NATURAL GAS ENGINES – PROBLEMS AND CHALLENGES

Andrzej Kowalewicz, Małgorzata Wojtyniak

Technical University of Radom
Chrobrego 45, 26-600 Radom, Poland
tel. +48 48 3617653, +48 48 3617671, fax +48 48 3617644
e-mail: andrzej.kowalewicz@pr.radom.pl
malgorzata.wojtyniak@op.pl

Abstract

At former KONES one of the co-authors presented a paper, is which general information about natural gas properties, reserves, production and distribution were given and application to SI and CI engines was presented, compared and discussed. It was shown, that more promising is dual-fuel CI engine.

There is a lot of information on combustion, emissions and performances of dual-fuel natural gas engines, but there are also blank areas and controversial opinions, which were pointed out and discussed in this paper. For example: why combustion processes are delayed in comparison with combustion of diesel fuel only. It is also not clear whether noise of dual-fuel engine is higher than that of diesel engine or lower (there are contradictory data). These problems are shown and discussed in this paper. The proposal of further research is presented.

Ignition and combustion in dual-fuel natural gas engines is yet not fully recognized, especially: combustion duration, mechanism at gaseous and condensed phase burning, kinetics and diffusion controlled combustion, noise, knock and cycle-by-cycle variation. Optimization of control parameters on account of efficiency and emissions is still an open problem. Influence of natural gas composition and its changes on engine performance and emissions still demand estimation.

Keywords: *combustion engine, natural gas, dual-fuel engine, combustion duration, knock*

1. Introduction

At previous KONES'2006 one of the co-authors presented a paper [1], in which it was shown that natural gas (NG) may be used as a fuel for diesel engine with pilot diesel fuel direct injection necessary for ignition, i.e. natural gas dual-fuel engine (DF NG engine). This type of engine shows benefits in comparison with spark ignition NG engine. NG is better fuel than LPG and pilot fuel may be replaced by rape oil methyl ester (RME).

In this paper focus is laid on the problems, which affect performances, emissions and noise and are yet not fully cleared out.

First dual-fuel engine built Rudolf Diesel (1896) in Maschinenbaufabrik Augsburg-Nürnberg, MAN. He injected directly petroleum and natural gas into CI engine (called after him diesel). This was the idea of gas-diesel engine. Further approach to dual fuelling of internal combustion engines was carried out by Karim [2-4] in Canada and by Zabłocki in Poland [5]. Karim carried out a lot of experiments and showed topic problems, which should be overcome in the field of combustion in DF NG engine. Zabłocki worked out a theoretical background of dual fuelling and showed how CI engine should be adapted to fuelling with natural gas. A comprehensive study of DF NG engine carried out Stelmasiak [6].

New generation of dual-fuel natural gas engines is fitted with electronically controlled multipoint port-injected sequential NG fuel system and Electronic Control Unit (ECU) that integrates with existing Electronic Control Modul (ECM). ECU precisely controls both fuels injection (metering and timing injection of each fuel) and optimizes combustion in view of emission and efficiency.

2. Natural gas dual-fuel engine as an object of operation

Emissions and brake fuel conversion efficiency (b.f.c.e) of dual-fuel engine depend - on one hand - on operating parameters (i.e. torque, T and speed, n) and on control parameters - on the other. Control parameters, that do not depend on driver but are set automatically, are:

- pilot fuel quantity, m_P and timing, φ_p,
- mass/energy of NG to total fuel,
- gas fuel – air equivalence ratio, ϕ_{NG},
- total fuel – air equivalence ratio, ϕ,
- exhaust gas recirculation ratio, EGR,

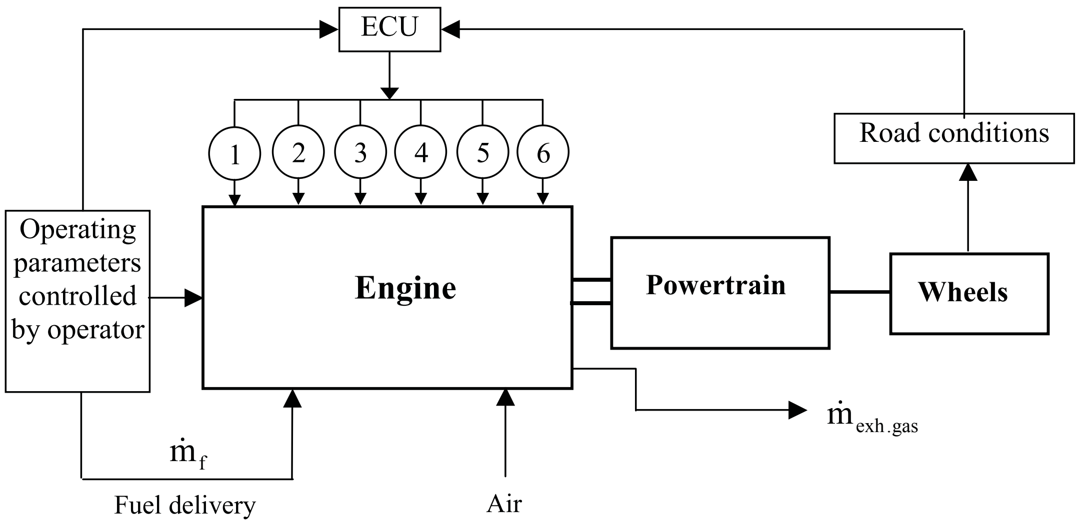
and in supercharged engine:

- charge pressure at the inlet.

