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Gaseous Fuel Control Valve – Issues And Solutions

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Abstract: The fuel delivery system includes a fuel tank, different valves, and an injector to send fuel to the engine or fuel cell, helping the vehicle move. This project focuses on the problems and solutions related to fuel control valves used with dry gases like hydrogen and compressed natural gas (CNG). These gases have special challenges that can affect how well the vehicle runs and how long the parts last. Common issues include hydrogen embrittlement, corrosion, leaks, and wear. To fix these problems, different coating and plating methods are used. The goal of this project is to study these issues in detail and find ways to make the valves more durable and long lasting.

Index terms **- Hydrogen, Natural gas, Hydrogen embrittlement, HTHA, corrosion, coating, plating, deposition process.**

I. INTRODUCTION

Gaseous fuel control valves are important parts that help control the flow of gas, like hydrogen or natural gas, to engines or fuel cells. They make sure the right amount of gas is delivered at the right time, helping the system run safely and efficiently. These systems rely on precise and safe transfer of fuel either hydrogen or natural gas from high-pressure storage tanks to the power generating units such as fuel cell stacks or internal combustion engines. The valves and associated components regulate pressure, control flow rates, prevent backflow, and ensure efficient fuel utilization. In hydrogen fuel cell systems, control valves like the supply shut-off valve (SSV), proportional control valve (PCV), pressure relief valve (PRV), purge valve, and water separator work together within subsystems—hydrogen supply, air supply, fuel cell stack, and cooling—to manage fuel flow and support the electrochemical reactions that generate electricity with water and heat as by products. Similarly, in natural gas systems, components such as pressure regulators, on/off valves, rotameters, needle valves, and check valves ensure safe fuel flow from compressed gas tanks to the engine, maintaining stable pressure and preventing leakages or reverse flow. This project focuses on improving the performance and reliability of gaseous fuel control valves by addressing key challenges such as hydrogen embrittlement, high-temperature hydrogen attack, corrosion, wear, and leakage. Proposed solutions include advanced coating and plating techniques, and the selection of suitable materials for valve components and seals to enhance efficiency, safety, and durability of power generation systems. Gaseous fuel control valves play a critical role in the fuel delivery systems of hydrogen fuel cells and natural gas powered engines. These systems rely on precise and safe transfer of fuel—either hydrogen or natural gas from high pressure storage tanks to the power-generating units such as In hydrogen fuel cell systems, control valves like the supply shut-off valve (SSV), proportional control valve (PCV), pressure relief valve (PRV), purge valve, and water separator work together within subsystems—hydrogen supply, air supply, fuel cell stack, and cooling to manage fuel flow and support the electrochemical reactions that generate electricity with water and heat as by-products. Similarly, in natural gas systems, components such as pressure regulators, on/off valves, rotameters, needle valves, and check valves ensure safe fuel flow from compressed gas tanks to the engine, maintaining stable pressure and preventing leakages or reverse flow. This project aims to make gas fuel control valves work better and last longer, especially in tough conditions. These valves often face problems like damage from hydrogen, high heat, rust, wear, and leaks. To fix this, the project suggests using special coatings and choosing stronger, more suitable materials for the valve parts and seals. This will help improve the safety, efficiency, and reliability of power generation systems.

II. PROBLEM STATEMENT

Using Hydrogen as a fuel poses different challenges as compared to generic fuel used in automobile industry. Widely known issue is hydrogen storage and transfer. Apart from this, there are multiple issues concerning the gas delivery components which affect performance and durability of stack in the fuel cell engine.

III. OBJECTIVES

To identify issues and solutions related to performance and durability of gas delivery components.

Technical Objectives:

- Optimize Fuel Flow Control: Design or improve control valves (SSV, PCV, PRV, etc.) for precise regulation of hydrogen and natural gas flow based on engine or fuel cell requirements.
- Enhance Safety Features: Ensure safe operation by incorporating reliable shut-off and pressure relief mechanisms to prevent overpressure, leaks, or backflow.
- Mitigate Hydrogen-Related Failures: Address hydrogen embrittlement and high-temperature hydrogen attack in metallic valve components through material selection and surface treatment.
- Improve Component Durability: Minimize wear and corrosion of valves and regulators through advanced coatings, plating techniques, and suitable sealing materials.
- Maintain System Efficiency: Reduce fuel losses and maintain consistent fuel pressure and flow to enhance the overall efficiency of the fuel cell stack or natural gas engine.

