Preignition

Or why pressure on design engineering increases

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How premature ignition of the fuel mixture limits petrol engine development.

Introduction

Even if current discussions on the emission of pollutants give a different impression - in the last 20 years the development of petrol engines has made enormous strides in the fields of fuel consumption and pollutant emission. This is associated with technical advances such as superchargers, direct injection and downsizing. The result is small, extremely powerful engines with much reduced consumption and pollutant emission values. Performance improvement had to be combined with a simultaneous reduction in harmful environmental effects to meet not only current but future standards. Preignition proved to be a phenomenon of increasing intensity and a limiting factor in so doing due to interaction of the innovations mentioned, to ongoing optimisation and to other influences both external and internal. The fuel mixture ignites before the actual ignition procedure begins and leads to very high pressure in the engine. Depending on design this can lead to severe and possibly irremediable engine damage even if it occurs only once. The causal factors have not yet all been identified but it is clear that if this remains so, then the petrol engine's fuel consumption and performance cannot be further improved or developed. Such engines would have to be able to withstand even higher pressures and loads than at present and the risk of preignition causing irremediable damage would be increased.

Current situation

Car manufacturers will have to meet increasingly high standards. By 2030 the EU will require new motor vehicles to emit an average 37.5 % less carbon dioxide than in 2021. The drop will have to be 15 % by 2025.[1] What has apparently quickly led to rejection by the automotive industry will subject manufacturers to enormous pressure. Currently the most optimistic prognoses assume that alternative fuels will not be able to make the necessary contribution to this goal. What is needed is petrol and diesel engine development. The Association of the German Automotive Industry pointed out that, “No one currently knows how to achieve the limits set in the time laid down”. The European Automobile Manufacturers' Association (ACEA) added that, “Achieving a CO2 reduction of 37.5 % may seem plausible but it is totally unrealistic in view of the *status quo*”. These statements make it clear that there are unsolved technical hindrances quite apart from fleet division and client demand making development of the petrol engine considerably more difficult.

[1] Europäische Kommission Pressemitteilung: Saubere Mobilität. Parlament und EU-Staaten einig über neue CO2-Grenzwerte für Autos, 18.12.2018. https://ec.europa. u/germany/news/20181218-co2-grenzwerte-autos_de on 10 January 2019.

Four-stroke engines as a basis

One barrier to more efficient design is the phenomenon of preignition of the fuel mixture in the combustion chamber. A glance at how a petrol engine works makes the scale of the challenges facing developers clear. In a four-stroke engine[2] the first stroke is suction. The piston is at TDC (Top Dead Centre) here, the outlet valve closes and the inlet valve opens. The piston moves toward the crankshaft and this downward movement sucks air into the cylinder. In this stroke the temperature is about 100 °C and the pressure around 0.1 to 0.3 bar. The inlet valve closes when the piston reaches BDC (Bottom Dead Centre). The next stroke is compression, fuel injection and ignition. The piston returns in this stroke toward TDC. The air in the combustion chamber is strongly compressed by the piston's upward movement. The ratio may be 8 to 1 or more depending on motor design. Fuel is injected directly into the chamber via the inlet valve and mixed with the compressed air. Combustion chamber pressure is now between 10 and 18 bar and the temperature 450 °C or more due to compression. The spark plugs initiate ignition just before the piston reaches TDC. In the third or power stroke the fuel/air mixture is combusted. Temperatures up to 2,500 °C and pressures up to 120 bar are generated. Combustion expansion causes the combusting mixture to generate mechanical force; the piston travels from TDC to BDC. In the fourth stroke the piston returns to TDC and expels the combustion exhaust gas from the cylinder.