The scheme of the engine considered as an object of control system is shown in Fig. 1.

The evaluation of the influence of engine operating parameters (b.m.e.p. and speed) on performances, emissions and efficiency should take into account control parameters, which – in the case of the engine installed on the vehicle – are adjusted according to the optional programme. This programme, which is encodered in ECU, controls engine operation at possible optimum efficiency and minimum emissions within the range of the obligatory standards.

Influence of operating parameters and control parameters on efficiency, emissions and noise are discussed and analyzed in the paper, which will be published in literature. Although there is vast literature on these problems, there are some blank areas, which are signalized further is this paper.



Control parameters:
1- m_f – mass of pilot fuel (MPF)2- φ_{pfi} – angle of MPF,
3- Ω mass (energy) ratio of NG to DF,
4- λ_{NG} air excess coeff. for NG,
5- related to total fuel λ_{NG+DF} air excess coefficient,
6- ERG ratio.

Fig. 1. Dual- fuel NG engine as an object of control

3. Problems which should be explained

3.1. The first main problem: Combustion duration

Reciprocal interaction of control parameters makes a lot of difficulties in evaluation of the influence of a given single parameter on efficiency and emissions and complicate the problem. All not cleared out problems concerned with DF NG engine are focused in combustion processes.

In some references, namely [6, 7, 8, 10] it may be found the opinion that combustion in dual-fuel natural gas engine is longer than in conventional diesel engine. Ignition delay and combustion duration vs. mass ratio of NG and vs. brake mean effective pressure are shown in Figs 2 and 3, respectively. Longer ignition delay may be the result of more difficult diffusion transport of air to diesel fuel droplets due to the presence of inert gas, i.e. natural gas before ignition. However, after ignition, NG-air homogeneous mixture should burn very quickly (kinetics controlled combustion).

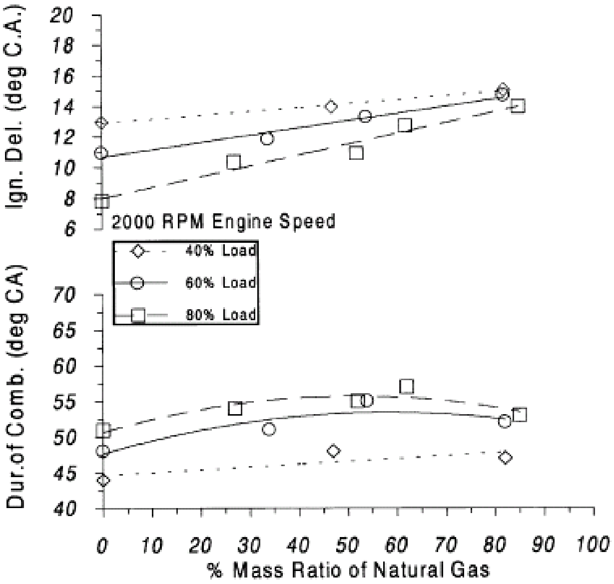


Fig. 2. Variation of ignition delay (a) and combustion duration (b) as function of NG mass ratio at 2000 rpm for various engine loads [7]

The visible prove of that is the first steep maximum of the heat release rate (HRR). Moreover, Stelmasiak says [6] that this first peak of the two (two maxima) of HRR is concerned with combustion of diesel fuel and the second one - with NG – Figs 4 and 5.

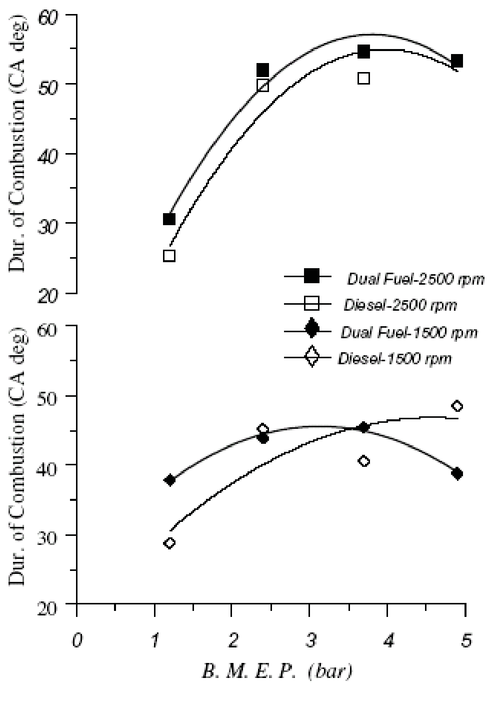


Fig. 3. Variation of combustion duration under normal diesel and dual fuel operation as function of load at 1500 and 2500 rpm engine speed [8]

