An Experimental and Numerical Study of Lifted Flame with the Stretch in Simulated SNG Fuel

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Abstract

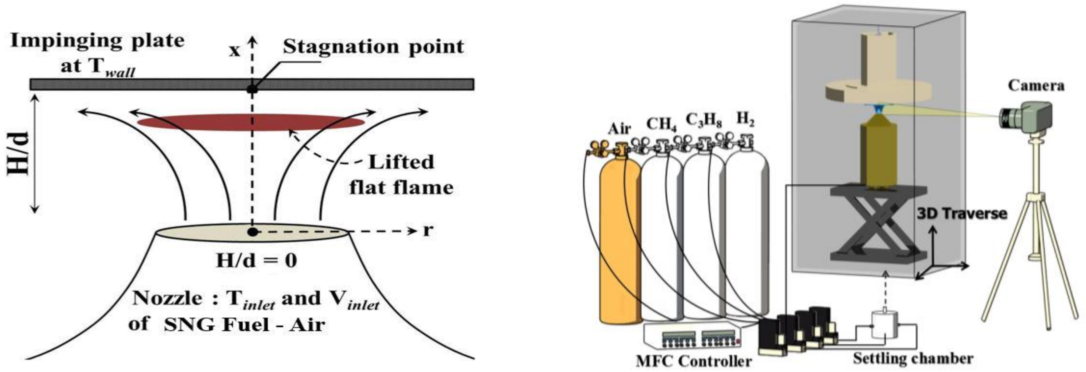
A study has been conducted numerical and experimental to determine the lifted flame heat transfer for simulated SNG fuel flame impinging on a flat flame. Effect of stretch on lifted flame in stagnation point was examined at different strain rates that were adjusted with Reynolds numbers of premixed SNG/air mixture. Results show that Maximum stagnation heat flux was obtained experimentally at maximum strain rate. The numerical results were calculated by SPIN application of the CHEMKIN package. Results were compared with those found experimentally. As strain rate has increase, flame temperature and velocity have decreased because of increasing flame heat loss when reaction zone was very close to the stagnation point.

Introduction

Flame impinging heating of solids has been used for many years. Some typical application include melting of scrap metal, shaping glass and heating metal bars. Another application is heating metal billets in a reheat furnace prior to rolling or shaping. In addition, it is also used in metal fabrication and assembly including soldering, brazing, cutting and welding. Use of direct flame impingement in industrial furnaces significantly enhances the convective heat transfer rates from combustion products to the load, which ultimately increases productivity, reduces fuel consumption and lowers pollutant emission. Convectional hydrocarbon fuels have been for uniform heating in the process using impinging jet flame. But, currently many countries that are abundant reserve of coal have competitively developed Synthetic Natural Gas (Hereafter, SNG) to meet the clean energy demand.[1-2] The components of SNG are methane (Hereafter, CH_4) 91%, propane (Hereafter, C_3H_8) 6% and hydrogen (Hereafter, H2) 3%. The C_3H_8, H_2 are added to maintain heat value of existing LNG regularly. It is estimated combustion reaction or flame behavior depends on the addition of the C_3H_8 and H_2.

We have been studied SNG fuel various H_2 content to investigate the combustion reaction and heat characteristics such as laminar burning velocity, heat flux, and temperature profiles in the impinging jet combustion system.[3-4] The coupling that occurs between fluid mechanics and chemical kinetics at the stagnation point is important in impinging jet flames, but it is difficult to confirm experimentally.

Numerical studies according to the equivalence ratio, impinging distance, Reynolds number and strain rate, which represent main parameters of impinging jet flame, are needed to study detail flame structure, especially at stagnation point. It seems that strain rate has a significant impact on flame structure of lifted impinging jet flame. In this case, the effects of strain rate are necessary to understand the combustion reaction and heat transfer that are practical interest. To understand the impinging jet flame structure, numerical studies by strain rate should be proceeded. Numerical analysis was conducted using SPIN code of CHEMKIN package at one-dimensional stagnation flow.[5-9] The results are calculated along the vertical position, i.e., x-direction to stagnation point from nozzle exit because of one dimensional analysis.



