Military Technical College
Kobry El-Kobbah,
Cairo, Egypt

14th International Conference on
Applied Mechanics and
Mechanical Engineering.

Experimental Investigation of Cyclic & Cylinder to Cylinder Variations in Spark Ignition Engine

By

Amr Bosila*, Ibrahem Saleh**, Moatasem Shahien***, Essam Haggag* and Aly Elmaihy**

ABSTRACT

A special SI engine designed to work with gasoline and compressed natural gas (CNG), in completely dedicated fashions, is tested while mounted in the vehicle using a chassis dynamometer and a complete set of measuring instruments. The main objective is to assess the cyclic and cylinder to cylinder variations of cylinder pressure under different operating conditions with both types of fuel. Four sets of pressure transducers and conditioning devices are installed to record the pressure-crank angle histories inside each of the four engine cylinders. Electronic data acquisition techniques and a specially developed software package are used to measure, record and analyze all the parameters at different test conditions. Observations show that Cyclic variations of pressure in each cylinder during the combustion process are 20 to 25% less with CNG.

The variations in the maximum rate of pressure rise are also 15-20% less while the average values are slightly higher. The deviations (from average) of the cyclic values of Pmax and its timing CAPmax, show large inverse correlation to each other. The increasing or decreasing trends in Pmax and its timing do not continue for more than 3-4 successive cycles. This is more apparent with natural gas fuelling at all engine operating conditions. The cross correlation coefficient has a certain degree of repetition every 2-3 cycles and even less with gasoline. The single-sided cross power spectrum also shows the existence of some periodic dependency within 5 engine cycles or less. Cyclic deviations in Pmax and CAPmax from average cylinder values converge to almost the same patterns when averaged over 3 or more cylinders in firing sequence, with nearly complete negative correlation. The cross spectrum also shows the presence of a high peak always near the frequency of 0.3 per cycle.

KEY WORDS: Cycle to cycle variation, cylinder to cylinder variation.

---

* National Defense Council.
** Egyptian Armed Forces.
***Modern university.

1. Introduction

Combustion in the cylinder of spark-ignition (SI) piston engines is characterized by a level of cyclic variability. Instead of observing the same time evolution of the cylinder pressure for all cycles, a scatter of the individual cylinder pressure curves around the phase averaged mean appears. Since the pressure is uniquely related to combustion processes, any variations observed reflect inherent variations in these processes from cycle-to-cycle. In addition to the variations in one cylinder, there also exist variations from one cylinder to another in multi-cylinder engines. Most of the variations are primarily influenced by the differences in mixture flow patterns, amount of fuel present, air entrainment, mixture quality, exhaust gas recirculation and the amount of residual gases from cycle to cycle especially in the vicinity of the spark plugs.

The optimum spark timing is usually determined on average basis and thus becomes inappropriate for cycles with fast or slow burning. As a result, the work provided by each individual cycle differs from the mean work which is the design target of engine developers. In extreme cases partial burns or even misfires may occur. Too large levels of variability can have negative impacts on the drivability of the vehicle, and can lead to increased levels of pollutant emissions and fuel consumption. This work presents an experimental investigation of the cyclic variability in cylinder pressure during the combustion process. The engine tested has a high compression ratio, an electronic ignition system and two complete sets of fuel supply and electronic control devices. This engine enjoys many unique features that enable its operation with Gasoline or Compressed Natural Gas in completely dedicated fashions.

2. Experimental Setup

The vehicle used is a Peugeot 406 powered by a 4-stroke water cooled engine having a compression ratio of 10.5 and two over head cam shafts. The engine is designed with nearly two completely separate fuel supply and electronic control systems, one for gasoline and the other for CNG. The fuel/air mixture is prepared using an electronic multi-point fuel injection system in case of gasoline, and a gas regulator and fuel/air mixer to be used with CNG. The engine type is EW7 and can deliver a maximum power of 85 kW at 4200 rpm and a maximum torque of 160 N.m at 4000 rpm. A schematic drawing for the used engine-instrumentation set-up is shown in Fig (1).

The test rig is equipped with a chassis dynamometer along with all instruments necessary to measure the vehicle speed and driving torque and power. The vehicle built in instruments and engine monitoring system, were also used to record the parameters needed to evaluate the general engine performance. An electronic data acquisition system with four sets of pressure transducers and conditioning devices were used to record the pressure-crank angle histories inside each of the four engine cylinders. The recorded data at different engine operating conditions are used to evaluate the combustion process parameters and their cylinder to cylinder and cycle to cycle variations. The experimental program was carried out with the engine fuelled by gasoline and then repeated with CNG. Results obtained are used later on to conduct a comparative study.

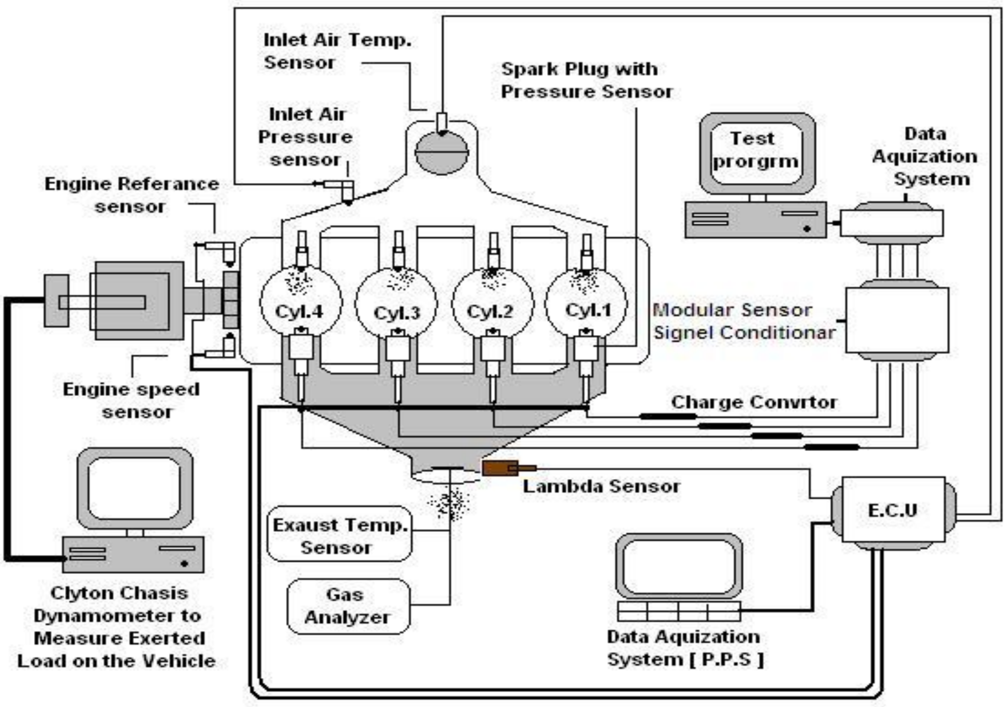

Figure (1) schematic drawing for instrumentation used in the work

3. Experimental Results

Tests at different engine speeds were carried out at various fixed brake loads using the dynamometer control facility and changing the engine intake air throttle. The parameters recorded (as averages) during each test are:

1- Engine speed (rpm)
2- Brake Load (N)
3- Inlet manifold air temperature (^oK)
4- Inlet manifold air under-pressure (bar)
5- Ignition advance angle (DCA before TDC)
6- Percentage of CO & CO2 in the exhaust gases (%)
7- Amount of HC in the exhaust gases (ppm)
8- Exhaust gas temperature before and after the catalytic converter (^oK)
9- Speed of air flow through the speedometer crossection
10- The Lambda sensors output voltage (V, before and after the catalytic converter)
11- The average fuel consumption (L/100Km).
12- Cylinder pressure-Crank angle (P–Φ) histories inside the engine four cylinders during a suitable number of successive engine cycles.

Figures (2 & 3) show sample P – Φ diagrams for the average of 40 consecutive cycles at different engine speeds and loads with gasoline and natural gas fueling. The figures also show, cylinder pressure and the relative standard deviation at each crank angle. The latter is used to validate the accuracy of measurements.

The engine performance parameters, needed for performance investigations, are calculated from the recorded data. These parameters included :

- Effective (brake) Engine Power (kW)
- Air Flow Speed (m/s)
- Volumetric Efficiency (%)
- Fuel Flow Rate (kg/hr)
- The equivalence ratio
- Brake Mean Effective Pressure (BMEP in bar)
- Brake Specific Fuel Consumption (bsfc in gm/kW/hr)

The P–Φ diagrams are assessed in order to evaluate the parameters mainly affected by the combustion process. The AHRR model, developed by Krieger-Brman [1] and used by many researchers [2,3,4 and5], is also applied to calculate other combustion related parameters. The main values calculated at each test conditions are :

- Maximum cylinder pressure, (bar) and its timing, (DCA)
- Standard deviation of the average maximum pressure for 40 cycles, (bar)
- Maximum working mixture temperature, (K)
- Ignition advance angle, (DCA before TDC)
- Timing of the start and end of combustion, (DCA)
- Fuel burning duration, (DCA and milliseconds)

The ignition advance angle (in crank degrees before TDC) is one of the experimentally recorded parameters. The maximum pressure (Pmax) of the working mixture during the engine cycle and the timing (in crank angles) at which it occurs are found from the averaged measured cylinder pressure. The crank angles at which fuel burning starts and ends are obtained from the calculated instantaneous heat release rate . The burning duration is the period elapsed between the instants of start and end of burning. The ignition advance and the burning duration are then recalculated in units of time (rather than crank degrees).

The fuel burnet amount in (M_f) in gm/cyc/cylinder is obtained by integrating the fuel burning rate curve. The indicated mean effective pressure (IMEP) is also evaluated from the area under the P-V diagram. These values are checked against the actual fuel consumption and the engine brake power in order to verify the experimental data.
Table (1) reports the results of applying the apparent heat release calculation procedure to the experimental data obtained with gasoline fueling. Table (2) gives the corresponding results obtained with natural gas. The reported results (grouped at constants brake loads) are plotted against engine speed in figs.(4 & 5).

