STATISTICAL APPROACH TO CHARACTERIZE COMBUSTION KNOCK IN THE HYDROGEN FUELLED SI ENGINE

Jeffrey D. Naber, Stanislaw Szwaja

Michigan Technological University
Mechanical Engineering, - Engineering Mechanics Department
815 R.L. Smith Bldg., 1400 Townsend Drive, 49931 Houghton, MI, USA
tel.: +1 906 487 1938, fax.: +1 906 487 2822
e-mail: jnaber@mtu.edu

Czestochowa University of Technology
Institute of Internal Combustion Engines and Control Engineering
Al. Armii Krajowej 21, 42-200 Częstochowa, Poland
tel.: +48 34 3250507, fax.: +48 34 3250555
e-mail: szwaja@imc.pcz.czest.pl

Abstract

Combustion knock in a hydrogen fuelled engine has many different characteristic as compared to knock occurring in the gasoline engine. This is a result of differences in the gasoline and hydrogen combustion mechanisms which lead to knock. Hydrogen as the engine fuel is able to produce combustion knock of significant intensity. This intensity can be determined by measurements, which have been successfully applied for examining knock generated by the gasoline fuelled engine. This paper describes the engine test bed, in-cylinder pressure traces and methods for determining knock intensity. Further, the statistical approach for characterizing combustion knock is also presented. It concentrates on applications of several probability distributions for expressing individual knock intensity metrics of hydrogen port fuelled spark ignited engine. It is assumed that knock metrics for engine working cycles are considered as random variables. The knock metrics are based on the fluctuation component of the in-cylinder pressure traces sampled at 100 kHz and are calculated for 300 consecutive engine working cycles. It was noticed that the knock metrics distribution profile changes as the knock intensity varies from light to heavy knock. In the paper, modelling of this knock distribution profile using several known stochastic distributions is also presented. Finally, usefulness of statistical distributions for characterizing combustion knock is shown.

Keywords: *internal combustion engines, combustion knock, hydrogen, statistical distribution*

1. Introduction

Knock occurring during combustion in the IC engine is an undesired phenomena which can lead to rapid damage of engine elements, particularly the piston crown. Hydrogen as an IC engine fuel is prone to generate knock as discussed by Tang et al. [1], although several of its properties such as a high flame speed and relatively high autoignition temperature suggest antiknock characteristics of this fuel. Furthermore, hydrogen combustion knock is different than gasoline knock because of the lower variance in ignition delay (0-10% mass fraction burned), and as the pressure fluctuations can follow immediately after the start of combustion as shown in Figure 1. In Figure 1, the filtered in-cylinder pressure (band-pass filter with 4.5kHz and 15kHz cutoff frequencies) of an individual combustion cycle is shown. As can be seen, the pressure oscillations, indicating combustion knock start only shortly after the ignition timing of -5°.

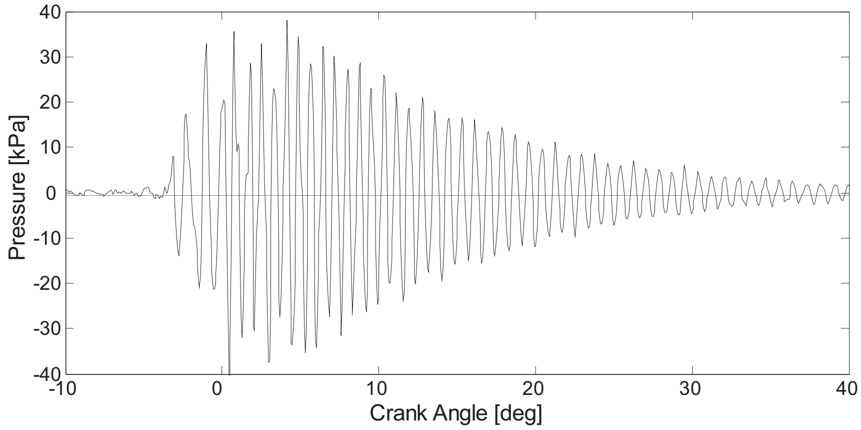

Fig. 1. High-frequency (band-pass filtered) fluctuating component of the in-cylinder pressure during hydrogen combustion ($\lambda=1$, Ignition Timing = -5°ATDC, CR=9)

