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THE MILLER CYCLE BASED IC ENGINE FUELLED WITH A CNG/HYDROGEN

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Abstract

The results of research conducted on a supercharged spark ignition gaseous engine are exposed in the paper. The engine was modified to work as an engine with the Miller cycle. Modification of the engine, that allowed it to work in the Miller cycle, dealt particularly with the camshaft. This modification allows changing both intake and exhaust timings independently with limitations of ±20 deg. During the research, the engine was fuelled with compressed natural gas or hydrogen optionally. It was for making comparison between selected engine parameters, while the engine was working on two significantly different fuels. Both fuels were delivered to intake manifold close to intake valve through a fuel mixer. During the research, pressure data was collected with various both spark ignition timings and equivalence ratios, and boost pressures. On the basis of obtained data the parameters as follows: indicated mean effective pressure, coefficient of variance from the indicated mean effective pressure, Normalized Mass Fraction Burn and Heat Release Rate were calculated and discussed. As observed optimal ignition, timing is advanced for the engine working on hydrogen or natural gas as fuel with the Miller cycle when compared to the classic Otto cycle applied to this engine. In all tests of the engine with the Miller cycle coefficient of variance from the indicated mean effective pressure indicates good stability of engine work. Finally, the engine working on hydrogen is characterized by shorter combustion period that resulted from higher laminar flame speed compared to the natural gas fuelled engine.

Keywords: *hydrogen, miller cycle, gaseous fuels, combustion engines*

1. Introduction

Nowadays, one of the major targets in developing spark ignition engines are decreasing in exhaust gases emission and finding the alternative energy carrier for fossil fuels. To achieve these goals such fuels as hydrogen and CNG (compressed natural gas) can be used. Hydrogen as an engine fuel has many properties, which lead to increasing combustion efficiency as well as lowering exhaust gas emission from internal combustion engines. These properties are wide flammability limits (4-75% by vol.) [17], high combustion flame speed (1.85 m/s) [17], high energy density by mass (120 MJ/kg) [5, 8, 17], zero carbon content in the fuel molecule, high self–ignition temperature (840 K) and low ignition energy (0.02 mJ) [8, 17]. Hydrogen wide flammability limits allows the engine to work with lean air – fuel mixture that causes decreasing in NO_x emission thanks to reduction of maximum combustion temperature. Running a hydrogen engine with lean air – fuel mixture provide to stabilization of combustion processes and smoother engine run but causes decreasing in engine performance such as lower IMEP (Indicated Mean Effective Pressure). This drawback can be reduce by charging the hydrogen combustion engine what was investigated by Grab-Rogaliński et al. [3]. Very important parameter in a hydrogen engine is valve timing. Improper valve timing, especially overlap period can affect unfavourably for engine performance and proper run. A hydrogen laminar flame speed compare to fossil fuels is significant higher. This property allows to close the engine cycle to the ideal one, what influences on the engine thermal efficiency. Because of low hydrogen density, (0.089 kg/m^3) energy carried with 1 m^3 of fuel is much lower than other fuels. This is one of the major drawbacks of hydrogen as a fuel, especially in terms of its storage. These properties can also cause some difficulties during the combustion process as "knock combustion", backfires or pre-ignitions what was investigate by Szwaja et al. during his work [13-16].

CNG as an engine fuel also have some properties, which in consequence can lead to increase in the engine thermal efficiency. These properties are wide flammability limits (4.3-15% by vol.) [17], high self – ignition temperature (723 K) [17], high octane number MON=127) [9]. Wide flammability limits allowed the engine to work at lean air – fuel mixture, what in consequence allowed to decrease maximum in – cylinder and decrease emission of NO_x. High self – ignition temperature allow the engine to work with avoiding the knock combustion region. High octane number allows to increase compression ration what in consequence increase engine efficiency. Also increasing the compression ratio has the aim to reduce loses in IMEP compared to gasoline engines what is caused by longer ignition delay and lower flame speed according to Aslam et al. [1]. Because of higher ignition temperature for CNG than for gasoline vapours, ignition system has to delivery more energy for properly ignition for CNG [11]. Using a hydrogen or CNG as an engine fuel decrease in emission of exhaust gas pollutants can be achieved as describe many researchers in their works [1, 6, 7, 9].