(a) (b)

Figure 1. (a) Schematic diagram of the configuration,
(b) Experimental setup of lifted impinging jet flame.

Numerical Approach

Figure 1 shows the schematics of lifted flat flame in impinging jet configuration. Mixtures with velocity V_i and temperature T_i exit from contraction nozzle. Impinging plate with temperature T_w positioned at a separation distance H/d. The radial dimension of impinging plate in numerical system is presumed to be large compared with H/d. This geometry exhibits a similarity behavior that can be exploited mathematically 3D shape flame into a system of one-dimensional approach. Hence, the temperature and composition fields only become a function of the vertical position x on the basis of stagnation point.

This approach has been followed in the development of the SPIN code of the CHEMKIN package. In this code, the species, temperatures and velocity profiles are calculated for steady-state one-dimensional stagnation flow while accounting for finite-rate gas-phase chemical kinetics and multicomponent molecular transport. The detailed flame structures of impinging jet flames were numerically investigated by employing the GRI3.0 kinetics mechanism (53species, 325 reactions) for SNG fuel.[10]

Experimental Approach

The schematic of the burner of interest is shown in Figure 2. In order to obtain an impinging flame, an impingement plate was mounted directly dimensionless separation distance (Hereafter, H/d) =2.0 above the burner. It consisted of an aluminium container filled with water, kept boiling, at atmospheric pressure. The burner consisted of two main parts. The top part was a convergent cylindrical nozzle with an area contraction ratio of 36 and an exit diameter D = 10mm. This geometry led to a uniform velocity flow at the burner exit. The injection holes of the nitrogen were drilled beside the nozzle exits in order to stabilize the oscillation flames on the impinging plate when they appeared. The bottom part of the burner was a tube where the fuel/air mixture were injected. The fuel was used SNG and the experimental were conducted at atmospheric pressure, with a Reynolds number (Hereafter, Re) up to 1950 and equivalence ratio (Hereafter, Φ) = 1.0

Numerical and Experimental method

Main parameters that could potentially control burning velocities and flame structures include: Re, H/d, Φ and composition ratio. However, the main parameters in present study were Re and global strain rates while others are fixed. These parameters are listed in Table 1 along with others relevant.

Table 1. Numerical and Experimental condition.

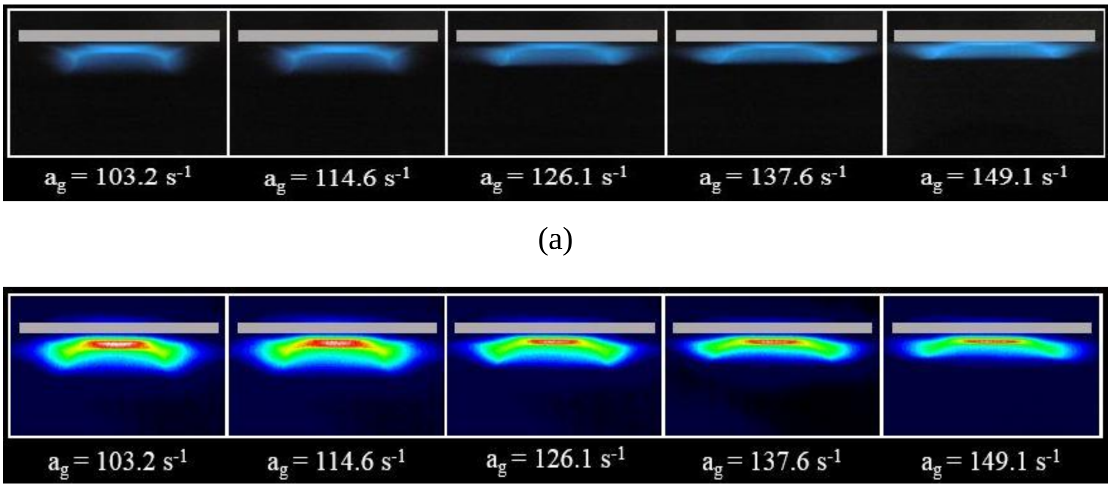
Fuel	CH_4, C_3H_8, H_2
Oxidizer	Air
Composition ratio	$CH_4 : C_3H_8 : H_2$ 91 : 6 : 3
Equivalence ratio(Φ)	1.0
Reynolds number(Re)	1350 - 1950
Strain rate(a_g)	103.2 – 149.1 s^{-1} (with Re)
Diameter of nozzle(d)	10mm
Impingement distance(H/d)	2.0

