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Influence of Valve Lift Timing on Producer Gas Combustion and Its Modeling Using Two-Stage Wiebe Function

M. Sreedhar Babu, Vishal Garg, S. B. Akella, Shibu Clement, N. K. S Rajan

***Abstract*—**Producer gas is a biomass derived gaseous fuel which is extensively used in internal combustion engines for power generation application. Unlike the conventional hydrocarbon fuels (Gasoline and Natural gas), the combustion properties of producer gas fuel are much different. Therefore, setting of optimal spark time for efficient engine operation is required. Owing to the fluctuating tendency of producer gas composition during gasification process, the heat release patterns (dictating the power output and emissions) obtained are quite different from conventional fuels. It was found that, valve lift timing is yet another factor which influences the burn rate of producer gas fuel, and thus, the heat release rate of the engine. Therefore, the present study was motivated to estimate the influence of valve lift timing analytically (Wiebe model) on the burn rate of producer gas through curve fitting against experimentally obtained mass fraction burn curves of several producer gas compositions. Furthermore, Wiebe models are widely used in zero-dimensional codes for engine parametric studies and are quite popular. This study also addresses the influence of hydrogen and methane concentration of producer gas on combustion trends, which are known to cause dynamics in engine combustion.

***Keywords*—**Combustion Duration, crank angle, mass fraction burnt, producer gas, wiebe combustion model, wide open throttle.

I. Introduction

INTERNAL combustion engines have played a vital role in power generation over many decades. The utility of engines as generator sets (gensets) has been a tremendous benefit to society, but at the cost of degradation to the environment, primarily due to harmful emissions. In order to reduce the dependency on fossil fuels and to mitigate climate change, alternative fuels are preferred. Producer gas (PG) is one such renewable and eco-friendly fuel [1], [2], having a potential to meet the twin requirement of offsetting the dependence on fossil fuels and also an ability to undergo a cleaner combustion resulting in lower emission levels. However, generation of PG with consistent fuel composition, due to controls on a number of process parameters across the gasifier plant, is very difficult. Literature review depicts a number of studies reporting variation in engine performance parameters, combustion parameters and emission characteristics. It was reported by [3] that dynamic variation in PG quality potentially can cause variation in engine torque, and therefore, power output. Another researcher [4] reported a computational work in which a 7% reduction in flame speed of PG was observed with a 1% drop in hydrogen concentration. These studies emphasize a requirement for setting up of optimal spark time against fluctuating composition of PG fuelled engines (like observed in onsite gasifier-engine system). The nature of mass fraction burn (MFB) in engines is influenced by engine operating conditions like spark time, engine speed and compression ratio. Thus, the variation in MFB influences the rate of heat release in engines. This study presents the detailed analysis on MFB curves and its modeling through Wiebe function when heavy valve overlap engines are fuelled with PG. It is believed that the present study would pave the way for efficient PG engines operation via closed loop engine control.

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II. Literature Review

A literature survey was pursued to study the technical gaps associated with PG engine combustion and the most relevant studies as a summary are presented in this section.

Shivapuji [5] presented a numerical sensitivity analysis using OD model to understand the influence of shape factors (1, 2 and 3) which represents the mixture quality variation. The combustion descriptors influencing the heat release pattern were examined. Position of peak pressure rise was found to be very sensitive to mixture quality. While the rest, pressure ratio management, peak pressure and maximum heat release position angles have shown independency.

Ghojel [6] presented the historical development of the Wiebe function. It is mentioned that Wiebe function has been used in the development of direct injection (DI) and indirect injection (IDI) diesel engines, classical spark ignition (SI) engines and gasoline direct injection (GDI) engines, engines with homogeneous charge compression ignition (HCCI) and premixed charge compression ignition (PCCI). Also, other combustion models based on Wiebe function have been discussed and are widely used since the 1950's.

Yasar [7] developed a HCCI combustion single zone model using double stage Wiebe function to predict in cylinder pressure traces and to simulate the combustion speed with variation of temperature inside the combustion chamber. The developed model is applicable for the fast burning charge in the core region and slower burning charge near the cooler boundary regions. It was observed that pressure traces predicted by double Wiebe matches with the experimental curves.

Firmansyah [8] conducted experiments in the constant-volume chamber (CVC) to study the effect of dual fuel in HCCI engines. It has been reported that standard Wiebe is not suited to represent dual fuel HCCI combustion, and thus, dual stage Wiebe function is used for predicting the HCCI combustion which showed better match with the experimental data than the former model. Also, the fuels with High Octane number (HON) and Low Octane number (LON) have large difference in combustion behavior which arises due to laminar flame speed and auto ignition temperature creating large variation in effective burn rates.

Shivapuji [9] addressed the influence of thermo-physical properties of hydrogen containing gaseous mixture on the SI engine. The study suggests that with the increase in hydrogen fraction in syngas, cooling load is increased, and as a consequence of this, brake thermal efficiency, which initially increases with H_2 fraction, reduces at higher H_2 levels. Further, analysis of the heat release curves indicated a reduction in flame kernel development and fast burn phase duration, while the terminal phase duration increases because of the enhanced cooling of the un-burned mixture in the boundary layer.

III. Scope of Present Work

Based on the above literature review, it was quite clear that, owing to unique thermo-physical properties of PG, a significant variation in burn rate of PG was observed. In this work, the effect of known variation in PG composition along with heavy valve lift configuration (engines converted from CI to SI mode) was taken up to address the in-cylinder aspects of PG engines through modeling study.