The combustion knock level occurring in an IC engine can be quantified based upon the high frequency fluctuating in-cylinder pressure component recorded during the combustion process. It can be expressed by the *PI* knock metric defined as follows by a number of investigators including Naber et al. [2]:

$$PI(N) = \frac{1}{t_2 - t_1} \int_{t_1=t(\theta_1)}^{t_2=t(\theta_2)} \left| p_f(t) \right| dt = \frac{1}{N} \sum_{i=1}^{N} \left| p_f(i) \right|, \tag{1}$$

where:

i - individual combustion event,
N - number of combustion events,
PI - pressure Intensity of the fluctuation component of the in-cylinder pressure,
p_f - fluctuation component of in-cylinder pressure (band-pass filter 4.5-15kHz in this work,
t_2-t_1 - window of combustion knock.

The *PI* metric calculated for an individual combustion event can vary significantly even if the engine works under strictly fixed operating conditions as the result of the stochastic characteristics during early flame propagation and other engine processes. Thus, the distribution of *PI* metrics can be assumed as random variable and several statistical tools can be applied for its description. (Fig. 2).

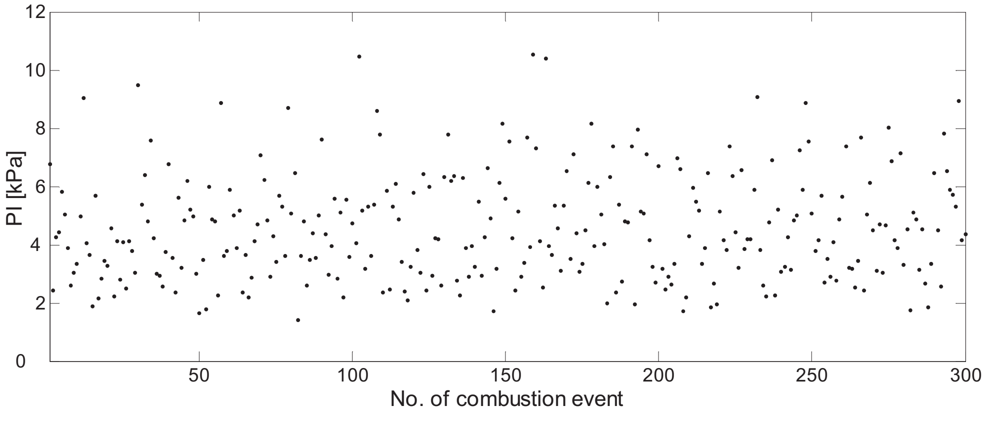

Fig. 2. The PI metrics for individual 300 consecutive combustion events pressure during hydrogen combustion ($\lambda=1$, Ignition Timing = -5°ATDC, CR=9)

2. Statistic Description

The data from in-cylinder combustion pressure consists of 300 consecutive combustion events, for which *PI* was determined from Eq. 1. For modelling the *PI* distribution, the following statistical distributions were examined:

a) Normal distribution: This is a common continuous distribution applied in various cases that is useful in describing many random processes.
b) Log-normal distribution: This is a continuous distribution in which the logarithm of the independent variable has a normal distribution.
c) Weibull distribution: This is a three parameter distribution that has been commonly applied in reliability analysis.

In the Table 1, the probability density functions (*pdf*) and cumulative distribution functions (*cdf*) for the three distributions are showed.

Tab. 1. Model distribution functions

Distribution Type	**pdf**	**cdf**
Normal Distribution	$P(x)=\frac{1}{\sigma\sqrt{2\pi}}\exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right)$	$C(x)=\frac{1}{2}\left(1+erf\,\frac{x-\mu}{\sigma\sqrt{2}}\right)$
Log Normal Distribution	$P(x)=\frac{1}{x\sigma_{\ln}^2\sqrt{2\pi}}\exp\left(\frac{-(\ln x-\mu_{\ln})^2}{2\sigma_{\ln}^2}\right)$	$C(x)=\frac{1}{2}\left(1+erf\,\frac{\ln(x)-\mu_{\ln}}{\sigma_{\ln}^2\sqrt{2}}\right)$
Weibull Distribution	$P(x)=\frac{\varphi}{\delta}\left(\frac{x-\gamma}{\delta}\right)^{\varphi-1}\exp\left(-\left(\frac{x-\gamma}{\delta}\right)^{\varphi}\right)$	$C(x)=1-e\left(-\left(\frac{x-\gamma}{\delta}\right)^{\varphi}\right)$

