconds of filling duration and tapers to 1 m/s at 12 seconds of filling duration. TKE reaches an optimum of $0.12 \text{ m}^2/\text{s}^2$ at a 0.05 kg/s flow rate that maximum turbulence intensity and unsteady flow occur in rapid filling of hydrogen. The high-intensity turbulent zone is recognized towards the inlet region and reduces along the axis, and the maximum TKE increases the structural fatigue due to flow-induced vibrations and localized wall stress.
4. Multi-layered structure plays a crucial role in heat transmission within the structure and the PTFE/PTFE layer acts as an insulator to protect the heat transmission from the inner to the outer layer and ensure material degradation by accumulation of heat localizing near the inlet.
5. This study identified the safe filling environment, such as a mass flow rate of 0.03 kg/s, an inlet temperature of 283 K, and a filling time of 6–8 s. Acceptable temperature rise towards 430 K leads to uniform flow behaviour and reduced peak turbulence.
6. This research presents detailed insights into transient thermo-fluid interactions in Type III hydrogen storage cylinders under fast-filling conditions and fills the existing gap by adapting quantitative information into temperature stratification, turbulence generation, pressure evolution, and material interaction in the operational range.

This research outcome reveals the valuable guidance for lower-scale hydrogen storage cylinders, especially for UAV applications. Future work can extend this model to include fluid-structure interaction (FSI), cyclic fatigue under repeated filling, and experimental validation through embedded sensors to further optimize design and safety.

Limitations

1. In this model used Redlich-Kwong equation for isotropic material limit the accuracy under extreme condition.
2. This simulation outcomes are lagging in experimental validation.
3. The work focused only PTFE coated aluminium cylinder but not explored various combination of materials.

Future recommendation

1. Analysis the anisotropic material properties and behaviours of real gas in extreme condition
2. Conduct experiments for validating the simulation outcome.
3. Conduct simulation of this model for up to 7MPa pressure.
4. Develop the sensor intergradation for real time monitoring system.

NOMENCLATURE

E	The gas's total energy (J/kg)
K	Kinetic energy of turbulent flow (m^2/s^2)
k_{eff}	Effective thermal conductivity (W/m.K)
M_t	Mach number of turbulences
p	Pressure absolute (MPa)
r	The radial length (meters)
t	Temporal (s)
u	The axial speed (m/s)
D_i	Measurement of diameter (mm)
L	Length in millimetres
m	The highest mass of storage (kg)
D_{in}	Diameter of inlet (mm)
T_1	Thickness of aluminium liner (mm)
T_2	Thickness of carbon epoxy coating (mm)
T_3	Thickness of PTFE coating (mm)
v	The temperature radial velocity (m/s)
x	Axial distance (m)
Y_M	Variable dilatation in compressible shear flow

Greek Letters

ρ	Density (g/m^3)
μ	Viscosity dynamic (Ns/m^2)
μ_t	Turbulence viscosity

Subscripts

t	Turbulent
eff	Effective
wall	Wall temperature
in	Inlet of gas
gas	Gas in the cylinder
amb	Ambient
inlet	Inlet pre-cooling hydrogen
i	Inner

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

No conflicts of interest are disclosed by the authors.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

REFERENCES

- [1] Bakker S, van Lente H, Meeus MTH. Credible expectations-the US Department of Energy's Hydrogen Program as enactor and selector of hydrogen technologies. *Technol Forecast Soc Change* 2012;79:1059–1071. [\[CrossRef\]](#)
- [2] Matsuo Y, Endo S, Nagatomi Y, Shibata Y, Komiyama R, Fujii Y. A quantitative analysis of Japan's optimal power generation mix in 2050 and the role of CO₂-free hydrogen. *Energy* 2018;165:1200–1219. [\[CrossRef\]](#)
- [3] Sgobbi A, Nijs W, De Miglio R, Chiodi A, Gargiulo M, Thiel C. How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system. *Int J Hydrogen Energy* 2015;41:19–35. [\[CrossRef\]](#)
- [4] Jain IP. Hydrogen the fuel for 21st century. *Int J Hydrogen Energy* 2009;34:7368–7378. [\[CrossRef\]](#)
- [5] Niaz S, Manzoor T, Pandith AH. Hydrogen storage: Materials, methods and perspectives. *Renew Sustain Energy Rev* 2015;50:457–469. [\[CrossRef\]](#)
- [6] Zheng J, Liu ZL, Hua Z, Guch WG, Chen L. Research status-in-situ and key challenges in hydrogen safety. *J Saf Environ* 2020;20:106–115.
- [7] Kirubadurai B, Jaganraj R, Vinothkumar M, Jegadeeswari G. A dual modelling approach: CFD and electrochemical impedance spectroscopy for enhanced PEM fuel cell design and operation. *Results Eng* 2025;26. [\[CrossRef\]](#)
- [8] Kirubadurai B, Jaganraj R, Vinothkumar M, Jegadeeswari G. CFD analysis of fuel cell performance: Insights into electrochemical and thermal processes. *Int Rev Appl Sci Eng* 2025;16:472–483. [\[CrossRef\]](#)

