SAE TECHNICAL
PAPER SERIES

982483

# The Knocking Syndrome - Its Cure and Its Potential

**Jürgen Willand, Rolf-Günther Nieberding, Guido Vent and Christian Enderle**
Daimler-Benz AG

**Reprinted From: SI Engines: Combustion and Emission Formation (SP-1393)**

The Engineering Society For Advancing Mobility Land Sea Air and Space®
INTERNATIONAL

**International Fall Fuels and Lubricants Meeting and Exposition**
**San Francisco, California**
**October 19-22, 1998**

**400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (724) 776-4841 Fax: (724) 776-5760**

**GLOBAL MOBILITY** DATABASE

***All SAE papers, standards, and selected books are abstracted and indexed in the Global Mobility Database***



**ISSN 0148-7191**




**Printed in USA**

982483

# The Knocking Syndrome - Its Cure and Its Potential

**Jürgen Willand, Rolf-Günther Nieberding, Guido Vent and Christian Enderle**
Daimler-Benz AG



## ABSTRACT

In his paper "The Knock Syndrome - its Cures and its Victims" (SAE 841339) Oppenheim proposed to change the whole process of the internal combustion engine replacing moving flames by homogeneous and simultaneous combustion. Intensive research work on flame propagation and auto-ignition phenomena led to new insights into combustion over recent years. The implementation of auto-ignition on two-stroke S.I. engines revealed the potential for simultaneous reductions in fuel consumption and NOx emission.

Deploying the principle for the four-stroke piston engine and standard fuel would provide optimum conditions for application in common vehicles. The basic problem of homogeneous combustion is presented and some options of control are discussed. A methodology is proposed to apply a new type of combustion simply through a consistent combination of modern technology available for the S.I. engine. The practical investigations and examination of the proposed concept will be realized as part of the joint European research project "4-SPACE".

## INTRODUCTION

The knocking phenomena can be traced back to the first days of combustion engineering in piston engines. Nikolaus Otto as the inventor of the four-stroke S.I. engine in his records pointed out a strong noise while the internal explosion process destroyed his engine [1]. In recent years the knock phenomena have been analyzed intensively, chiefly to be avoided. Far less work has been invested to understand the phenomena physically, whilst a lot more work was spent on the creation and use of technologies to measure and show the effect of knocking.

Oppenheim [2] initially discussed several options to cure the main constraint increasing the specific power and efficiency of the S.I. engine: the knocking phenomena. All approaches showed some effect, but none really solved the problem. He proposed a radical approach to the problem: changing the whole process of moving flames in the internal combustion engine to a homogeneous and simultaneous combustion process.

Recent studies on knocking attribute the pressure peaks to an increased rate of heat release. It was discussed that the heat release was caused by a detonation wave passing through the end gas or alternatively by its spontaneous ignition. Nowadays the auto-ignition theory is most widely accepted [3]. Piston and burned gas behind the flame front compress the end gas simultaneously. The gas temperature increases until some elements of the end gas ignite. Releasing their energy they ignite other elements until the end gas has been fully consumed. The high heat release rate indicates the nearly homogeneous combustion process.

Knocking itself is seen as a nearly homogenous combustion process. Utilizing the homogeneous combustion as a new combustion process requires the understanding of auto-ignition. An interesting model was proposed [4] decades ago describing auto-ignition as an integral summing up of energy until heat release starts. In the meantime research focused on the detailed reaction kinetics in the oxidation of hydrocarbons. With the Shell model [5] as mathematical formulation of the basic oxidation kinetics during the auto-ignition process, it was possible to have a qualitative representation of the two-stage ignition. Gray [6] and Yang [7] even implemented the thermal effects in the mathematical simulation.

The accuracy of the model increases with more parameters, being applied, which in turn requires higher numerical performance. For the development of homogeneous combustion the scientific accuracy in describing auto-ignition processes in pure gases is not helpful. A simplified model and a reduction of parameters to the key factors would be helpful. In a recent release [8] a further simplified model was presented depending on relatively few parameters (15). The mathematical formulation is resolvable as an integral, the integral value may by utilized as a criterion for auto-ignition. The accuracy of prediction is slightly reduced, but the efficiency in predicting auto-ignition is drastically improved. Practical engine tests revealed a good correlation of the simple model and the highly complex reality of thermal and kinetic feedback reactions. The model reduces auto-ignition to the dominant effects and key processes with the highest probability or impact. The reduction is understood as a key to understanding auto-ignition and to exploiting it as a new combustion process.

## HOMOGENEOUS COMBUSTION

POTENTIAL OF HOMOGENEOUS COMBUSTION – Homogeneous combustion represents the parallel energy release of the whole charge instead of the serial energy release by the flame front passing through the charge. Homogeneous combustion requires a homogeneous or de-central activation of the reaction in contrast to ignition by spark or injection. Ignition represents partial chemical activation initiating a serial consumption of the charge. De-central activation provides each charge element with sufficient activation energy to reach the level of energy release.