where:

x - independent variable,
μ - mean value of x,
σ - standard deviation of x,
$\mu_{\ln}$ - mean value of distribution of $\ln(x)$,
$\sigma_{\ln}$ - standard deviation of distribution of $\ln(x)$,
δ - shape parameter,
γ - location parameter,
φ - scale parameter,
erf - error function,

For the purpose of combustion knock distributions, we will assume that the Weibull location parameter $\gamma = 0$, such that the Weibull modelled distribution fit starts from 0.

3. Test-bed Description

The engine used for this research is a single cylinder CFR (Cooperative Fuels Research) engine manufactured by the Waukesha Motor Company. The engine was chosen for its versatility and robustness of construction which is important because of the intended study of combustion knock. A specialized attribute of this engine is the ability to vary the compression ratio without disassembling the engine. Numerous modifications to the engine were made to meet the requirements in these studies. This included changing the compression ratio of the engine by modifying the piston. The modified piston increased the range of compression ratio, that could be studied from 4–10 to 4.5–17.5.

Engine control and monitoring was performed using a target-based rapid-prototyping system [3] with the electronic sensors and actuators installed on the engine. Sensors monitored flow rate, pressure, and temperature of the working fluid at various regions of the engine along with engine position determined from a sensor on the crankshaft. Sensors included mass-air-flow (MAF), manifold absolute pressure (MAP), wide-band air/fuel ratio (UEGO), and crank position sensor. Electronic actuators included a digital ignition coil, throttle, EGR valve, and port fuel injectors for both liquid (gasoline) and gaseous (hydrogen) fuels.

The pressure data were acquired with a National Instruments BN-2111 analog to digital converter (100 kSamples/second-channel) on the Waukesha CFR engine test bed.

The data were recorded at constant air to fuel ratio respective for stoichiometric combustion (λ=1) and at variable spark timings and compression ratios.

The complete test bed is presented in the Figure 3.