The ignition point in terms of crank angles seems to have little dependence on engine speed. In time units however, the ignition point significantly retards as engine speed increases. The ignition advance is also retarded by the electronic control unit with the increase of brake load. This action is more apparent with gasoline fueling despite the expected higher speed of flame propagation.

The point at which combustions commences varies in a limited range and seems to have little dependence on engine speed. The timing of the end of combustion follows similar trends. With natural gas, the effect of brake load is almost negligible. Besides, combustion starts few degrees (5-6) later compared to gasoline and ends at nearly the same timing. The late ignition is mainly attributed to the higher self ignition point of natural gas. Thus, shorter burning durations and faster combustion rates, due to higher pressure and temperature at the actual ignition point, are to be expected. In time units however, the burning duration decreases only with engine speed and is only slightly higher with gasoline.

Maximum cylinder pressure typically increases with brake load and slightly decreases with engine speed. With both types of fuel and at similar operating conditions, Pmax exhibits almost the same values. Besides, the crank angle at which Pmax occurs is always optimized at typical values, (in the range of 12-13 DCA after TDC). The similarities with both types of fuels are understood, since the area of the p-V diagram should be nearly the same at the same brake load (BMEP).

The relative variance, in averaging the maximum cylinder pressure, seems to increase with both engine speed and brake load. With natural gas however, this trend is less apparent and the effect of speed could be neglected. The slightly higher values at lower speeds are attributed to the less favorite conditions for mixture preparation. The 4-5% lower values obtained with natural gas at similar operating conditions indicate that cycle to cycle variations are expectedly less by this margin.
The maximum cylinder temperature increases with brake load and slightly decreases as engine speed increases. The trend, similar to that of maximum pressure, is found with both types of fuel.

4.3.1 Cycle to Cyclic Pressure Variation

Figure (6) shows the recorded pressure-crank angle histories inside the engine four cylinders for a single experiment (engine speed=2607 rpm and BMEP=4.06 bar, gasoline fuel). The 40 successive traces of cylinder pressure for the first cylinder are plotted against crank angle in a 3D format. The combustion and expansion periods of the cycles are expanded to clarify the significant cyclic variations in the pressure during this period. The mean values and standard deviations of variations in the cylinder pressure are also shown at each crank angle. The recorded data at almost the same operating conditions but with natural gas fueling are given in fig.(7). It could be seen that the mean values of the cylinder pressure are nearly the same at similar operating conditions. However, the standard deviations are always less during the combustion period with natural gas fuelling, an indication of less cycle to cycle variations.. This evidence is supported by noticing the margins of variations of the cylinder pressure during the pressure rise period, see figs.(6 & 7). Another important observation is that cyclic variations are mostly observed during the fast pressure rise period, and the variations are only slight after the point of maximum cylinder pressure. This proves that the fuel air mixture is slightly lean`. It is also noticed that the pressure curve starts to increase over the pumping line at nearly the same crank angle in each cycle in the case of CNG especially at higher loads. The crank angle at which this event is noticed is believed to be the dynamic ignition point.
The cycle by cycle variations in maximum cylinder pressure and its timing in the first engine cylinder are plotted against the cycle number in fig.(8) in the case of gasoline fuelling, 2600 rpm and 4.06 bar BMEP. Similar plots are given in fig.(9) for higher brake load, (namely 7.29 bar BMEP). The figures show high degrees of inverse correlation between the changes in the maximum pressure and its crank angle timing. Investigating this correlation may then reveal the efficiency of the electronic control and how fast it works to maintain the optimum timings for fuel injection and spark ignition with both types of fuel used. It could also provide more understanding about the cyclic variations in cylinder pressure in different engine cylinder.

The cyclic change of maximum cylinder pressure and its timing in each cylinder were cross correlated using common signal processing techniques. Figs.(10) show the results obtained with gasoline fuelling at two different operating conditions. The corresponding results obtained with natural gas at nearly the same operating conditions are plotted in figs.(11).

The cross correlation coefficient at no signal shift was found to vary in the range of -0.6 to -0.85 at all operating conditions. Slightly higher negative values are observed with natural gas as the diagrams show. The high inverse correlation confirms the effectiveness of the electronic control system, which attempts to improve the performance by continually changing the ignition advance angle. It is also noticed that the cross correlation coefficient has a certain degree of repetition every 2-3 cycles and even less in case of gasoline. This degree of repetition lies in the range of 30-40%, which means that cyclic variations in maximum cylinder pressure follow the changes in timing within 2-3 cycle period and are nearly 70-80% dependant.

The cumulative curves of maximum cylinder pressure and its crank angle timing seem to have much less dependence. This suggests that the relations between cyclic variations of pressure in different cylinders are much more random.

The single-sided cross power spectrum between the cyclic variations of maximum cylinder pressure and its crank angle timing was carried out at different engine operating conditions, figs.(12 & 13). Despite the apparent noise and random behavior, it is noticed that the two sets of data are coherent at frequencies near 0.2 per cycle. It is also observed that at multiples of this frequency fewer coherencies appear with different amplitudes. This suggests that the existence of a periodic dependency between the variations in Pmax and CAPmax within every 5 engine cycles or less. This is true with both types of fuel used, however slightly longer periods of repetition are observed with natural gas.

4.3.2 Cyclic Pressure Variations from Cylinder to Cylinder

The cyclic variations in dPmax and dCAPmax averaged over 4 or more successive firings are seen to have negative correlations. Figure (14) shows the correlations between the cyclic changes of dPmax and dCAPmax when averaged over 5 successive cycles in the case of gasoline, rpm=2625 and BMEP=5.18 bar. The auto correlation coefficient reaches -0.8 and less at zero cycle shift confirming the high negative correlation between the two cyclic changes. The pattern of correlation with other averages is found to be nearly the same for the first 10 to 15 cycles. This proves that the trend is valid in a repetitive manner during at least such period.

The cross spectrum between the averaged dPmax and dCAPmax are also shown in the same figure (fig.14). The presence of a high peak in the spectrum always near the frequency of 0.3 per cycle confirms that a governing harmonic with this frequency always exists. Other peaks seem to be affected by frequency aliasing. Proving this may require the use of aliasing filters which is however difficult due to the limited frequency of observation (tied up by cycle to cycle interval).

The corresponding correlation and cross spectrum in the case of natural gas are shown in fig.(15). The high negative correlation and the 10 to 15 cycle period of repetition are also noticed. The cross spectrum on the other hand shows more clearly the presence of the dominant frequency at nearly 0.3 per cycle. The correlations and power spectrum at all other operating conditions and with both types of fuel showed almost the same trends which confirms the observations mentioned above.

5. Conclusions:

The study of cyclic variations of pressure in a single cylinder revealed that at the same operating conditions, the standard deviations in averaged cylinder pressure are always 20-25% less during the combustion period with natural gas fuelling, an indication of less cycle to cycle variations. The mean values of the maximum rate of pressure rise variation are always 15-20% less in the case of natural gas. The average maximum rate of pressure increase is slightly higher with CNG. The maximum pressure reached with both fuels is almost the same but at slightly earlier timing with gasoline. The deviations (from average) of the cyclic values of Pmax and its timing CAPmax, (dPmax vs dCAPmax), show large inverse correlation to each other. The increasing or decreasing trend in dPmax and its crank angle position does not continue for more than 3-4 successive cycles. This is more apparent with natural gas fuelling at all engine operating conditions. The cross correlation coefficient has a certain degree of repetition every 2-3 cycles and even less in case of gasoline. This degree of repetition lies in the range of 30-40%, which means that cyclic variations in maximum cylinder pressure follow the changes in timing within 2-3 cycle period and are nearly 70-80% dependant. The single-sided cross power spectrum between the cyclic variations of maximum cylinder pressure and its crank angle timing proves the existence of some periodic dependency within every 5 engine cycles or less. This is true for both types of fuel but slightly longer periods of repetition are to be expected with natural gas. Cycle to cycle variations in cylinder pressure seem to decrease at high speeds with gasoline fuelling with maximum variations at speeds near 3500 rpm. Similar trends are observed at low and medium brake loads (BMEP less than 9 bar). The engine with natural gas fueling shows less cyclic variations in cylinder pressure. However, at speeds below 2500 rpm these variations are relatively higher. This is also true at high loads specially with gasoline.

The results of studying the Cylinder-to-Cylinder Variations revealed that the cyclic variations in dPmax and dCAPmax when averaged from values obtained from cylinders in firing sequence, converge to almost the same pattern. With natural gas, the variations in both averaged maximum pressure and its timing are nearly halved. The cyclic variations in dPmax and dCAPmax averaged over 4 or more successive firings have negative correlations. The correlation pattern is nearly the same for the first 10 to 15 cycles in almost all cylinders. The cross spectrum between the averaged dPmax and dCAPmax show the presence of a high peak in the spectrum always near the frequency of 0.3 per cycle. This confirms the presence of a governing harmonic at such frequency.

The cyclic variations of dPmax and dCAPmax are tied to their previous variations in all cylinders in firing sequence. The number of previous firings greatly affecting the variations is found to be 3 to 4. It is therefore believed that the engine as a control system responds within nearly one cycle to the changes in the inputs that cause combustion variations.

References:

[1] Krieger, R.B. and Borman, G. L. "The combustion of apparent heat release for internal combustion engines." ASME paper 66 – WA/DGP-4, 1966.

[2]Mohamed I.Amin " Characterisation and Modelling of Cycle-to-Cycle Variations in Spark-Ignition Engines" PHD thesis ,University of Waterloo, Ontario, Canada, 2004.

[3] M.A Ceviz, et al "Cyclic Variations on LPG and Gasoline-Fuelled lean burn SI Engine" University of Ataturk , Erzrum, Turkey, 2005.