Decentralized activation has fundamental advantages and disadvantages. The major advantage expected is to extend combustion beyond the known lean limits [9]. Lean limits of combustion depend on the specific heat release and the heat transfer within the flame front. Increased small-scale turbulence may compensate for the lowered reaction enthalpy by improved heat transfer and extend the lean limit of combustion. Due to decentralized activation extremely lean mixtures can be activated in a decentralized manner and completely consumed. The low heating value of extremely lean mixtures lowers the peak temperature of combustion. Keeping combustion below the temperature of NOx formation is seen as the major potential of this combustion method in addition to the by principal soot-free burning of homogeneous and lean mixtures.

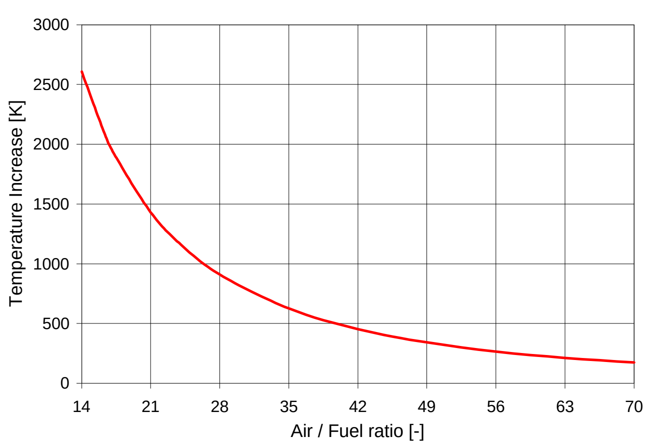


Figure 1. Calculated temperature increase of the charge assuming ideal adiabatic energy release in a constant volume

The calculated local temperature increase indicates where the potential might be exploited. Compressed and burned mixtures with AF ratios beyond 25 might burn below the NOx formation limit ($T_{NOx}$ = 1800 K). Therefore, homogeneous combustion offers itself for part load combustion. Efficiency improvement in part load is mainly required for S.I. engines. In addition, S.I. engines operate with high-octane fuels. A high-octane number of a fuel is good indication of simultaneous auto-ignition. It is more likely to realize a stable and controllable homogeneous combustion with high-octane fuels.

Homogeneous combustion is known by many names and acronyms. ATAC [10], TS [11] and ARC [12] represent homogeneous combustion on a two-stroke engine with gasoline, aiming at reduced HC emissions and increased efficiency. HCCI [13] and CIHC [14] aim at NOx-avoiding combustion in a four-stroke engine with gasoline, UNIBUS [15] with diesel.

PRINCIPLE OF HOMOGENEOUS COMBUSTION – Homogeneous combustion is not comparable to any combustion principle industrially applied today. The homogeneous combustion process can be distinguished from different processes by the temperature profile before combustion starts. Zel'dovich [16] presented a theoretical discussion and one-dimensional calculation of the impact of temperature distribution in combustible gases before ignition on the nature of energy release. He found out that the initial temperature distribution within the one-dimensional system determines the evolving combustion process. In a three-dimensional system the temperature profile is a spatial one.

A steep temperature gradient before ignition forms a "shock wave" propagating away from the initial reaction. This process is called "deflagration". This pressure wave corresponds in a three-dimensional system to the passing flame front. During deflagration, pressure increases in a balanced way on both sides of the wave. The burned gas shows a lower density due to the released heat. A constant or almost constant temperature profile leads to the so called „thermal explosion". During thermal explosions, the gas density changes corresponding to gas pressure and temperature. The calculation for a temperature profile with an intermediate gradient leads to a „detonation" wave. During detonations, steep pressure changes occur within the burning charge.

Zel'dovich took the knocking phenomena for a detonation caused by an initial deflagration combined with a temperature profile of an intermediate gradient in the end gas. The author assumes knocking to be a homogeneous combustion. The end gas is compressed nearly adiabatically and shows a near-to-constant temperature profile. Figure 2 symbolically shows the spatial distribution (x) of relative temperature (Θ) yielding each type of combustion.

The expression „thermal explosion" clearly indicates the increasing heat release but neglects the chemical and kinetic factors of combustion. Auto-ignition is understood as a kinetically driven process of low-temperature oxidation. The reactivity depends on the energy absorbed (integral of temperature over time) and the energy contained in the mixture (Air-Fuel ratio). With a certain energy obtained one mixture element releases energy, compresses the surrounding mixture and increases the gas temperature.