In this study, the global strain rate, hereafter known as the strain rate (Hereafter, a_g), was defined as following equation (1):

$$a_g = du/dh, \quad du \equiv Re, \quad dh \equiv H/d. \tag{1}$$

Therefore, this paper used a_g instead of Re, H/d for calculating strain rate. To exclude the effects of H/d and Φ, the conditions were fixed with H/d = 2.0, Φ = 1.0, respectively. To investigate a_g dependent, computations were conducted the impinging jet flames of SNG at increasing Re from 1350 to 1950. In simulation, the surface temperature of impinging plate was 323.15 K and the mixture temperature of SNG-air was 298 K.

Results and Discussion

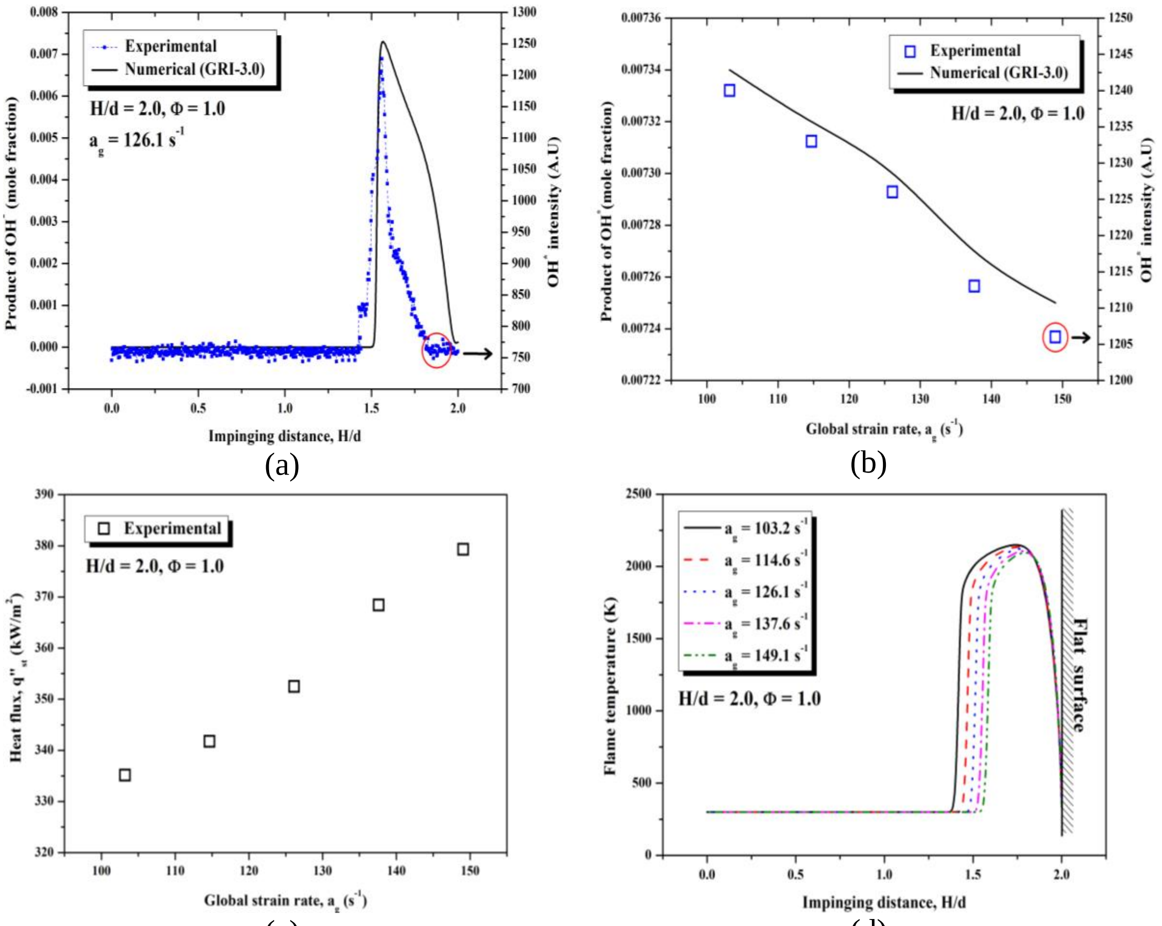


(a)

(b)

Figure 2. Lifted impinging jet flame with a_g for Φ=1.0
(a) Direct image, (b) OH radical intensity using ICCD camera.

The area of stabilization of the flame was conducted by the equivalence ratio. The equivalence ratio was 1.0, and it was confirmed that the lifted flat flame which is object flame in the present study was distributed most widely. Macroscopic shapes of flame with a_g = 103.2, 114.6, 126.1 137.6, 149.1 s^{-1} and Φ = 1.0 are shown in Figure 2 (a) direct image, (b) OH radical intensity image using ICCD camera. The increase in a_g is observed to move flame zone from nozzle to impingement plate, and the thickness of the flames had been thinned.



(a) (b)

(c) (d)

Figure 3. Profiles with a_g for Φ=1.0 (a) Comparison of OH radical from the experiment and calculation data using SPIN code at $a_g = 126.1s^{-1}$, (b) OH radical intensity (c) Heat flux distribution of stagnation point, (d) Flame Temperature.

Figure 3.-(a) shows OH radical production of calculation data using SPIN code and OH radical intensity of experimental result using ICCD camera. The calculation data using SPIN code displays excellent agreement with experiment the maximum position of OH radical. Therefore, the computed data of the SPIN code, which is the one - dimensional theoretical