Investigation on the Combustion of Hydrocarbon Fuel Enriched by Hydrogen for a Cleaner Environment

Nader Nabhani, Vahid Sharifi

Abstract—Hydrogen, as a carbon-free energy carrier, is likely to play a more important role in a world with severe constraints on greenhouse gas emissions. This paper investigates possibilities of burning hydrogen in a large size, heavy-duty boiler designed to run on natural gas and possibility of using product combustion as a gas inlet steam turbine for electric generation, for greenhouse gas emission reduction regardless of the process used to produce hydrogen. Fuel cells and H₂-O₂ boiler fuels may represent future options for power generation under several possible scenarios, depending on the mode of H₂ production. The paper discusses these issues by considering some possible adaptation techniques, by discussing their operational Limits. Results showed that hydrogen addition sustains a progressive improvement in flame stability and reduction in flame length, especially for relatively high hydrogen concentrations. Hydrogen-enriched flames found to have a higher combustion temperatures and reactivity than natural gas flame. Also, it was found that hydrogen addition to natural gas is an ineffective strategy for NO and CO reduction in the studied range, while a significant reduction in the %CO₂ (in present of specific hydrogen percent).

Keywords—Enriched fuel, Hydrogen, Environment.

I. INTRODUCTION

In today’s world, the problem of climatic change is one of the serious drawbacks driving mainly from the emission of large quantities of CO₂, the inevitable product of fossil fuel combustion [1]. This is not the only environmental hazard from fossil fuels, but its emission of noxious gases such as NOx, CO and SO₂, results in critical environmental problems throughout the world [2]. In addition, the declining of fossil fuels supplies at an alarming rate exhibits the desire to use it economically [3]. In view of these problems, it will unquestionably require long-term changes in the fuels and technologies that we use to meet our energy needs. Hydrocarbon-hydrogen hybrid fuel has become as an attractive option for reducing the dependency on the fossil fuels, and provides a transition strategy to carbon free energy systems. The choice of hydrogen as an essential participant in hybrid fuels is due to: firstly, its superior combustion characteristics such as wide flammability range, high laminar flame speed, and low ignition energy, in addition to its high molecular diffusivity [4,5]. Secondly, the environmental benefits of its combustion, as there is no CO₂, CO, SOx and UHC emissions. Furthermore, hydrogen can be produced from a variety of feed stocks; from fossil resources and renewable resources [6]. In that manner, the utilization of hydrogen in blended form would reduce the problems of storage and flashback [4]. NG–H₂ hybrid fuel, in particular, became the NG-1 subject of extensive research in recent years. A series of experimental and numerical investigations has been done to present a clearer understanding for its combustion characteristics. Addition of hydrogen to natural gas combustion showed an increase in flame adiabatic temperature, a reduction in flame thickness and quenching distance and further enhances the auto-ignition characteristics and the global rate of heat release [7–8]. Compared to fossil fuels, using hydrogen as an energy is advantageous in terms of volumetric and gravimetric energy storage density and ignition energy. Also, in case of hydrogen-fueled vehicles, care must be taken to ensure that the Well-to-wheel greenhouse gas emission reduction compared to hydrocarbon fuel turns out to be positive [9]. Nevertheless, the advantages offered by hydrogen are significant enough to warrant the exploration of its possibilities [10].

II. MOTIVATIONS TO USE HYDROGEN FUEL AND ENRICHED FUEL BY HYDROGEN BURNERS AND APPLICATIONS

Hydrogen fuel and enriched fuel by it combustion releases more net heat value in comparison to the natural gas (at same mass) that it effect to the cost of fuel. The benefits achieved with hydrogen-fuel and enriched fuel by hydrogen burners must be greater than the cost such as by adding hydrogen to natural gas pollutant like CO₂ and when percentage of hydrogen greater than 30% volume co emission decrease,[11] for using hydrogen-fuel and enriched fuel by hydrogen burners in an industrial heating. Some of the benefits are applicable in all cases such as boiler fuel, gas turbine fuel and everything that consume fuel. The following points briefly review some of the major motivators.