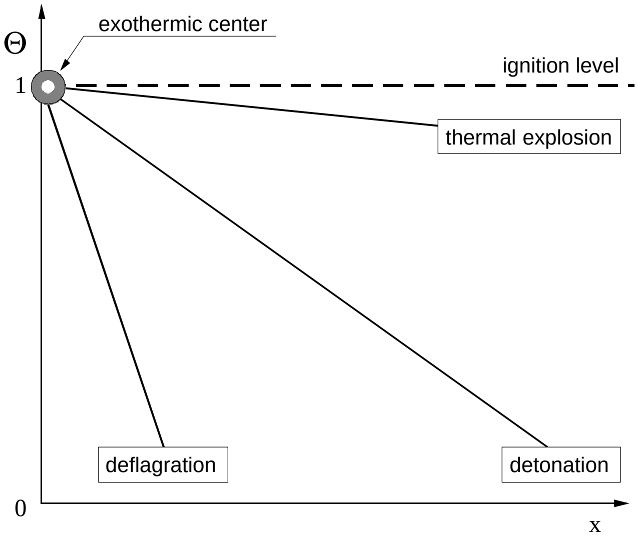


Figure 2. Distinction of combustion principles by their initial conditions

Due to homogeneous and simultaneous compression the entire mixture shows a near to constant and homogeneous temperature profile and the similar energy level close to auto-ignition. The released energy causes more elements to react and leads to higher heat release rates. Oppenheim [17] called the single energy releasing element "exothermic center" and defined the "inevitable runaway character" of spontaneous ignition causing the knocking phenomena. Knocking corresponds to decentralized activation or homogenous combustion. The self-accelerating or "runaway character" was already defined by Frank-Kamenetzki [18] with the fundamental differential equation of "thermal explosions". Θ symbolizes the dimensionless relative temperature:

$$\frac{d\Theta}{dt} = e^{\Theta}$$

If the auto-ignition is understood as a process to thermally activate the local kinetic processes, this explains the self-accelerating character as feedback loops of both parameters: temperature and concentration. Initial feedback is dominated by kinetic effects (symbol: σ), their intensity depends on concentration. Enhanced exothermic kinetic reactions increase the temperature of the reacting mixture (symbol: T). A higher temperature further boosts kinetic reactivity and accelerates homogeneous combustion. With increasing temperature the heat release grows. The growing heat-release self-accelerates the combustion intensity. The dominant feedback effect shifts from concentration to temperature during energy release. Figure 3 visualizes the feedback reaction of homogeneous combustion changing during energy release. Therefore the more precise term "thermo-kinetic explosion" is preferred for this physical process.

Homogeneous combustion depends on local temperature and concentration. Their homogeneity is ensured by a certain level of turbulence in the gas and can be expected in a common piston engine. Turbulence is a helpful external influencing parameter for the heat release of flame-front combustion. With homogeneous combustion, the pressure-induced homogeneous temperature rise outweighs any different energy transmission.

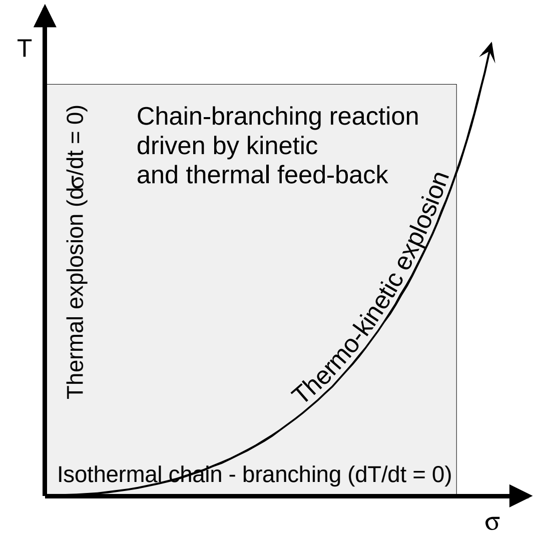


Figure 3. Schematic presentation of thermo-kinetic explosion

IMPLEMENTATION OF HOMOGENEOUS COMBUSTION – When aiming at a NOx-free, lean-burn, part-load combustion in a four-stroke S.I. engine decentralized activation is required for homogeneous combustion. The required homogeneous temperature profile can be achieved by heating the gaseous mixture. Gas can be heated quickly and homogeneously by turbulent convection or compression. Both options have been applied showing NOx-free combustion with a good efficiency but limited in load by increasing steep pressure rises [19,20].

Two reasons speak against simply increasing the compression ratio to reach the auto-ignition level. Firstly with increasing compression ratio the relative volume changes relatively faster leaving the combustion less time to occur at constant volume. Figure 4 shows the impact of an increased compression ratio around top dead center. Increasing the volume during homogeneous combustion will cause the combustion to falter due to quickly decreasing temperature and volumetric concentration. Decreasing heat release lowers the gas temperature, which in turn delays or stops the combustion. Incomplete combustion causes high emissions and low efficiency.