Environmental Objectives:

- Minimize Harmful Emissions: Design the fuel delivery system to support low-emission technologies like hydrogen fuel cells and natural gas engines, contributing to reduced CO_2, NO_x, and particulate emissions.
- Promote Clean Energy Adoption: Facilitate the use of cleaner fuels (hydrogen and natural gas) as alternatives to conventional gasoline and diesel, supporting a transition to greener transportation systems.
- Prevent Fuel Leakage and Waste: Develop valves and sealing systems that prevent fuel leakage, reducing environmental hazards and conserving resources.
- Improve Fuel Utilization Efficiency: Enhance hydrogen and natural gas utilization through recirculation systems and precise control mechanisms to reduce unburnt fuel and associated emissions.
- Support Water Reuse and Management: Integrate systems such as water separators and humidifiers that efficiently manage and reuse water produced or used in fuel cell reactions, minimizing environmental impact.
- Reduce Heat Waste: Incorporate efficient cooling systems that minimize unnecessary heat dissipation into the environment, improving overall thermal efficiency.
- Enable Sustainable Material Use: Use eco-friendly and recyclable materials for valve components and system construction to lower the environmental footprint.
- Extend System Lifespan: Improve durability and reliability of fuel delivery components to reduce frequent replacements and associated waste generation.
- Support Renewable Hydrogen Integration: Ensure compatibility with hydrogen sourced from renewable energy (green hydrogen) to further reduce lifecycle emissions.
- Comply with Environmental Regulations: Design the system in accordance with global environmental standards and policies related to clean fuel technologies and emissions.

Economic Objectives:

- Fuel Cost Reduction
  - Gases

IV. SCOPE

This research project focuses on the design, analysis, and optimization of gaseous fuel delivery systems for hydrogen and natural gas, aimed at enhancing the efficiency and sustainability of internal combustion engines. Both fuels are better for the environment because they produce fewer greenhouse gases and burn more cleanly than regular fuels made from petroleum. The scope includes studying the behaviour of these fuels under various operating conditions, evaluating system components such as regulators, injectors, storage tanks, and pipelines. A key objective is to ensure precise fuel-air mixture control for optimal combustion and minimal energy loss. However, several technical challenges must be addressed. Hydrogen poses issues such as high leakage potential due to its small molecular size, and material degradation caused by hydrogen embrittlement. Natural gas systems face problems related to pressure drops, inconsistent combustion, and cold start difficulties. Storage constraints and high-pressure handling are also critical concerns for both fuels. Proposed solutions include using advanced sealing technologies, hydrogen-compatible alloys, and composite storage cylinders. Additionally, implementing ECU based fuel injection, fuel pre-heating systems, and leak detection sensors enhances system reliability and safety. By addressing these issues, the project aims to develop an efficient, durable, and safe delivery system tailored for hydrogen and natural gas. The outcomes support the broader goal of cleaner, low-carbon energy adoption in transportation and industrial sectors.

V. METHODOLOGY

Problem Formation:

The gaseous fuel control valve plays a crucial role in regulating fuel flow and ensuring safety in hydrogen and natural gas systems. However, current designs face issues such as leakage, hydrogen embrittlement, HTHA and material incompatibility under high-pressure conditions. This research aims to identify these challenges and develop optimized valve solutions for improved performance and reliability.

V.I Issues identified:

V.I.I Hydrogen Embrittlement:

Hydrogen embrittlement occurs when metals absorb hydrogen, causing cracking and brittle failure. It is influenced by factors such as exposure time, pressure, and temperature. The hydrogen diffuses into metal lattices, accumulating at grain boundaries or vacancies, and creates trapped hydrogen, which initiates cracks. The interaction of hydrogen with the crystal lattice not only leads to crack propagation but also alters the material's composition, causing hydrogen attack, which further weakens the material.

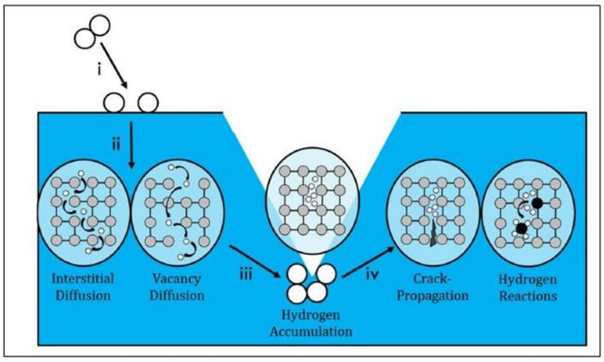

Fig. Hydrogen interaction with metal lattices [1]

V.I.II High-Temperature Hydrogen Attack (HTHA):

HTHA is a degradation process occurring at temperatures above 200°C, where hydrogen interacts with carbon steel. The hydrogen atoms react with carbon at the steel's surface to form methane, leading to a loss of carbon. This causes voids and fissures within the steel, weakening its structure and mechanical properties. Over time, these gas pockets increase the vulnerability of the material to catastrophic failure.