- [9] Manoharan Y, Hosseini SE, Butler B, Alzhahrani H, Senior BTF, Ashuri T, et al. Hydrogen fuel cell vehicles: Current status and future prospect. *Appl Sci (Basel)* 2019;9:2296. [\[CrossRef\]](#)
- [10] Valencia L, Blanc-Vannet P, Domergue D, Heudier L, Jamois D. Thermal history resulting in the failure of lightweight fully-wrapped composite pressure vessel for hydrogen in a fire experimental facility. *Fire Technol* 2015;52:421–442. [\[CrossRef\]](#)
- [11] Zhang M, Lv H, Kang H, Zhou W, Zhang C. A literature review of failure prediction and analysis methods for composite high-pressure hydrogen storage tanks. *Int J Hydrogen Energy* 2019;44:25777–25799. [\[CrossRef\]](#)
- [12] Ahluwalia RK, Hua TQ, Peng JK. On-board and off-board performance of hydrogen storage options for light-duty vehicles. *Int J Hydrogen Energy* 2012;37:2891–2910. [\[CrossRef\]](#)
- [13] Pépin J, Lainé E, Grandidier JC, Benoit G, Mellier D, Weber M, et al. Replication of liner collapse phenomenon observed in hyperbaric type IV hydrogen storage vessel by explosive decompression experiments. *Int J Hydrogen Energy* 2018;43:4671–4680. [\[CrossRef\]](#)
- [14] Sun Y, Lv H, Zhou W, Zhang C. Research on hydrogen permeability of polyamide 6 as the liner material for type IV hydrogen storage tank. *Int J Hydrogen Energy* 2020;45:24980–24990. [\[CrossRef\]](#)
- [15] Yersak TA, Baker DR, Yanagisawa Y, Slavik S, Immel R, Mack-Gardner A, et al. Predictive model for depressurization-induced blistering of type IV tank liners for hydrogen storage. *Int J Hydrogen Energy* 2017;42:28910–28917. [\[CrossRef\]](#)
- [16] Durbin DJ, Malardier-Jugroot C. Review of hydrogen storage techniques for on board vehicle applications. *Int J Hydrogen Energy* 2013;38:14595–14617. [\[CrossRef\]](#)
- [17] Maus S, Hapke J, Ranong CN, Wüchner E, Friedlmeier G, Wenger D. Filling procedure for vehicles with compressed hydrogen tanks. *Int J Hydrogen Energy* 2008;33:4612–4621. [\[CrossRef\]](#)
- [18] Yang JC. A thermodynamic analysis of refueling of a hydrogen tank. *Int J Hydrogen Energy* 2009;34:6712–6721. [\[CrossRef\]](#)
- [19] Zhang J, Fisher TS, Ramachandran PV, Gore JP, Mudawar I. A review of heat transfer issues in hydrogen storage technologies. *J Heat Transfer* 2005;127:1391–1399. [\[CrossRef\]](#)
- [20] Zhao Y, Liu G, Liu Y, Zheng J, Chen Y, Zhao L, et al. Numerical study on fast filling of 70 MPa type III cylinder for hydrogen vehicle. *Int J Hydrogen Energy* 2012;37:17517–17522. [\[CrossRef\]](#)
- [21] Sapre S, Pareek K, Rohan R, Singh PK. H₂ refueling assessment of composite storage tank for fuel cell vehicle. *Int J Hydrogen Energy* 2019;44:23699–23707. [\[CrossRef\]](#)