Secondly, the intention to develop a part-load concept for S.I. engines prevents an increasing compression ratio too far beyond the ratios common for S.I. engines. The charge cannot be activated in a decentralized manner by compression but by gas heating. For the non-stationary application quickly adaptive activation is required.

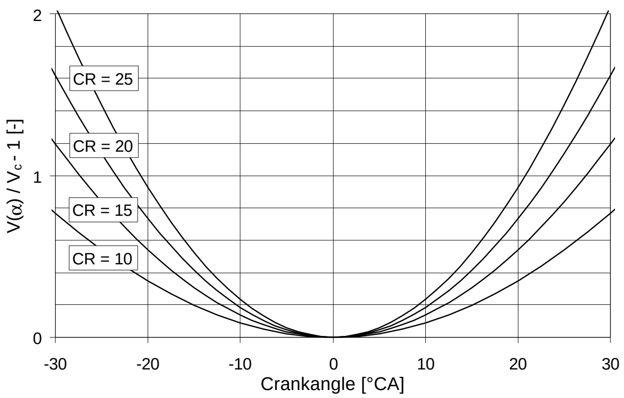


Figure 4. Relative volume change during combustion increases with compression ratio

Pre-inlet heating would not be applicable for a piston engine operated in the non-stationary mode. The differential equation of heat transfer brings about decreasing energy fluxes with decreasing temperature gradients. Large amounts of energy would be required at the intake for transient control of homogeneous combustion. Moreover the activation requires a certain energy level. The energy level sufficient for auto-ignition is accumulated through temperature exposure over time. Homogeneous combustion in the piston engine is induced during the compression phase. With increasing engine speed the decreasing time base for activation has to be compensated by an increased gas temperature. A viable speed range would also require exorbitant heating capacities.

The approach of adapting the charge temperature in the combustion chamber fast enough is mixing the charge there with hot gas. Mixing internally extends the speed range by compensating for the decreasing time for activation by increased temperatures due to decreasing heat losses. The internal combustion engine provides the required hot gas in the form of the exhaust gas. For the internal mixture, the exhaust gas has to be retained in the cylinder comparable to the two-stroke application [21]. In a four-stroke engine, valve overlap allows exhaust gas to flow back into the combustion chamber. In that case the exhaust gas is cooled down through a turbulent mixture with fresh charge. The mixture around charging-TDC reduces the gas temperature relatively early in comparison to a different valve timing strategy.

Valve timing with early exhaust closing and delayed inlet opening retains exhaust gas in the combustion chamber, compressing and expanding it again. The compression phase keeps up the gas temperature until the gas is mixed with fresh gas. One can expect that the exhaust of lean and homogeneous combustion will be relatively cold and extreme amounts of exhaust gas have to be retained to initiate homogeneous combustion of the fresh charge during the following compression phase.

The retained energy in the cylinder has to combine the opposite prerequisites of the two combustion principles in one mechanical design. The compression ratio is chosen to avoid decentralized activation of the stoichiometric mixture (maximum concentration) compressed by a burned charge in a high-temperature environment: knocking in S.I. operation at full load. Homogeneous combustion requires decentralized activation of low-concentration mixtures by hot retained exhaust gas. The expected amount of retained exhaust gas can be estimated by the fuel amount required for part load. In throttled part load S.I. operation a remarkable share of the fuel energy is charged to compensate for throttling losses.

Homogeneous combustion without throttling reduces the required amount of fuel. For homogeneous combustion at part load operation, between 20 % and 40 % of the displacement should be charged with a stoichiometric mixture. For a sufficient compression to activate the gaseous charge, the displaced volume is filled up with exhaust gas and excess air. The retained mass determines the volumetric efficiency. This principle may be called “internal de-throttling”. Retaining more than 40 % of exhaust gas is manageable by a reduced valve opening duration. The technology of variable valve timing will allow these valve timings and enable a study of the effects. Another application may combine special cams and a throttled exhaust to control the combustion. The second compression phase in a four-stroke design omits the stress cycle for the piston pin and will require a two-stroke concept for the piston bearing.