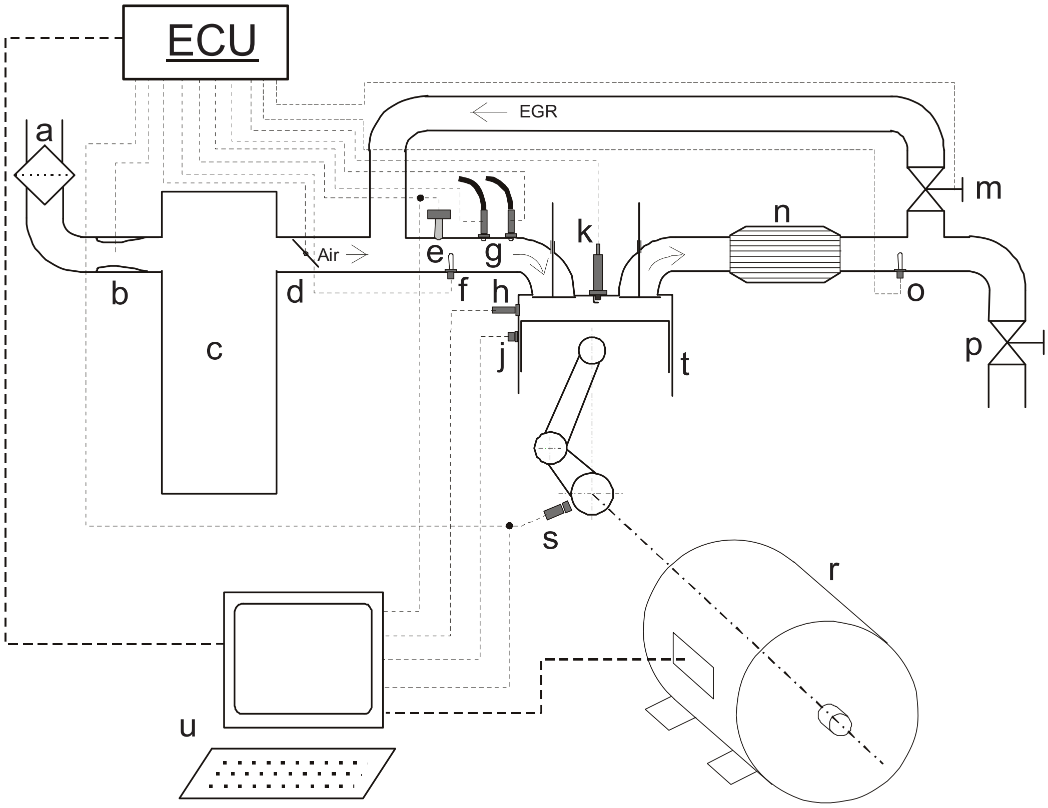

Fig. 3. Test-bed

where: a – dust filter, b – MAF, c – surge tank, d – throttle, e – MAP, f, o – UEGO sensors, g – gasoline and hydrogen injectors, h – pressure transducer, j – accelerometer, k – ignition system, m – EGR valve, n – 3-way catalytic converter, p – gate valve, r – dynamometer, s – crank angle encoder, u – workstation, ECU – electronic control unit

4. Results

The individual test series consists of 300 consecutive combustion events, for the each combustion event the *PI* was determined. The set of these values can be presented as the experimental probability density function (*pdf*) of the *PI* as shown in the data bars in the plots in Figure 3. Figure 3 shows the *pdfs* of data in separate plots for light, moderate and heavy knock with PI levels extending to 10.5, 35, and 80kPa respectively. The test conditions for these three tests are listed in Table 2.

Tab. 2. Test conditions for knock levels

Knock Level	Ignition Timing	Compression Ratio	λ	EGR (%)
Light	-5 deg ATDC	9	1.0	0
Moderate	5 deg ATDC	12	1.0	0
Heavy	0 deg ATDC	12	1.0	0

In addition to the experimentally measured data distributions shown in Figure 3 are *pdf* fits to the data distributions of the three model distributions given in Table 1 (normal, log-normal, and Weibull). In reviewing Figure 3 a number of observations are made. First, the log-normal model estimates the peak in the *pdf* at a lower *PI* and with a higher value than either the normal or Weibull models. Examining the fits for the low levels of *PI*, the log-normal fits are closer to the experimental data than either the normal or Weibull *pdf* models. Additional details with respect to the models and there fit to the data will be examined later in comparison of the *cdf*s.