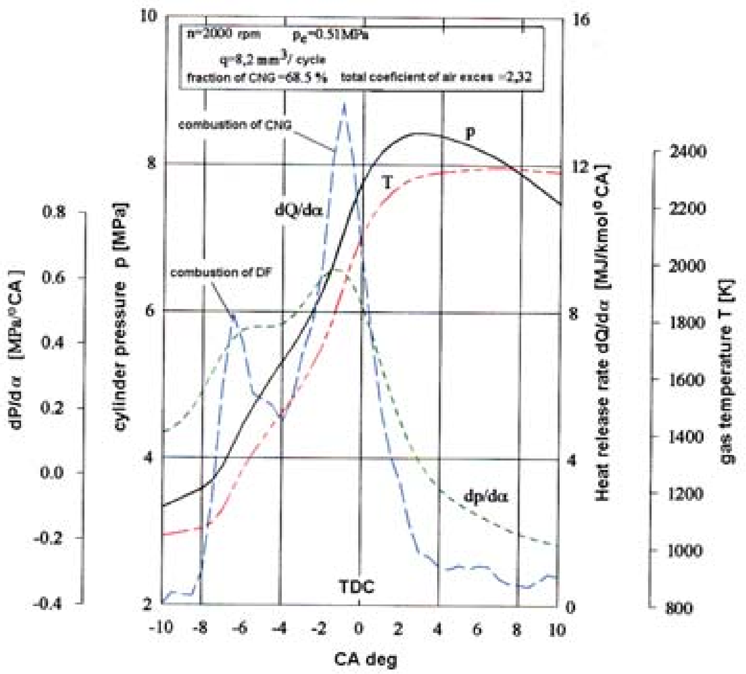


Fig. 4. Cylinder pressure p, rate of pressure rise dP/dα, temperature of gases in cylinder T and HRR in fraction of CA [6]

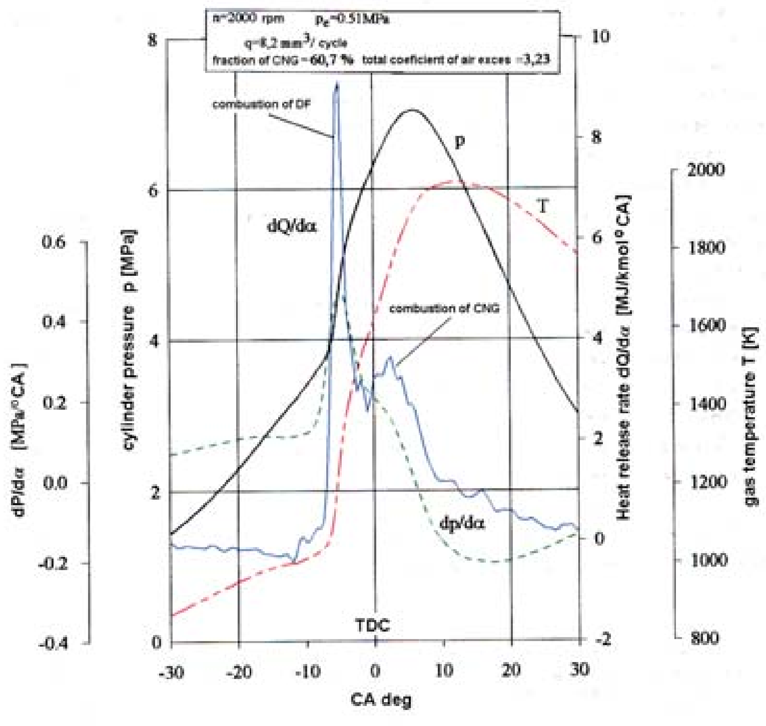


Fig. 5. Cylinder pressure p, rate of pressure rise dP/dα, temperature of gases in cylinder T and HRR dQ/dφ in fraction of CA [6]

In the case of fuelling with ethanol (injected into the inlet port during the expansion stroke) and diesel fuel [9] the first maximum was connected with burning of gaseous mixture ignited by diesel fuel and the second maximum (if it appeared) was diffusion controlled combustion of diesel fuel droplets, i.e. on the contrary to Stelmasiak's statement – Fig. 6. Although combustion is retarded at the beginning of the process, afterwards becomes faster and is finished earlier than combustion of neat diesel fuel (Fig. 7.)