[4] Z. Huang1, et al " Study of Cycle-by-Cycle Variations of Natural Gas Direct Injection Combustion using a rapid Compression Machine " 2002.

[5] Haggag, E.E.F " performance of petrol engines using different types of ignition systems. "Ph . D. thesis . Ain Shams university,1997.

Nomenclatures:

BMEP	Brake Mean Effective Pressure
CA	Crank angle
CNG	Compressed Natural Gas
dCAPmax	variations in maximum cylinder timing
dPmax	variations in maximum cylinder pressure
IMEP	indicated mean effective pressure
Kw	kilo watt
M_f	Fuel burnet amount
TDC	Top dead Center
N.m	Newton Meter
SI	Spark-ignition

Table (1) Apparent Fuel Burning Rate Calculations (Gasoline)

Evaluated from Measured Values (2nd Gear Shift, Tr.Ratio = 2.5)

File	RPM	Load (N)	Ign. Adv. (Deg)	Pmax. (bar)	Pmax at DATDC	Pmax Rel Var (%)	Tmax (K)	Burn. Start (DBTDC)	Burn. Ends (DATDC)	Burn. Dur. (DCA)	Burn. Dur. (msec)	Fuel Burnt gm/cyc/c	IMEP (bar)	BMEP
MP 2400 - 200	2410	200	34.0	26.9	13.8	9.0	1372.9	-6.0	44.0	50.0	3.5	0.0133	1.75	0.73
MP 3300 - 200	3290	200	32.0	23.7	13.8	10.0	893.7	-22.0	22.0	44.0	2.2	0.0085	1.90	0.73
MP 2200 - 400	2210	400	37.0	32.3	13.8	16.0	1211.4	-22.0	23.0	45.0	3.4	0.0110	2.15	1.99
MP 2600 - 400	2600	400	36.0	31.5	13.8	16.0	1175.9	-22.0	20.0	42.0	2.7	0.0110	2.22	1.99
MP 3300 - 400	3310	400	35.0	29.1	13.8	14.0	1074.6	-22.0	20.0	42.0	2.1	0.0107	2.22	1.99
MP 2200 - 600	2220	600	35.0	38.0	13.8	10.0	1380.9	-21.0	20.0	41.0	3.1	0.0129	4.30	3.25
MP 2600 - 600	2610	600	32.0	36.9	13.8	11.0	1368.0	-21.0	21.0	42.0	2.7	0.0136	4.34	3.25
MP 3300 - 600	3320	600	30.0	34.5	13.8	11.5	1276.3	-22.0	21.0	43.0	2.2	0.0133	4.41	3.25
MP 4000 - 600	3990	600	29.0	32.1	13.8	11.0	1205.3	-23.0	21.0	44.0	1.8	0.0130	4.52	3.25
MP 1800 - 800	1800	800	28.0	45.2	13.8	10.0	1617.4	-17.0	17.0	34.0	3.1	0.0161	5.62	4.52
MP 1900 - 800	1856	800	27.0	44.8	13.8	10.0	1618.0	-18.0	19.0	37.0	3.3	0.0155	5.65	4.52
MP 2200 - 800	2225	800	30.0	43.5	13.8	12.0	1567.8	-22.0	18.0	40.0	3.0	0.0154	5.72	4.52
MP 3300 - 800	3330	800	28.0	39.8	13.8	13.5	1453.3	-24.0	21.0	45.0	2.3	0.0144	5.78	4.52
MP 4000 - 800	4030	800	28.0	37.4	13.8	13.0	1378.8	-24.0	20.0	44.0	1.8	0.0144	5.72	4.52
MP 4000 - 900	4090	900	32.0	39.9	13.8	12.0	1455.2	-21.0	22.0	43.0	1.8	0.0146	6.21	5.15
MP 1900 - 1000	1856	1000	26.5	50.3	13.8	10.0	1814.6	-19.0	18.0	37.0	3.3	0.0184	6.32	5.78
MP 2200 - 1000	2240	1000	29.0	49.0	13.8	10.0	1773.1	-22.0	20.0	42.0	3.1	0.0187	6.43	5.78
MP 2600 - 1000	2600	1000	28.0	47.5	13.8	11.5	1717.5	-25.0	19.0	44.0	2.8	0.0178	6.52	5.78
MP 3400 - 1000	3390	1000	27.0	44.6	13.8	12.0	1627.8	-22.0	21.0	43.0	2.1	0.0162	6.62	5.78
MP 4000 - 1000	4060	1000	27.0	42.8	13.8	12.0	1611.3	-21.0	22.0	43.0	1.8	0.0167	6.78	5.78
MP 1900 - 1200	1888	1200	24.0	55.2	13.8	10.0	1974.5	-19.0	18.0	37.0	3.3	0.0206	8.15	7.04
MP 2000 - 1200	2050	1200	26.0	54.5	13.8	10.0	1933.2	-21.0	20.0	41.0	3.3	0.0216	8.25	7.04
MP 2200 - 1200	2260	1200	27.0	53.7	13.8	11.0	1948.7	-24.0	20.0	44.0	3.2	0.0209	8.30	7.04
MP 2600 - 1200	2635	1200	27.0	52.5	13.8	12.0	1886.6	-22.0	19.0	41.0	2.6	0.0196	8.45	7.04
MP 1900 - 1400	1888	1400	22.0	60.5	13.8	10.0	2132.4	-19.0	17.0	36.0	3.2	0.0228	9.74	8.31
MP 2000 - 1400	2060	1400	24.0	60.0	13.8	10.0	2139.4	-21.0	21.0	42.0	3.4	0.0248	9.74	8.31
MP 2700 - 1400	2680	1400	25.0	57.6	13.8	11.0	2062.0	-20.0	19.0	39.0	2.4	0.0212	10.14	8.31
MP 1950 - 1600	1920	1600	20.0	65.3	13.6	9.0	2294.7	-18.0	18.0	36.0	3.1	0.0265	10.98	9.57
MP 2000 - 1600	2070	1600	22.0	65.0	13.9	13.0	2298.7	-18.0	18.0	36.0	2.9	0.0262	11.24	9.57
MP 1950 - 1800	1952	1800	18.0	71.0	13.8	15.0	2484.1	-15.0	16.0	31.0	2.6	0.0294	12.78	10.83
MP 2000 - 1800	2070	1800	13.0	70.9	13.8	15.0	2473.4	-20.0	22.0	42.0	3.4	0.0334	12.94	10.83
MP 1950 - 2000	1984	2000	12.0	76.2	13.8	12.0	2671.0	-16.0	21.0	37.0	3.1	0.0489	14.10	12.09
MP 2000 - 2000	2080	2000	11.0	76.5	13.8	16.0	2678.7	-22.0	23.0	45.0	3.6	0.0495	14.25	12.09

Table (2) In-Cylinder Combustion Parameters (Natural Gas)

Evaluated from Measured Values (2nd Gear Shift, Tr.Ratio = 2.5)

File	RPM	Load (N)	Ign. Adv. (Deg)	Pmax. (bar)	Pmax at DATDC	Pmax Rel Var (%)	Tmax (K)	Burn. Start (DBTDC)	Burn. Ends (DATDC)	Burn. Dur. (DCA)	Burn. Dur. (msec)	Fuel Burnt gm/cyc/c	IMEP (bar)	BMEP (bar)
MN 1800 - 200	1800	200	33.0	28.5	13.8	12.0	1006.2	-18.0	18.0	36.0	3.3	0.0088	1.75	0.65
MN 2200 - 200	2230	200	32.0	27.3	13.8	1.5	1011.5	-19.0	20.0	39.0	2.9	0.0088	1.80	0.65
MN 3300 - 200	3296	200	31.0	23.4	13.8	11.0	929.5	-19.0	20.0	39.0	2.0	0.0078	1.85	0.65
MN 2200 - 400	2240	400	31.0	32.7	13.8	10.5	1117.0	-19.0	18.0	37.0	2.8	0.0108	3.01	1.78
MN 2600 - 400	2560	400	31.0	31.3	13.8	10.0	1148.9	-18.0	18.0	36.0	2.3	0.0108	3.12	1.78
MN 3300 - 400	3328	400	30.0	28.8	13.8	9.0	1122.1	-18.0	20.0	38.0	1.9	0.0098	3.20	1.78
MN 4000 - 400	4064	400	33.0	26.4	13.8	11.0	1086.2	-19.0	20.0	39.0	1.6	0.0103	3.22	1.78
MN 1880 - 600	1850	600	28.0	39.3	13.8	9.0	1355.2	-16.0	18.0	34.0	3.1	0.0138	3.25	2.92
MN 1881 - 600	1881	600	28.5	39.2	13.8	9.0	1353.5	-16.0	18.0	34.0	3.0	0.0137	3.18	2.88
MN 2200 - 600	2260	600	31.0	38.1	13.8	10.5	1336.2	-18.0	17.8	35.0	2.6	0.0129	3.20	2.85
MN 2600 - 600	2592	600	31.0	36.6	13.8	9.0	1312.3	-18.0	19.0	37.0	2.4	0.0127	3.22	2.92
MN 3300 - 600	3328	600	29.0	34.2	13.8	9.0	1307.3	-19.0	19.5	39.0	2.0	0.0120	3.28	2.92
MN 4000 - 600	4096	600	32.0	31.8	13.8	9.0	1241.8	-19.0	20.5	38.0	1.5	0.0122	3.32	2.92
MN 1800 - 800	1856	800	27.0	44.7	13.8	9.0	1546.6	-16.0	18.0	34.0	3.1	0.0167	5.55	4.05
MN 2200 - 800	2290	800	28.0	43.1	13.8	10.0	1506.2	-18.0	18.0	36.0	2.6	0.0153	5.60	4.05
MN 2600 - 800	2592	800	29.0	42.0	13.8	9.0	1484.5	-18.0	19.0	37.0	2.4	0.0152	5.65	4.05
MN 3400 - 800	3360	800	27.0	39.5	13.8	9.0	1468.0	-18.0	19.5	37.0	1.8	0.0141	5.75	4.05
MN 4000 - 800	4096	800	31.0	37.2	13.8	9.0	1447.8	-18.0	20.0	37.0	1.5	0.0149	5.80	4.05
MN 1800 - 1000	1880	1000	28.0	48.5	13.9	9.0	1710.4	-17.0	17.0	34.0	3.0	0.0194	6.81	5.18
MN 1900 - 1000	1950	1000	27.0	49.6	13.8	9.0	1701.7	-15.0	18.0	33.0	2.8	0.0190	6.85	5.18
MN 2200 - 1000	2295	1000	28.0	48.5	13.8	10.0	1685.0	-18.0	18.0	36.0	2.6	0.0180	6.92	5.18
MN 2600 - 1000	2624	1000	28.0	47.5	13.8	8.0	1687.4	-18.0	19.0	37.0	2.4	0.0183	6.89	5.18
MN 3300 - 1000	3392	1000	26.0	44.9	13.8	8.0	1644.0	-18.0	20.0	38.0	1.9	0.0168	7.01	5.18
MN 4000 - 1000	4128	1000	30.0	42.6	13.8	7.0	1634.8	-18.0	21.0	39.0	1.6	0.0178	7.22	5.18
MN 1800 - 1200	1880	1200	24.0	55.3	13.8	8.0	1846.9	-17.0	17.0	34.0	3.0	0.0218	2.30	6.31
MN 1900 - 1200	1980	1200	25.0	55.4	13.8	8.0	1855.5	-16.0	17.5	32.0	2.7	0.0214	8.40	6.31
MN 2200 - 1200	2301	1200	26.0	55.0	13.8	8.0	1931.1	-18.0	18.5	37.0	2.7	0.0224	8.50	6.31
MN 2600 - 1200	2656	1200	27.0	53.8	13.8	7.0	1942.0	-18.0	19.3	38.0	2.4	0.0223	8.60	6.31
MN 2601 - 1200	2656	1200	27.0	53.3	13.8	7.5	1948.7	-18.0	19.5	36.0	2.3	0.0597	8.70	6.31
MN 1800 - 1400	1888	1400	23.0	61.0	13.8	8.0	2030.9	-18.0	18.0	36.0	3.2	0.0258	9.70	7.45
MN 1900 - 1400	1888	1400	23.0	61.8	13.8	7.0	2107.7	-18.0	18.0	36.0	3.2	0.0270	9.75	7.45
MN 1900 - 1600	1920	1600	20.0	67.5	13.8	8.0	2276.1	-18.0	18.0	36.0	3.1	0.0313	10.82	8.58

