Early flame development image comparison of low calorific value syngas and CNG in DI SI gas engine

Ftwi Yohaness Hagos¹, A. Rashid A. Aziz¹ and Shaharin A. Sulaiman¹
¹Centre for Automotive Research and Electric Mobility, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia
E-mail:ftwi@yahoo.com

Abstract. The early flame development stage of syngas and CNG are analysed and compared from the flame images taken over 20° CA from the start of ignition. An imitated syngas with a composition of 19.2% H₂, 29.6% CO, 5.3% CH₄ and balance with nitrogen and carbon dioxide, which resembles the typical product of wood biomass gasification, was used in the study. A CCD camera triggered externally through the signals from the camshaft and crank angle sensors was used in capturing of the images. The engine was accessed through an endoscope access and a self-illumination inside the chamber. The results of the image analysis are further compared with the mass fraction burn curve of both syngas and CNG analysed from the pressure data. The analysis result of the flame image of syngas validates the double rapid burning stage of the mass fraction burn of syngas analysed from in-cylinder pressure data.

1. Introduction
The history of in-cylinder combustion and flow visualization is associated to Rossweiler and Withrow in 1938 when for the first time they modified a spark ignition engine to have an optical window [1]. The combustion behavior of fuel in an internal combustion engine can be studied with the help of flame imaging. This technique is mainly helpful in the study of flame development stage of the combustion. There are different techniques of capturing flame images in the literature. Among these, the most common ones are planar laser-induced fluorescence (PLIF) imaging with the help of laser diagnostic technique and direct visualization techniques like single shot camera or continuous video recording and imaging the chemiluminescence signals of combustion gas radicals. Detail techniques of the visualization techniques are explained elsewhere [2]. The general objective of this study is to explore the employment of syngas in a direct injection spark ignition internal combustion gaseous engine as a potential replacement for fossil derived fuels. A direct visualization technique is preferred that use a self-luminosity assisted by an image intensifier to compare the flame characteristics of syngas and CNG. Further the flame visualization analysis result is compared with the mass fraction burn results if any relationship can be drawn.

2. Methodology
The study was conducted in a four-stroke, single cylinder, direct injection spark ignition research engine setup with a compression ratio of 14:1, schematic diagram, its specification and description about the operation stated elsewhere [3]. The fuel injection pressure was set to be at 18 bar and the engine was run at 1800 rev/min wide open throttle. The injection timing was set to be 120° CA BTDC and the ignition timing at 30° CA BTDC for both fuel types.
2.1. Combustion Analysis

The combustion analysis mainly the mass fraction burn (MFB) was analysed from the pressure readings from the in-cylinder combustion. MFB is a fraction of a chemical energy release as a function of crank angle with a scale of 0 to 1 determined based on burn rate analysis, a method originally developed by Rassweiler and Withrow. The rate of burning process is slower at the time of ignition, reaches its maximum midway and then decreases to close to zero at the charge extinction stage. For a spark-ignition engine, it is commonly represented by the Wiebe Function as:

\[
X_b(\theta) = 1 - e^{\left[-a \frac{(\theta - \theta_o)^{m+1}}{\Delta \theta}\right]}
\]

where \(X_b\) - MFB, \(\theta_o\) - Start of combustion, \(\Delta \theta\) - Duration of heat release, \(m\) - Weibe form factor and \(a\) - Weibe efficiency factor [4].

2.2. Flame Imaging

In this study flame image was captured with the help of a Charge-Coupled Device (CCD) camera assisted by an image intensifier to overcome the weak luminescence. The image was taken through the endoscope access installed at 30° from the horizontal in between the two intake valves. The main requirement in the flame imaging was the synchronization of the imaging system with the engine operations like speed and piston position. In the current study, the synchronization was done with a LabVIEW control program along with the cam position, crank angle and TDC signal. Figure 1 shows the setup arrangement of the flame imaging. These all three signals were calibrated and synchronized with the help of a four channel oscilloscope. LabVIEW program was then used to control the external camera triggering position taking the crank angle cam position signals an input from NI-DAQ system.

![Flame imaging setup](image)

**Figure 1.** Flame imaging setup

Flame image was captured starting from the ignition up to 20 CA degrees for every 2° CA interval. It is impossible to capture image beyond 10° BTDC as the piston do obstruct the endoscope. A total of 40 flame images were captured at every required crank angle in order to get the average properties of the developing flame for the specific crank angle.

2.3. Fuel Used

A pre-mixed imitated syngas was preferred for this investigation. This was similar in composition with that of syngas used by Papagiannakis et al. [5]. It was supplied in a gas bottle with 160 bar pressure and the net heating value is 7.67 MJ/Nm³. The CNG used in this test was obtained from local NGV stations pressurized in a bottle with 200 bar. The net heating value was in the range of 38.13-38.96
MJ/kg. Engine warming up and stabilization operation was done with CNG as imitated syngas cost was much higher. Fuel switchover was done once the engine attained stable operation. Since a common injector was used, the engine remained to operate with syngas for more than 5 minutes before formal reading was taken. This pre-condition was to avoid fuel contamination. Besides this, the endoscopic access has a cooling system with a continuous compressed gas at 6 bar flowing. To avoid an image distortion and damage to the endoscope, the engine was shut down after every 10 minute data collection.