III. POTENTIAL BENEFITS

Every fuel can liberate a fixed amount of energy when it reacts completely with oxygen to form water. This energy content is measured experimentally and is quantified by a

**TABLE 1**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Higher heating value At 25°C &amp; 1 atm</th>
<th>Lower heating value At 25°C &amp; 1 atm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>141.86 kg/l</td>
<td>119.93 kg/g</td>
</tr>
<tr>
<td>Methane</td>
<td>55.53 kg/l</td>
<td>50.02 kg/g</td>
</tr>
<tr>
<td>Propane</td>
<td>50.36 kg/l</td>
<td>46.6 kg/g</td>
</tr>
<tr>
<td>Gasoline</td>
<td>47.5 kg/l</td>
<td>44.5 kg/g</td>
</tr>
<tr>
<td>Diesel</td>
<td>44.8 kg/l</td>
<td>42.5 kg/g</td>
</tr>
<tr>
<td>Methanol</td>
<td>19.96 kg/l</td>
<td>18.05 kg/g</td>
</tr>
</tbody>
</table>

fuel’s higher heating value (HHV) and lower heating value (LHV). The difference between the hhv and the lhv is the “heat of vaporization” and represents the amount of energy required to vaporize a liquid fuel into a gaseous fuel, as well as the energy used to convert water to steam. The higher and lower heating values of comparative fuels are indicated in table 1. Although the terms hhv and lhv do not apply to batteries, the energy density of a lead acid battery is approximately 46 bzu/lb (0.108 kg/l). Gaseous fuels are already vaporized so no energy is required to convert them to a gas. The water that results from both a combustive reaction and the electrochemical reaction within a fuel cell occurs as steam; therefore the lower heating value represents the amount of energy available to do external work. Both the higher and lower heating values denote the amount of energy (in bzu’s or joules) for a given weight of fuel (in pounds or kilograms)[12].

### IV. FLAME CHARACTERISTICS

Hydrogen flames are very pale blue and are almost invisible in daylight due to the absence of soot. Visibility is enhanced by the presence of moisture or impurities (such as sulfur) in the air. Hydrogen flames are readily visible in the dark or subdued light. A hydrogen fire can be indirectly visible by way of emanating “heat ripples” and thermal radiation, particularly from large fires. In many instances, flames from a hydrogen fire may ignite surrounding materials that do produce smoke and soot during combustion. Hydrogen fires can only exist in the region of a leak where pure hydrogen mixes with air at sufficient concentrations. For turbulent leaks, air reaches the centerline of the leakage jet within about five diameters of a leakage hole, and the hydrogen is diluted to nearly the composition of air within roughly 500 to 1000 diameters. This rapid dilution implies that if the turbulent leak were into open air, the flammability zone would exist relatively close to the leak. Therefore, when the jet is ignited, the flame length is less than 500 diameters from the hole (for example, for a 0.039 in/1 mm diameter leak, the flame length will be less than 19.7 in/0.5 m) [10].

#### A. Flammability

Three things are needed for a fire or explosion to occur: a fuel, oxygen (mixed with the fuel in appropriate quantities) and a source of ignition. Hydrogen, as a flammable fuel, mixes with oxygen whenever air is allowed to enter a hydro-gen vessel, or when hydrogen leaks from any vessel into the air. Ignition sources take the form of sparks, flames, or high heat[12].

#### B. Flammability range

The flammability range of a gas is defined in terms of its lower flammability limit (LFL) and its upper flammability limit (ULF). The LFL of a gas is the lowest gas concentration that will support a self-propagating flame when mixed with air and ignited. Below the LFL, there is not enough fuel present to support combustion; the fuel/air mixture is too lean. The ULF of a gas is the highest gas concentration that will support a self-propagating flame when mixed with air and ignited. Above the ULF, there is not enough oxygen present to support combustion; the fuel/air mixture is too rich. Between the two limits is the flammable range in which the gas and air are in the right proportions to burn when ignited. One consequence of the ULF is that stored hydrogen (whether gaseous or liquid) is not flammable while stored due to the absence of oxygen in the cylinders. The fuel only becomes flammable in the peripheral areas of a leak where the fuel mixes with the air in sufficient proportions. Two related concepts are the lower explosive limit (LEL) and the upper explosive limit (UEL). These terms are often used interchangeably with LFL and ULF, although they are not the same. The LEL is the lowest gas concentration that will support an explosion when mixed with air, contained and ignited. Similarly, the UEL is the highest gas concentration that will support an explosion when mixed with air, contained and ignited. An explosion is different from a fire in that for an explosion; the combustion must be contained, allowing the pressure and temperature to rise to levels sufficient to violently destroy the containment. For this reason, it is far more dangerous to release hydrogen into an enclosed area (such as a building) than to release it directly outdoors. Hydrogen is flammable over a very wide range of concentrations in air (4 – 75%) and it is explosive over a wide range of concentrations (15 – 59%) at standard atmospheric temperature. The flammability limits increase with temperature.

#### C. Flame stability

The combustion characteristics of NG- H. hybrid fuel with different compositions in a free jet turbulent diffusion flame with a slow co-flowing air stream were investigated. By the addition of hydrogen to the fuel stream, in the range of 0–50% by volume, the following can be concluded: an increase in the flame stability appeared as a significant enhancement in the flame liftoff and blowout limits, which can be attributed to the high burning velocity of hydrogen fuel [11].