When applying these fuels to the engine with the Miller cycle decrease in probability of occurrence combustion knock can be obtained, especially for the hydrogen engine. One of the major Miller cycle advantages is decrease the temperature of the end of compression stroke, which also decreases the maximum combustion temperature [2, 4, 10, 12]. However, decrease in IMEP caused by lower volumetric efficiency is observed. To reduce this drawback supercharging or turbocharging can be used as a satisfactory way to increase IMEP [3, 10].

2. Test bed description and experimental setup

All tests were done at Czestochowa University of Technology in Institute of Thermal Machinery. The test stand has been equipped with a single cylinder engine manufactured by Andoria-Mot model S231 coupled to a synchronous generator. The synchronous generator coupled with the engine works not only as an engine dynometer but also – as a starter for the engine and is controlled by a frequency converter. This engine has been modified from the diesel engine to the spark ignition one. The modifications consisted of:

- reducing the compression ratio from ε=16 to ε=11,
- mounting spark plug instead of diesel fuel injector,
- equipment intake manifold with a throttle and a mixer for gaseous fuel.

The test stand has been equipped with following sensors from which signals were recorded during measurements:

- in-cylinder pressure sensor with charge amplifier (Kistler 6055sp100),
- MAP sensor (Motorola MPX 4150),
- crank shaft angle and TDC pulse (encoder with resolution of 1024 impulse per revolution),
- fresh air temperature (Dallas DS18B20),
- air consumption (Rotor flow meter Common CGR-1),
- fuel consumption (Rotor flow meter Common CGR-1).

Recorded signals through data acquisition system NI USB 6251 were stored in a PC computer. Inlet duct of the engine has been equipped with a supercharger (EATON M65) and an intercooler placed in a tank filled with water to provide fixed temperature of fresh air during the research. The supercharger allows to increase boost pressure from 0 bar to 1 bar overpressure in this configuration.

The tested engine also can work as the engine with the Miller cycle. Modification of the valve timing system is primarily based on changing the angle of the intake valve closing from 40° CA ABDC to 10° CA BBDC. In addition, modified valve timing can change the intake and exhaust valves in both directions – delaying or accelerating in the range of 20° rotation of the camshaft.

