

# The Effect of Exhaust Throttling on HCCI - Alternative Way to Control EGR and In-Cylinder Flow

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## ABSTRACT

Homogeneous Charge Compression Ignition (HCCI) has emerged as a promising technology for reduction of exhaust emissions and improvement of fuel economy of internal combustion engines. There are generally two proposed methods of realizing the HCCI operation. The first is through the control of gas temperature in the cylinder and the second is through the control of chemical reactivity of the fuel and air mixture. EGR trapping, i.e., recycling a large quantity of hot burned gases by using special valve-train events (e.g. negative valve overlap), seems to be practical for many engine configurations and can be combined with any of the other HCCI enabling technologies. While this method has been widely researched, it is understood that the operating window of the HCCI engine with negative valve overlap is constrained, and the upper and lower load boundaries are greatly affected by the in-cylinder temperature. Boosting has been found very effective in increasing the upper load boundary of HCCI but very little has been published about the effect of raised exhaust back pressure when a turbocharger is used. This paper presents a study of the effect of increased exhaust back pressure on gas exchange processes in a HCCI engine with an exhaust throttling valve. The work has included 1-D gas dynamic modelling using Ricardo WAVE™ and experiment on a Ford/Jaguar V6 HCCI engine with a fitted exhaust throttling orifice. Appropriate boundary and initial conditions in the engine have been created and information from the 1-D simulations is visualized.

## INTRODUCTION

Homogeneous Charge Compression Ignition (HCCI) combustion is a promising technology with potential to improve the fuel economy of Internal Combustion Engine as well as to reduce exhaust emissions mainly of NO<sub>x</sub> by using lower average temperatures during combustion<sup>1</sup>. In a HCCI engine the control of auto

ignition process is realized partially by retaining a portion of hot residual gases which have high heat capacity and temperature compared to fresh charge<sup>2</sup>. Residual gases change chemical reactivity and thermodynamic properties of the diluted mixture and influence the duration and maximum temperature of combustion. Hence exhaust gases have important role in active control of combustion phasing. The amount of residual gases available in cylinder chamber and method of ensuring the presence of hot gases has global impact on BSFC (Brake-Specific Fuel Consumption) and BMEP (Brake Mean Effective Pressure).

In theory a further improvement of engine fuel economy, emissions and engine operating windows can be achieved by linking both concepts of HCCI combustion and turbo-charge boosting technologies<sup>3</sup>. Besides, the HCCI combustion technology is inseparably associated with high rate of internal EGR management by systems such as variable cam timing (VCT) and cam profile switching (CPS).

The HCCI engine load is a function of specific amounts of EGR in the cylinder and therefore it is a crucial factor for the control of auto-ignition and main combustion phase. Any variation of EGR rate can be a cause of disturbance and lead to a misfire or knock combustion with high value of coefficient of variation (COV)<sup>4</sup>. Extension of the HCCI operating window by application of a boosting device such as a Turbo-Charger or Wave Pressure Exchanger seems a next step to improve fuel efficiency and create ultra-low polluting engine systems, since a lean mixture is combusted and a wider operating window can be achieved.

Mergers of both technologies – HCCI and Energy Recovery Devices such as Turbocharger are under an extensive investigation over past few years as possible future part of Hybrid Drive Systems for the cars<sup>5, 6</sup>. It is well known that for the control of auto-ignition (HCCI) in



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the Internal Combustion Engine a special valve-train as mentioned before<sup>3</sup> and a thermal management system<sup>7</sup> as well as detailed analysis of the auto-ignition chemistry with kinetics<sup>8</sup> and interaction of gas dynamic effects<sup>9</sup> must all be brought in.

To provide appropriate EGR and cycle to cycle variation parameters in the cylinder during end of compression phase in the negative valve overlap (NVO) engine concept, not only the general flow pattern must be considered but also compressible gas flow effects inside engine ducts. Unsteady gas behavior has a direct influence on pressure losses and in-cylinder pressure change and a spatial-thermal decomposition of the EGR<sup>10</sup>.

