INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2017) 1–16

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/he

An experimental and numerical study on the combustion and flame characteristics of hydrogen in intersecting slot burners

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ARTICLE INFO

Article history:
Received 27 August 2017
Received in revised form
18 December 2017
Accepted 19 December 2017
Available online xxx

Keywords:
Impinging jets
Flame structure
Hydrogen
Interferometry
Mach-Zehnder

ABSTRACT

In the present study, two impinging slot jets of hydrogen gas at different angles and distances are investigated experimentally using the Mach-Zehnder interferometry. The obtained temperatures from the interferometry method were validated against the thermocouple measurements. The generated temperature field is studied using infinite fringe interferometry. Slot burners with high length-to-width ratio are utilized to ensure producing a uniform 2D flow. The slot burners' angle and the distance between the burners are varied from 60 to 100° and 10 mm–25 mm in the increment of 20° and 5 mm, respectively. The Reynolds number is varied from 70 to 150, and the equivalence ratio is changed from 0.8 to 2.5. The results indicated that the Reynolds number does not have a considerable effect on increasing the maximum temperature, while, it has a significant influence on the flame structure. The equivalence ratio has a substantial effect on both maximum temperature and flame structure. Also, the variations in angle of burners have a considerable effect on the flame stability. Furthermore, the distance of burners strongly affects the maximum flame temperature and the flame structure. It was observed that by increasing the burners distance, the domain of maximum temperature is descended. The results from numerical modeling were also validated with experiments. The effect of temperature on the NO_x emissions was clearly shown in the CFD simulations.

Introduction

Hydrogen is a highly combustible gas and, therefore, burns in air at a wide range of concentrations. Besides traditional techniques, novel methods are also proposed for the production of hydrogen, e.g. thermochemical and photosynthesis [1,2]. The adiabatic flame temperature and higher heating value (HHV) of hydrogen are 2380 K and 141 MJ/kg, respectively [3,4]. Furthermore, hydrogen is the essential resource for a wide range of energy conversion technologies [5], since it has especial combustion characteristics [6] and flame modes [7,8].

The rate of heat transfer, flame temperature, and emissions depend on the arrangement of burners in various industries. Intersecting and parallel burners are usually utilized in heating applications including melting scrap metal, forming substance, and heating metal bars [9]. Significant studies have been performed to investigate the flame structure and heat transfer of impinging flame jets. However, information about temperature field and structure of flames are rare. Widely, the burners with the low-Reynolds number and low-pressure premixed gas-fuel flames are utilized for the domestic and industrial purposes. The advantages of these

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https://doi.org/10.1016/j.ijhydene.2017.12.126

Abbreviations/Acronyms

FN	Fringe number

List of Symbols

D_h	Hydraulic diameter (mm)
H	Vertical distance between the nozzles outlet and specified plane (mm)
L	Slot nozzle length (mm)
n	Refractive index
P	Pressure
Re	Reynolds number
S	Distance between the nozzles outlet (mm)
t	Slot nozzle width (mm)
T	Temperature (K)
V	Velocity of premixed gas (m/s)
MW	Molecular weight (kg/mole)
x, y, z	Cartesian axes coordinate
Y	Mole fraction

Greek Symbols

λ	Wavelength of the laser beam (m)
μ	Viscosity (kg/m.s)
ρ	Density (kg/m^3)
θ	Angle of jet-to-jet impinging
$\varnothing$	Phase angle of light wave (radian)
φ	Equivalence ratio

Subscripts

exit	At exit position
i	Mixture component comprising hydrogen and air
mix	Mixture of fuel and air

burners are efficient combustion and quick heat transfer. Some research studies help to obtain better consideration of the thermal features of impinging premixed flames [10–12]. Knowing the effects of local temperatures on the reaction rate of species, equilibrium concentration, and even the emission characteristics, investigating temperature field of flame is an essential parameter in designing the burners. Moreover, the critical point in examining the heat transfer rate is data related to the temperature field of the premixed flames. In addition, the heat released from combustion is transferred to a receiving medium such as impingement plate. Therefore, this content seems to be one of the major concerns in both experimental and numerical simulation studies. To obtain a better understanding of the flame structure and heat transfer characteristics of intersecting slot flame jets; this study was performed to investigate the temperature field of impinging laminar premixed hydrogen flames. Conventional methods for experimental measurement of temperature field are using thermocouples and resistance thermometers [13,14]. It should be mentioned that using thermocouple which leads to direct contact of the external body with the flame, disturbs the flow regime of the flame. On the other hand, Interferometry methods measure the flame temperature and combustion products in conversion energy systems, such as boiler and gas turbine. Optical methods are capable of instant measurement of the temperature field. High flame temperature can be obtained without any contact, using optical methods. This problem may result in considerable errors during measurements [15].

All of the interferometry methods are based on the variation of refractive index of the flames and combustion products. Tian et al. [16] investigated the flame stabilization modes with Schlieren optical technique in a hydrogen-fueled combustor and reported the unstable criteria under different conditions. Mach-Zehnder interferometry (MZI) technique was primarily applied to obtain interferograms of varying flame types and is currently used in other energy conversion applications [17–19]. To visualize the temperature isolines, alignment of the fringes are studied in the flow field. Consequently, the temperature field along various fringes in the domain can be obtained by a high spatial resolution [20]. For methane/air mixtures, Mach–Zehnder interferometry has rarely been employed to achieve temperature field of an axisymmetric partially premixed flame [21]. For local temperature measurement, Glad-Stone relation can be computed by the flame gaseous products. Also, the increment of local flame temperature decreases the relation refractive index of air accordingly [22]. The complexity of Interferometry methods is because the refractive index of air and combustion products is not equal. Gardiner [23] proposed an average refractive index of combustion production instead of the air refractive index. The results indicate that interferometry techniques yield an acceptable outcome for diffusion flame. Enough experimental tests for laminar premixes fuel-air have been performed to show that the condition can be more simplified. Reuss [24] and Merzkrich [25] proposed that a constant Gladstone-Dale factor could be applied with good agreement for a homogenous premixed flame since the change in its amount during combustion process did not exceed ±2%. These errors for gas composition variation of a luminous flame region are calculated by Stella et al. [26], and VanDerWege et al. [27]. Their results express that these errors are less than ±2%. Therefore, the adopted coefficient refractive index of air can be used for premixed flames with good agreement.

Bradley and Mathew [28] suggested that enhancing the aspect ratio of nozzles can reduce the error of the end effects of rectangular burners. When the target plate is too much greater than the scale of the utilized burner, we need a larger flame. Thus, several burners are used next to each other in these cases. On the other hand, multiple burners have been investigated due to their extensive applications. The structure and temperature field of the flame created by premixed methane-air in laminar flow regime with slot flame is studied by Najafian and Ashjaee [29]. They pointed out in their works that maximum temperature has not any sensitivity to the Reynolds number, while it can be effective on the flame structure. Kwok [30] investigated heat transfer on multiple slots and annular impinging flame jets. In their studies, all of the burners were vertical and without any relative angle. They found that heat transfer of the central jet of a compound slot jets system for small jet-to-jet spacing was higher than that of single slot jet. The structure of laminar opposed-flow diffusion flames with syngas fuel was studied by Drake and Blint [31] in a wide range of stretch conditions ($\alpha = 0.1–5000\ s^{-1}$). The results showed that non-equilibrium assumption must be