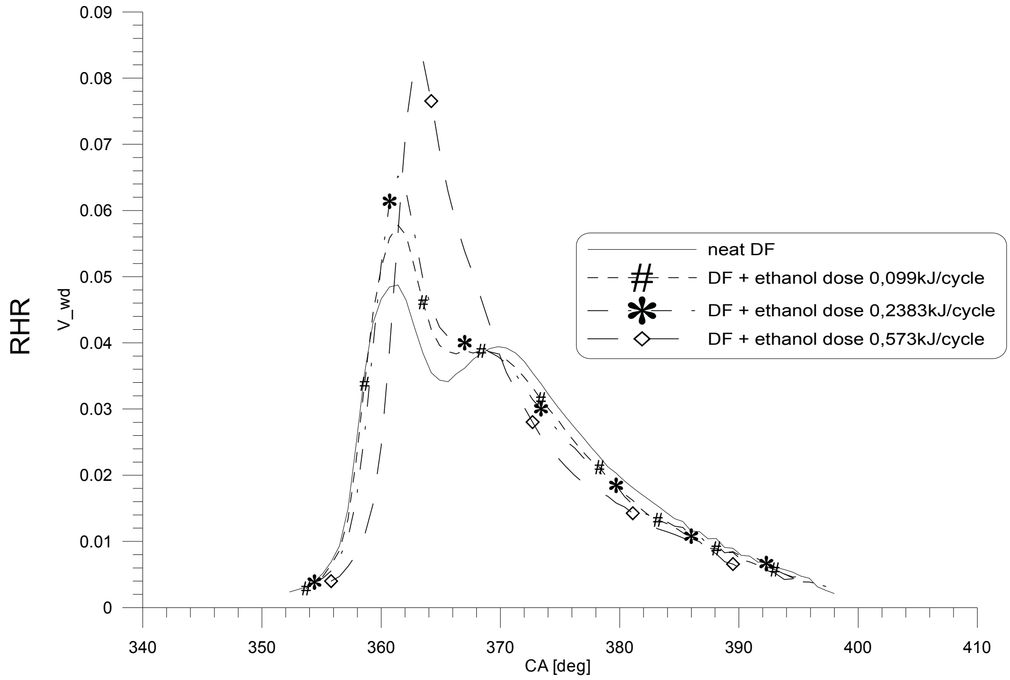


Fig. 6. Rate of heat release for M = 40 Nm, n = 1200 rpm, alpha DF = 25 deg BTDC [9]

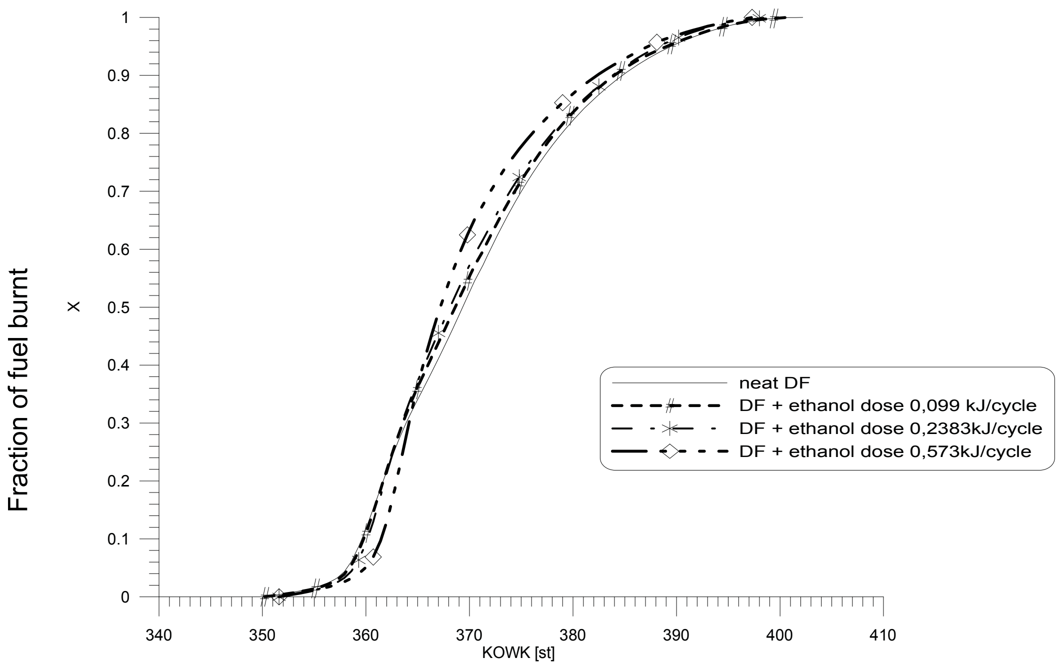


Fig. 7. Mass fraction of fuel burnt for M = 40 Nm, n = 1200 rpm, alpha DF = 25 deg BTDC [9]

In the reference [6] there is not shown diagram of fraction of fuel burnt vs. energy fraction of NG, so it is not clear how long the combustion duration is. According to [10], the last stage of combustion is diffusion combustion stage (of liquid diesel fuel droplets, of course).