model used in this study, is sufficient to represent the experimental data of the impinging jet flame. Figure 3-(b) shows the simulated maximum OH radical production OH radical intensity of experimental result using ICCD camera with a_g, Φ = 1.0. Both results are continuously declines. The OH intensity and concentration is maximized in the flame zone for all flames that were simulated. This is to be examined in detail in Figure 3-(c), (d).

Figure 3-(c) shows the heat flux distribution of stagnation point with variation in the value of a_g = 103.2, 114.6, 126.1, 137.6, 149.1 s^{-1} at constant H/d=2.0, Φ=1.0. On increasing a_g, it was found that the heat flux was very high till the tip of the inner reaction zone started touching the impingement plate. As the tip of the inner reaction zone touched the impingement plate, a sudden rise in heat flux was obtained with heat flux attaining the peak value. This magnitude of peak heat flux increased with increased in the value of a_g.[11-13] Figure 3-(d) shows axial temperature variation different a_g and it is the magnified view of the temperature profiles near the stagnation point. The temperature gradient at the impingement plate was very sharp. Maximum temperature in the flame zone is found in the flame with the lowest $a_g = 103.2s^{-1}$. Flame temperature declined when the reaction zone approached closer to the impingement plate. This was because of greater heat loss to the surface from the flame when it was closer to impingement plate.

Conclusion

This study has been conducted experimental and numerical to investigate the lifted flat flame structure in impinging jet flame of SNG with various global strain rates. The conclusion was derived as follows: Axial velocity is affected by the flame temperature. When the global strain rate (a_g) increase, the flame reaction zone is narrower and moves to stagnation point. At this time, flame temperature and axial velocity declined due to heat loss increased.