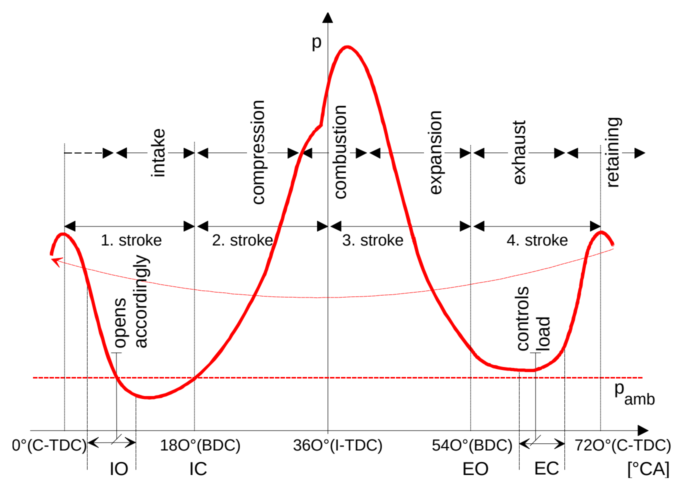


Figure 5. Indicated cylinder pressure with retained exhaust gas

Retaining the majority of exhaust gas also includes a control concept for combustion as give-away. The auto-ignition corollary was already found in two-stroke application [22, 23]; it describes the influence of one combustion cycle onto the next via the exhaust gas temperature. Late combustion provides hot exhaust gas causing the next cycle to ignite earlier and reduce exhaust gas temperature again. The combustion timing is controlled internally and therefore in the most reliable and fastest possible way. Even with fluctuations in auto-ignition timing the decentralized activation will be more stable by principle. Decentralized activation initiates the combustion at the one element ready to ignite. The centrally ignited combustion depends on local conditions around the igniting area, such as the spark plug.

After mixture, during decentralized activation and homogeneous combustion, homogeneity of the gas is assumed. The homogeneous exhaust gas of the lean combustion contains excess air. The retained excess air further dilutes the lean charge. Homogeneous combustion with high ratios of retained exhaust gas burns leaner internally than it is measured externally. Figure 6 shows the impact of retained excess air on the combustion, with the impact increasing with higher amounts retained and leaner mixtures. The Air-Fuel ratio (AF) in the charge and measured in the exhaust gas is transformed to the real Air-Fuel ratio (AF*) during combustion.

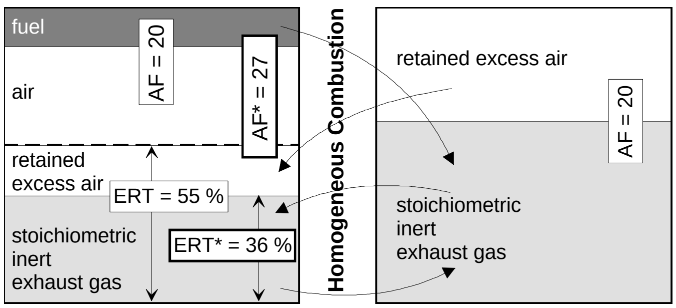


Figure 6. AF-ratio during combustion with retained excess air

The following formula for the real AF-ratio (AF*) takes the retained excess air into account. The two externally measured quantities: retained exhaust mass fraction, symbolically ERT [%], and AF-ratio [-] are transformed into internal quantities.

$$AF* = \frac{AF - ERT \cdot ST}{1 - ERT}$$

ST means stoichiometric AF-ratio (ST ~ 14,5 kg Air / kg Fuel). The retained exhaust mass fraction can be transformed into the retained inert mass fraction (ERT*).

$$ERT* = \frac{ERT \cdot ST}{AF}$$

The quantities before and after transformation contain the same information. The transformation distinguishes between the kinetically active masses (AF*) and inactive masses (ERT*) to simplify the combustion analysis.

The injected fuel related to the whole in-cylinder mass (air and retained exhaust) describes an equivalent energy ratio Φ. It ranges between 0 and 1 expressing the charged energy relative to the stoichiometric full-load charge. The equivalent energy ratio corresponds to the equivalence ratio minus the inert gas mass fraction.

$$\Phi = \frac{(1 - ERT) \cdot ST}{AF} = f - ERT*$$

CONTROL OF HOMOGENEOUS COMBUSTION – Frank-Kamenetzki already described the self-accelerating character of homogeneous, decentralized and pressure-induced combustion. Meyer and Oppenheim [24] described the increasing rates of heat release as strong ignition and discussed the transition from mild to strong ignition as the strong ignition limit. The limit depends mainly on the momentary equilibrium of heat release and heat loss. Increasing the  loss in the combustion engine was not seriously considered. This leaves only strong ignition and alternative ways to restrict it to an acceptable level must be found.

The self-accelerating heat release of the thermo-kinetic explosion accounts for the steep pressure rises measured in homogeneous combustion with increasing load [25]. With non-throttled operation, increasing load goes along with increasing fuel concentration. The higher the concentration the faster the heat release and the more energy to be released. With increasing gas temperature the heat release rate increases more steeply than the speed of sound increases. With high concentrations and high release rates the energy is locally released faster than the speed of sound is able to level out. The pressure sensor measures the local pressure around the sensor plate instead of the homogeneous cylinder pressure. The measured and published gas vibrations look quite similar to knocking cycles of S.I. combustion. But in contrast to S.I. knocking the pressure oscillations induced by homogeneous lean combustion are not expected to damage the mechanical design of the engine. Presumably the reaction enthalpy of the lean and NOx-free burning mixture will cause neither the thermal conditions nor the mechanical shock wave to harm the surface.