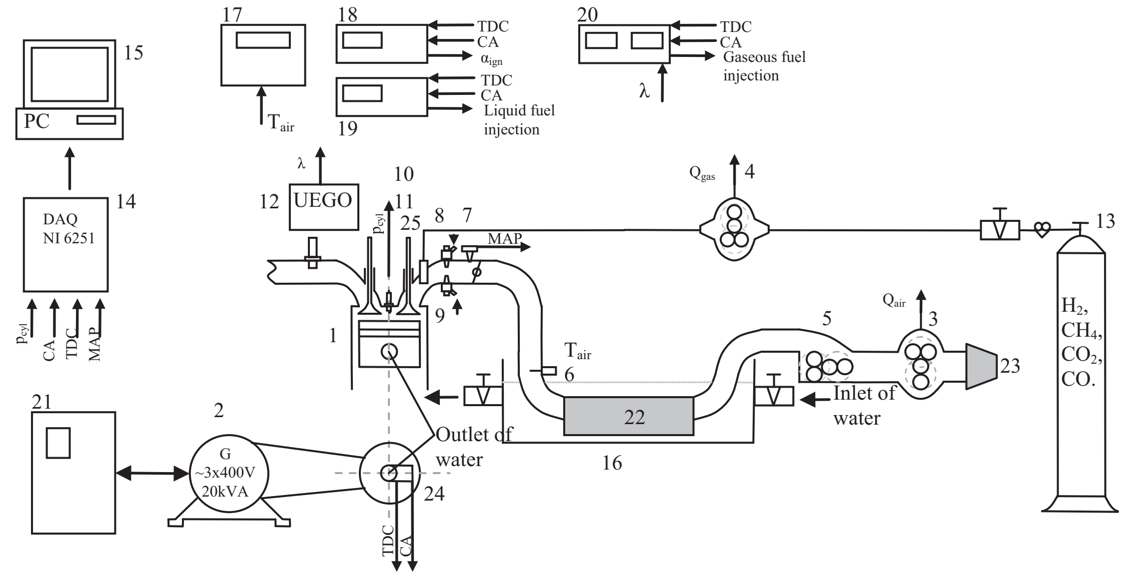

Fig. 1. Test stand: 1 – test engine, 2 – synchronous generator, 3 – air flow meter, 4 – gaseous flow meter, 5 – supercharger, 6 – air temperature sensor, 7 – MAP sensor, 8 – gaseous fuel injector, 9 – liquid fuel injector, 10 – spark plug, 11 – pressure sensor, 12 – wide band oxygen sensor NTK/NGK, 13 – gaseous fuel pressure tank, 14 – data card, 15 – PC computer, 16 – water tank, 17 – Temperature gauge, 18 – ignition timing control unit, 19 – liquid fuel injection timing control unit, 20 – gaseous fuel injection timing control unit, 21 – frequency converter, 22 – intercooler, 23 – air filter, 24 – encoder, 25 – fuel mixer

During this research in-cylinder, pressure data for hydrogen and CNG were collected. Both fuels were delivered to the engine by a mixing device mounted on intake port. For both cases of fuel, the engine was worked as NA and supercharged with overpressure equal to 0.3 bar. Excess air ratio for the hydrogen was λ=1.5 and for CNG λ=1.0. Temperature of fresh air during measurements was kept on constant level for the each case. Parameters of experimental setup are shown in Tab. 1.

Tab. 1. Experimental setup

	p_{boost} bar	α_{ign} °CA	λ	T_{air} °C
CNG	NA	32-10	1	20
	1.3	26-8	1	21
H_2	NA	10-4	1.5	23
	1.3	10-4	1.5	24

On the basis of measurements, the following parameters have been defined: IMEP, COV_{IMEP}, NMFB, HRR. All parameters shown on figures are for ignition timing corresponds to maximum value of IMEP.

3. Results and discussion

Figure 2 shows the dependence of IMEP against ignition timing. As can be seen in this case for both the naturally aspirated (NA) engine and the supercharged one fuelled with CNG optimal ignition timing is nearly the same. IMEP for the supercharged engine with overpressure 0.3 bar is higher than for the NA engine for about 30%. Although for the engine with Miller cycle optimum, ignition timing for IMEP is earlier than for the classic one. Despite the lower volumetric efficiency for the engine with Miller cycle, the values of IMEP are higher in both cases than for the engine with Otto cycle.

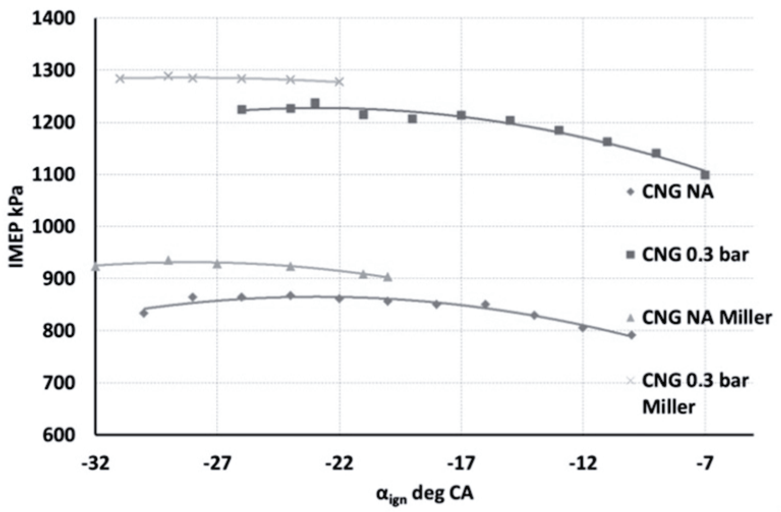

Fig. 2. IMEP as a function of ignition timing for NA and SC engine fuelled with CNG

Figure 3 shows COV (coefficient of variation) for IMEP. In all cases, this value does not exceed 3.5% and for optimal ignition, timing is below 1% that is a pretty perfect result. It shows that the engine was working very stable at optimal ignition timing. This stability decreased with ignition timing being delayed.