TABLE I
Optimal Compositions of PG Fuel Sets with Varying Hydrogen and Methane Concentration

PG composition (% Vol.)	A	B	C	D	E	F	G	H	I	CNG
Hydrogen	16	16	16	19	19	19	22	22	22	--
Methane	1	2.5	4	1	2.5	4	1	2.5	4	95
Carbon-monoxide	18	18	18	18	18	18	18	18	18	--
Carbon-dioxide	12	12	12	12	12	12	12	12	12	--
Nitrogen	53	51.5	50	50	48.5	47	47	45.5	44	--
Ethane	--	--	--	--	--	--	--	--	--	5

TABLE II
Combustion Properties of PG blends at NTP condition

Properties	Units	A	B	C	D	E	F	G	H	I	CNG	Gasoline
Mol. Wt	g/mole	25.61	25.43	25.25	24.86	24.66	24.55	24.02	23.90	23.74	16.73	114
Phi	Kg/kg	1.09	1.06	0.94	1.15	1.13	1.16	1.15	1.18	0.97	1.00	1.44
Spark	BTDC	18	18	16	18	15	16	14	15	15	16	10
Density	Kg/m^3	1.065	1.058	1.05	1.034	1.026	1.021	0.999	0.994	0.987	0.695	4.73
$(A/F)_{sto}$	Kg/kg	1.028	1.189	1.36	1.133	1.308	1.484	1.276	1.438	1.614	17:1	14.7:1
LHV	MJ/kg	3.850	4.318	5.066	4.224	4.742	5.257	4.738	5.204	5.717	49.88	*44.4
$MHV_{Stoi.}$	MJ/kg	1.898	1.973	2.044	1.98	2.055	2.116	2.082	2.135	2.187	2.771	2.828

IV. Materials and Method

To estimate the influence of PG composition (hydrogen and methane) on engine combustion, nine optimal combinations of PG fuel sets (A to I) were formulated based on the moisture content of biomass feedstock which leads to hydrogen [15] and methane concentration variation via methanation reaction in the gasifier. These nine PG fuel sets represent the quality of PG produced from an open top, downdraft gasifier developed by the Indian Institute of Science, India [10]-[12]. The nine PG fuel set compositions are listed in Table I and the corresponding combustion properties are shown in Table II. Further, by adapting an electronic governor, the engine was operated at a constant speed of 1500 rpm. The engine was step-wise loaded via an eddy current dynamometer from no-load to full load. All engine data was acquired after the engine reached a stable operation condition. The data analyses presented in this work are specific to naturally aspirated, full load and CR: 11.

V. Experimental Set-up

Owing to the higher octane number of PG fuel and to explore the higher thermal efficiencies, a diesel engine with a higher compression ratio (18) was modified to spark ignition mode [13]. The specifications of engine are set out in Table III.

The cylinder head was equipped with a flush mounted uncooled Kistler make (6613CA) piezoelectric pressure transducer along with a built-in charge amplifier. Piston position was measured by a crank angle encoder of Kuebler make (8.5000.8352.0360) with 1° CA resolution. A pressure pegging was carried out to convert differential to absolute mode pressure signals based on the absolute manifold

pressure. Cylinder gas pressure and crank angle signals were acquired at 1 MHz acquisition frequency through a high speed data acquisition unit (SAM3X8E-MCU). The in-cylinder pressure traces and their derived parameters presented in this paper are of ensemble average values of 200 consecutive cycles. All engine experiments were performed close to stoichiometric condition. Gasoline carburetor was set to operate with factory settings itself. The PG flow rate was measured through a calibrated Orifice meter, while the CNG flow rate was measured through an electronic scale having 10 gram accuracy and gasoline through the standard burette method. Absolute output values ranging from 50% to full load were considered for the comparative studies of fuels. The induction system suitable for PG engine operation is an established work of the author and the details are presented elsewhere [14].

TABLE III
ENGINE SPECIFICATIONS

Parameters	Specifications
Engine make/ Model	Greaves Cotton Ltd., Model - 1533
Engine type	4-Stroke, single cylinder, air cooled.
Bore × stroke	82 × 68 mm
Displacement volume	0.359 Liters
Power output in SI mode	2.2kW at 1500 rpm for Gasoline

The experimental set-up is shown in Fig. 1 and a customized PG-air mixer was installed in the induction system, as shown in Fig. 2.

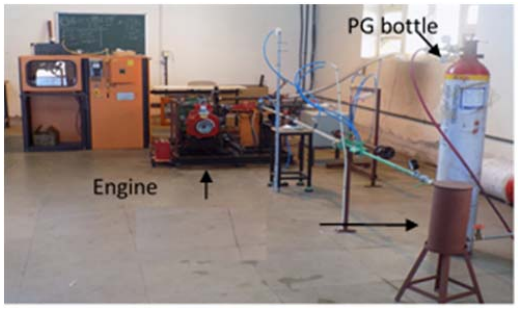

Fig. 1 PG experimental set-up

Fig. 2 PG air mixer

VI. METHODOLOGY

The methodology used to acquire and to calculate and engine data is given in the following steps:

1. All the combustion parameters discussed in this study were derived from in-cylinder pressure and crank angle.
2. Mass fraction burnt values were determined with an in-house developed MATLAB code based on the well-established Rassweiler and Withrow method, as described by (1) [16]-[18].

$$\mathrm{MFB} = \frac{m_b(i)}{m_b(\mathrm{total})} = \frac{\sum_{SOC}^{i} \Delta P}{\sum_{SOC}^{EOC} \Delta P} \quad (1)$$

3. Using the data obtained from Rassweiler and Withrow method MFB curves were drawn – representing the experimental plots.
4. The heat release values were calculated, by using energy equation derived from first law of thermodynamics, as expressed by (2) [19].

$$dQ/d\theta = (\gamma/(\gamma-1)\, P\, dV/d\theta + 1/(\gamma-1)\, V\, dP/d\theta)\, J/CA \quad (2)$$

where, $^{dQ}/_{d\theta}$ is the rate of heat release (J/CA), $^{dV}/_{d\theta}$ is the rate of volume change and $^{dP}/_{d\theta}$ is the rate of pressure variation with reference to crank angle.