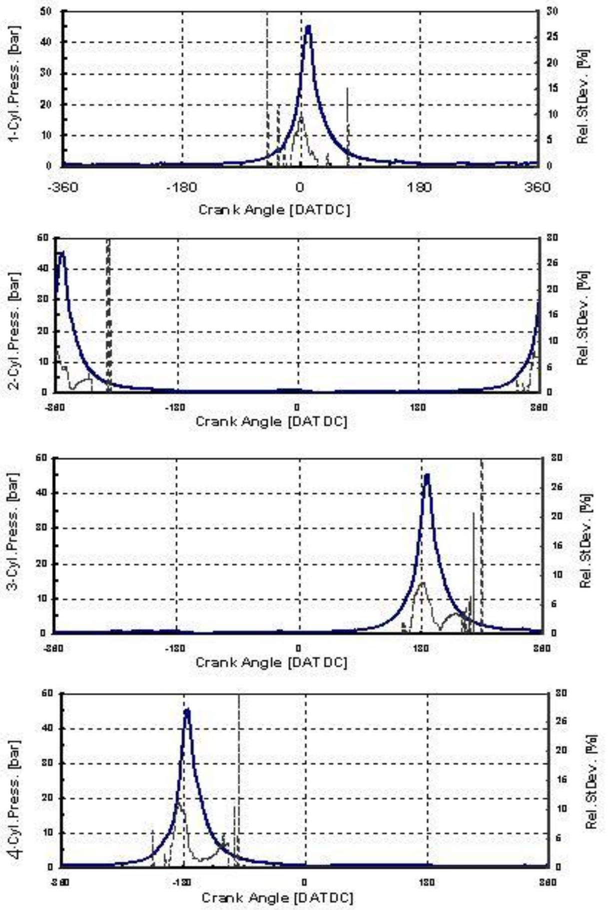

Fig.(2) Averaged Measured Cylinder Pressure

Fuel : (Gasoline)