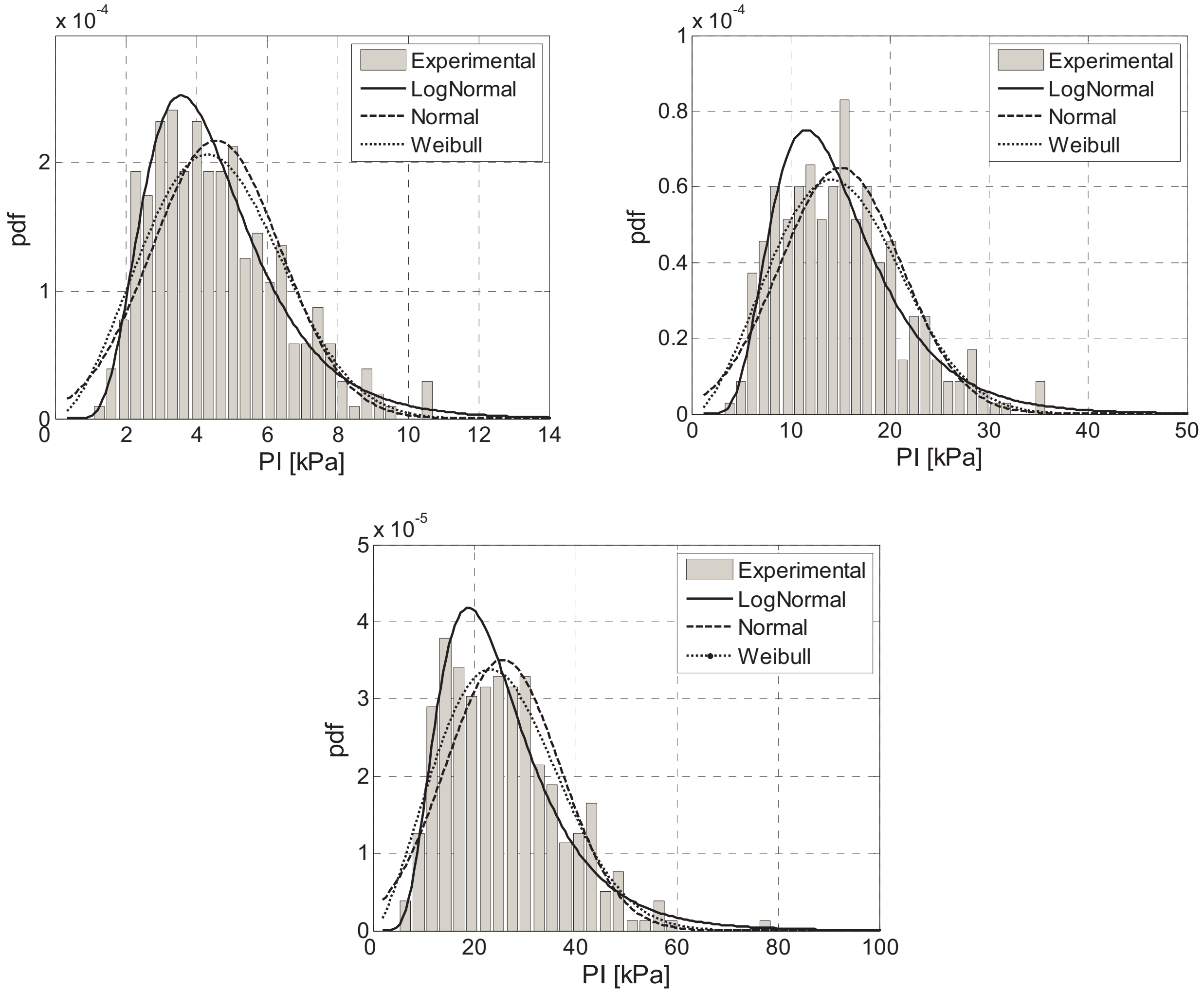

Fig. 4. PI distributions of light (top left), moderate (top right), and heavy (bottom) knock

As showed in the diagrams in Figure 3, all the experimental distributions of *PI* are skewed. The skewness of the each distribution is presented in the Table 3, as determined by the skewness parameter given in Eq. 2. For the skewness parameter, a value greater than 0 indicates a positive skewness, that is a longer tail in the positive direction and a value of 0 indicates no skewness. The skewness parameters are all positive as listed in Table 3 and they are nearly at the same value, although experimental distribution of ultra heavy knock becomes more symmetric as presented by Szwaja et al. [4].

$$Skewness = \frac{\sum_i \left(PI_i - mean\left(PI\right)\right)^3}{\left[\sum_i \left(PI_i - mean\left(PI\right)\right)^2\right]^{\frac{3}{2}}}. \tag{2}$$

Tab. 3. Skewness of the experimental data

Knock Level	Skewness
Light	0.738
Moderate	0.717
Heavy	0.812

Examining Figure 3 one notes that only the log-normal and Weibull distributions can produce skewed distributions as a normal distribution is symmetric.

One can make a comparison of the goodness of the fits of the model distributions to the experimental data distributions by the coefficient of multiple determinations (CoMD) [2] which was determined from:

$$CoMD = \frac{\sum_{j=1}^{n}\left(y_j - \bar{y}_j\right)^2 - \sum_{j=1}^{n}\left(y_j - \hat{y}_j\right)^2}{\sum_{j=1}^{n}\left(y_j - \bar{y}_j\right)^2}, \tag{3}$$

where:

y - *pdf* from the experimental distribution,

$\bar{y}$ - mean of the experimental *pdf*,

$\hat{y}$ - *pdf* from the model distribution,

j - evaluations of experimental and model distributions as shown in Figure 3 by the data bars.