5. Through curve fitting, the model constants of double stage Wiebe function were determined.

The overall steps of the analysis and dtaa acquisition can be seen in the methodology chart depicted in Fig. 3.

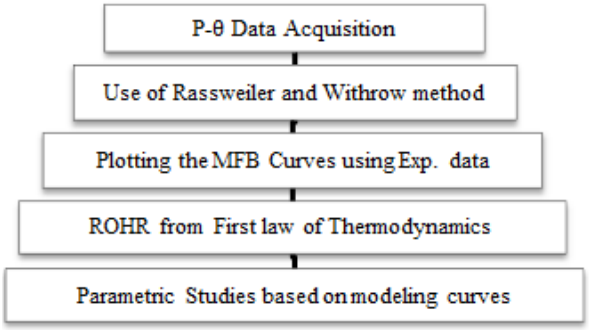

Fig. 3 Methodology Chart

VII. MODEL

A. Single Wiebe Function

Single Wiebe function is also known as the standard Wiebe function, which is based on the law of normal distribution of a continuous random variable. The model was developed by Russian engineer Ivanovitch Wiebe to study chain chemical reactions and later attempted to link it with fuel reaction rate in IC engines [6]. Now, standard Wiebe is widely used to study the burn rate characteristics in gasoline, dual fuel engines and other unusual engines to analyze combustion processes. The single Wiebe function can be expressed by (3):

$$x_b = 1 - \exp\left(-a\left(\frac{\theta-\theta_0}{\Delta\theta}\right)^{m+1}\right) \quad (3)$$

where 'x_b' represents the mass fraction burned, 'θ' is the crank

angle, $'\theta_0'$ is the crank angle at Start of combustion (SOC), $'\Delta\theta'$ is the combustion duration, 'a' is known as the Wiebe efficiency factor and 'm' is known as the Wiebe form or shape factor.

B. Double Wiebe Function

Double Wiebe function is a combination of two Wiebe functions that were developed by researchers to accurately simulate the heat release characteristics in diesel engine. Fuels with different thermo-physical properties are commonly represented by different values of 'a', 'm' and $'\Delta\theta'$ that cannot be implemented in the single Wiebe function [8]. As a result, the modified Wiebe function i.e. a combination of two Wiebe (dual stage Wiebe) is used to simulate the combustion characteristics. The double stage Wiebe function is expressed in (4):

$$x_b = X\left(1 - exp\left(-a_1\left(\frac{\theta-\theta_0}{\Delta\theta}\right)^{m_1+1}\right)\right) + (1-X)\left(1 - \exp\left(-a_1\left(\frac{\theta-\theta_0}{\Delta\theta}\right)^{m_1+1}\right)\right) \quad (4)$$

where 'x_b' represents the mass fraction burned, $'\theta'$ is the crank angle, $'\theta_0'$ is the crank angle at the start of combustion (SOC), $'\Delta\theta'$ is the combustion duration, '$a_1 and\ a_2$' are known as the Wiebe efficiency factors and '$m_1\ and\ m_2$' are known as the Wiebe shape factors and 'X' is known as the Scaling factor.

VIII. Inadequacy of Single Wiebe function

The single Wiebe function represents the fraction of fuel energy released (mass fraction burned) against the crank angle. The energy released typically takes the characteristic S shape in an SI engine. The 'S' shape mass fraction burnt profile is characterized by three parameters, namely:

i. Flame development angle (FDA) – representing the 10% MFB on abscissa,
i. Rapid burning angle (RBA) – representing the duration from 10% to 80% of MFB on abscissa. For the present work, 80% MFB was considered to understand the influence of hydrogen concentration, beyond which no significant improvement in combustion is observed.
i. Overall burning angle (OBA) – including the combustion duration from spark time to 90% MFB.

Depending upon the nature of mass fraction burnt curve the coefficient, 'a' and 'm' are adjusted to represent the experimental heat release analytically. For gasoline application, a =5 & m=2 was found to fit the experimental data [20].

Shivapuji [21] reported that significant deviation in the heat release profiles have been observed between conventional fuels and PG after 50% of MFB. Therefore, coefficients 'a' and 'm' were curve fitted accordingly, as 2.4 and 0.7, for PG fuelled in a gas engine. However, the exact PG composition, for which the MFB curves were analyzed, was not clear. When MFB curves were analyzed through single Wiebe function based on the present engine configuration, the burn rate trend was not captured adequately, as shown in Figs. 4 (a)-(c).

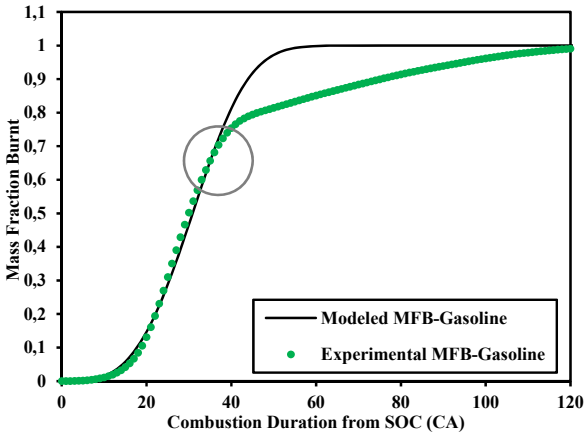

Fig. 4 (a) Comparison of Experimental and single Wiebe modeled curves of Gasoline operation at WOT, Phi=1.44, rpm=1500 and modeled coefficients a=140, m=2.4