Engine Speed : 1800 rpm Brake Load : 800 N.m

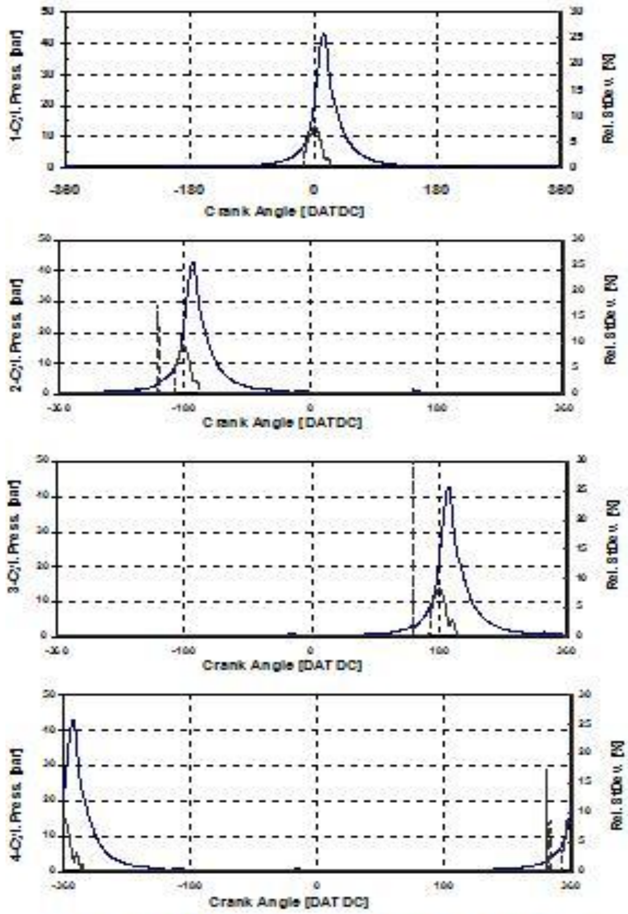

Fig.(3) Averaged Measured Cylinder Pressure

Fuel : CNG

Engine Speed : 1856 rpm Brake Load : 800 N.m

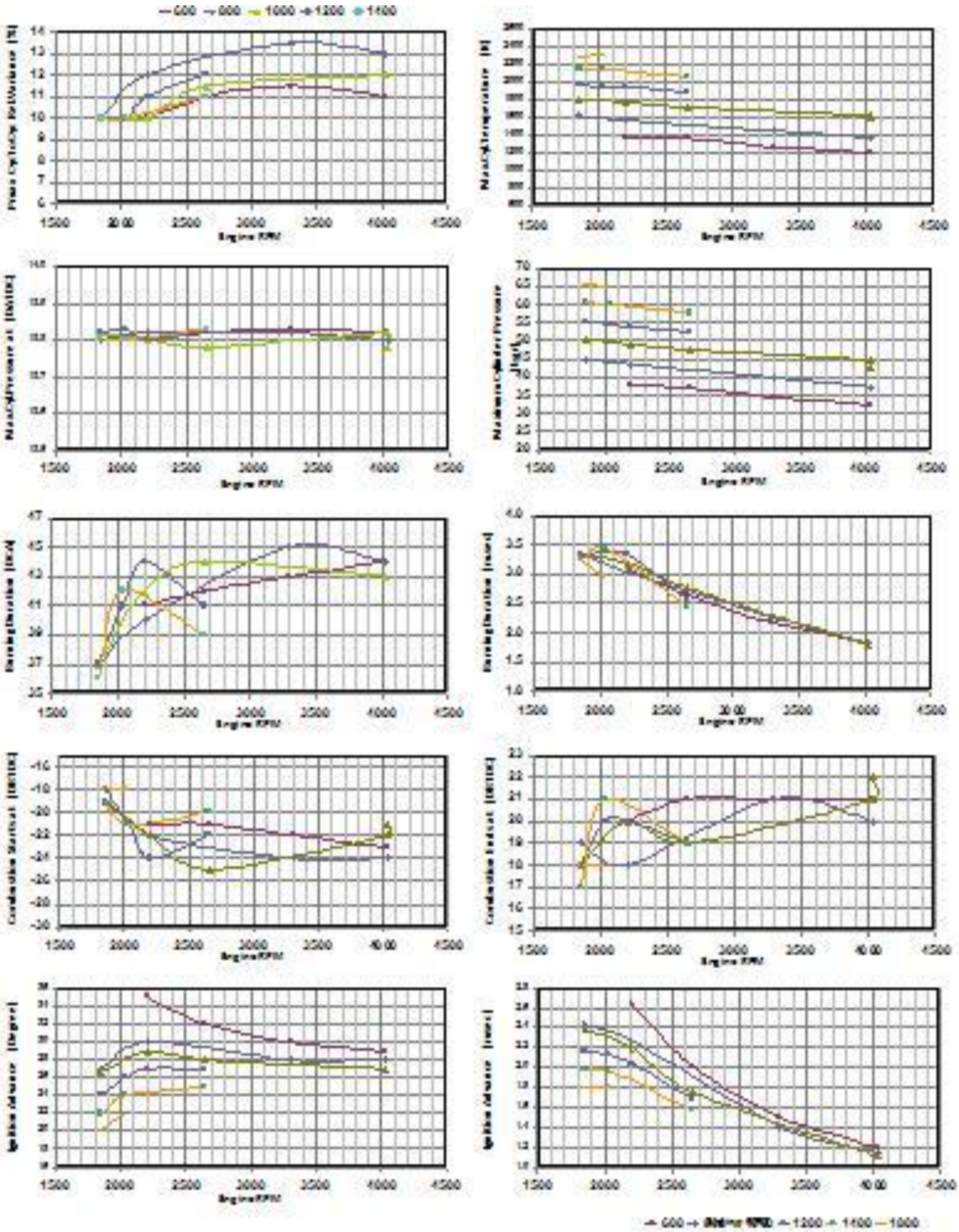

Fig.(4) In-Cylinder & Combustion Parameters

Effect of Engine speed at Fixed Loads
Gasoline Engine

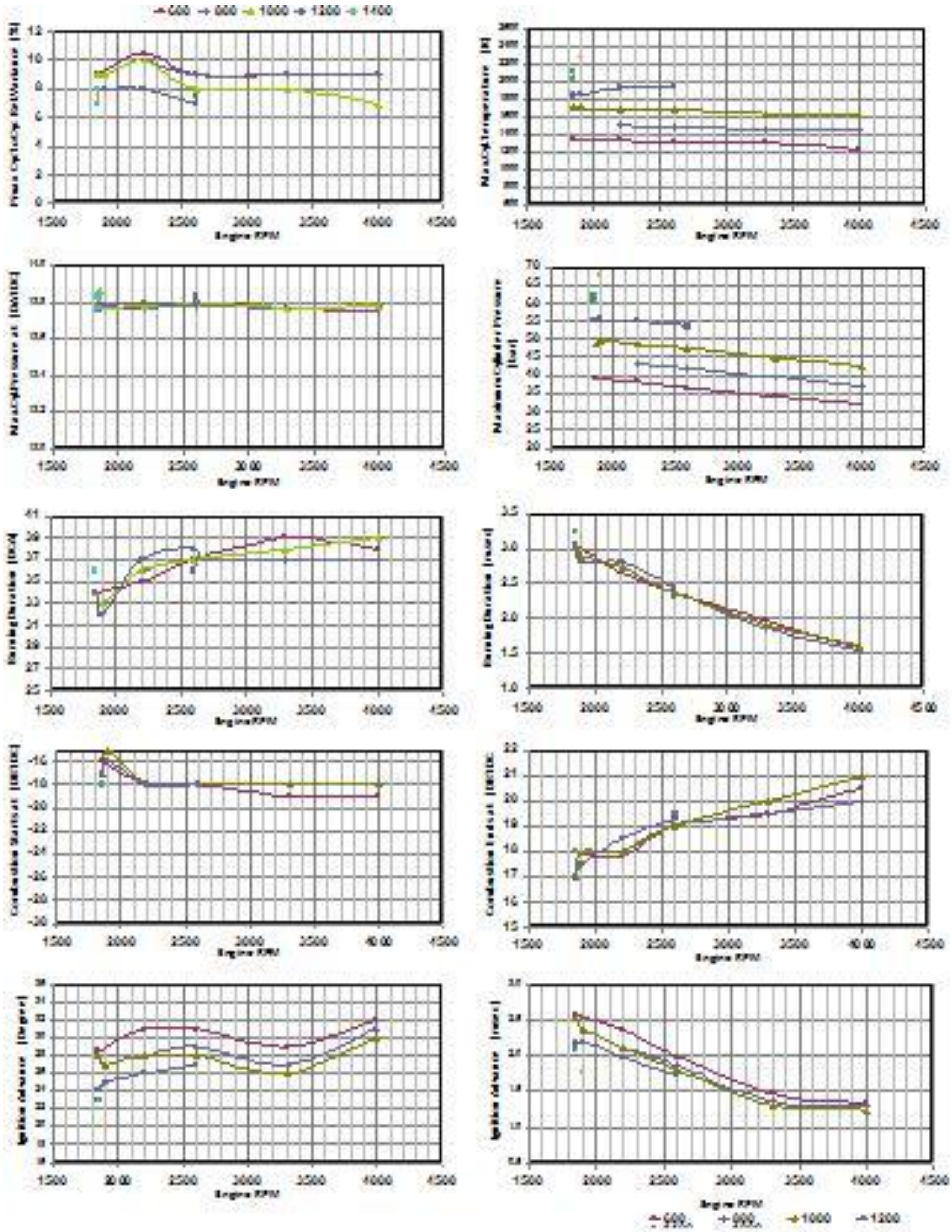

Fig.(5) In-Cylinder & Combustion Parameters

Effect of Engine speed at Fixed Loads
Natural Gas Engine

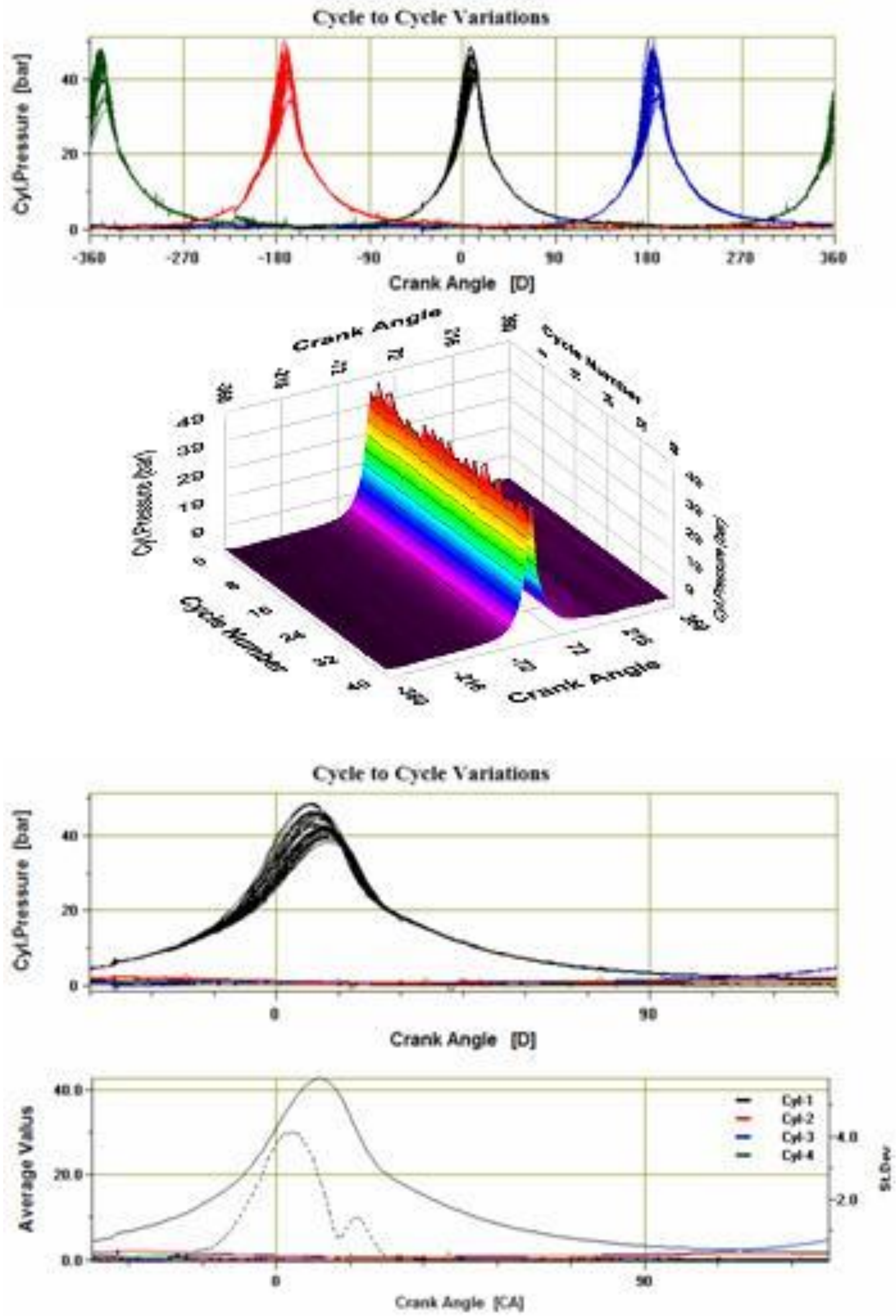

Fig.(6) Cycle To Cycle Variations
Single Cylinder
Gasoline Fuel / RPM =2607 / BMEP(bar) =4.06