V.I.III Material Compatibility Issues:

Different metals react differently to hydrogen, causing various forms of degradation in valves used in hydrogen systems (e.g., fuel cells, hydrogen storage). Metals like ferrite and martensitic stainless steels, cast iron, nickel alloys, titanium, and aluminum are susceptible to hydrogen embrittlement and other failures. These materials can lose strength, toughness, and ductility upon hydrogen exposure, leading to potential valve failure.

V.I.IV Leakage:

Leaks are a common problem in hydrogen fuel cell valves because hydrogen molecules are very small and the system uses high pressure. Since hydrogen moves quickly, it can escape more easily through tiny gaps. Internal leaks degrade system components and reduce their lifespan, while external leaks can be hazardous, as hydrogen may ignite in the environment. Valve leaks are often caused by worn seals, improper installation, corrosion, and material wear.

V.I.V Dry Lubrication/Poor Lubrication:

Poor lubrication in hydrogen and natural gas valves leads to increased friction, wear, and component degradation. Hydrogen's carbon-free nature increases friction between valve components, which can result in wear and improper mating of parts. Similarly, the dryness of natural gas also affects lubrication, causing oxidation and nitration of lubricants, which leads to deposits and increased wear on valve components.

V.I.VI Corrosion:

Corrosion can occur in valves due to hydrogen absorption or contamination in natural gas. In hydrogen fuel cell valves, the electrochemical reaction between hydrogen and metal causes pressure build-up, eventually cracking the material. In natural gas systems, contaminants like H_2S and CO_2, or the presence of moisture, accelerate corrosion, leading to material degradation, leakage, and reduced valve lifespan.

V.I.VII Valve Seat Recession:

Valve seat recession is a problem in compressed natural gas (CNG) engines, primarily caused by a lack of lubricity. The combustion of natural gas generates abrasive particles, which grind against the valve seat, causing material wear. Over time, friction from this process leads to the recession of the valve seat. Additional factors include high engine load, speed, thermal stress, and chemical reactions from combustion by-products.

V.I.VIII Wear and tear:

Wear and tear in gaseous valves result from normal mechanical action and environmental factors like high operating pressure, temperature fluctuations, and contaminants in the gas stream. The continuous contact between moving parts leads to surface degradation, thinning of valve walls, and potential failure. Repeated heating and cooling cycles cause thermal fatigue, contributing to cracking and further damage over time. This summary highlights the primary issues faced by gaseous valves in hydrogen and natural gas applications. Each of these factors requires careful material selection and design considerations to ensure optimal performance and longevity.

V.II Solutions defined:

V.II.I Material Selection for Hydrogen and Natural Gas Environments:

- **Austenitic Stainless Steels (304, 316):** Known for resistance to hydrogen embrittlement, corrosion, and maintaining mechanical properties over wide temperatures. Ideal for components like pipelines and storage tanks.
- **Copper Alloys (Brass, Bronze):** Excellent thermal and electrical conductivity, corrosion resistance, and low hydrogen permeability, making them suitable for electrical connectors and hydrogen storage systems.

V.II.II Sealing Materials:

- **Hydrogen Nitrile Butadiene Rubber (HNBR):** Excellent resistance to heat, oil, and chemicals, with high tensile strength and durability in dynamic sealing applications.
- **Nitrile Rubber (NBR):** Effective for sealing in natural gas and hydrogen environments due to oil and fuel resistance.
- **Perfluoroelastomers (FFKM) and Fluoroelastomers (FKM):** Exceptional chemical resistance, high temperature tolerance, and low permeability to gases like hydrogen.
- **Polytetrafluoroethylene (PTFE):** Excellent chemical resistance, high tensile strength, and low permeability, beneficial for hydrogen applications.