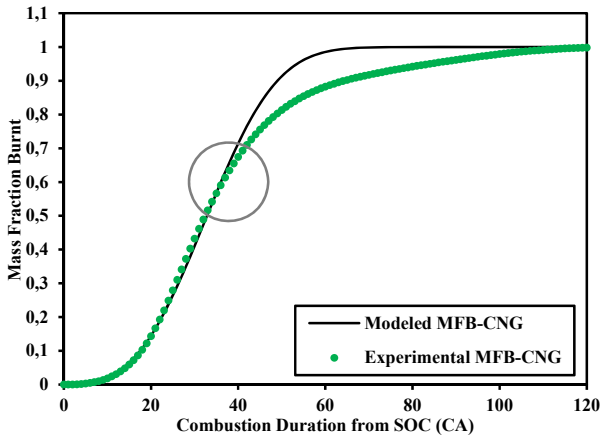

Fig. 4 (b) Comparison of Experimental and single Wiebe modeled curves of CNG operation at WOT, Phi=1.09, rpm=1500 and modeled coefficients a=45, m=2

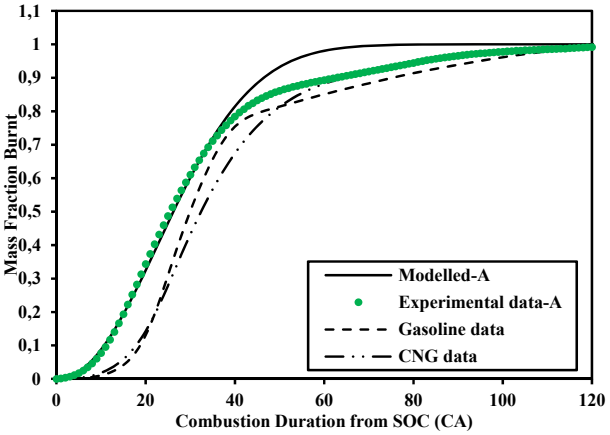

Fig. 4 (c) Comparison of Experimental and single Wiebe modeled curves of PG Set-A operation at WOT, Phi=1, rpm=1500 and modeled coefficients a=22, m=1.1

Based on the observation from Figs. 4 (a)-(c), it is clear that in present work also, the MFB curves have undergone a significant change in slope after 50% MFB, indicating a slow burning of fuels. The reason for the undesirable slope variation is attributed to (i) Typical valve lift setting of the engine, since the present engine was modified from CI to SI engine mode, and secondly, (ii) Unique combustion properties of PG blends. Therefore, it is clear that single stage Wiebe function was not suitable for the present engine configuration.

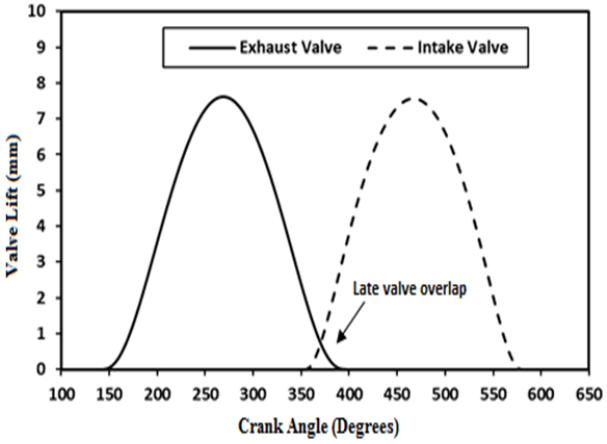

Fig. 5 Unsymmetrical negative valve overlap for specified engine

A. Influence of Valve Lift Timing on Engine Operation

The valve lift timing for the present engine is shown in Fig. 5. The valve timing depicts a negative asymmetrical overlap period of 41° CA, which typically dilute the fresh incoming change by the left over residual gases of the previous cycle. This response from the gasoline and CNG operation is shown in Figs. 4 (a) and (b). Further, a similar observation was reported by [22] when a heavy overlap valve timing engine was operated with gasoline. The research shows single stage Wiebe function's inadequacy to fit the experimental MFB curve, as shown in Fig. 6. Therefore, it may be concluded that, irrespective of the fuel used in present engine configuration, the valve lift timing has a significant impact on engine operation and its performance.

B. Suitability of two Stage Wiebe Function for PG

The advantage of the two stage Wiebe function lies in modeling the unique mass fraction burned curves by adjusting the coefficients. For the kind of response shown in Figs. 4 (a)-(c), a need for modeling the MFB curve in two phases arises, as shown in Fig. 7. Therefore, the two stage Wiebe function was considered as an ideal function to approximate the MFB trend for PG with the present engine configuration (valve timing).

IX. Results and Discussions

The effect of variation in PG composition on combustion characteristics were investigated through mass fraction burned curves. For each load the engine was operated at to Maximum Brake Torque spark time, by following the spark sweep test.

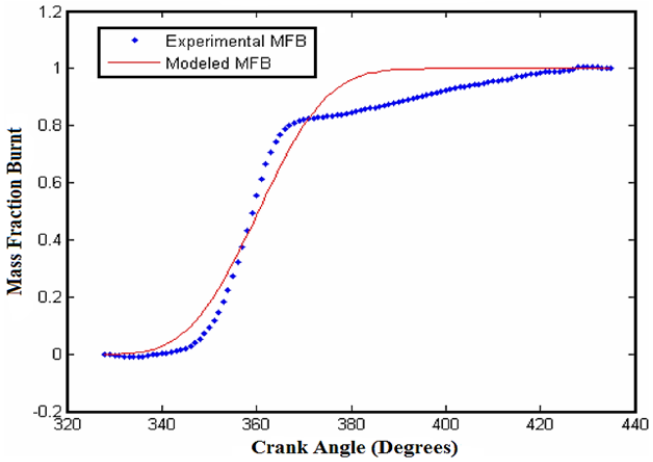

Fig. 6 Inadequacy of Single Wiebe for heavy valve overlap [20]