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Nomenclature

Φ	fuel/air equivalence ratio
d	diameter of the circular nozzle (mm)
H	axial distance of the impingement plate from the burner exit plate
H/d	dimensionless separation distance
q''	heat flux (kW/m^2)
Re	Reynolds number
T	Temperature (K)
a_g	global strain rate(s^{-1})
u	flow velocity (m/s)
h	enthalpy (kJ/kg)
v	flow velocity in x or r direction (m/s)

Subscripts

r	radial direction
x	axial direction

Superscripts

i	inlet
st	stagnation point
w	wall

References

[1] Park, S.I., Kim, U.S., Lee, M.C., Kim, S.C., Cha, D.G., "The effects and characteristics of hydrogen in SNG on gas turbine combustion using a diffusion type combustor", *Hydrogen energy*. 38: 12847-12855 (2013).

[2] Kopy, J., Schil, T.J., Biollaz, S.MA., "Production of synthetic natural gas (SNG) from coal and dry biomass a technology review from 1950 to 2009", *Fuel*. 89: 1763-1783(2010).

[3] Jeong, B.G., Lee, Y.H., Lee, K.M., "A Study on Combustion and Heat Transfer in Premixed Impinging Flames of Syngas (H2/CO)/Air Part I: Characteristics of Combustion", *Trans. of the Korean Hydrogen and New Energy Soc.*, Korea, paper V25-1, pp. 47-58.

[4] Sim, K.S., Jeong, B.G., Lee, Y.H., Lee, K.M., "A Study on Combustion and Heat Transfer in Premixed Impinging Flames of Syngas (H2/CO)/Air Part : Heat

Transfer Characteristics", *Trans. of the Korean Hydrogen and New Energy Soc*., Korea, paper V25-1, pp. 59-71.

[5] Coltrin, M.E., Kee, R.J., Evans, G.H., Meeks, E., Rupley, F.M., Grear, J.F., "Spin(Version 3.83): A Fortran Program for Modeling One-Dimensional Rotating Disk/Stagnation Flow Chemical Vapor Deposition Reactor", *Sandia National Lab*., (1991).

[6] Kee, R.J., Rupley, F.M., Miller, J.A., "CHEMKIN-II: A Fortran Chemical Kinetics Package for the Analysis of Gas-Phase Chemical Kinetics", *Sandia National Laboratories Report*, SAND89-8009, (1989).

[7] Kee, R.J., Dixon Lewis, Warnatz, G.J., Conltrin, M.E., Miller, J.A., "A Fortran Computer Code Package for the Evaluation of Gas-Phase Multi Component Transport", *Sandia National Laboratory Report*, SAND86-8246, (1986).

[8] Coltrin, M.E., Kee, R.J., Rupley, F.M., "SURFACE CHEMKIN (Version 3.7): A Fortran Package for Analyzing Heterogenous Chemical Kinetics at a Solid Surface Gas Phase Interface", *Sandia National Laboratory Report*, SAND90-8003, (1990).

[9] Grcar, J.F., "The Twopnt Program for Boundary Value Problems", *Sandia National Laboratory Report*, SAND91-8230, (1991).

[10] Smith, G.P., Golden, D.M., Frenklach, M., Moriarty, N.W., Eiteneer, B., Goldenberg. M., Bowman, T., Hanson, R.K., Song, S.H., Gardiner, W.C., et al. "GRI-Mech 3.0", Available from:http://www.me.berkeley.edu/gri_mech/.

[11] Bouvet, N., Davidenko, D., Chauveau, C., Pillier, L., Yoon, Y.B., "On the simulation of laminar strained flames in stagnation flows: 1D and 2D approaches versus experiments", *Proc. Comb. And Flame.* 161:438-452 (2014).

[12] Chander, S.H., Ray, A.J., "An experimental and numerical study of stagnation point heat transfer for methane/air laminar flame impinging on a flat surface", *Heat and Mass Transfer.* 51:3595-3607 (2008).

[13] Chander, S.H., Ray, A.J., "Flame impingement heat transfer: A review", *Energy Conversion and Management.* 46:2803-2837 (2005).