The exhaust backpressure is another important thermo / fluid parameter which is closely coupled with the gas exchange process and can influence the EGR ratio and combustion and also give appropriate information about system losses. Generally during the exhaust stroke a vast amount of thermal energy from the combustion process is available in expelled gases (partially in the form of pressure wave) and could be used to increase thermal efficiency of the engine. Devices such as Turbocharger or Wave Pressure Exchanger convert part of exhaust gas enthalpy and recover it as a potential energy of air pressure on the compressor side but the costs is increased backpressure on exhaust side and changes in the cylinder gas exchange process.

The major advantage of a boosted HCCI engine is its use of lean-combustion technology with low BSFC as well as possibility of engine 'downsizing' with an extension of operating windows compared to the naturally aspirated HCCI engine. J. Hyvonen and G. Haraldsson achieved brake efficiency of 42% on a 1.6 litre turbocharged 5-cylinder engine at 5 bar BMEP with high backpressure. Olsson and Tunestal<sup>11</sup> demonstrated Brake Mean Efficiency of 41% on a 6-cylinder truck engine which was modified for a dual fuel (methanol, n-heptane) turbocharged HCCI engine operation and efficiency of 45% for Diesel engine respectively. They achieved very low NOx emission of 4 ppm level and a wide range of BMEP loads with a maximum of 16 bar. However, turbocharged HCCI engine has some drawbacks as mentioned before. The HCCI Engine working with a low load with massive amount of EGR in the cylinder with high indicated efficiency with more dilute mixture has reduced amount of thermal enthalpy available in the exhaust gases. Erlandsson and Einewall<sup>12</sup> simulated the performance and efficiency of a HCCI engine based on a zero-dimensional model developed to analyze the effects of turbo-charging and influence of changes of compression ratio on thermodynamics parameters. They proved that the effect of higher indicated efficiency is reduced thermal energy in exhaust gases; hence lower enthalpy of the air is recovered from compressor side. The lower thermal energy on exhaust side has an impact on turbine work ability under unsteady conditions and increases the

backpressure on exhaust system, while pumping work causes smaller brake efficiency. On the other hand preheating of the inlet to ensure that auto-ignition is reliable increases gas specific volume and reduces mass flow rate through the turbine. These problems make turbo-charging difficult to apply in HCCI system without any auxiliary devices.

Another system which has a potential to be used to recovery energy from the exhaust gasses in HCCI combustion system application is the Wave Pressure Exchanger (COMPRES). It is a state of the art device with a system of continuous exchange of the energy of pressure waves and thermal energy between exhaust gas and fresh air and with complex physics of mixing processes, heat transfer and turbulence<sup>13</sup>. Compared to the turbocharger system, a Wave Pressure Exchanger has a much faster response<sup>14</sup> to changed conditions, similar to supercharger system but without constraints resulting from the fact that the exhaust gas thermal energy is wasted<sup>15</sup>. Unfortunately this technology is not exploited enough in HCCI combustion technology.

The present work involves extensive study of the gas dynamics effects with and without exhaust throttling and different NVO for a HCCI engine. Exhaust throttling had on purpose simulated the exhaust backpressure caused by a device such as Turbocharger, Catalyst, PWE or the fact that geometry of inlet and exhaust pipes has effect on this parameter. The information about the gas dynamic processes and their impact on the quality of gas exchange process and on the variation of the amounts of residuals remaining in the cylinder during intake and exhaust has been analyzed. It is generally assumed that residual gas fraction controls the phasing of HCCI combustion which is mainly governed by in-cylinder chemical kinetic process. Therefore for better control of combustion any additional information obtained from the simulation of the gas dynamics process is helpful and should be useful during the study of the HCCI engine operating characteristic.