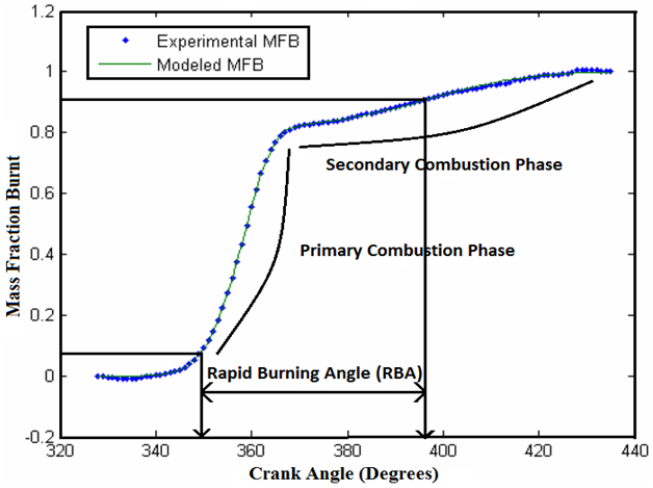

Fig. 7 Phases of combustion processes in dual Wiebe function [22]

TABLE IV
Variation in Model Constants for Fuels

Coefficient	Literature reported values for Gasoline [22]	Present Work for all PG fuel sets	Accuracy
x	0.5 to 0.9	0.76 to 0.86	--
a_1	10 to 2000	30 to 375	± 5
m_1	2 to 9	1.26 to 2.77	± 0.02
a_2	3 to 37	5 to 6.4	± 1
m_2	2 to 8	1.7 to 2	± 0.02

Fig. 8 shows modeled and experimental MFB curves of nine PG blends individually with conventional fuels i.e. gasoline and CNG. The combustion modeling was done using the experimental mass fraction burned (MFB) curves as a reference and the modeled curves were curve fitted using the double stage Wiebe model to approximate the overall burning trend of PG fuel sets. The operating parameters and experimental MFB duration data are listed in Table V.

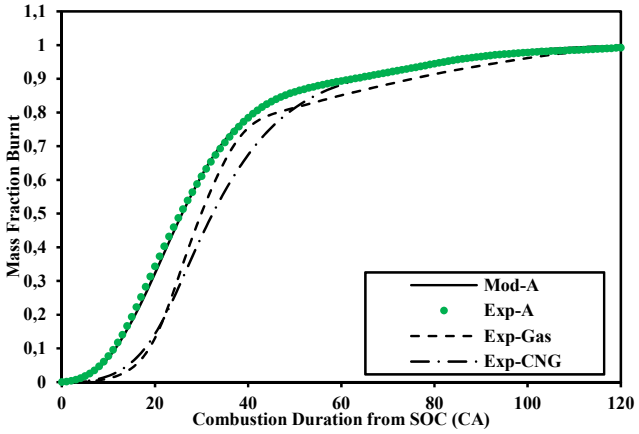

Fig. 8 (a) Comparison of Experimental and dual Wiebe modeled curves of PG Set-A operation at WOT, Phi=1.09, rpm=1500 and modeled coefficients x=0.82, a_1=52, m_1=1.43, a_2=6, m_2=2

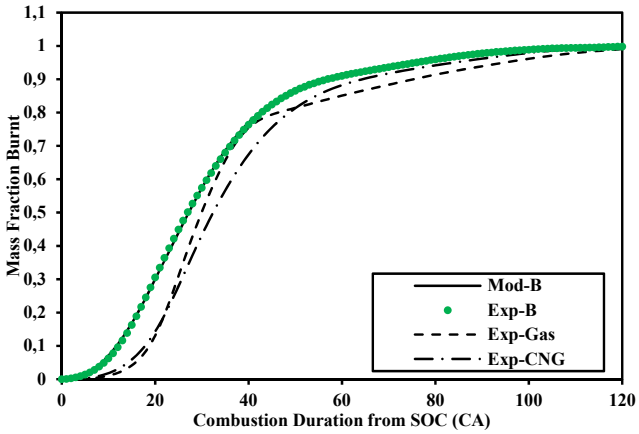

Fig. 8 (b) Comparison of Experimental and dual Wiebe modeled curves of PG Set-B operation at WOT, Phi=1.06, rpm=1500 and modeled coefficients x=0.85, a_1=30, m_1=1.31, a_2=5, m_2=2

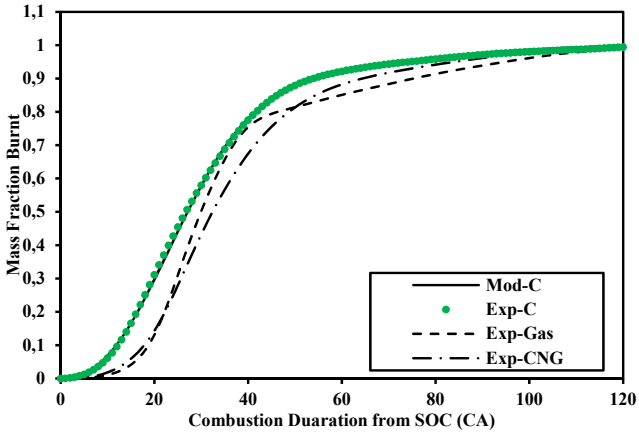

Fig. 8 (c) Comparison of Experimental and dual Wiebe modeled curves of PG Set-C operation at WOT, Phi=0.94, rpm=1500 and modeled coefficients x=0.86, a_1=35, m_1=1.35, a_2=5, m_2=1.75