3. Result and Discussion

Figure 2 shows the comparison of MFB of low calorific value syngas (producer gas) and CNG at 1800 rev/min analyzed based on Equation (1). MFB of syngas is observed to deviate from the normal s-curve, experiencing a double s-curve with a plateau shape around 60-70% MFB. This is similar to the Double-Weibe function used to model the combustion process in HCCI [6].

![Figure 2. Mass fraction burn](image)

The main purpose of the flame imaging process is to validate the double-Weibe shape of the MFB of syngas in Figure 2. Though the image capturing should last from the start of ignition up to 10° ATDC to see the full picture of the variation of MFB, there is limitation with the endoscopic access of the engine. It gets obstructed in the region from 10° CA BTDC to 10° CA ATDC due to the piston covering the endoscopic access. Therefore, flame is captured from the start of ignition up to 10° CA BTDC.

![Figure 3. Flame equivalence radius with time for 1800 rev/min](image)

![Figure 4. Flame growth rate with time for 1800 rev/min](image)

Images captured by CCD camera are rich in information. Besides, they are accompanied by noises. As a result, the images are pre-processed with an image filtering process before they are subjected to
analysis. A detail procedure of the image processing was reported elsewhere [2]. The images are processed for the equivalence radius and flame growth rate. Figure 3 and 4 show the profile of the flame equivalence radius and flame growth rate versus time after the start of ignition for both syngas and CNG. The flame equivalence radius of syngas gets its maximum at 1.1 ms after the onset of the ignition and then start declining up to 1.82 ms. After this it again starts rising. For CNG, the flame equivalence radius starts rising at around 1.75 ms. The flame equivalence radius trend indicates that another peak radius for syngas is projected to appear sometime after 2 ms. This matches with the double rapid burning stage of the MFB of syngas, double-Wiebe function in Figure 2. The flame growth rate is observed to start at higher rate and it dropped sharply for both fuels. This is attributed to the shock wave of plasma plasma kernel [7]. Syngas started with higher radius compared to CNG with 30.4 m/s and 22.36 m/s for syngas and CNG, respectively. The minimum value of flame growth rate for syngas is observed at 1.1 ms from the onset. For CNG the minimum value of flame growth rate is observed at 0.75 ms from the onset. The flame growth rate remained constant for both fuels until a rise at around 1.75 ms and 1.82 ms for CNG and syngas, respectively. Both fuels experience different flame-growth rate profiles.

4. Conclusion
The experimental data from a four-stroke, single-cylinder, direct injection spark ignition engine is analyzed for the MFB and compared with the flame image analysis taken over 20 CA degrees for every 2° CA interval. The current fuels under investigation are syngas (a multi-component fuel with five constituent gases in the makeup with different proportions) and CNG. The profile of the equivalence radius of both CNG and syngas observed to match the mass fraction burn curves. While CNG remained in its early flame development stage in this duration, Syngas observed to experience its first rapid-burning stage. Due to the endoscope access limitation in the region from 10° CA BTDC to 10° CA ATDC, the second rapid-burning of syngas and the rapid-burning stage of CNG could not be observed. However, there is indication for such occurrence from the profile of equivalence radius profile as the profile start rising around 1.75 ms for both fuels. Therefore, this conform that the combustion of syngas takes the double-Weibe function of mass fraction burn, experiencing a double rapid burning stage. The reason behind is unknown and needs further investigation. The flame growth rate is also analyzed and presented, both fuels experiencing differently at the early stage.

References
[1] Ferguson, C. R. and A. T. Kirpatrick, Internal Combustion Engines: Applied Thermosciences: John Wiley and Sons, Inc., 2001
[2] Anbese, Y. T., "Early Flame Characteristic Study in a Lean CNG DI Combustion," PhD, Mechanical Engineering Department, Universiti Teknologi PETRONAS, 2011
[3] Hagos, F. Y., A. R. A. Aziz, S. A. Sulaiman, and Firmansyah. Combustion Characteristics of Late Injected CNG in a Spark Ignition Engine under Lean Operating Condition. 2012 J. Applied Sci. 12 2368-2375
[4] Heywood, J. B., Internal Combustion Engine Fundamentals. New York: McGraw Hill International, 1988
[5] Papagiannakis, R. G., C. D. Rakopoulos, D. T. Hountalas, and E. G. Giakoumis. Study of the Performance and Exhaust Emissions of a Spark-Ignited Engine Operating on Syngas Fuel 2007 Int. J. Altern. Propul. 1 190-215
[6] Yasar, H., H. S. Soyhan, H. Walmsley, B. Head, and C. Sorusbay. Double-Wiebe Function: An Approach for Single-Zone HCCI Engine Modeling. 2008 Appl. Therm. Eng. 28 1284-1290
[7] Anbese, Y. T., A. R. A. Aziz, and Z. A. B. A. Karim. Flame Development Study at Variable Swirl Level Flows in a Stratified CNG DI Combustion Engine using Image Processing Technique 2011 J. Applied Sci. 11 1698-1706