The 1-D simulation study of EGR variations in the cylinder for specific exhaust conditions was developed for a single cylinder engine model based on the Jaguar V6 cylinder geometry with a simple model of combustion generated by Wiebe function<sup>16</sup>. For this simulation, four different NVO values with and without throttling were also examined on the experimental Jaguar V6 HCCI engine with exhaust throttling device fitted.

In order to achieve and control the auto ignition timing, the HCCI experimental Jaguar V6 engine is equipped with cam profile switching (CPS) and variable cam timing (VCT) systems. The mechanism and efficiency of obtaining the desired residual fraction in cylinder with regards to engine speed in V6 HCCI have been examined by presenting the net specific fuel consumption (NSFC) and torque. A way to increase the fuel economy of the HCCI concept combustion is presented by introducing optimization strategy for control

and obtaining the appropriate residual fraction<sup>17</sup>. Therefore a numerical study of the quality of gas exchange process is useful.

Summary of the study:

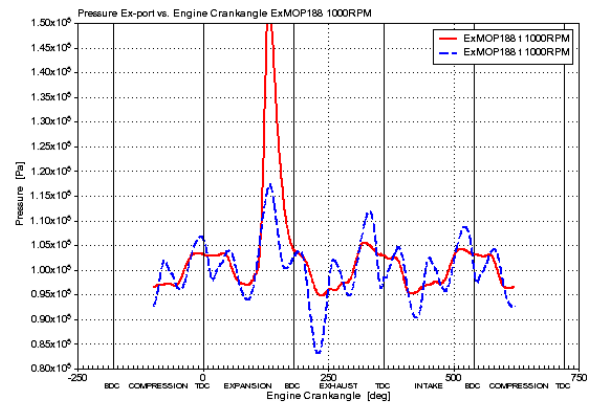
- Analysis of unsteady process of gas exchange and variations of EGR parameter in a single cylinder engine (numerical study - single cylinder engine)
- Analysis of effect of backpressure on the amount of gas residual fraction in the cylinder (numerical study – single cylinder engine)
- Influence of exhaust back pressure on engine parameters and HCCI combustion (experimental work - Jaguar V6 HCCI engine)

## GAS EXCHANGE PROCESS IN EXHAUST MANIFOLDS

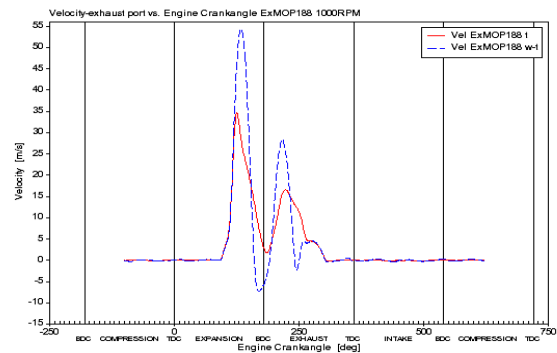
Gas Dynamics is one of the crucial phenomena that control the engine operation conditions<sup>18</sup> with combustion process and pollutant emission. The effect of gas exchange process is widely apparent in all phases of engine operation since has a vast influence on air scavenging and combustion ending with the blow down process to exhaust manifold. An aerodynamically complex and highly unsteady behaviour of flow must be set-up for appropriate conditions. For example in turbo-charged multi cylinder HCCI engine when the turbine is under unsteady conditions with increasing backpressure the geometry of exhaust manifold and valve timing needs specific optimization compare to the naturally aspirated engine<sup>19</sup>.