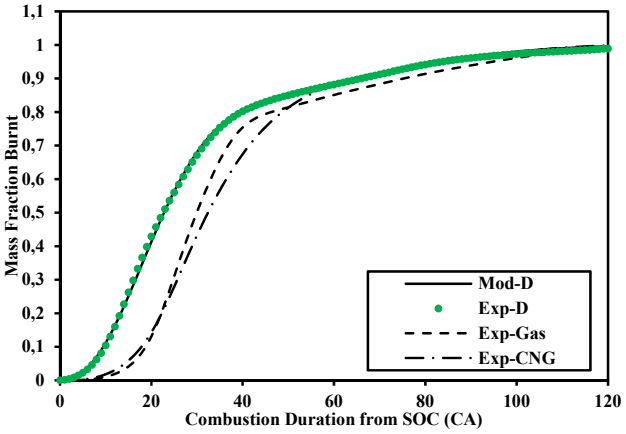

Fig. 8 (d) Comparison of Experimental and dual Wiebe modeled curves of PG Set-D operation at WOT, Phi=1.15, rpm=1500 and modeled coefficients x=0.80, a_1=60, m_1=1.26, a_2=6.3, m_2=1.88

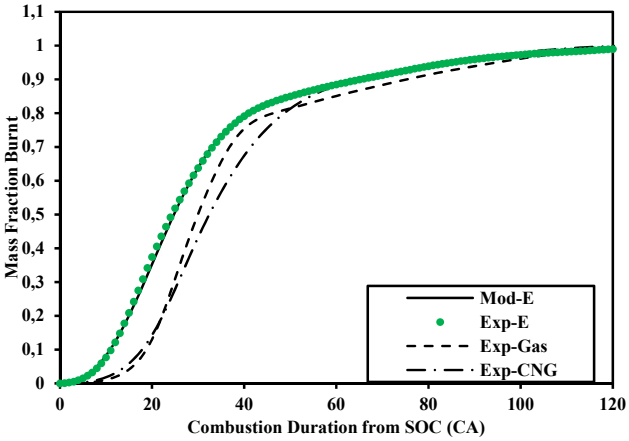

Fig. 8 (e) Comparison of Experimental and dual Wiebe modeled curves of PG Set-E operation at WOT, Phi=1.13, rpm=1500 and modeled coefficients x=0.80, a_1=60, m_1=1.41, a_2=5.3, m_2=1.8

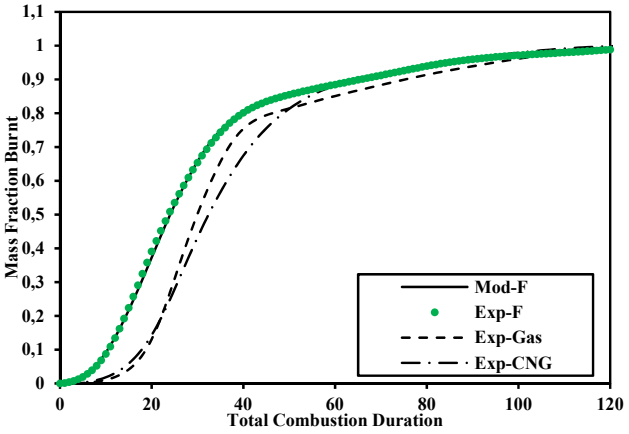

Fig. 8 (f) Comparison of Experimental and dual Wiebe modeled curves of PG Set-F operation at WOT, Phi=1.16, rpm=1500 and modeled coefficients x=0.82, a_1=66, m_1=1.35, a_2=6, m_2=1.85

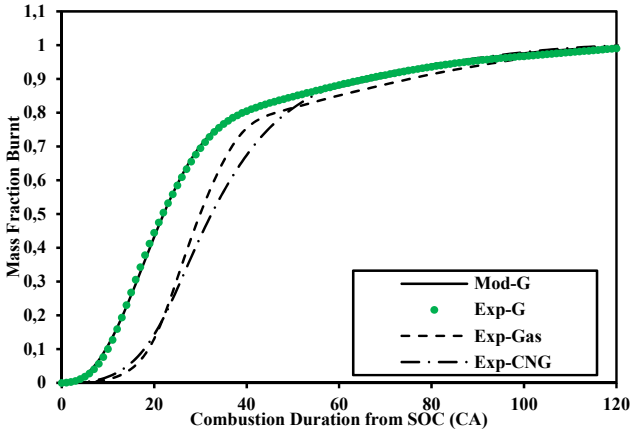

Fig. 8 (g) Comparison of Experimental and dual Wiebe modeled curves of PG Set-G operation at WOT, Phi=1.15, rpm=1500 and modeled coefficients x=0.785, a_1=75, m_1=1.38, a_2=5, m_2=1.7

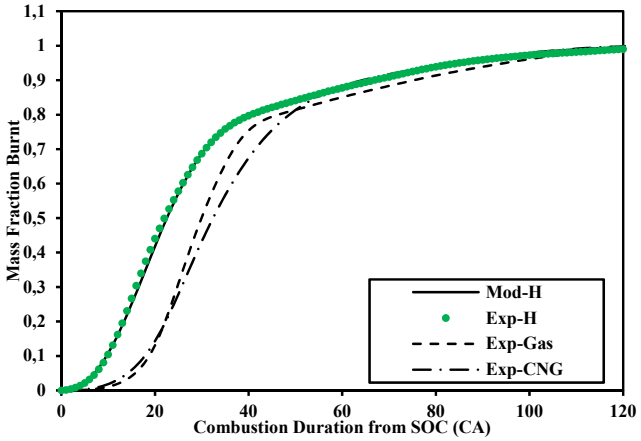

Fig. 8 (h) Comparison of Experimental and dual Wiebe modeled curves of PG Set-H operation at WOT, Phi=1.18, rpm=1500 and modeled coefficients x=0.783, a_1=70, m_1=1.35, a_2=5.7, m_2=1.8