#### D. Effect of H₂ addition on distribution temperature

Comparison the temperature distributions in the burner fed with mixtures containing mass fractions of H₂ up to 20% obtained with the EDC combustion model and the GRI-3.0 kinetic mechanism. The addition of H₂ determines the increase of the temperature levels in the burner as well as the reduction of the lift-off length and the shift of the reaction zone towards the burner exit[19].

The temperature increase is not only due to the higher specific energy content of the H₂ blended fuel with respect to methane, but also to the reduced radiation losses from the flame, determined by the decrease of CO₂ formation [20,21].
V. HEAT TRANSFER

Heat transfer plays a critical role in industrial combustion processes where the primary objective is to transfer heat from the hot combustion products to some type of load. In industrial processes, radiation is often the dominant mechanism and forced convection also plays an important function[16].

A. Radiation

Thermal radiation is one of the most important heat transfer mechanisms in industrial furnaces[17]. Radiation is a unique method of heat transfer because no medium is required for energy transport. It can be transmitted through a vacuum or through a medium. Radiation is simply the transmission of energy by electromagnetic waves, which are characterized by their wavelength or frequency.

B. Luminous radiation

Luminous flames are produced by the continuous radiant emission of particles in the flame, such as soot, that radiate approximately as blackbodies. Cause of hydrogen and gaseous fuels don’t produce soot and something like this luminous radiation is usually not significant for gaseous fuel (e.g. natural gas), [18].

C. Nonluminous gaseous radiation

The equation of radiative transfer will not be considered here, as it is discussed in many radiation textbooks and not commonly used as such to solve industrial combustion problems.

The complete combustion of hydrocarbon fuels produces, among other things, CO₂ and H₂O. These gaseous products generate nonluminous radiation, which has been extensively studied [19]. This heat transfer mode depends on the gas temperature level, the partial pressure and concentration of each species, and the molecular path length through the gas. Based on the study of co flames, Concluded that most of the radiant energy from the flames was primarily chemiluminescence[20]. But this was later proven wrong [21]. The individual emissivity of either CO₂ or H₂O is given by [22]:

\[ \varepsilon = \text{emissivity of the individual gas, } p_a = \text{partial pressure of the gas, } L = \text{path length through the gas, } T_g = \text{absolute temperature of the gas, and } \varepsilon_0 = \text{emissivity of the individual gas at a reference.} \]

The first term in equation is calculated using:

\[ \varepsilon_0 = \text{emissivity of the individual gas at a reference.} \]

\[ (1) \]

Where \( \varepsilon \) is the total emissivity of water vapor at the reference state of a total gas pressure \( p = 1 \) bar and \( p_a \rightarrow 0 \).

\[ (2) \]

Graphical results for H₂O and CO₂ are shown in figure 1 and figure 2, respectively. The total emissivity is then calculated using:

\[ (3) \]

Where \( T_0 \) is the absolute reference temperature of the gas (1000K) and \( c_{ij} \) are constants. The second term of the equation is calculated from:

\[ (4) \]

\[ (5) \]

\[ (6) \]
VI. HYDROGEN ENVIRONMENTAL EFFECT

The most important purpose of using hydrogen in this paper to investigate the effect of enriched hydrocarbon fuel by addition hydrogen to emission pollutant like NO,NOx,CO and CO2.

A. No emission index (EINO)

For turbulent diffusion fuel, the amount of no emission and, consequently, EINO level is assuredly increased with %H2 addition, as can be observed in fig. 6. All references studied the different configurations of NG-H2 diffusion flames agree unanimously on that; any hydrogen addition to natural gas is an ineffective strategy for no reduction, although, the disparity in the reasons for which the researchers had ascribed these increase [11]. That mild combustion is effective in reducing significantly NOx emissions and can use it for reduce NOx emission.

B. CO emission index (EICO)

The EICO level increases rapidly with % H2 fraction, reaches the maximum value at 30% H2, and then decreases faintly with the further increase of % H2 as shown in figure 4.

C. Exhaust CO2

The monotonic reduction of %CO2 with the fuel hydrogen content is compatible with the dramatic increase of the CO concentration, even when the H2 fraction is on the order of 30%, while, the continuation for this reduction is believed to be due to the effect of carbon input diminution. It is also clear that the 50% H2 flame can generate approximately 30% less CO2 as compared to the pure natural gas flame. This decrease in the % CO2 concentration is the most significant gain for the NG-H2 hybrid fuel application [11].