Comprehensive study of combustion in DF NG engine was carried out in [12]. Retardation of pilot fuel injection results in pilot fuel combustion delay and decrease of charge temperature, which is not enough to propagate the flame in gaseous fuel – air mixture, leading to incomplete combustion and delay of NG-air mixture. Simultaneously with opinion that combustion in NG DF engine is longer than in conventional diesel engine and extends for expansion stroke, in [6] one can find, that in DF NG engine combustion is 1,8÷2,3 times shorter (!) and decreases for lower pilot diesel fuel quantity.

Also it is not clear, why strength of the mixture has so high influence on burring of NG and DF:

- for lean mixture, DF burns more quickly than CNG (Fig. 4),
- for the rich one – CNG burns more quickly than DF (Fig. 5) (for diesel fuel quantity = idem [6]).

3.2. Second main problem: Rate of pressure rise (RPR) and noise

Rate of pressure rise (RPR) is the measure of noise emitted by the engine. In some publications, namely [6] RPR for DFNG engine is lower than for conventional diesel engine, in other – vice versa, Fig. 8 and Figs 9÷11 respectively.

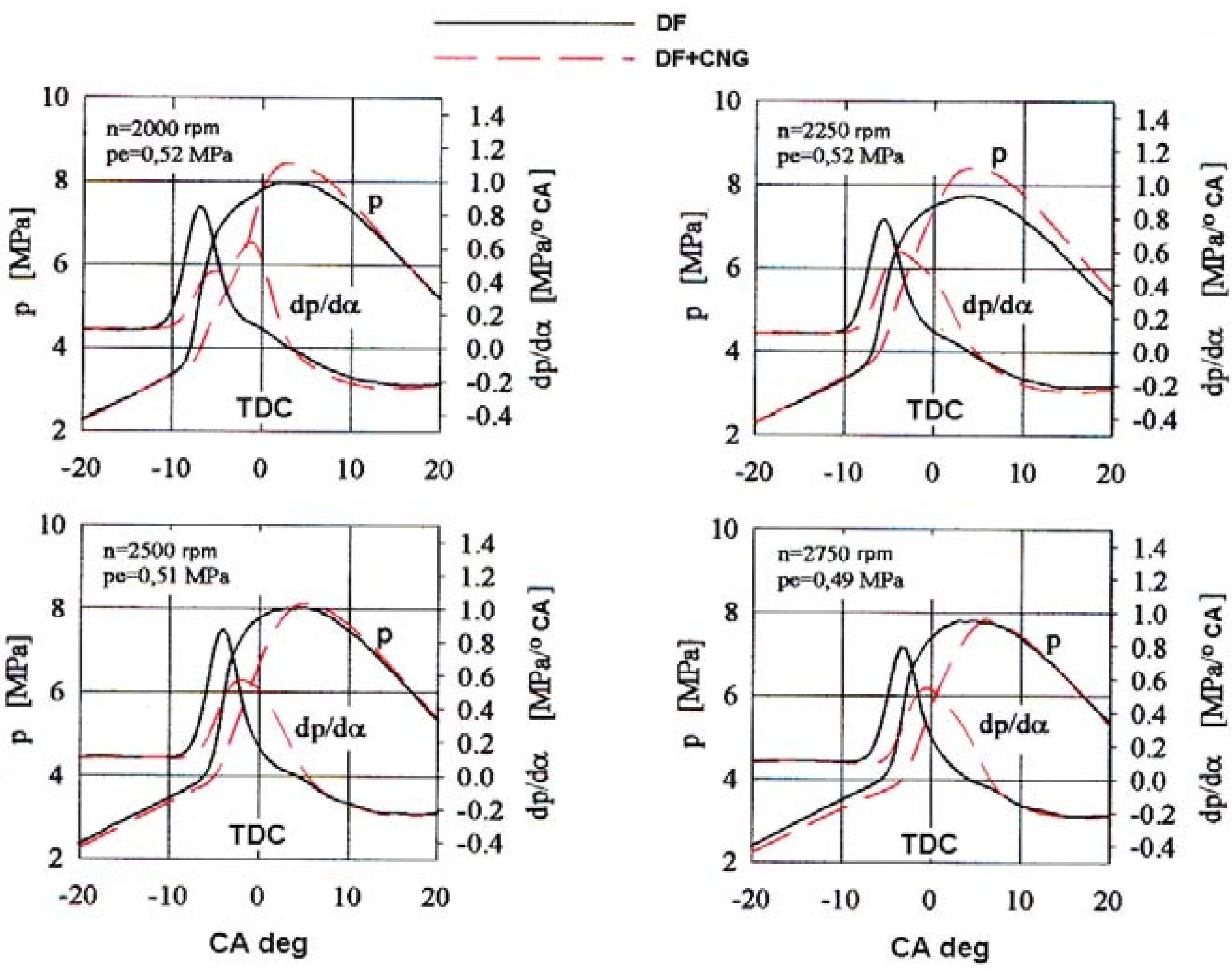


Fig. 8. Comparison of cylinder pressure p and rate of pressure rise dP/dα in conventional engine and DF CNG engine [6]