But even if steep pressure rises are not harmful they should nevertheless be avoided. Steep pressure rises increase the loss of heat flux, requires costly design measures and are not accepted by the consumer. The high rates of heat release during homogeneous combustion are caused by the homogeneous heat release. Since heat release starts after receiving a critical amount of energy, all elements of the compressed homogeneous mixture receive the same energy and show the identical readiness to react. The approach by Meyer and Oppenheim [26] of describing the decentralized activation as a stochastic process is seen as helpful for understanding the process and its potential. It has been theoretically shown that a small deviation in temperature homogeneity causes a drastic decrease in the intensity of the exothermic power pulse. The exothermic power pulse can be understood as pressure peak during combustion.

For significant but controllable deviations in the temperature profile during compression, direct injection of gasoline is utilized. Direct injection is used in the two-stroke concept to stratify fuel at compression ignition with retained exhaust gas [27]. The stratification increases the local concentration resulting in a higher reactivity. The faster combustion enables a complete consumption at light load. The stratification allows a reduction of heat losses caused by combustion at the combustion chamber wall.

The potential to distort the homogeneously heated mixture by injecting small amounts of liquid fuel under high pressure has not yet been analyzed at all. Enhanced local concentration will increase local reactivity. Nevertheless, the vaporization of liquid fuel absorbs energy and reduces temperature locally. The heat release of the affected volume will be delayed for some instances. Delaying the heat release will extend the entire self-acceleration, decreasing the pressure rises over all. Increasing pressure and temperature of a self-accelerating combustion ensures consumption of all fuel injected before ignition-TDC. The relatively low gas temperature prevents fuel injected at a late point in time to cause soot. The theoretically derived effect can only be expected for a very limited amount of fuel combined with a certain injection timing and quick vaporization. Otherwise the local enrichment will accelerate the initial heat release leading to even steeper pressure rises.

Stratifying the charge by high-pressure direct injection of liquid fuel causes the homogeneous combustion to lose its homogeneity. Therefore, combustion depends not only on temperature and concentration, but also on the interaction of volumes with different temperatures and concentrations. Direct fuel injection enables shaping of an Air-Fuel ratio profile in the compressed charge of air and exhaust gas. The wide range of combustible AF-ratios for themo-kinetic explosion enables to control of the overall heat release by the profile. The stratification by direct injection can be produced more easily for the homogeneous combustion than for a stratified combustion in a GDI engine. To control combustion by injection strategies rather than by amounts of retained exhaust gas or adaptable compression ratios is considered more elegant.

EXTENDING THE HOMOGENEOUS COMBUSTION – Retaining sufficient levels of exhaust gas requires a new technology to be used on the engine as just the lengthening of homogeneous combustion does, too. Usually, a new technology would be added for one specific purpose only. By systematically scanning the added degrees of freedom the individual opportunities are multiplied resulting in potentials of enhanced quality. Applying the combination here leads to the following results:

Decentralized activation of the charged mixture by retained exhaust gas will work for certain compression ratios, combined with a sufficient exhaust retention resulting in a given area of load and speed. Extending the operable area can be achieved by extending and controlling the kinetic condition and reactivity of the retained exhaust gas. The strategy of reduced valve timing enables fuel injection to be used in the new cycle just after exhaust closing (EC). Injecting fuel into exhaust gas will not cause additional emissions, because thereafter fresh air is charged. The exhaust gas temperature is not sufficient to form soot. By injecting fuel into the retained and compressed hot exhaust gas, the hot excess air and the injected fuel will start a chemical reaction. The local chemical reaction will have a noticeable and accelerating impact on the kinetics of auto-ignition during the next compression cycle. By injecting fuel earlier in the exhaust compression the time during which the injected fuel receives activation energy is extended. The auto-ignition level will be reached earlier in the next compression cycle. The process of fuel injection in retained exhaust gas is called activation phase. The phase is placed between the phases of exhaust and intake. Figure 7 shows the cylinder pressure during the activation phase. The dashed line corresponds to an early injection timing for activation.