A CoMD of 1 indicates an exact fit of the model distribution to the data distribution, and as the CoMD decreases it indicates a poorer fit. In Table 4 the coefficients of multiple determinations for the three modelled distributions and three knock levels are shown. Table 4 shows that the log-normal and Weibull distributions have improved fits (higher CoMD's) as compared to the normal distribution which as discussed above does not characterize the experimental skewness. Comparing the log-normal and Weibull distributions, they have similar CoMD's, with only the log-normal having a significantly higher CoMD at the light knock level.

Tab. 4. Coefficients of Multiple Determinations for model distributions

Knock Level	Normal Distribution	Log Normal Distribution	Weibull Distribution
Light	0.818	0.931	0.871
Moderate	0.845	0.872	0.883
Heavy	0.866	0.924	0.922

Figure 5 compares the experimental cumulative distribution functions (*cdf*) to the model *cdf*s for the moderate knock level shown in the top right plot of Figure 4 and details given in the tables above. Figure 5 is broken into four plots. The first plot (i) at the top left shows the entire *cdf* over the *PI* range from 0 to 50kPa, the second (ii) at the top right the *cdf* in the low range (0 to 0.15), the third (iii) at the bottom left the *cdf* in the mid-range (0.45 to 0.55), and the fourth (iv) at the bottom right the *cdf* in the high range (0.85 to 1.0). Examining Figure 5(i) it can be seen that all three model *cdf*s cover a similar domain in *PI* as the experimental *cdf*. For plot 5(ii) only the log-normal fits the experimental *cdf* in the range 0-0.05. This is consistent with the observations previously discussed with respect to the *pdf*s. For plot 5(iii) the log-normal under predicts the median *PI* (*cdf* = 0.5) while the normal and Weibull over predict the median *PI*. In plot 5(iv) through the *cdf* range of 0.85 to 0.99, the experimental *cdf* is between the log-normal and Weibull models. It appears at that the Weibull model and experimental *cdf* converge at the 0.99+ cdf level; however, with only 300 combustion events in the data set, the extreme tails of the distribution are not well characterized.

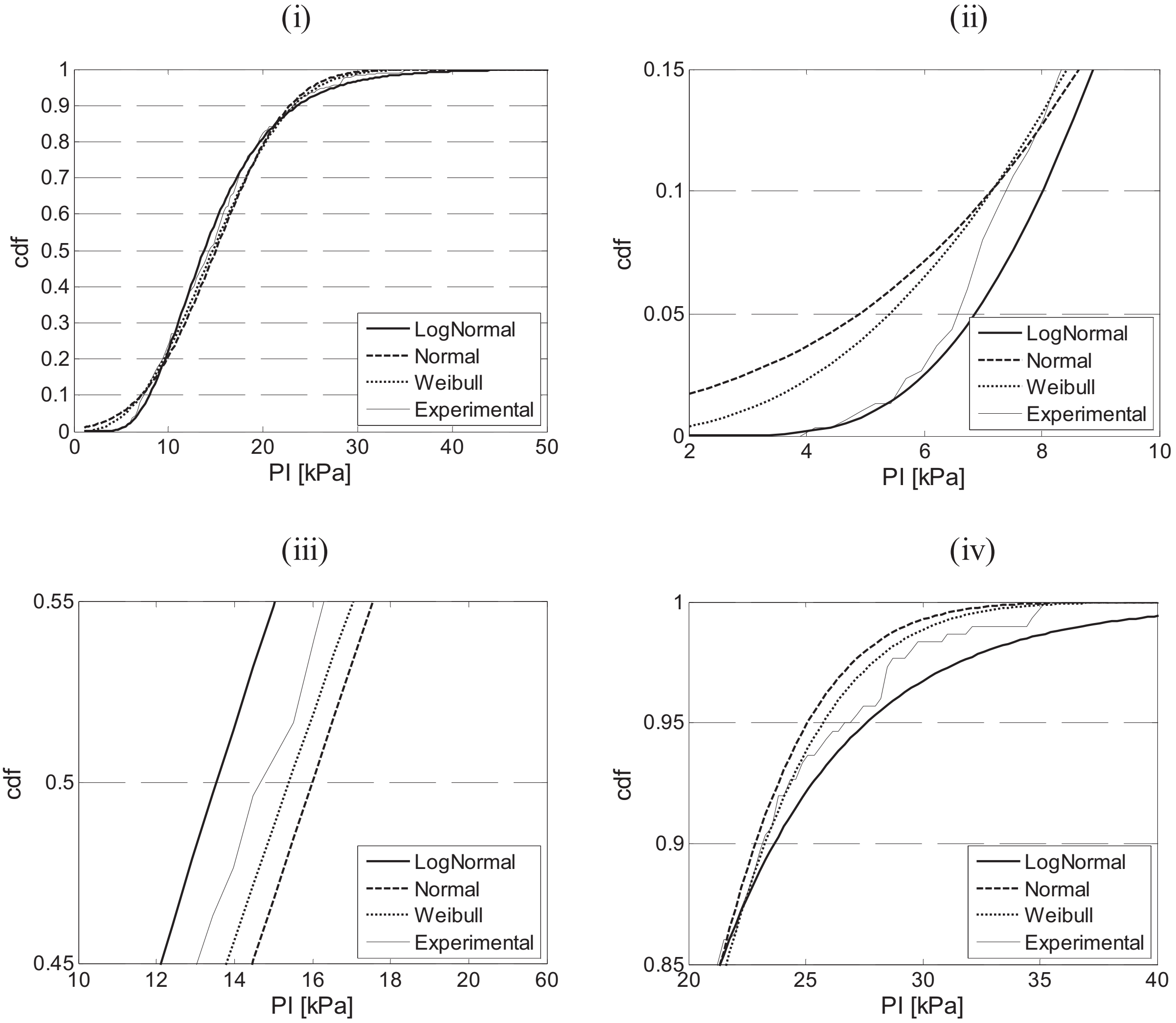
(i) (ii) (iii) (iv)