- [22] Xiao J, Wang X, Bénard P, Chahine R. Determining hydrogen pre-cooling temperature from refueling parameters. *Int J Hydrogen Energy* 2016;41:16316–16321. [\[CrossRef\]](#)
- [23] Schneider J, Meadows G, Mathison S, Veenstra M, et al. Validation and sensitivity studies for SAE J2601, the light duty vehicle hydrogen fueling standard. *SAE Int J Altern Powertrains* 2014;3:257–309. [\[CrossRef\]](#)
- [24] J-Q, Myoung NS, Kwon JT, Jang SJ, Lee T. A study on the prediction of the temperature and mass of hydrogen gas inside a tank during fast filling process. *Energies (Basel)* 2020;13:6428. [\[CrossRef\]](#)
- [25] Li JQ, Myoung NS, Kwon JT, Jang SJ, Lee T, Lee YH. A theoretical analysis of temperature rise of hydrogen in high-pressure storage cylinder during fast filling process. *Adv Mech Eng* 2014;12. [\[CrossRef\]](#)
- [26] Gromov NV, Medvedeva TB, Lukoyanov IA, Panchenko VN, Prikhod'ko SA, Parmon VN, et al. Hydrolysis-oxidation of cellulose to formic acid in the presence of micellar vanadium-containing molybdophosphoric heteropoly acids. *Results Eng* 2023;17:100913. [\[CrossRef\]](#)
- [27] Oh SJ, Yoon JH, Jeon KS, Choi J. A numerical study on characteristics of heat transfer in hydrogen filling storage vessel by charging conditions. *Int J Hydrogen Energy* 2022;47:25679–25695. [\[CrossRef\]](#)
- [28] Molina S, Ruiz S, Gomez-Soriano J, Olcina-Girona M. Impact of hydrogen substitution for stable lean operation on spark ignition engines fueled by compressed natural gas. *Results Eng* 2022;17:100799. [\[CrossRef\]](#)
- [29] Özdoğan E, Hüner B, Süzen YO, Eşiyok T, Uzgören İN, Kısı M, et al. Effects of tank heating on hydrogen release from metal hydride system in VoltaFCEV Fuel Cell Electric Vehicle. *Int J Hydrogen Energy* 2022;48:6811–6823. [\[CrossRef\]](#)
- [30] Vlaskin MS, Grigorenko AV, Gromov AA, Kumar V, Dudoladov AO, Slavkina OV, et al. Methane pyrolysis on sponge iron powder for sustainable hydrogen production. *Results Eng* 2022;15:100598. [\[CrossRef\]](#)
- [31] Ahmadi P, Khoshnevisan A. Dynamic simulation and lifecycle assessment of hydrogen fuel cell electric vehicles considering various hydrogen production methods. *Int J Hydrogen Energy* 2022;47:26758–26769. [\[CrossRef\]](#)
- [32] Li JQ, Li JCL, Park K, Kwon JT. Investigation on the changes of pressure and temperature in high pressure filling of hydrogen storage tank. *Case Stud Therm Eng* 2022;37:102143. [\[CrossRef\]](#)
- [33] Wu X, Liu J, Shao J, Deng G. Fast filling strategy of type III on-board hydrogen tank based on time-delayed method. *Int J Hydrogen Energy* 2021. [\[CrossRef\]](#)
- [34] Melideo D, Baraldi D, Acosta-Iborra B, Cebolla RO, Moretto P. CFD simulations of filling and emptying of hydrogen tanks. *Int J Hydrogen Energy* 2016;42:7304–7313. [\[CrossRef\]](#)