VII. RESULTS AND DISCUSSION

As mentioned before, this work is particularly focused on an industrial gaseous by-product flame characteristic and hydrogen safety that were investigated. The main results are discussed below.

A. Potential benefit

• Hydrogen has the highest energy-to-weight ratio of any fuel since hydrogen is the lightest element and has no heavy carbon atoms. It is for this reason that hydrogen has been used extensively in the space program where weight is crucial. Hydrogen releases about 2.5 (on base of weight) heat in comparison other hydrocarbon that effect on the fuel consumption.

• fuel efficiency increases therefore the consumption of excess air decreases.

B. Excess air

When hydrogen content increases from a special percent, the percent of oxygen consumption decreases. The effect of decreasing the oxygen consumption and then decreasing of excess air are.

• When low amount of excess air is used, the flue-gas mass flow will be low, low amount of hot gases leaving the stack and a low amount of fuel will be necessary.

• But on the base of experiment case in turbulent flame the concentration of oxygen that is consumed by increasing hydrogen content, first it increases till the amount of hydrogen reached to 50 percent as compared to 40 percent, that is depend on how hydrogen and hydrocarbon like natural gas is premixed.

• Decreasing excess air in the furnace maximizes radiant heat transfer, will increase furnace temperature around the burners and decrease fuel consumption.

• When excess air is decreased, a temperature shift does not occur as heat is moved away from the burners. Higher temperatures aren’t found in the upper section of the firebox.

• heat transfer increases in the lower section of the firebox because the decreasing CO2 emission.[13,14].

• High consumption of excess air is caused. Temperatures in the convection section and stack will also rise significantly. This will reduce the amount of heat available for heating the hot oil and more fuel will be burned in order to maintain process specifications. This process reduces the amount of heat transferred in the convection section and lowers the temperature in both the upper convection section and stack.

C. Flame characteristic

• An increase in the flame stability appeared as a significant enhancement in the flame liftoff and blowout limits, which can be attributed to the high burning velocity of hydrogen fuel[25].

• An obvious transition from a fully lifted to a burner attached configuration was occurred, accompanied by an evident change in the flame shape. This change was
upto 40% of hydrogen addition, followed by a clear emergence for the hydrogen combustion characteristics[25].

• a slight increase in the visible flame length was occurred initially, with hydrogen addition upto 20%, then, an expected decrease was observed. The decrease in the lift-off height with hydrogen addition explained the first increase, whereas the higher hydrogen reactivity explained the Subsequent decrease[11], in that manner, the utilization of hydrogen in blended form would reduce the problems of storage and flashback[25].

• A continuous increase in flame temperatures, a broadened in the high temperature zones as well as a gradual shifting of the reaction zone in the upstream direction was observed, which was related to the hydrogen higher reactivity and adiabatic temperature[25].

• The addition of H₂ determines the increase of the temperature levels in the burner as well as the reduction of the lift-off length and the shift of the reaction zone towards the burner exit [13].

• The temperature increase is not only due to the higher specific energy content of the H₂ blended fuel with respect to methane, but also to the reduced radiation losses from the flame, determined by the decrease of CO₂ formation.

D. Heat transfer

• Heat transfer increase because of decreasing CO₂ emission.

E. Fuel saving

• High content energy and low excess air are caused that the consumption of fuel gas burner decrease.

F. Hydrogen environmental effect

• Adding hydrogen to the fuel burner is caused that in overall case the CO and CO₂ emission decreases and Increase NOx emissions unless proper timing and mixture adjustments are used when temperature is too high.

G. Hydrogen safety

like many non-hydrogen gas technologies, hydrogen installations need to be tight in order to prevent leaks or at least keep them as small as ever possible. Since hydrogen is the smallest element in the periodic table of elements and its affinity to oxygen is high, leak tightness is of utmost importance. If, however, leakage occurs or in an accident hydrogen is released to the outside, there is a good chance that no ignitable hydrogen/oxygen mixture is built, or that an ignitable mixture lacks a near-by ignition source, because hydrogen quickly disperses vertically upwards into the air by environment; its diffusivity in air is a powerful acceleration source and, thus, a (sort of) safety element. That is the case when hydrogen is handled in open spaces [26].

REFERENCES


[14] The mild combustion in an industrial burner fed with Hydrogen enriched fuels”, int ernational j ourna l o f hy drogen energy 35 (2 0 0 8 ) 7 5 5 3 – 7 5 6 4


[18] .j.m. béer and n.a. chigier, impinging jet flames, Comb. Flame, 12, 575–586, 1968

[19] E. Talmor, combustion hot spot analysis for fired process heaters, gulf publishing, houston, 1982


[21] W.E. Garner,” Radiant energy from flames”, first symposium (international) on combustion, the