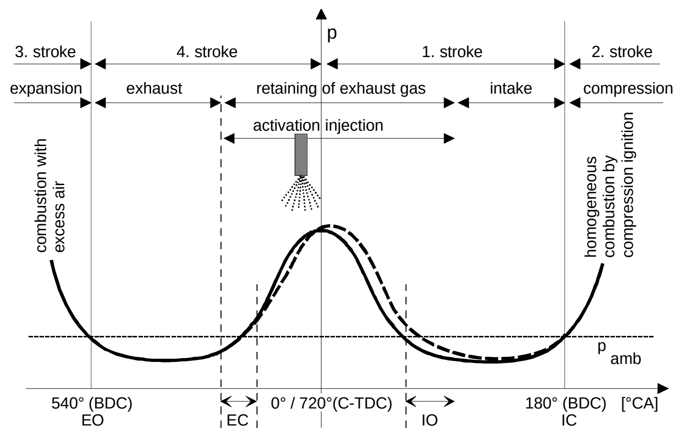


Figure 7. Activation of retained exhaust gas by fuel injection

The timing of activation injection will most probably be very important. Injecting fuel during compression of the retained exhaust gas increases the temperature and local concentration of the injected fuel. The impact of the activation reaction will be intensified. Injecting fuel while the combustion chamber expands the exhaust gas, the kinetic reaction will be slowed down. A late activation will have a less intense effect. It stands to expect that the activated elements and chemical compounds will survive the addition of a fresh and cold charge and initiate combustion during the next compression.

The control strategy of a non-stationary-operation engine applying homogeneous combustion might comprise several levels. The basic level of control will be to retain exhaust gas by narrowed cams. The retaining cams replace the WOT-cam and throttled operation by a mechanical shifting system. The control would be binary, most probably with a VTEC system. An exhaust throttle controls the exhaust pressure during the closing of the exhaust valve. Exhaust pressure controls the amount of exhaust gas retained. Due to the gas-dynamic effects one central exhaust throttle may not control the retained mass of exhaust in a multi-cylinder engine. Homogeneous combustion requires a quicker and more selective response control. The option of controlling homogeneous combustion by the injection timing and the distribution of fuel injected seems fast and robust. The theoretically found combination substantiates the expectations for an affordable realization of a new combustion system and justifies intensive research activity on a third combustion principle Homogeneous Combustion (H.C.) in addition to the well-known Compression Ignition (C.I.) and Spark Ignition (S.I.) process.

The above topics will be closely investigated as part of a joint research program called 4-SPACE. The project is set up by the Institut Français du Petrol, Daimler-Benz, Ford and PSA, supported by the universities of Heidelberg and Brunell and subsidized by the European Commission.

## CONCLUSION

In 1984 Oppenheim wrote in his conclusion: “According to the arguments presented here, combustion technology may be advanced in our life-time by a quantum jump, comparable in significance to that exerted by the advent of transistor upon the electronic industry, or it may remain essentially unchanged.“

His visionary sight has put him far ahead of the current growing movement in research developing a third kind of internal combustion for engines.

## ACKNOWLEDGEMENTS

The author would like to express his gratitude to all the responsible managers of the European combustion research in industry, in persona to Dr. Krämer and Mr. Willand, and to the European Commission for allowing us a new approach to maintain the advantages of the combustion of hydrocarbons-air mixtures in piston engines avoiding harm to our environment and the descendants.

Further, he wishes to express his profound appreciation for the shared experience and joint discussions with his colleagues Mr. KW Schmidt, Dr. Schöffel and Dr. Otto of Daimler-Benz Research and Technology. Also he thanks Mr. Enderle for his permission to publish the concept and Mr. Vent for his personal support.

Special thanks are dedicated to Professor Dr. Kleinschmidt and his associate Mr. Flörchinger at the University of Siegen for their support in learning about the non-stationary combustion processes, the inspiring insights into the kinetics of auto-ignition and especially in imparting the understanding of the four-dimensional thermodynamic effects in the piston engine.

