Prospects of Using Hydrogen–Methane Blends

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The use of methane–hydrogen mixtures in internal combustion engines improves their performance and emission characteristics. The most important aspect is the concentration of hydrogen in the fuel mixture, which affects the combustion process of the fuel and determines the optimal operating conditions of the engine. When using methane–hydrogen mixtures with low hydrogen content, the safety measures and risks are similar to those that exist when working with natural gas. Serious logistical problems are associated with the difficulties of using the existing gas distribution infrastructure for transporting methane–hydrogen mixtures.

hydrogen methane low-carbon fuel

1. Introduction

Increasing the fuel efficiency and reducing pollutant emissions, including carbon dioxide emissions, have become the leading trends in modern energy. The impossibility of a global solution for the problem of reducing the carbon footprint of the energy sector through the transition of industrial energy to renewable energy sources is already obvious [1]. An analysis of various methods for separating CO_2 from flue gases [2], in which its content is less than 10%, and their subsequent utilization [3] or disposal demonstrated the need for additional energy costs. These costs are commensurate with the initially generated energy [4], that is, a minimum doubling of the consumed resources and the cost of energy for the consumer is required. Therefore, an approach to solving the problem of CO_2 emissions by the global energy industry based on the replacement of hydrocarbon energy carriers with hydrogen is gaining popularity. Such a transition is actually proclaimed the goal of the Paris Agreement [5].

The trend towards low-carbon energy has contributed to the popularization of the concept of “hydrogen energy” and has intensified research on the use of hydrogen as a fuel [6]. In the long term, after adopting the energy of thermonuclear fusion, hydrogen, the oxidation of which produces only water, can become a universal environmentally friendly energy carrier.

The main difference between hydrogen as a fuel and traditional hydrocarbon fuels is the significantly higher burning rate, which under standard conditions is at least six times higher than for methane and approximately eight times for temperatures and pressures typical of internal combustion engine (ICE) operating conditions. Hydrogen has much wider concentration limits of flame propagation compared to hydrocarbons. Therefore, along with the use of hydrogen directly as a fuel, its use as an additive to traditional fuels, primarily to compressed natural gas (CNG), is widely discussed.

Addition of hydrogen to methane increases the velocity of flame propagation, reducing the duration of fuel combustion. This leads to a sharper increase in pressure in the ICE, high rates of heat release and a shorter time interval between fuel ignition and the peak of heat release compared to methane. At the same time, the presence of methane in the methane–hydrogen mixture reduces the risks of abnormal combustion, such as flashback and detonation in the engine, which are characteristic of hydrogen combustion [7]. The use of mixed fuels based on hydrogen and natural gas can significantly increase the thermal efficiency of combustion and reduce greenhouse gas emissions in the ICE [8][9].

2. Energy Characteristics of Hydrogen and Methane–Hydrogen Mixtures

The main parameters characterizing the combustion of fuels include the normal combustion rate Un, the concentration limits of flame propagation, and the ignition delay. The normal combustion rate of the laminar flame determines the stability of the combustion process, and the conditions under which blow off is possible, or vice versa, its reverse flashback towards the flow. The difference in the combustion rate of methane and hydrogen is associated with a difference in the concentration and kinetics of the formation of H, O, and OH radicals, which determine the course of the process [10].

3. The Practice of Using Hydrogen in Power Plants and Transport

Hydrogen, as well as methane–hydrogen mixtures (MHM), can be used directly as a fuel for power plants, providing high efficiency and good environmental performance. It is believed that mixtures of compressed natural gas with hydrogen will allow, with a minimum increase in capital investments and a minimum of additional equipment, to eliminate a number of disadvantages inherent in traditional gasoline and diesel engines [11]. The main difference between gaseous fuels and liquid fuels is that the former mix better with air, resulting in more complete combustion of the mixtures with significantly less carbon deposits and emissions of toxic products of incomplete combustion. According to available data, the use of methane–hydrogen fuel contributes to the reduction of toxic emissions, greenhouse gas emissions (by 8–15%) and reduced fuel consumption.

In the early 1980s, the use of a mixture of hydrogen with natural gas at ratios of 100:0, 80:20, 50:50 and 0:100 as a fuel for automobile engines was tested by the AVL company [12]. Subsequently, in order to improve the combustion characteristics and reduce the toxicity of engine exhaust gases, fuel mixtures of hydrogen and natural gas of various compositions were studied. In many countries, methane–hydrogen mixtures are successfully used in vehicles with an internal combustion engine. Tests of the possibility of using MHM with a hydrogen content of up to 20% were also carried out in housing and communal services, including such domestic appliances as cooking burners [13][14][15].

4. Emission and Performance Characteristics of Methane–Hydrogen Mixtures

It is noted that at present the most effective way to use hydrogen additives in internal combustion engines are dual-fuel systems. Low-temperature combustion in such engines makes it possible to use all types of modern fuels, and their thermal efficiency exceeds that of classic engines, which makes it possible to further reduce CO_2 emissions. Further research should be aimed at reducing the emission of other greenhouse gases such as N_2O and CH_4.

The total emission of CO_2 in the entire technology for the production and use of MHM will depend on the method of hydrogen production. For example, if steam reforming of methane, which currently produces more than 70% of the world's hydrogen, is not combined with carbon capture and storage technologies, then the total CO_2 emissions will still be very high.

Because hydrogen enrichment promotes faster and more complete combustion of methane, it reduces exhaust emissions of methane and incomplete combustion products. Internal combustion engines running on HCNG, unlike fuel cells with a hydrogen proton exchange membrane, do not pollute the air with carbon monoxide [16].