- [35] Simonovski I, Baraldi D, Melideo D, Acosta-Iborra B. Thermal simulations of a hydrogen storage tank during fast filling. *Int J Hydrogen Energy* 2015;40:12560–12571. [\[CrossRef\]](#)
- [36] Melideo D, Baraldi D, Galassi MC, Cebolla RO, Iborra BA, Moretto P. CFD model performance benchmark of fast filling simulations of hydrogen tanks with pre-cooling. *Int J Hydrogen Energy* 2014;39:4389–4395. [\[CrossRef\]](#)
- [37] Melideo D, Baraldi D. CFD analysis of fast filling strategies for hydrogen tanks and their effects on key-parameters. *Int J Hydrogen Energy* 2014;40:735–745. [\[CrossRef\]](#)
- [38] Melideo D, Baraldi D, De Miguel Echevarria N, Iborra BA. Effects of some key-parameters on the thermal stratification in hydrogen tanks during the filling process. *Int J Hydrogen Energy* 2019;44:13569–13582. [\[CrossRef\]](#)
- [39] Wang L, Ye F, Xiao J, Bénard P, Chahine R. Heat transfer analysis for fast filling of on-board hydrogen tank. *Energy Procedia* 2019;158:1910–1916. [\[CrossRef\]](#)
- [40] Xiao J, Bénard P, Chahine R. Estimation of final hydrogen temperature from refueling parameters. *Int J Hydrogen Energy* 2016;42:7521–7528. [\[CrossRef\]](#)
- [41] Molkov V, Dadashzadeh M, Makarov D. Physical model of onboard hydrogen storage tank thermal behaviour during fuelling. *Int J Hydrogen Energy* 2019;44:4374–4384. [\[CrossRef\]](#)
- [42] Wang GX, Zhou JQ, Hu SJ, Li QF. The influences of L/D ratio and inlet diameter on the temperature rise and temperature distribution within a high pressurized hydrogen cylinder during refueling. *Eng Mech* 2014;31:225–232.
- [43] Zhang RY, Wang HZ, Zhao GJ. Design and simulation of a vehicle-mounted high-pressure hydrogen staged charging system. *Acta Energ Sol Sin* 2022;43:427–432.
- [44] Deymi-Dashtebayaz M, Farzaneh-Gord M, Nooralipoor N, et al. The complete modelling of the filling process of hydrogen onboard vehicle cylinders. *Braz J Chem Eng* 2016;33:391–399. [\[CrossRef\]](#)
- [45] Zhao Y, Liu G, Liu Y, et al. Numerical study on fast filling of 70 MPa type III cylinder for hydrogen vehicle. *Int J Hydrogen Energy* 2012;37:17517–17522. [\[CrossRef\]](#)
- [46] Li Q, Zhou J, Chang Q, Xing W. Effects of geometry and inconstant mass flow rate on temperatures within a pressurized hydrogen cylinder during refueling. *Int J Hydrogen Energy* 2012;37:6043–6052. [\[CrossRef\]](#)
- [47] Dicken C, Mérida W. Modeling the transient temperature distribution within a hydrogen cylinder during refueling. *Numer Heat Transf A Appl* 2007;53:685–708. [\[CrossRef\]](#)
- [48] Bourgeois T, Ammouri F, Weber M, Knapik C. Evaluating the temperature inside a tank during a filling with highly pressurized gas. *Int J Hydrogen Energy* 2015;40:11748–11755. [\[CrossRef\]](#)
- [49] Suryan A, Kim HD, Setoguchi T. Three dimensional numerical computations on the fast filling of a hydrogen tank under different conditions. *Int J Hydrogen Energy* 2012;37:7600–7611. [\[CrossRef\]](#)
- [50] Harle S, Wankhade RL. A review of green building research: Key findings, challenges, energy efficiency and proposed solutions. *Sigma J Eng Nat Sci* 2025;43:685–703. [\[CrossRef\]](#)
- [51] Sommer TP, So RMC, Zhang HS. Near-wall variable-Prandtl-number turbulence model for compressible flows. *AIAA J* 1993;31:27–35. [\[CrossRef\]](#)
- [52] Subran N, Ajit K, Krishnan H, Pachiyappan S, Ramaswamy P. Synthesis and performance of a cathode catalyst derived from areca nut husk in microbial fuel cell. *Chemosphere* 2023;312:137303. [\[CrossRef\]](#)
- [53] Zhao Y, Liu G, Liu Y, Zheng J, Chen Y, Zhao L, et al. Numerical study on fast filling of 70 MPa type III cylinder for hydrogen vehicle. *Int J Hydrogen Energy* 2012;37:17517–17522. [\[CrossRef\]](#)
- [54] Li M, Yang Q, Zhang C, Huang S, Zhang M, Zhang G, et al. Experimental and numerical study of the temperature evolution in hydrogen cylinder under fast-refueling process. *Int J Heat Mass Transf* 2023;211:124220. [\[CrossRef\]](#)
- [55] Sanaka SP, Ramanaiah K, Rao KD, Gunda NSP. Design and parametric evaluation of proton exchange membrane fuel cell for enhanced performance. *J Therm Eng* 2025;11:1705–1716. [\[CrossRef\]](#)
- [56] Li M, Yang Q, Zhang C, Huang S, Zhang M, Zhang G, et al. Experimental and numerical study of the temperature evolution in hydrogen cylinder under fast-refueling process. *Int J Heat Mass Transf* 2023;211:124220. [\[CrossRef\]](#)
- [57] Kim SC, Lee SH, Yoon KB. Thermal characteristics during hydrogen fueling process of type IV cylinder. *Int J Hydrogen Energy* 2010;35:6830–6835. [\[CrossRef\]](#)