## REFERENCES

1. Sass, F.; *Die Geschichte des deutschen Verbrennungsmotorenbaus von 1860 bis 1918;* Springer Verlag, Berlin-Göttingen-Heidelberg, 1962
2. Oppenheim, A.K; *The Knock Syndrome - its Cures and its Victims,* SAE 841339
3. Heywood, J.B.; *Combustion engine fundamentals,* McGraw Hill, Inc., pg. 457 ff
4. Livengood, J.C.; Wu, P.C.; *Correlation of Autoignition Phenomenon in Internal Combustion Engines and Rapid Compression Machines;* Proceedings of Fifth international Symposium on Combustion, p. 347, Reinhold, 1955
5. Halstead, M.P.; Kirsch, J.P.; Prothero, A.; Quinn, C.P.; *A mathematical model for hydrocarbon auto-ignition at high pressures,* Proc. R. Soc., London, A 346, p. 515-538, 1975
6. Gray, B.F.; *Unified Theory of Explosions, Cool Flames and Two Stage-Ignitions;* University of Leeds; Trans. Faraday. Soc. 65; (1969); S.2133f
7. Yang, C.H.; Gray, B.F.; *The Determination of Explosion Limits from a Unified Thermal and Chain Theory;* Defense Research Corporation; Santa Barbara; 11th Symp. Combustion; 1967; S.1099ff
8. Kleinschmidt,W.; Flörchinger, T.; *Selbstzündung und Wärmeübergang an der Klopfgrenze von Ottomotoren;* Zwischenbericht zum Vorhaben Kl 600/2-1 der Deutschen Forschungsgemeinschaft, Gesamthochschule Universität Siegen, Februar 1998
9. Lenz, H.P.; Klepatsch, M.; Gruden, D.O.; *The Influence of Fuel on the Lean Limits of Spark-Ignition Engines;* Technical University of Vienna, Porsche R&D Center; SAE 90545, 1990
10. Onishi, S.; Jo, S.H.; Shoda, K.; Jo, P.D.; Kato, S.; *Active Thermo-Atmosphere Combustion (ATAC) - A new Combustion Process for Internal Combustion Engine*; Nippon Clean Engine Research Institute Co. Ltd., SAE 790501, 1979
11. Noguchi, M.; Tanaka, Y.; Tanaka, T.; Takeuchi, Y.; *A Study on Gasoline Engine Combustion by Observation of Intermediate Reactive Products during Combustion*; Toyota Motor Co. Ltd., Nippon Soken Inc., SAE 790840, 1979
12. Ishibashi,Y.; Tsushima,Y.; A Trial for Stabilizing Combustion in Two-stroke Engines in part Throttle Operation; Honda R&D, Asaka Research Center, 1993 in: Duret, P.; A new generation of two stroke engines for the future?, IFP, Paris, 1993
13. Thring, R.H.; *Homogeneous-Charge Compression Ignition (HCCI) Engines*; Southwest Research Institute, SAE 892068, 1989
14. Najt, P.; Foster, D.; *Compression Ignited Homogeneous Charge*; University of Wisconsin-Madison, SAE 830264, 1983
15. Yanagihara, H.; SatoY.; *A Simultaneous Reduction of NOx and Soot in Diesel Engines under a new Combustion System (Uniform Bulky Combustion System)*; Toyota Motor Corporation et Mizuta, J., Toyota Central R&D Labs. Inc ., Wiener Motorensymposium, 1996
16. Zel'dovic, Y.; Librovich, V.B.; Makhviladze, G.M.; Sivashinsky, G.I.; *On the Development of Detonation in a Non-Uniformly Preheated Gas;* Acta Astronautica, Vol.15

Pergamon Press, 1970, S.313-321

17. Oppenheim, A.K; *Dynamic features of combustion,* Phil. Trans. R. Soc. Lond., A 315, 471-508; 1985
18. Frank-Kamenetzki, D.A.; *Stoff- und Wärmeübertragung in der chemischen Kinetik;* Springer Verlag, Berlin, 1958
19. Najt, P.; Foster, D.; *Compression Ignited Homogeneous Charge*; University of Wisconsin-Madison, SAE 830264, 1983
20. Thring, R.H.; *Homogeneous-Charge Compression Ignition (HCCI) Engines*; Southwest Research Institute, SAE 892068, 1989
21. Onishi, S.; Jo, S.H.; Shoda, K.; Jo, P.D.; Kato, S.; *Active Thermo-Atmosphere Combustion (ATAC) - A new Combustion Process for Internal Combustion Engine*; Nippon Clean Engine Research Institute Co. Ltd., SAE 790501, 1979
22. Ishibashi,Y.; Tsushima,Y.; *A Trial for Stabilizing Combustion in Two-stroke Engines in part Throttle Operation*; Honda R&D, Asaka Research Center, 1993
23. Iida, N.; Hosonuma, S.; Yoshimura, K.; Takase, S.; *Combustion and Emission of Low Heat Rejection Ceramics Methanol ATAC Engine;* Keio University, JSME International Journal, Series B, Vol. 39, No.1, 1996
24. Meyer, J.W.; Oppenheim, A.K.; *Coherence Theory of the Strong Ignition Limit;* Combustion and Flame; 17, 65, 1971
25. Stockinger, M.; *Möglichkeiten der Verbesserung des Arbeitsprozesses im gemischansaugenden Verbrennungsmotor durch Verdichtungszündung;* Bundeswehrhochschule Hamburg, VDI-Verlag, 1992
26. Meyer, J.W.; Oppenheim, A.K.; *Coherence Theory of the Strong Ignition Limit;* Combustion and Flame; 17, 65, 1971
27. Morikawa, K.; Watanabe, H.; Furuya, A.; *Comparison of fuel injection systems and a new combustion method for a direct injection two-stroke-cycle automobile engine;* Subaru Research Centre Co., Osawa, Japan; JSAE 9635719, 1996