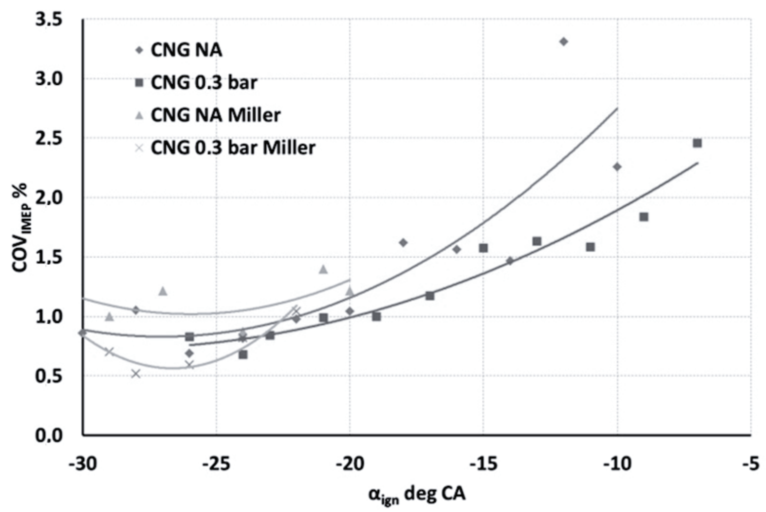

Fig. 3. COV_{IMEP} as a function of ignition timing for NA and SC engine fuelled with CNG

NMFB reaches 50% when crank angle equals about 10° after TDC for the engine fuelled with CNG, which indicates optimal ignition timing for the engine with Otto cycle. For the engine with the Miller cycle 50% of NMFB occurs earlier of approximately 5° after TDC. As can be seen for all cases there is no significant differences in NMFB progress (Fig. 4). The angle to complete the combustion for CNG is about 70° CA.

Figure 5 proves that there are no significant differences in combustion progress except the max. HRR, which obviously is higher for the supercharged engine. Maximum value in all cases is reached when NMFB reaches 50%. For the engine with Miller cycle, HRR peak is reached earlier what is caused by earlier ignition timing.

Figure 6 shows the maximum value of IMEP for hydrogen. The maximum value for IMEP for the engine fuelled with hydrogen is obtained earlier for the case with the Miller cycle than for Otto cycle applied. Also compared to the engine fuelled with CNG optimal ignition timing for hydrogen is significantly retarded and closed to TDC.