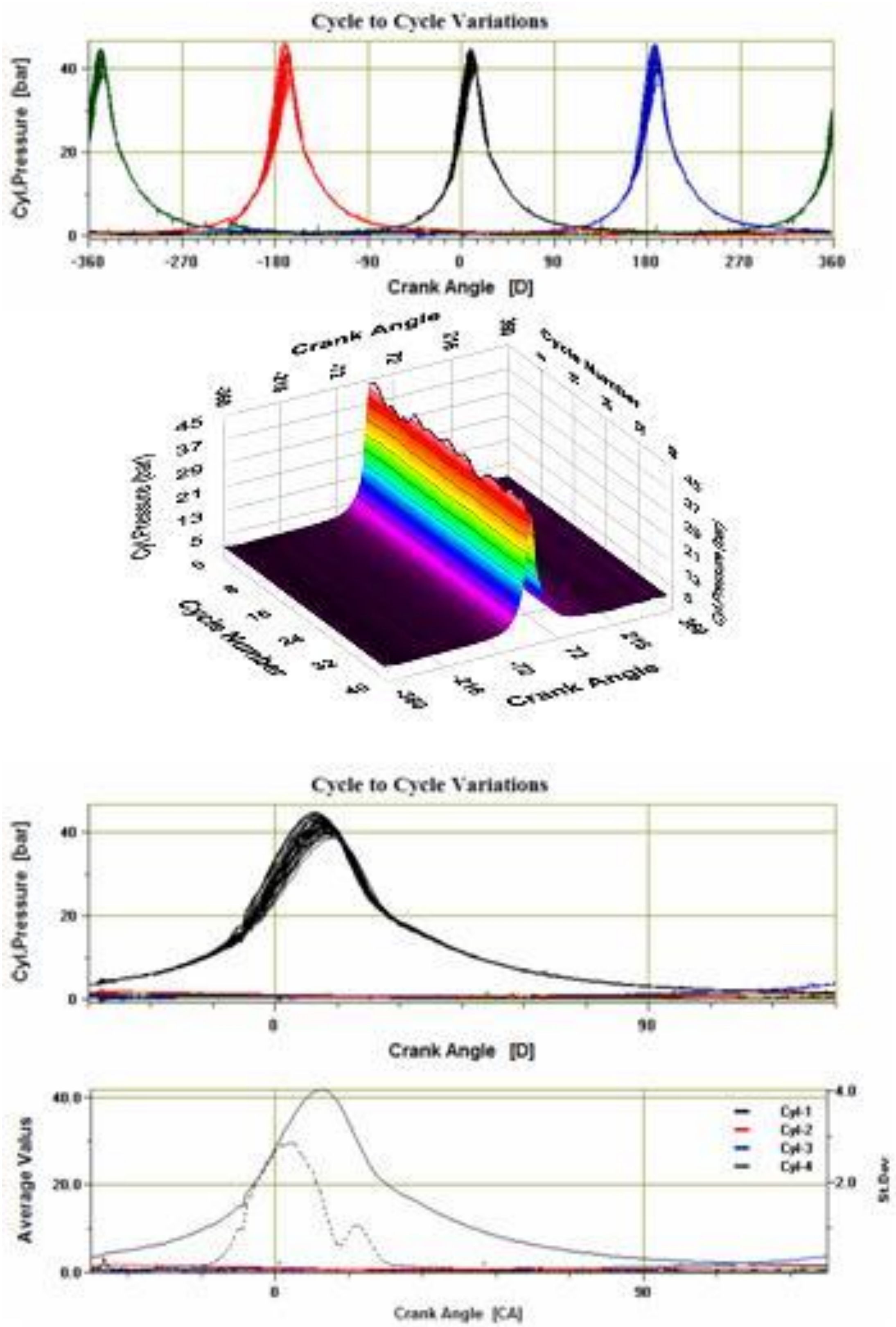

Fig.(7) Cycle To Cycle Variations
Single Cylinder
Natural Gas / RPM =2603 / BMEP(bar) =4.06