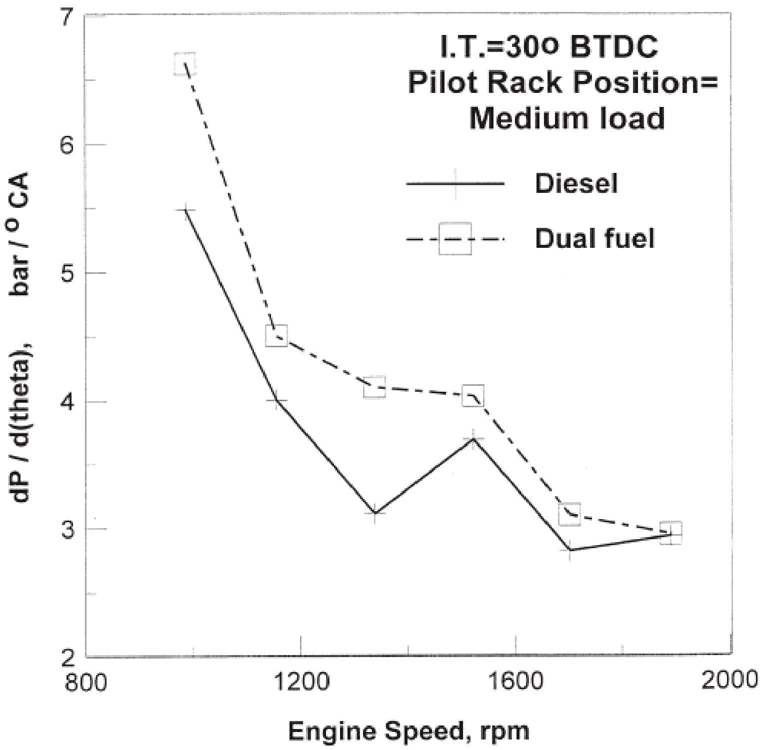


Fig. 9. Effect of engine speed on the rate of pressure rise for the diesel and dual- fuel engines [12]; indirect injection (IDI), compression ratio CR = 21, medium load injection angle = 30 CA BTDC

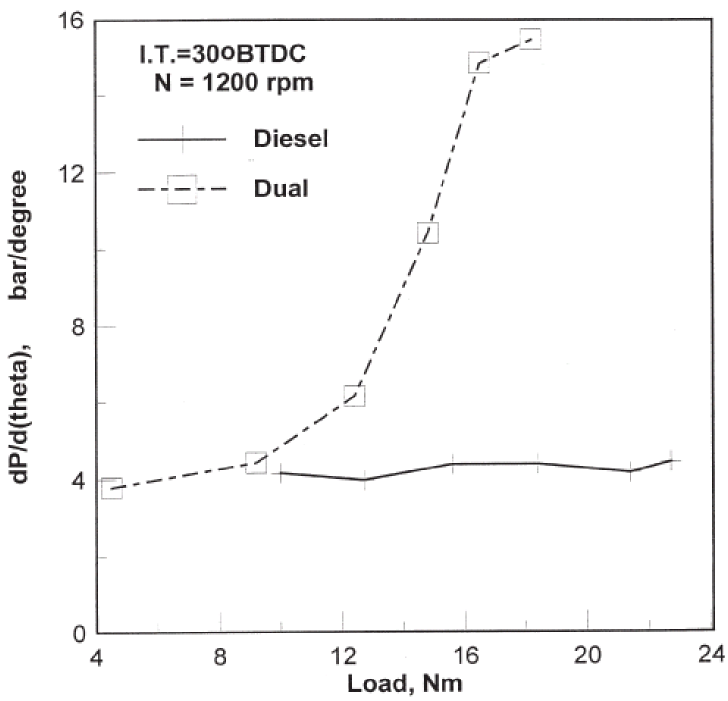


Fig. 10. Effect of engine load on the rate of pressure rise for the diesel and dual-fuel engines [12]; indirect injection (IDI) engine, compression ratio CR = 21, engine speed = 1200 rpm, injection angle = 30 CA deg. BTDC

The difference is big, when angle of beginning of injection is greater than about 30 CA deg BTDC i.e. really injection (the same phenomenon may be observed for conventional CI engine), and for medium and high load (Fig. 11).