Table1. Elastomers compatible for sealing in gaseous valves

Elastomers	Temperature range (°C)	Durability	Tensile strength	Application area	Limitations to application	Durometer range(shore)	Density
Nitrile	(-40) to 121.11°C	can withstand relatively high temperatures and pressures.	3.5MPa-21MPa	high wear, oil, petrolium	ozone, tear, ketons & ester	30-95 shore A	1.22g/cm3
silicone	(-60) to 230°C	at 200°C withstand for 10000hrs or more	7.9MPa	ozone, oxidation, UV light, corona discharge, cosmic radiation, ionizing radiation and weathering in general	poor tear strenght	55-65 Shore A	0.95 to over 1.20 g/cm3
EPDM	(-40) to 150°C	30 years	7MPa-9MPa	durable, flexible, and resistant to UV exposure, ozone, aging, weathering, acids, and many other chemicals, water-resistant rubber materials	poor flame resistance, poor resistance to mineral oil/petroleum oil.	60-70 Shore A	1.22-1.30 g/cm3
fluoroelastomer	(-40) to 230°C	20 years	3.4-6.89MPa	Flame Resistance, Gas Permeability, Ozone Resistance, Oxidation Resistance, Radiation Resistance, Steam Resistance Sunlight Resistance, Weather Resistance, Water Resistance	Susceptibility to tear under high pressure	50-95 Shore A	1.85 g/cm3
Neoprene	(-20) to 110°C	3-5 years	5MPa	resistance to weathering, UV light, water, chemicals, and ozone.	non degradible, non-composible	55-65 Shore A	1.23 g/cm3
fluorosilicone	(-50) to 260°C	15 years	1.32-10.34MPa	Flame Resistance, Gas Permeability, Ozone Resistance, Oxidation Resistance, Radiation Resistance, Steam Resistance Sunlight Resistance, Weather Resistance, Water Resistance	dynamic sealing applications	35 – 80 Shore A	1.30 to 1.70 kg / cm3

V.II.III Coating and Plating Processes:

- **Coating:**
  Applied as a barrier between the base metal and fuel, providing corrosion and wear resistance. Steps include surface preparation, pre-treatment, coating application, and curing.

- **Plating:**
  Involves surface preparation, activation, plating, and post-treatment for improved adhesion and durability. Electroless nickel plating provides a uniform metal layer without external power sources.

- **Nedox Coating:**
  A combination of nickel-phosphorus alloy and polymer, providing wear resistance, low friction, and superior corrosion protection in harsh environments.

Sr No.	Name of Coating	Operating temperature	Thickness of coating	Coating hardness	Benefits
1	Nedox-10K3-Coating	-157 to 454°C	0.3-2µm	48-68Rc	Offers corrosion resistance up to 454°C
2	Nedox-CR+-Coating	157 to 204°C	0.3-2µm	62-68Rc	Max. wear resistance
3	Nedox-FM5-Coating	73 to 149°C	0.7-1.5µm	62-68Rc	combination of proprietary polymers & dry-lubricants, COF is less after burnishing
4	Nedox-MR3-Coating	-157 to 204°C	0.5-1.5µm	60-115Rc	Excellent mold release for plastic, Black color
5	Nedox-NH1-Coating	-157 to 260°C	0.3-1.5µm	42-50Rc	Excellent wear and corrosion resistance
6	Nedox-SF2-Coating	157 to 204°C	0.3-1.2µm	62-65Rc	Hardness as well as lubricity
7	Nedox-SLK-Coating	-157 to 260°C	0.3-1.5µm	60-65Rc	Wear resistance, hardness and lubricity

Table2. Various Nedox coating types

- **Physical Vapor Deposition (PVD):**
  PVD is a coating method that takes place in a vacuum. It works by turning a solid material into vapor, moving that vapor through the vacuum, and then turning it back into a thin, protective layer on a part. This coating is very strong, sticks well, and helps protect parts from wear, making it great for high precision components.

- **Chemical Vapor Deposition (CVD):**
  CVD is a coating process where gases react on the surface of a part to create a thin, solid layer. This method produces high-quality, even coatings, even on parts with complex shapes. It includes steps like moving the gas to the surface, making it react, and growing the coating. CVD is often used in industries like electronics, aerospace, and energy because it gives strong, smooth, and reliable coatings.

- **Baking Process:**
  To stop metal from becoming weak and cracking due to trapped hydrogen during manufacturing, a special process is used. The part is first cleaned, then heated to about 190°C for several hours. This helps the hydrogen escape. After that, the part is slowly cooled down in a controlled way.

This summary explains the important materials and methods used to make parts stronger and last longer in systems that use hydrogen or natural gas.

VI. CONCLUSION

The fuel delivery system is very important for running a vehicle. If there are problems with it, the vehicle may not perform well. That's why it's important to fix common issues with gas fuel valves like hydrogen embrittlement (HE), high temperature damage (HTHA), rust (corrosion), wear and tear, leaks, and poor lubrication. Solving these problems helps keep the system safe, reliable, and efficient. By selecting appropriate materials for sealing and the component, applying protective coatings like EN plating then Nedox coating, PVD and CVD processes, implementing regular maintenance, we can significantly mitigate wear, corrosion, HE, HTHA. These solutions not only enhance the performance and longevity of the valves but also contribute to the overall operational efficiency and safety of the fuel systems.

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