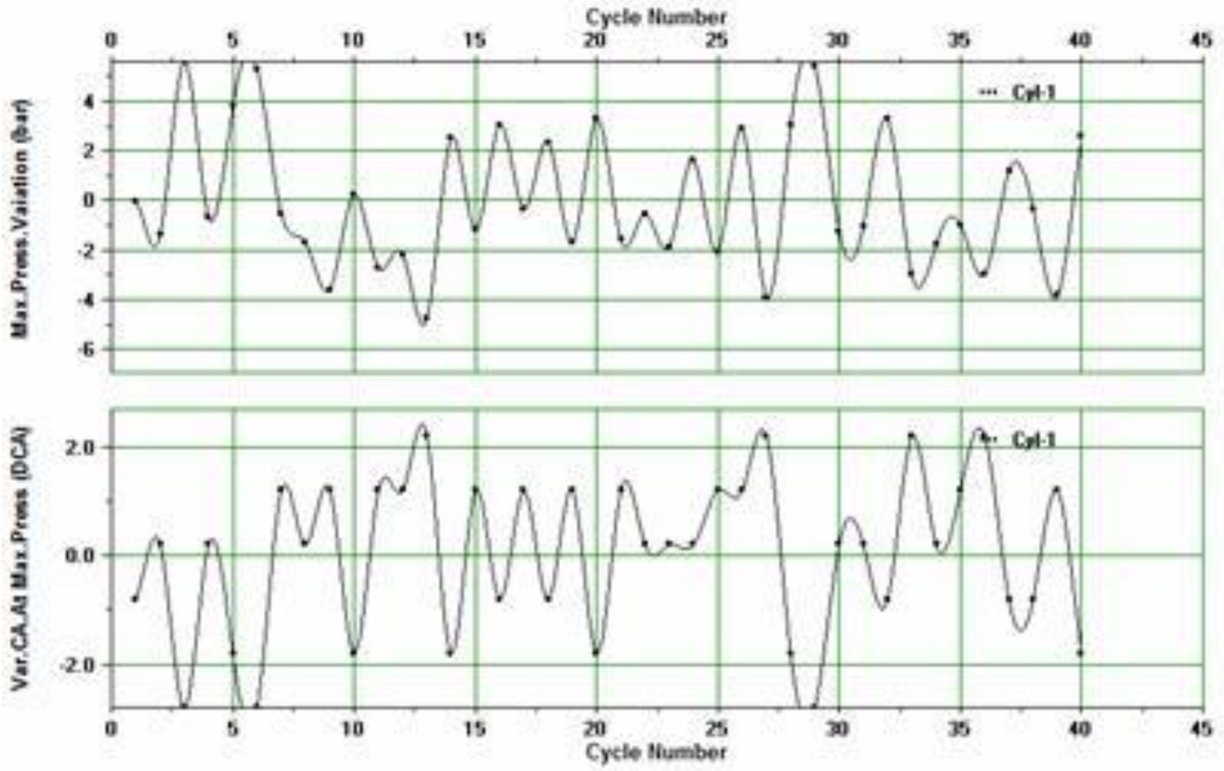

Fig.(8) Pmax and its CA vs Cycle Number

Gasoline Fuel / RPM=2607 / BMEP(bar)=4.06

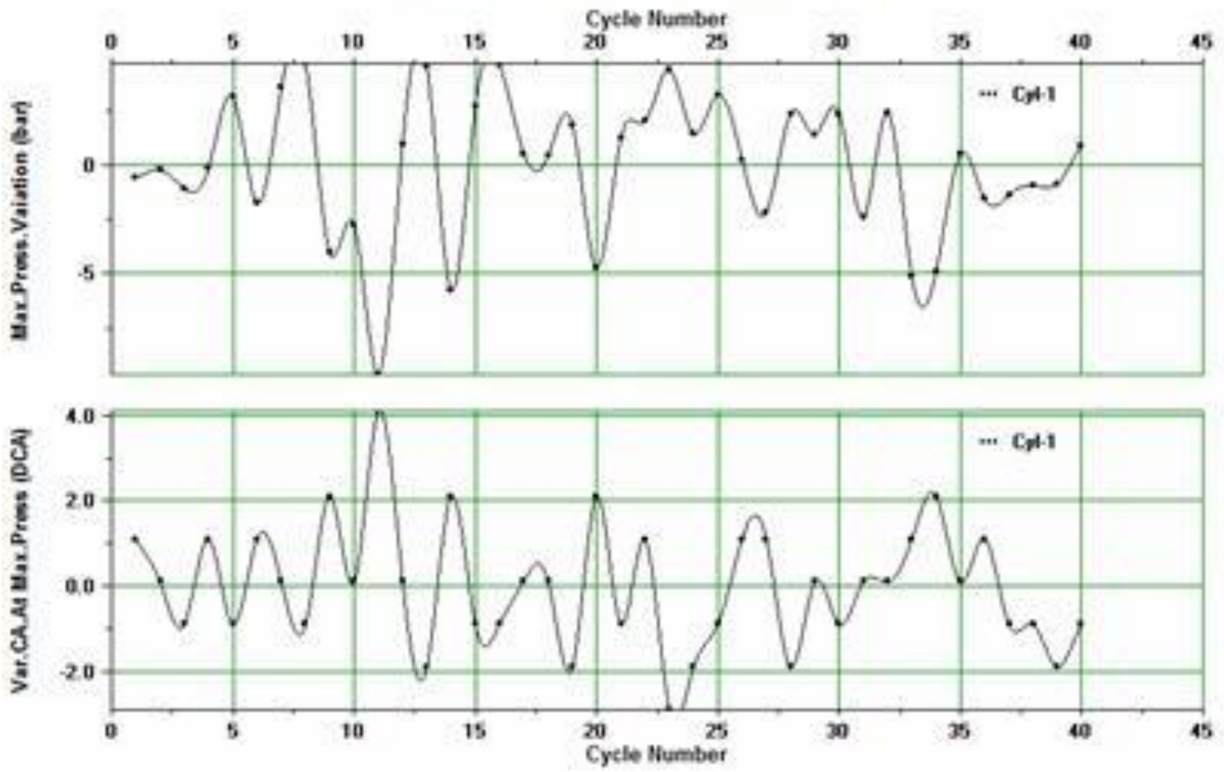

Fig.(9) Pmax and its CA vs Cycle Number

Gasoline Fuel / RPM=2607 / BMEP(bar)=7.29

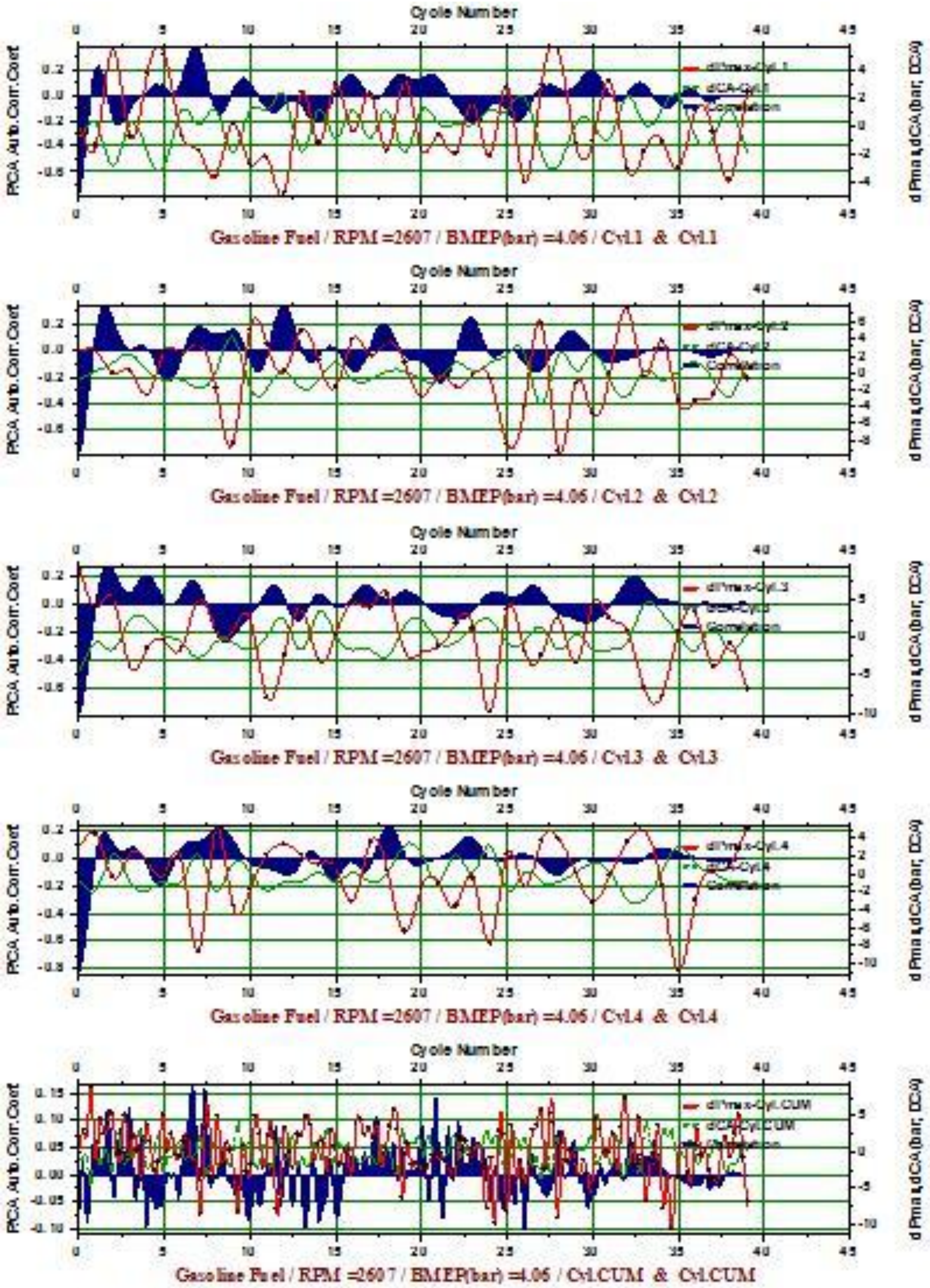

Fig.(10) dPmax and its dCAPmax Cross Autocorrelation
Single Cylinders

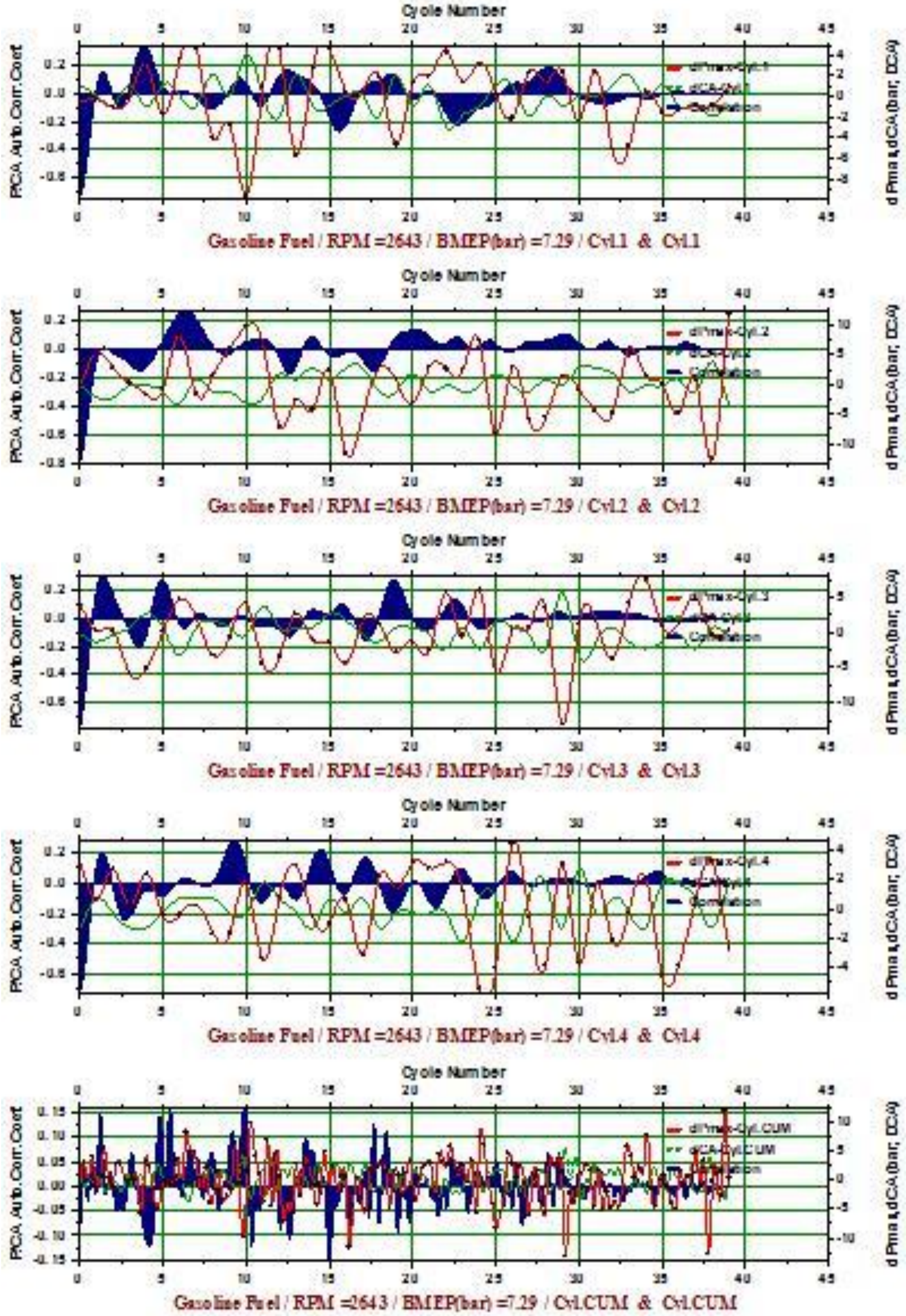

Fig.(11) dPmax and its dCAPmax Cross Autocorrelation
Single Cylinders

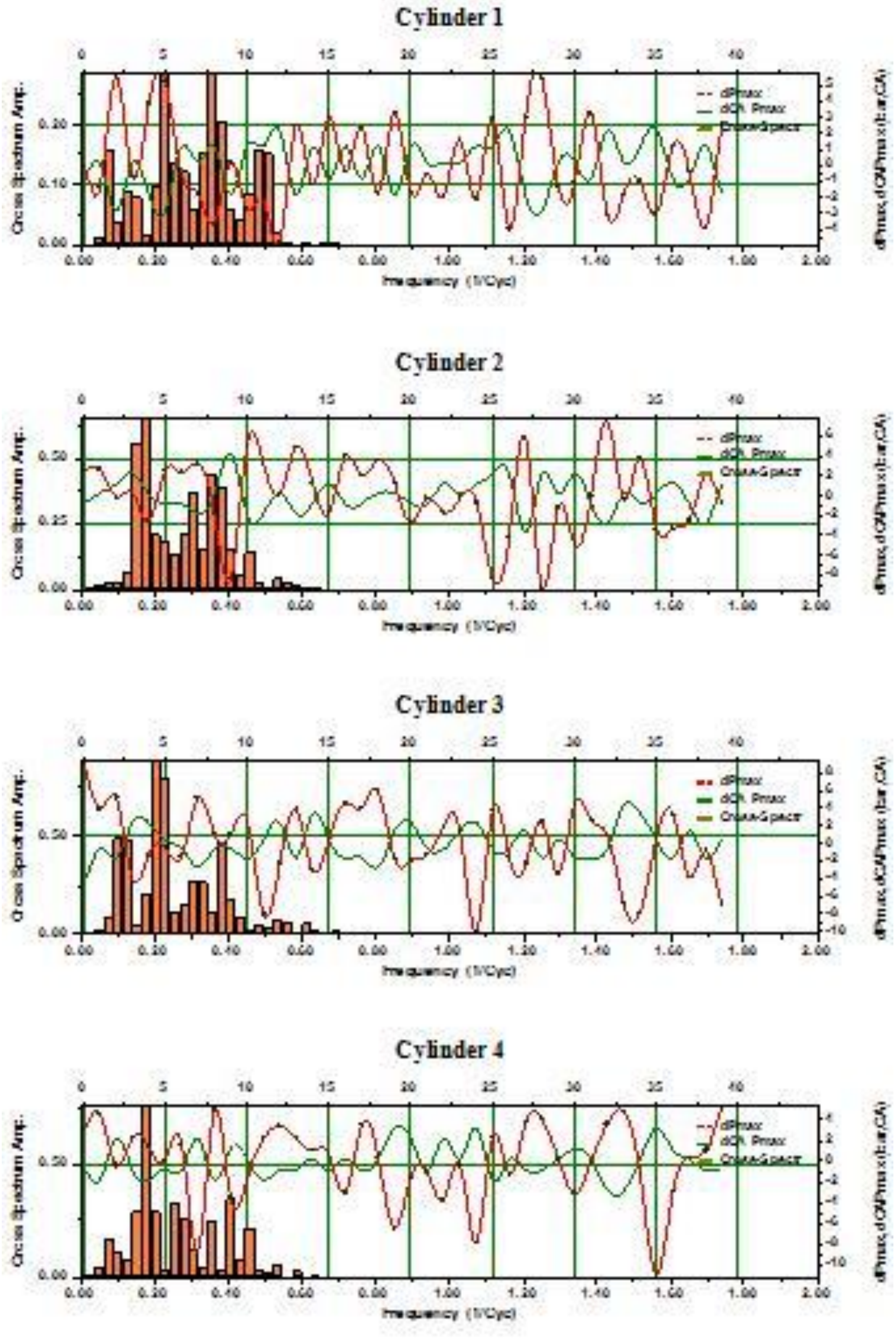

Fig.(12) Cross Power Spectrum

Cyclic variations of Maximum Pressure & its Crank Angle Timing