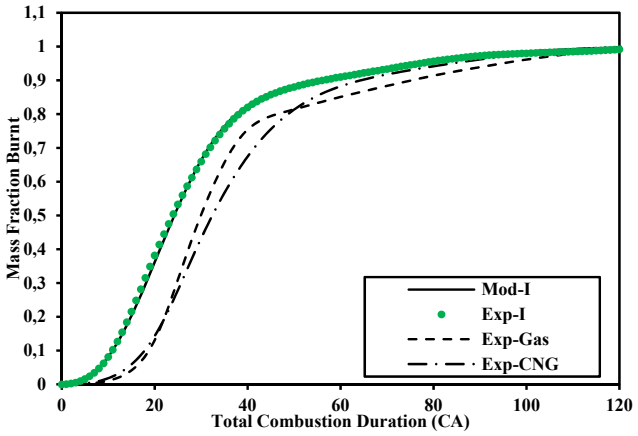

Fig. 8 (i) Comparison of Experimental and dual Wiebe modeled curves of PG Set-I operation at WOT, Phi=0.97, rpm=1500 and modeled coefficients x=0.84, a_1=65, m_1=1.45, a_2=6, m_2=1.8

The model constants for the nine PG blends are tuned to the experimental curves and are mentioned in Table VI. The Wiebe coefficients for the double stage model are found to be very sensitive. Accuracy of curve fitting for the present work is set out in Table IV. Among the coefficients of the double stage Wiebe function, form or shape factors were very sensitive, as shown in Table IV, signifying the importance of combustion dynamics. It can be seen from Table V that the conventional fuels i.e. gasoline and compressed natural gas (CNG) are lagging in the combustion process during the entire combustion duration (FDA, 50% MFB, RBA) in comparison to all the nine PG blends. The reason for slow burning (RBA= 39° CA) of the baseline gasoline fuel can be attributed to the higher equivalence ratio owing to the factory settings of the gasoline carburetor and heavy asymmetrical overlap which leads to lower peak pressure and lower break thermal efficiency in comparison to PG blends (RBA< 31° CA). Similar observation related to combustion behavior has been made with CNG fuel, which burns slowly (RBA= 32° CA) as compared to the all the PG blends (RBA< 31° CA) due to the presence of slower burning methane molecules in higher concentration and unsymmetrical overlap which leads to a lag in the overall combustion period.

A. Parametric Studies

From Fig. 8, Set-(A, D, G), (B, E, H), (C, F, I), with increasing hydrogen percentage (16-22%) while keeping the methane concentration constant (1 or 2.5 or 4%), it is evident that the slope of the MFB curves tend to increase during the primary phase of combustion, which indicates potential for rapid combustion owing to higher mixture reactivity. This fact is in agreement with the literature and can be observed from a decreasing trend in values of 10%, 50%, and 80% MFB and RBA duration. However, in the secondary phase of combustion, PG blends with higher hydrogen concentration reflected slow burning characteristics after a rapid burning period, leading to overall increase in combustion duration and can be seen with increasing values of 90% MFB duration.

PG Set-(A, B, C), (D, E, F), (G, H, I), with increasing methane percentage (1-4%) while keeping the hydrogen concentration constant (16%, 19% or 22%), it can be observed that the slope of the MFB curves is decreasing during the primary phase of combustion which tends to increase the rapid burning period from a 1% to 2.5% increase, while the opposite trend has been observed with further increase in the methane percentage from 2.5% to 4%. Contrary to this, the PG set with the higher methane concentration is burning faster during the secondary phase of combustion.

The reason for rapid combustion of PG in the primary phase is attributed to the presence of hydrogen (releasing many O and OH radicals) in the PG mixture combustion – known as combustion accelerator. While the reason for faster burning of methane in the secondary phase is attributed to the tetrahedral structure of methane molecules requiring a higher temperature to break the bond strength. This required temperature at the secondary phase is complemented by the combustion temperature arising from the primary phase. The other reason

that can be attributed, is the large differences in the thermo-physical property of the two fuel components (Hydrogen and Methane), such as laminar flame speed (365-325 cm/s for H_2 and for 37-45 cm/s for CH_4) and volumetric energy density (8.4-10.4 MJ/L for H_2 and 21MJ/L for CH_4 [23]).

TABLE V
COMBUSTION DURATION AND OPERATING PARAMETERS FOR DIFFERENT PG SETS

PRM	A	B	C	D	E	F	G	H	I	GAS	CNG
Phi	1.09	1.06	0.94	1.15	1.13	1.16	1.15	1.18	0.97	1.44	1.0
Spark	18	18	16	18	15	16	14	15	15	10	16
Peak Pr.	31.9	31.3	31.3	37.3	34.1	33.1	35.6	35.8	34.8	33.2	32.3
Experimental MFB values from spark time											
10%	12	13	13	10	12	11	10	10	11	19	18
50%	26	27	27	23	25	24	22	23	24	30	32
80%	42	44	42	38	41	39	37	39	38	54	48
90%	63	57	54	67	66	66	66	67	57	76	63
RBA	30	31	29	28	29	28	27	29	27	35	30

TABLE VI
CURVE FITTED MODEL CONSTANTS OF SPECIFIC ENGINE GEOMETRY AT WOT FOR PG BLENDS

Parameters	A	B	C	D	E	F	G	H	I	Gasoline	CNG
x	0.82	0.85	0.86	0.80	0.80	0.82	0.785	0.783	0.84	0.76	0.818
a_1	52	30	35	60	60	66	75	70	65	375	49
m_1	1.43	1.31	1.35	1.26	1.41	1.35	1.38	1.35	1.45	2.77	1.93
a_2	6	5	5	6.3	5.3	6	5	5.7	6	6.4	5.5
m_2	2	2	1.75	1.88	1.8	1.85	1.7	1.80	1.8	1.98	2

X. CONCLUSION

The main objective of the paper was to address the influence of heavy valve overlap on the PG combustion process using a double stage Wiebe combustion model. The main outcomes of the work are as follows:

1. Owing to asymmetrical negative valve overlap and the unique combustion properties of PG, the MFB curves of PG fuel sets were observed to undergo change in slope after 70% MFB. This type of MFB trends potentially affects the power output of engine by prolonging overall combustion duration.
2. Double stage Wiebe function was found to be the best suitable combustion model to estimate the heat release for PG fuelled engine with heavy valve overlap valve timing.
3. Wiebe model constants for all the nine optimal PG blends were established and validated against experimental curves. This data is useful in predicting the engine performance.
4. Based on the MFB trends, it was observed that, the combustion process in the secondary phase of a MFB curve was complemented by the combustion temperature arising due to presence of hydrogen concentration in the primary phase.
5. In comparison, 50% MFB crank angle was inferred as the robust combustion parameter for closed loop engine control.