5. Transportation Logistics of Hydrogen and Methane–Hydrogen Mixtures

The development of hydrogen energy and the hydrogen market is constrained by the lack of economically viable technical solutions for a full-cycle hydrogen economy, including for transporting large volumes of hydrogen over long distances. A serious logistical problem is the lack of an appropriate infrastructure for the storage, transportation and distribution of industrially significant volumes of hydrogen [17], for the creation of which there are still no practically acceptable solutions. Most of the metals from which existing gas pipelines are made are subject to destruction under the influence of hydrogen diffusion in them, especially at high pressures. This imposes much more stringent requirements on the manufacture of pipelines for transporting hydrogen compared to pipelines for transporting natural gas [18] and dramatically increases their cost. Therefore, already existing gas pipelines cannot be used to transport hydrogen, and the cost of special pipelines will be many times higher than the existing ones.

The influence of the composition of methane–hydrogen mixtures on the materials of pipelines of the existing natural gas infrastructure was experimentally studied. The results obtained were compared with the literature data [19]. At a pressure of 2 bar in an environment of 100% hydrogen, a mixture of 20% hydrogen with methane and 100% methane, materials such as polyethylene, steel, cast iron, copper and brass worked. At the same time, there was no negative effect of a mixture of 20% hydrogen with methane on the characteristics of metal and polymer (PE80 pipe polyethylene) materials, as well as on the places of connecting of pipelines. It was concluded that all tested materials of the existing gas transmission pipeline infrastructure are suitable for transporting mixtures of natural gas and hydrogen in the range of hydrogen concentrations up to 20% and pressures up to 2 bars.

The possibility of transporting hydrogen in liquefied form is also being considered. However, the low temperature of liquid hydrogen, only 20.3 K, requires a large amount of energy to liquefy it and presents the problem of its long-term storage. However, the storage and transportation of hydrogen in a chemically bound form (hydrides, solid and liquid carriers, etc.) does not yet provide the hydrogen capacity necessary for economically justified use [20].

6. Safety Problems of Using of Hydrogen and Methane–Hydrogen Mixtures

The possibility of practical use of methane–hydrogen mixtures is already being successfully implemented in public transport. However, there are still little literature data on the risk analysis and safety of the use of such fuels. The authors of [21] came to the conclusion that the use of Hythane mixtures is safer not only using hydrogen, but also methane. This is due to the fact that methane–hydrogen mixtures combine the positive qualities of hydrogen (high diffusion coefficient) and methane (lower flame propagation velocity and narrower ignition limits). Modeling has shown that the explosive property of the Hythane is not much higher than that of methane, and that for both of these fuels the explosion pressure is significantly lower than that of hydrogen.

Since feasibility studies show that the use of pipelines for pumping large volumes of hydrogen over long distances is currently the most profitable, the requirements for their design and conditions for safe operation were carefully analyzed [17]. Among the key provisions related to the use of methane–hydrogen mixtures analyzed in the NREL report [18] were the safety issues of their use. One of the most important issues is the maximum allowable concentration of hydrogen in methane–hydrogen mixtures, which is explained by the special physicochemical properties of hydrogen, primarily its high flammability. It is known that, in general, the risks associated with dealing with natural gas, accompanied by severe consequences, are less significant compared to other large energy systems. Small, up to 20%, hydrogen additions to natural gas pipelines lead to a slight increase in the risk of ignition. The introduction of more than 50% hydrogen already leads to a significant increase in all risks, including the probability and consequences of their occurrence. Great attention is also paid to the strength of the pipeline material, especially in the case of high hydrogen concentrations in high pressure systems. Greater risks are also associated with the possibility of gas leakage from pipelines. Therefore, when using methane–hydrogen mixtures, additional leak detection devices are required; this increases the cost of equipment and its maintenance. In general, the modification of the safety of natural gas distribution systems when transitioning to methane–hydrogen mixtures leads to an increase in costs by about 10%.

7. Conclusions

An analysis of the literature data indicates a wide front of research and development in the field of the use of methane–hydrogen mixtures as a promising environmentally friendly low-carbon fuel. The influence of the composition of such mixtures on the performance characteristics of various types of engines, the level of emission of CO_2, CO, nitrogen oxides and unburnt hydrocarbons, the safety of operation and their durability is studied. The general conclusion of most of these studies is that the use of methane–hydrogen mixtures in internal combustion engines improves the performance of engines operating with a separate supply of natural gas and hydrogen. The most important is the concentration of hydrogen in the fuel mixture, which affects the main characteristics of fuel combustion and determines the optimal operating conditions for engines. The analysis shows that the safety measures and risks when working with methane–hydrogen mixtures with a small content of hydrogen are similar to those that exist when working with natural gas.

Serious logistical problems are associated with the difficulties of using the existing gas distribution infrastructure for transporting methane–hydrogen mixtures. Further research is needed on the compatibility of pipeline materials with hydrogen and methane–hydrogen mixtures and safety conditions for the operation of equipment with hydrogen or methane–hydrogen mixtures. It is possible that, despite the need for huge investments, it will be necessary to create a new infrastructure for the production, storage and transportation of hydrogen and its mixtures with natural gas.

Serious studies are also needed on the economic and environmental feasibility of transition to such energy carriers as hydrogen and methane–hydrogen mixtures in the near future.

Thus, it is believed that the most promising areas for the development of hydrogen energy in the near future will be the increasingly widespread use of methane–hydrogen mixtures with a hydrogen concentration of up to 20% for energy production and in the domestic sector, as well as the wide appearance of low-tonnage hydrogen production plants for use in urban transport.

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