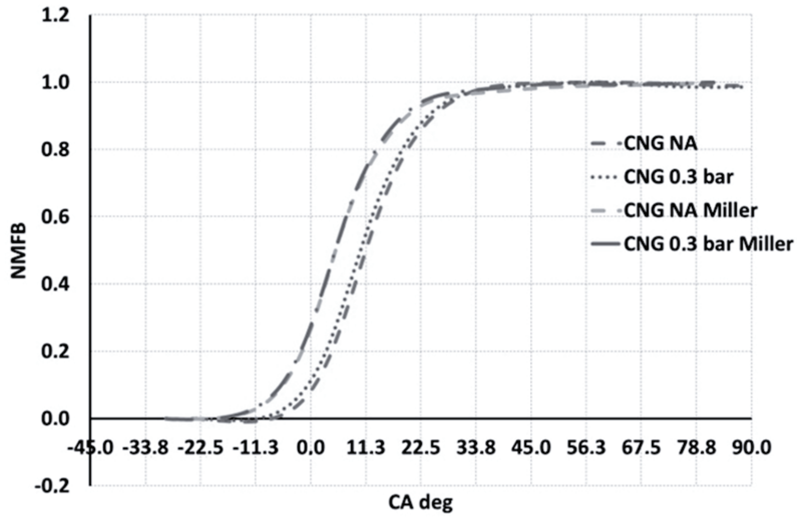

Fig. 4. NMFB as a function of CA for NA and SC engine fuelled with CNG

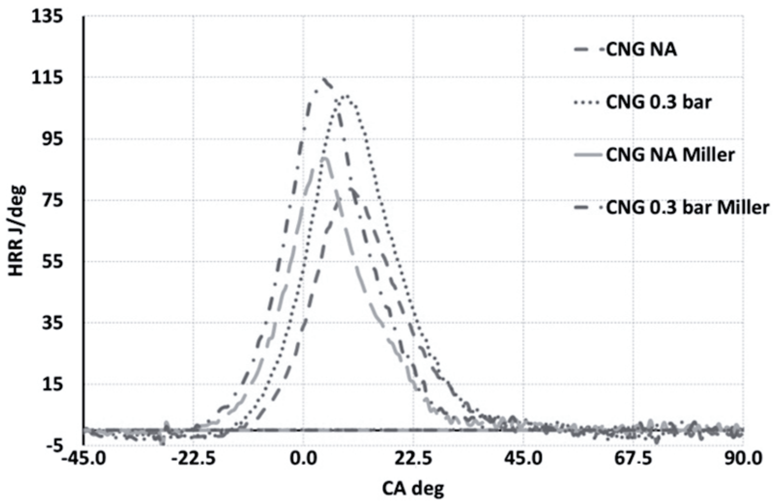

Fig. 5. HRR as a function of CA for NA and SC engine fuelled with CNG

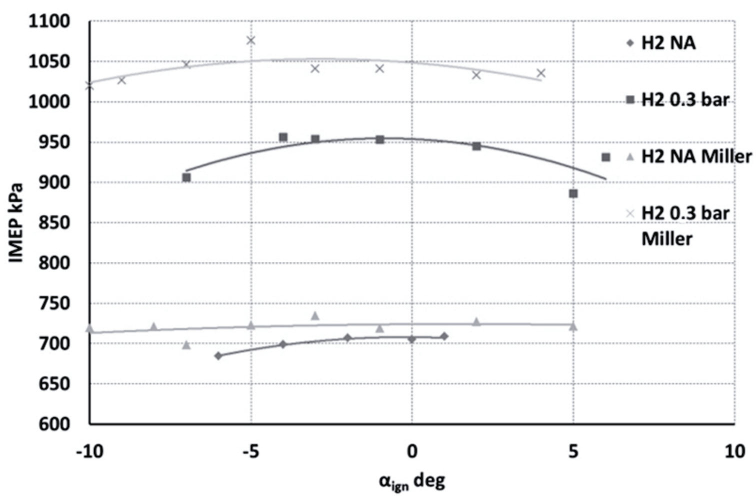

Fig. 6. IMEP as a function of CA for NA and SC engine fuelled with Hydrogen

As can be seen in Fig. 7 also in this case COV_{IMEP} does not exceed 3%. What indicates a good stability during engine operation. In optimum spark timing region COV_{IMEP} is near 1%.

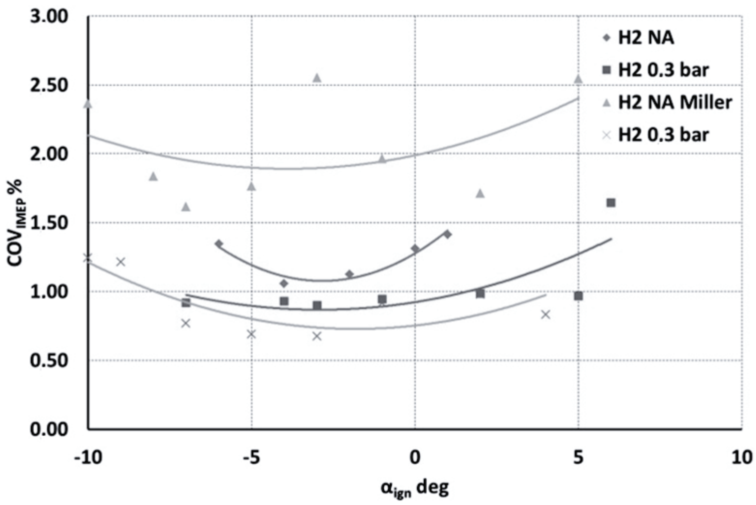

Fig. 7. COV_{IMEP} as a function of CA for NA and SC engine fuelled with Hydrogen

Figure 8 shows course of normalized mass fraction burnt (NMFB) for engine fuelled with hydrogen. In these case can be seen that time required (expressed by the crankshaft angle) to totally combust air – hydrogen mixture is very short and is equal approximately 20 deg CA. There are no significant differences in total combustion angle for both Miller and Otto cycle engine.