Gasoline Fuel / RPM=2607 / BMEP(bar)=4.06

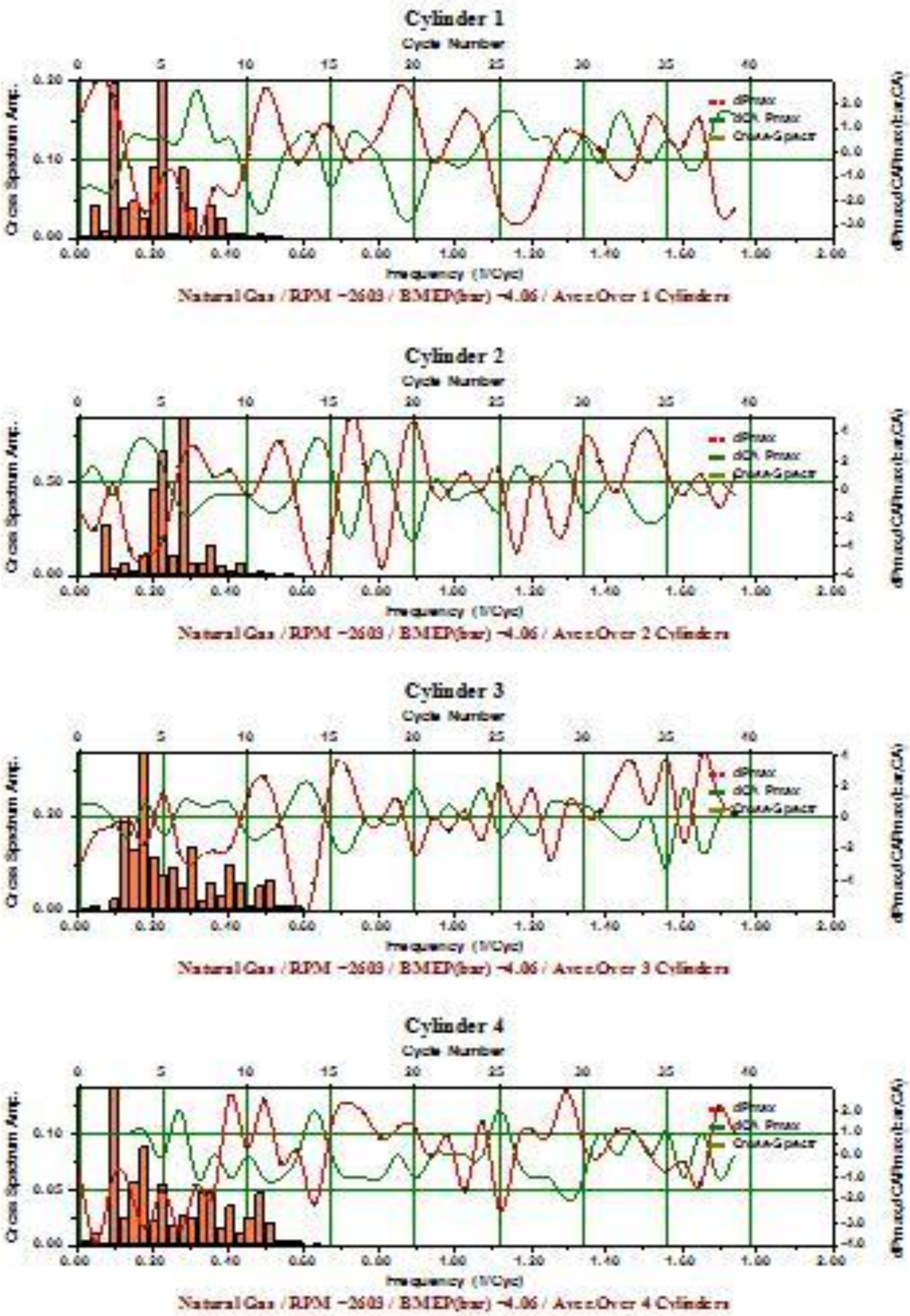

Fig.(13) Cross Power Spectrum

Cyclic variations of Maximum Pressure & its Crank Angle Timing

Natural Gas / RPM=2603 / BMEP(bar)=4.06

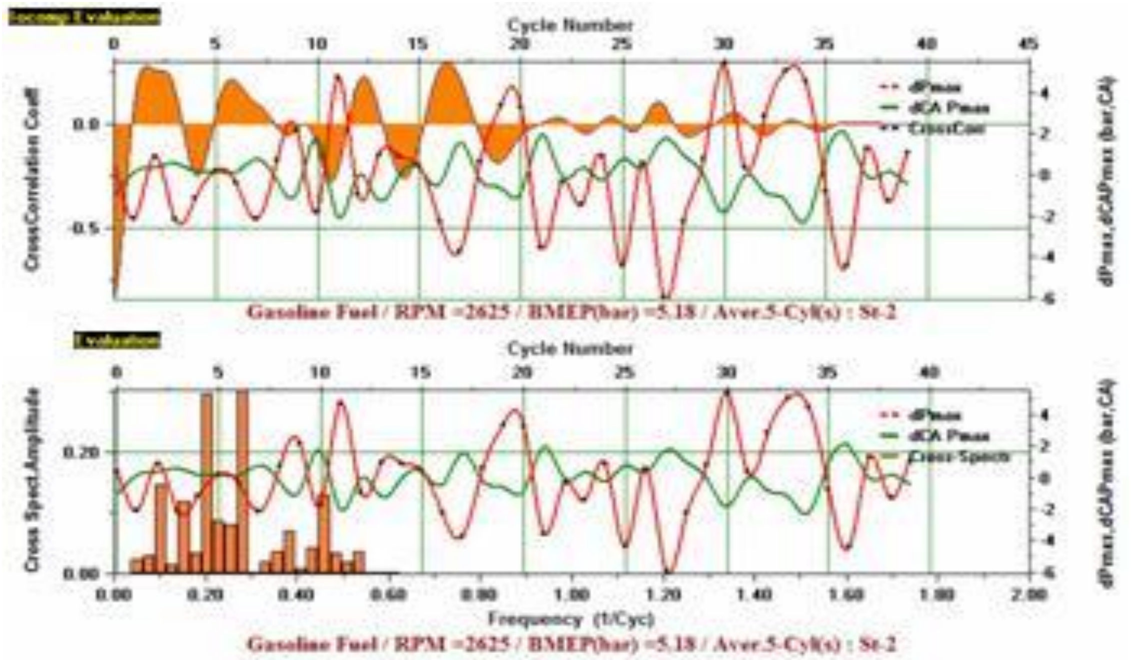

Fig.(14) dPmax and its dCAPmax Cross Correlation
Average of five cylinders in sequence of firing order
Gasoline, RPM=2625, BMEP=5.18bar

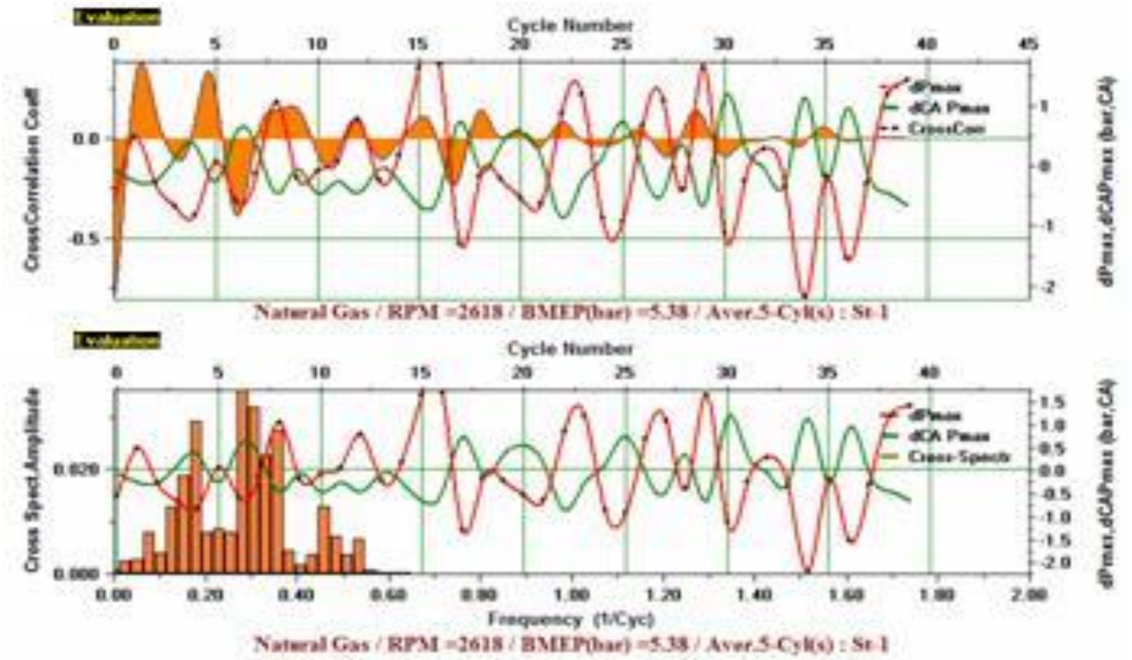

Fig.(15) dPmax and its dCAPmax Cross Correlation
Average of five cylinders in sequence of firing order
Natural Gas, RPM=2618, BMEP=5.38bar