Preignition occurrence

In preignition the fuel/air mixture combusts prematurely without proper ignition by the spark plugs. This irregular combustion occurs during transition from stroke two to stroke three. The piston is travelling up to TDC after the second stroke. The fuel/air mixture ignites prematurely before the piston reaches TDC. The combusted gas generates counterpressure against the piston travelling upwards that may be of 200 to 300 bars. Many engines are not designed to withstand such pressure. The constant pressure limit is often 90 bar with a peak limit of 120 bar. This is of great concern to developers as higher pressure in the cylinders is essential to further improve engine efficiency. The manufacturers will have to come up with designs able to tolerate higher pressures among much else. This includes solutions to avoid preignition: if the phenomenon occurs then the engine must be so designed that it can tolerate the pressures thus generated; appropriate designs that prevent preignition altogether will also be needed. Engines should also reliably exclude preignition even at

[2] cf. Reif, Konrad: Grundlagen des Ottomotors, pp. 20-25.

higher temperature or pressure. A number of studies have been made over the last decade of this subject. Decisive for an answer is first of all the understanding of the causes.

Background

Preignition has numerous causes, not all as yet completely clarified, that are closely linked to efforts to optimise engines, lubricants and fuels. Engine development [3] to date has involved an increase in factors favouring preignition. Downsizing petrol engines as well as the use of turbochargers and direct fuel injection have in particular been features of the development of such engines. Design engineers at a number of manufacturers managed to reduce the cubic capacity of petrol engines and simultaneously increase performance using high supercharging and turbocharging levels. One way to achieve this is via smaller combustion chambers with consequences where the formation of the fuel/air mixture is concerned, another via permanent or temporary reduction in the number of cylinders. In the final analysis the operating characteristics favour higher specific load due to smaller size[4]. Compressors and exhaust gas turbochargers increase effective average pressure resulting in associated higher loading here. Direct injection lowers fuel consumption as the combustible fuel/air mixture is first generated in the cylinders and very precisely controlled[5]. Fuel loss due to piping, hosing and space in the engine are avoided and at the same time the required fuel quantity can be much more precisely determined and supplied. The air compressed in turbochargers supplied to the combustion chamber ensures more efficient combustion as it has a higher oxygen content. This resulted in smaller cubic capacity that helped achieve CO2 limits in petrol engines. Optimisation resulted in highly charged smaller engines with higher pressures generating more power combined with lower fuel consumption. These characteristics and achievements are a challenge to further development both individually and in their interaction with one another as they create an environment favouring preignition.

[3] Reif, Konrad: Grundlagen des Dieselmotors, in Reif, Konrad (Ed.): Dieselmotor-Management im Überblick einschließlich Abgastechnik, pp. 14-31, Springer Fachmedien, Wiesbaden 2014; Ibid.: Grundlagen des Ottomotors. Ibid. (Ed.): Ottomotor-Management im Überblick, pp. 2-23, Springer Fachmedien, Wiesbaden 2015.
[4] Rüden, Klaus von: Beitrag zum Downsizing von Fahrzeug-Ottomotoren, Dissertation an der Fakultät V Verkehrs- und Maschinensysteme der Technischen Universität Berlin, Berlin 2004.
[5] Basshysen, Richard van (Ed.): Ottomotoren mit Direkteinspritzung und Direkteinblasung, Springer Fachmedien, Wiesbaden 2017.

Preignition causes

Various studies show that this optimisation affects irregular combustion occurrence[6]. They make it clear that further improvements in efficiency are limited thereby[7]. According to those studies downsizing involves lower efficiency than in previous designs resulting from a compromise between charging levels and possible compression ratios. This latter must be reduced to prevent a tendency to knock that is heightened by comparison with older designs. "Higher charging pressure increases the risk of irregular ignition"[8]. Undesirable ignition processes include knocking and surface self-ignition[9] as well as the preignition referred to that is a challenge to further development. Research is in part devoted to fuels and their influence on these problems in the hope of finding answers[10]. That fuel and its chemical composition have major influence here is becoming ever more clear. Some studies show that e.g. the tendency to preignition falls the higher the ethanol content in fuel is[11]. Other studies infer that there are relationships between fuel self-ignition behaviour and the pressure and temperature in the combustion chamber[12].