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REFERENCES

[1] H.C. Butterman, M.J. Castaldi, "CO2 as carbon neutral source via enhanced biomasss gasification." Envir. Sci. Tech. No.23, 2009; Vol. 43, pp. 9030 – 9037.

[2] Babu MS, Clement S., Rajan NKS, "Biomass based green technologies-Potential and sustainability." Bio-Energy India. 2011; Vol. 9&10: pp. 20 – 23. Access Link: http://biomasspower.gov.in/document/Magazines/Bioenergy%20Magazine-MNRE/Issue%209%20&%2010%20-%20Jul%20-%20Dec%202011.pdf

[3] G. Litak, T. Kamińsk, J. Czarnigowski, A. K. Sen, M. Wendeker (2009), "Combustion process in a spark ignition engine: analysis of cycle peak pressure and peak pressure angle oscillations", Int. J. of Meccanica, vol. 44, pp. 1 -11.

[4] G. Sridhar, P.J. Paul, H.S. Mukunda (2005), "Computational studies of the laminar burning velocity of a producer gas and air mixture under typical engine conditions", Proc. IMechE, Int. J. of Power and Energy, vol. 219(3), pp. 195 – 201.

[5] A.M. Shivapuji, S. Dasappa, "In-cylinder investigations and analysis of a SI gas engine fuelled with H_2 and CO rich syngas fuel: Sensitivity analysis of combustion descriptors for engine diagnostics and control", Int. J. of Hydrogen Energy, Vol.39, September 2014, pp. 15786–15802.

[6] J I Ghozel, "Review of the development and applications of the Wiebe function: atribute to the contribution of Ivan Wiebe to engine research" International Journal of Engine Research, Vol.11, DOI: 10.1243/14680874JER06510, May 2010.

[7] Yasar, H., Soyhan, H. S., Walmsley, H., Head, B., and Sorusbay, C. Double-Wiebe function: an approach for single-zone HCCI engine modelling. Appl. Thermal Engng, 2008, Vol. 28, pp. 1284–1290.

[8] Firmansyah, Abdul Rashid, Abdul Aziz and Morgan Raymond Heikal, "Double Stage Wiebe: An approach to Single Zone Modeling of Dual Fuel HCCI Combustion", Asian Journal of Scientific Research, Vol. 6, Number 2, pp. 388-394, 2013

[9] Anand M Shivapuji and S Dasappa, "Influence of fuel hydrogen fraction on syngas fueled SI Engine: Fuel Thermo-physical property analysis and in-cylinder experimental investigations", Int J of Hydrogen energy, Vol. 40, pp. 10308-10328, August 2015.

[10] S. Dasappa, HS Mukunda, PJPaul, NKS Rajan, G. Sridhar, HV Sridhar (2008), "A process and apparatus for cleaning Tar and Dust laden gas to

highest level of purity using Cn Technology", Indian Patent granted No. 215917 DATE 2008.
[11] H.S. Mukunda (2011), "Understanding clean energy and fuels from biomass" Wiley India, Publications, New Delhi, India.
[12] A. Arunachalam, D.B. Oslen (2012), "Experimental evaluation of knock characteristics of producer gas", Int. J. of Biomass and Bioenergy, vol. 37, pp. 169 – 176.
[13] M.S. Babu, S. Clement, N.K.S Ranjan, "Fuel conversion benefit of producer gas over gasoline: An Experimental study", *Energy procedia*, Volume 100, pp. 203 – 209. International Conference on Power and Energy Systems Engineering, CPESE 2016, Kitakyushu, Japan.
[14] M.S. Babu, S. Clement, N.K.S. Rajan (2016), "Development and testing of laboratory scale induction system fuelled with bottled producer gas", Int. J. of Applied Mechanics and Materials, vol. 852, pp. 659 – 665.
[15] M. Kumar, B. Paul, D.S. Yadav, "Effect of Moisture content and equivalence ratio on the gasification process for different biomass fuel", Int. J of Mech Engneering and Tech. (IJMET), Vol. 7, Nov–Dec 2016, pp.209–220
[16] Gerald M. Rassweiler and Lloyd Withrow, "Motion Picture of Engine Flames Correlated with Pressure cards", SAE Technical Paper 380139, 1938, doi: 10.4271/380139.
[17] P.J. Shayler, M.W. Wiseman and T. Ma, "Improving the Determination of Mass Fraction Burnt", SAE Technical Paper 900351, 1990, doi: 10.4271/900351.
[18] J.B. Heywood, *Internal combustion engine fundamentals*, Tata McGraw Hill, New Delhi, 2011.
[19] C.R. Ferguson and Allen T. Kirkpatrick, Internal combustion engines, Wiley India publications, 2nd Edition, 2011.
[20] B.P. Pundir, IC Engines: Combustion and Emissions, Narosa publications, 1st Edition, 2010.
[21] A.M. Shivapuji, S.Dasappa (2012)," Experimental and zero D Modelling studies using specific Wiebe coefficient for producer gas as a fuel in spark ignited ignines", Proc. IMechE, Int.J.of Power and Energy, vol. 227(3), pp. 504 - 519.
[22] J. Meyer, Engine modeling of an internal combustion engine with twin independent cam phasing, undergraduate thesis, Ohio State University, 2007.
[23] G. Thomas, "Overview of hydrogen development DOE Hydrogen program", Hydrogen program review. Accessed on 27/11/2016 http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/storage.pdf