Fig. 5. Cumulative Distribution Functions (cdfs) of models and experimental data for the moderate knock level

5. Conclusions

I. Cycle-by-cycle hydrogen combustion knock intensity at steady state operation were measured and observed to change significantly event to event resulting in a disperse distribution of the *PI* metrics. From this point of view the *PI* distribution can be considered as stochastic process and can be modelled by us of statistical models for the *pdf* and *cdf*.

II. The *PI* distributions of the test series of combustion cycles under the conditions examined in this work are not symmetric. This leads to the conclusion that the symmetric Gaussian normal distribution is not a satisfactory model to be applied as the distribution for combustion knock statistical characterisation.

III. Both Weibull and log-normal distribution models provide more accurate fits with the experimental data of the *PI*. However, the log-normal distribution seems to be more practical because of the characteristic parameters, which directly correspond to the distribution.

IV. Statistical based models of hydrogen combustion knock can be useful tool for quantifying and characterizing the intensity metrics and makes it possible to evaluate the overall knock level and threshold which is important quantity for the knock detection and control system installed on the engine.

Acknowledgements

We would like to acknowledge the support of Michigan Technological University's Mechanical Engineering - Engineering Mechanics Department and the Research Office for support of this work.

References

[1] Tang, X., Kabat, D. M., Natkin, R. J., Stochausen, W. F., Heffel, J. W., *Ford P2000 Hydrogen Engine Dynamometer Development*, SAE Paper 2002-01-0242, 2002.

[2] Naber, J. D., Blough, J. R., Frankowski, D., Goble, M., Szpytman, J. E., *Analysis of Combustion Knock Metrics in Spark-Ignition Engines*, SAE Transactions Journal of Engines, V115, pp 223-243, 2007.

[3] Naber, J. D., Szpytman, J. E., Bradley, E., *Target Based Rapid Prototyping Control System for Engine Research*, SAE Transactions Journal of Passenger Cars, V115 pp 395-406, 2007.

[4] Szwaja, S., Bhandary, K. R., Naber, J. D., *Comparisons of Hydrogen and Gasoline Combustion Knock in a Spark Ignition Engine*, International Journal of Hydrogen Energy, (submitted), 2007.