Currently the following possible causes of preignition are cited, among others:

- Pressure and temperature conditions
- Hot Spots
- Residual gas
- Temperature fluctuations in working gas
- Separation of lubricant drops from the cylinder wall
- Critically high compression temperature[13]
- Particle quantities[14]

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[6] cf. Zarcardi, Jean-Marc; Lecompte, Matthieu; Duval, Laurent: Vorentflammung an hoch aufgeladenen Ottomotoren. Visualisierung und Analyse, in: Motorentechnische Zeitschrift, 12/2009, pp. 938-945.
[7] Willand, Juergen; Daniel, Marc; Montefrancesco, Emanuela; Geringer, Bernhard; Hofmann, Peter; Kieberger, Markus: Grenzen des Downsizing bei Ottomotoren durch Vorentflammung, in: Motorentechnische Zeitschrift, 05/2009, pp. 423-429.
[8] Dyckmans, Jan: Untersuchungen zum Einsatz von Alkoholen in modernen Ottomotoren, in: Berichte aus dem ivb, Volume 12, Shaker Verlag, Aachen 2016, p. 12.
[9] Ibid.
[10] Adomeit, Philipp; Dohmen, Juergen; Thewes, Matthias; Matthias, Ewald; Guenther, Marco; Morcinkowski, Bastian; Pischinger, Stefan: Einfluss von Kraftstoff und Brennverfahren auf die Vorentflammung beim aufgeladenen Ottomotor, in: Fortschritt-Berichte VDI, Serie 12: Verkehrstechnik/Fahrzeugtechnik; 764; 34. Internationales Wiener Motorensymposium; Düsseldorf 2013; pp. 235-259.
[11] Dykmans, p. 44.
[12] cf. Dedl, Geringer, Budak, Pischinger, p. 78.
[13] cf. Kadunic, Samir: Einfluss der Ladelufttemperatur auf den Ottomotor. Ein Potenzial zur Steigerung von Wirkungsgrad und Leistung aufgeladener Motoren, p. 23, Springer Vieweg, Berlin 2014.
[14] cf. Graf, Philipp: Untersuchung von irregulären Verbrennungsphänomenen an aufgeladenen Ottomotoren mit Direkteinspritzung, Dissertation an der Fakultät für Maschinenbau der Universität Karlsruhe, Karlsruhe 2015, pp. 87-98.

- and certain fuel characteristics[15].

Drops and deposits

Fuel drops are among the major causal factors of preignition[16]. When injecting fuel in the transition between strokes 2 and 3 the cylinder wall, which is oil lubricated, is covered by that fuel. This yields a mixture of oil and fuel which may result in drops being released during the compression phase just before the piston reaches TDC. The cause is the lower surface tension and viscosity of this mixture. This mixture also has higher ignition propensity than plain petrol[17]. Increased pressures and temperatures may lead to spontaneous ignition of the drops that may result in preignition of the entire fuel/air mixture in the combustion chamber.

Solids such as particles or deposits may also exist in that chamber in addition to the gaseous fuel/air mixture that can also cause preignition given the right temperature[18]. Although manufacturers and suppliers do their best to prevent deposits forming in the combustion chamber these cannot be wholly avoided in petrol engines with direct fuel injection[19]. The reasons include major differences in use habits on the part of the millions of drivers out there that cannot all be catered for in their entirety in any design. Major differences in fuel composition and engine oils are a further contributory factor[20]. The influencing factors given can basically cause sooty combustion and/or the entry of oil in the combustion chamber. The soot and oil particles that result adhere to walls or components such as pistons and valves. Vibration and fuel injection may loosen particles. Particles moving freely soon reach the same temperature as that obtaining in the combustion chamber and this cannot be dissipated via walls or components. Ignition causes the smallest particles to smoulder. If they are big enough not to be extinguished promptly this may result in preignition of the fuel/air mixture during subsequent transition between strokes 2 and 3 [21] with the consequences aforementioned.