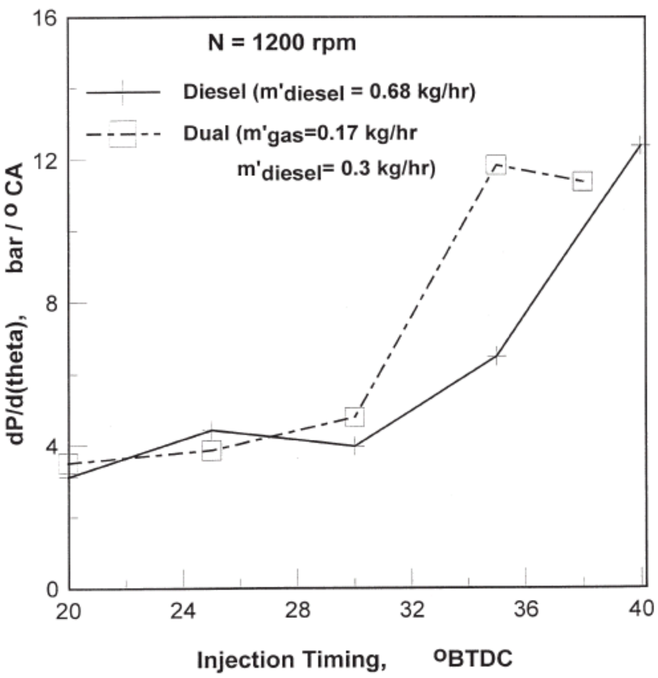


Fig. 11. Effect of pilot fuel injection timing on the rate of pressure rise for the diesel and dual-fuel engines [12]; indirect injection (IDI) engine, compression ratio (CR) = 21, engine speed = 1200 rpm, injection angle = 30 CA deg. BTDC

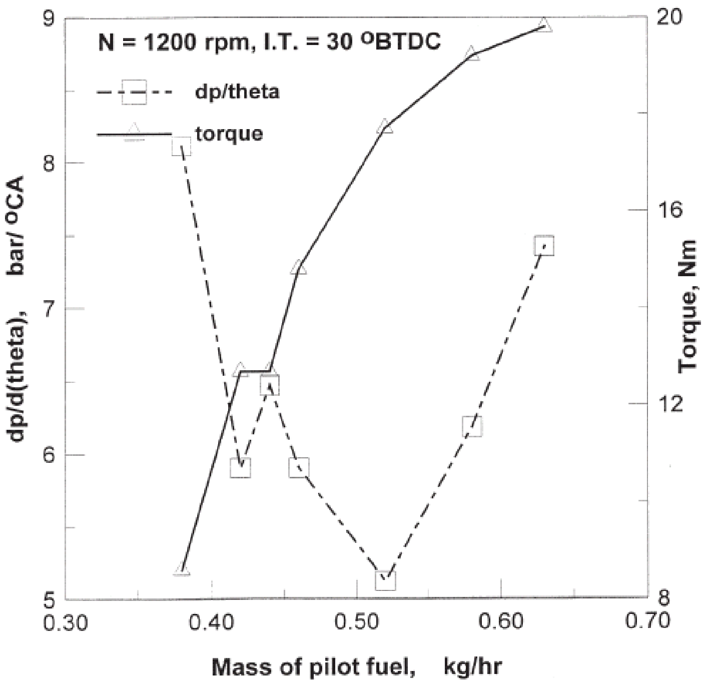


Fig. 12. Effect of pilot fuel mass on the rate of pressure rise and torque for the dual- fuel engine [12]; indirect injection (IDI) engine, compression ratio (CR) = 21, engine speed = 1200 rpm, injection angle = 30 CA deg. BTDC

According to [13], increase of pilot fuel quantity results in decrease of dP/dφ (noise), due to the increase of pilot fuel volume and lower HRR and leads to smooth gaseous fuel combustion.

3.3. Third main problem: Knock and unstable engine operation

What is knock? Commonly accepted definition of knock is abnormal combustion in SI engine, when autoignition of the end gas results in flame propagation in opposite direction than this initiated by the spark accompanied by high frequency noise (4,5 – 7,0 kHz) [14]. In diesel engine there appears "diesel knock", which is visible on cylinder pressure diagram as ripple, also accompanied by noise. In dual-fuel engine knock also appears, which is identified to be due to autoignition of the end gas (like in SI engines).

Nwafor [10] identifies three types of knock in dual-fuel engines:
- "diesel knock" due to combustion of premixed pilot fuel (DF),
- "spark knock" due to autoignition of end gas,
- "erratic knock" due to secondary ignition of gaseous fuel.

Knock prediction for dual-fuel methane engines using eleven chemical reactions was worked out in [15]. Autoignition of end gas takes place at low equivalence ratio (of end gas) in temperature range 800 - 1200^{o}C.

It is a well known fact that knocking combustion appears for early injection and lean mixtures, when conditions for autoignition of the "reset gas" are feasible. According to [16], increasing of NG fraction at high load promotes knock. However, this statement is incompatible with suggestions of [4].

Knocking combustion (especially in dual-fuel engines) is still not cleared out, there is need to examine its physical nature and formulate criterion, when it may appear.