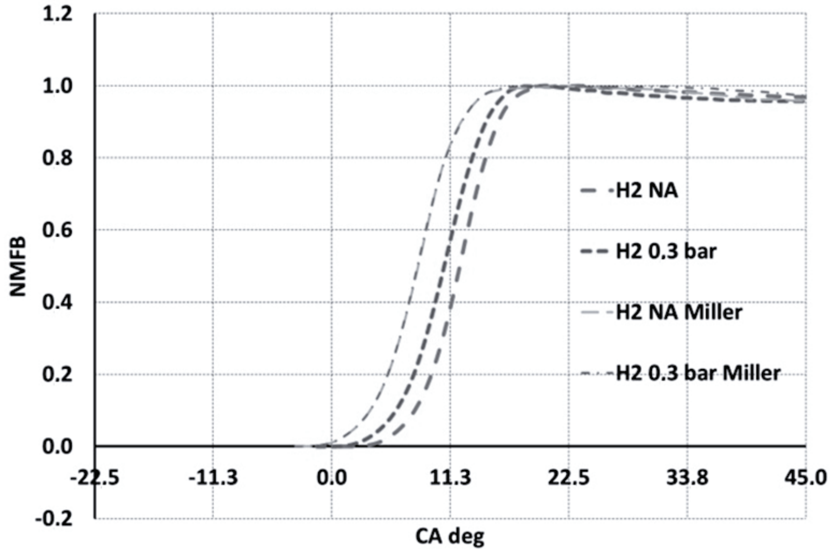

Fig. 8. NMFB as a function of CA for NA and SC engine fuelled with Hydrogen

HRR progress shown in Fig. 9 indicates that optimum timing for the engine with the Miller cycle is more advanced than for the engine with the Otto cycle. As can be seen for NA engine in both cases of engine with Otto cycle and Miller cycle.

4. Conclusions

On the basis of data processing and analysis the following conclusions have been done:

- in both cases optimal ignition timing is advanced for the engine working on hydrogen or CNG fuel with the Miller cycle when compared to the classic Otto cycle applied to this engine,
- in all cases of engine configuration COV_{IMEP} indicates good stability of engine work,
- the engine working on hydrogen is characterized by shorter period of air – H2 mixture combustion what corresponds to higher laminar flame speed compared to the engine fuelled

CNG.

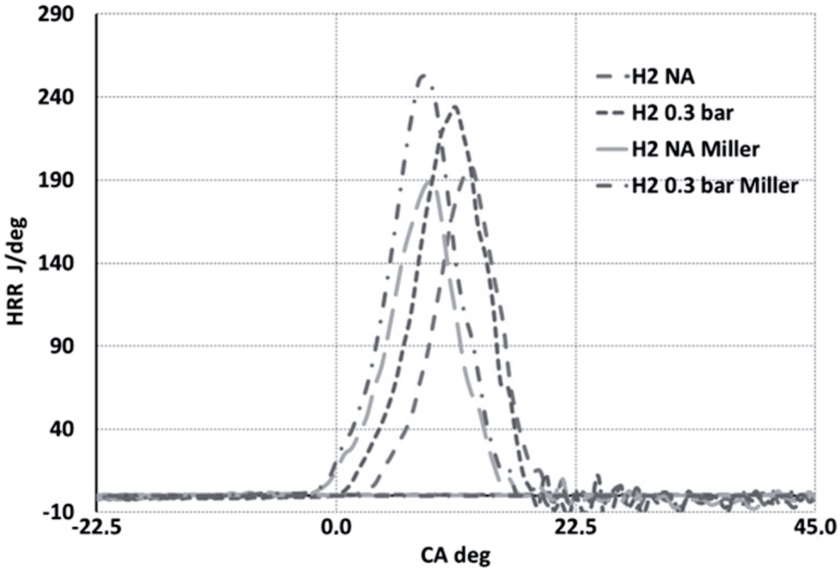

Fig. 9. HRR as a function of CA NA and SC engine fuelled with Hydrogen

5. Nomenclature

ABDC	– After Bottom Dead Centre;
BBDC	– Before Bottom Dead Centre;
BDC	– Bottom Dead Centre;
CA	– Crank Angle;
CNG	– Compressed Natural Gas;
COV_{IMEP}	– Coefficient of Variation for IMEP;
HRR	– Heat Rate Release;
IMEP	– Indicated Mean Effective Pressure;
MON	– Motored Octane Number;
NA	– Natural Aspirated engine;
NMFB	– Normalized Mass Fraction Burn;
SC	– Supercharged engine;
TDC	– Top Dead Centre.

Acknowledgments

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