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[15] Dedl, Joerg; Geringer, Bernhard; Budak, Oguz; Pischinger, Stefan: Kraftstoffkennzahlen zu Beschreibung von Vorentflammung in Ottomotoren, in: Motorentechnische Zeitschrift 05/2018, pp. 76-81.
[16] Graf, p. 14.
[17] Ibid.
[18] Ibid., p. 13.
[19] Ibid., p. 73.
[20] Kalghatgi, Gautam T.: Combustion Chamber Deposits in Spark-Ignition Engines. A Literature Review, Shell Research Ltd, Chester (UK), 1995.
[21] Graf, p. 77 und p. 96.

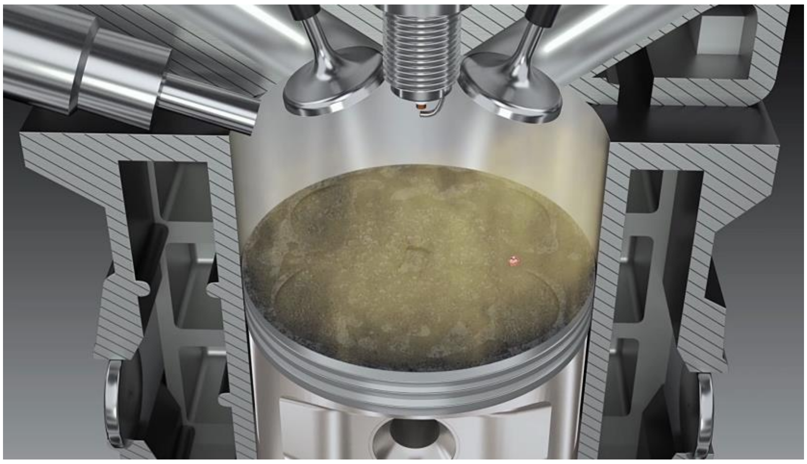

Illustration 1. A drop of oil detaches from the cylinder wall
Source: TUNAP Group

Illustration 2. Explosion of the drop of oil before ignition
Source: TUNAP Group

Solution approaches

In the main two major situations resulting in preignition which in turn are influenced by differing factors can be determined: fuel-oil drops and glowing/smouldering particles[22]. Researchers and developers worldwide are well aware that solutions need to be more holistic. "We know that preignition occurs in the combustion chamber. The most practicable solution is a holistic approach that makes all due allowance for engine design, oil formula and fuel quality" says Ian Bell, Research and Development Director of Afton Chemical in Richmond/Virginia (USA) [23]. Whilst these points play a role, above all in further optimisation of petrol engines, where the problems mentioned above are

[22] Ibid., p. 101.
[23] Chabot, Bob: Resolving Low-Speed Pre-Ignition, in: Motor Magazin, Januar 2017, https://www.motor.com/magazine-summary/resolving-low-speed-pre-ignition am 10.01.2019.

concerned, owners of vehicles with petrol engines exposed to such risks need remedies for the danger of preignition. Comprehensive developments in the fuel and lubricants fields have already been made - most of them more focussed on future engine generations but possibly including improvements for current ones - but the design of extant engines cannot be altered retroactively. Solutions are needed. They must approach the problem in the components used and ensure that particle formation due to deposits being formed and the generation of fuel/oil drops are avoided or at least reduced. Fuel additives that keep engines clean have been around for many years. To date most of them are effective ahead of the places where preignition originates. They have been proven to have good cleaning effects on fuel system piping, hosing, filters and injection nozzles. However, they often do not have satisfactory effect where combustion chamber cleaning is concerned, i.e. getting rid of adhesions on walls or pistons. Their chemical structure means some of them promote particle generation in the combustion chamber and hence preignition. Newer approaches focus on the deposits in cylinders and ensure adequate cleaning here. The result is that they contribute to the approach aforementioned to deal with preignition, as do developments in the fuel and oil fields. Their interaction gives developers room to manoeuvre where engine design is concerned.

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