In order to improve stable operation and decrease emission, mainly NO_x, NG reformer was applied [17]. In the reformer, NG reacts with recirculated hot exhaust gases (which contain water vapour) from the engine and forms synthesis gas:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

which is introduced to the engine. Amount of hydrogen in reformulated fuel may reach 30% at exhaust gases temperature 800÷700^{o}C and 20% at 500÷700^{o}C. Reforming of NG may results in uniform engine rotation speed and coefficient of variation of indicated mean effective pressure (COV_{imep}) below 5% [17].

4. Conclusions

From the above analysis the following conclusions may be drawn:

- Ignition and combustion in dual-fuel natural gas engines is yet not fully recognized, especially:
  - combustion duration,
  - mechanism at gaseous and condensed phase burning (kinetics and diffusion controlled combustion),
  - noise (RPR),
  - knock and cycle-by-cycle variation (COV_{imep}).
- Optimization of control parameters on account of efficiency and emissions is still an open problem.
- Influence of natural gas composition and its changes on engine performance and emissions still demand estimation.

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References

[1] Wojtyniak, M., *Application of Natural Gas to Compression Ignition Engines,* Journal of KONES Powertrain and Transport, Vol 13 No p.p. 443 – 448, Warsaw 2006.

[2] Karim, G. A., *A review of combustion processes in the dual fuel engine - the gas diesel engine*, Progr. Energy Combust. Sci, 1980, Vol. 6, pp. 277-285, 1980.

[3] Karim, G. A., Wierzba I., *Comparative studies of methane and propane as fuels for spark ignition and compression ignition engines*, SAE paper 831196, 1983.

[4] Karim, G. A., Jones, W., Raine, R. R., *An examination of the ignition delay period in dual fuel engines*, SAE paper 891222, 1989.

[5] Zabłocki, M., *Dwupaliwowe silniki z zapłonem samoczynnym napędzane paliwem ciekłym i gazowym,* (Dual-fuel compression ignition engines fuelled with liquid and gas fuels), Wydawnictwo Naukowo – Techniczne, Warszawa 1969 (in Polish).

[6] Stelmasiak, Z., *Studium procesu spalania w dwupaliwowym silniku o zapłonie samoczynnym zasilanym gazem ziemnym i olejem napędowym*, Wydawnictwo ATH, Bielsko – Biała.

[7] Shengua, E., Longbao, Z., Ziyan, W., Jiang, R., *Combustion characteristics of compressed natural gas/diesel dual-fuel turbocharged compression ignition engine,* Proc. Instn Mech. Engrs, Part D: Journal of Automobile Engineering, 2003 Vol. 217, No. D9, pp.833-838, 2003.

[8] Papagiannakis, R. G., Hountalas, D. T., *Combustion and exhaust emission characteristics of a dual fuel compression ignition engine operated with pilot diesel fuel and natural gas*, Energy Conversion and Management, Vol. 45 (2004) pp. 2971-2987, 2004.

[9] Pajączek, Z., *Biofuelled Comparison Ignition Engine with Additional Injection of Ethanol*, Paper Nr P05-C019 at PTNSS Kongres, Bielsko – Biała 2005.

[10] Nwafor, O.M.I., *Knock characteriscics of dual-fuel combustion in diesel engines using natural gas as primary fuel*, Sadhana, Vol. 27 Part 3, p. 275 – 382, 2002.

[11] Papagiannakis, R. G., Hountalas, D. T., *Experimental investigation concerning the effect of natural gas percentage on performance and emissions of a DI dual fuel diesel engine*, Applied Thermal Engineering 2003, Vol. 23, pp. 353-365, 2003.

[12] Abd, Alla, G. H., Soliman, H. A., Badr, O. A., Abd, Dabbo, M. F., *Combustion quasi-two zone predictive model for dual fuel engines*, Energy Conversion & Management 42, p. 1477-1498.

[13] Selim, M. Y. E., *Pressure-time characteristics in diesel engine fuelled with natural gas,* Renewable Energy 2001, Vol. 22, pp. 473-489, 2001.

[14] Dues, S. M., Adams, J. M., Shinkle, G. A., *Combustion knock sensing: sensor selection and application issues,* SAE Paper 900488, 1990.

[15] Shao – Mei, F. E. I., Zhen-Lao, Liu, Zhao-da, Yan, *Knock prediction for dual-fuel engines using a simplified combustion modul*, Journal Zhejiang University SCIENCE, vol. 4 No 5, p. 591-594, 2003.

[16] Selim, M. Y. E., *Sensivity of dual fuel engine combustion and knocking limits to gaseous fuel comparison*, Energy Conversion Management 45, 411-425, 2004.

[17] Wyszyński, M., *Zielone silniki – wodór z reformingu paliw poprzez technologię "leaf",* Archiwum Spalania vol. 3, Nr 2-4 p. 5-18, 2003.