As mentioned before, NVO in a HCCI engine is important to control the amount of residuals<sup>20</sup>. It is interesting to analyse the unsteady gas flow process for this sequence of valve events and its interaction with the exhaust backpressure. Figure 1 shows development of instantaneous pressure and velocity inside the exhaust port for two different conditions with and without throttling at 1000 RPM. The unsteady flow in engine manifold depends on following conditions:

- Geometric shape of valve and ports.
- Dimensions of manifolds.
- Valve events (NVO, MOP).
- Type of combustion (DI, SI, HCCI) and method of fuel delivery (DI, PI)
- Thermodynamics properties of the fluid and engine conditions (engine speed, throttling)



A)



B)

Figure 1. Instantaneous pressure and velocity in the exhaust port at 1000RPM. Valve timing ExMOP 188 degCA and InMOP 500 degCA. Solid red line represents throttled case, dashed blue line dot – case without (w/t) throttle.

A) instantaneous pressure resulting from inlet port throttling compared with not-throttling case, B) instantaneous velocity pressure resulting from inlet port throttling compared with not-throttling case.

## EXPERIMENT AND TEST PROCEDURE - JAGUAR V6 HCCI ENGINE WITH THROTTLING DEVICE.

The engine used in this work was an experimental HCCI Ford/Jaguar 3 litre V6 four valves per cylinder engine with a pent roof combustion chamber, details of which are presented in Table 1. The engine intake and exhaust camshafts were built-up with variable cam timings (VCT) and cam profile switching (CPS) systems that made it possible to change the valve lift from high 9 mm reserved for SI mode to 3 mm for HCCI combustion mode. The maximum range of variable cam timing for negative valve overlap was 120 deg. Except for the wall guided direct injection and specially derived train system for camshafts the engine block was similar to the production engine with compression ratio kept at 11.3. The fuel used was the standard unleaded gasoline of RON 95 and the fuel/ratio was near stoichiometric (14.3). The engine was coupled to an eddy-current dynamometer for speed and load control. The two engine banks were equipped with exhaust manifold

into 1 type with throttled device shown in Figure 2 and connected through the catalyst element with near-ambient pressure exhaust extraction system by 3 m long exhaust pipe each.

| Engine type                       | 4 valve per cylinder, 6 cyl. (V6) |
|-----------------------------------|-----------------------------------|
| Bore                              | 89.0 mm                           |
| Stroke                            | 79.5 mm                           |
| Compression Ratio                 | 11.3                              |
| Intake valve timing               | InMOP500CA                        |
| Exhaust valve timing              | variable                          |
| Intake Temperature                | 300 K                             |
| Air/Fuel ratio                    | 14.3                              |
| Exhaust Throttled                 | 15 mm diameter orifice            |
| Valve Lift HCCI mode (all valves) | 3 mm                              |

Table 1. The Jaguar AJ V6 Engine with CPS.

The in-cylinder pressure measurements were obtained from six piezo-electric KISTLER 6125A transducers mounted one in each cylinder. For measuring the pressure in exhaust manifold an EUROSENSOR pressure transducer has been used. Twelve thermocouples type K were installed to monitor the exhaust and inlet temperature. During the HCCI tests the inlet throttle was kept wide open and mass flow rate was affected by varying cam timing and exhaust throttling. Engine data was obtained in this study at 4 specific cam timings which are presented in Table 2, exhaust throttling was used to check the effect on HCCI combustion and to extend information about the effect of backpressure on engine operation. For each cam timing the engine ran at different load thus exhaust throttle phasing is expected to change, resulting in different loads.

| Exhaust Valve Max. Open Point | Inlet Valve Max. Open Point |
|-------------------------------|-----------------------------|
| ExMOP188 CA                   | InMOP500 CA                 |
| ExMOP196 CA                   | InMOP500 CA                 |
| ExMOP201 CA                   | InMOP500 CA                 |
| ExMOP207 CA                   | InMOP500 CA                 |

Table 2. MOP used in numerical and experimental study.

Intake and exhaust cam timings for minimum residuals were chosen to start the engine with spark ignition combustion. When engine block achieved steady condition of temperature level in SI mode, the HCCI combustion mode was started. All experiments were carried out when the engine coolant reached 90 C in order to minimize the effects of coolant temperature.

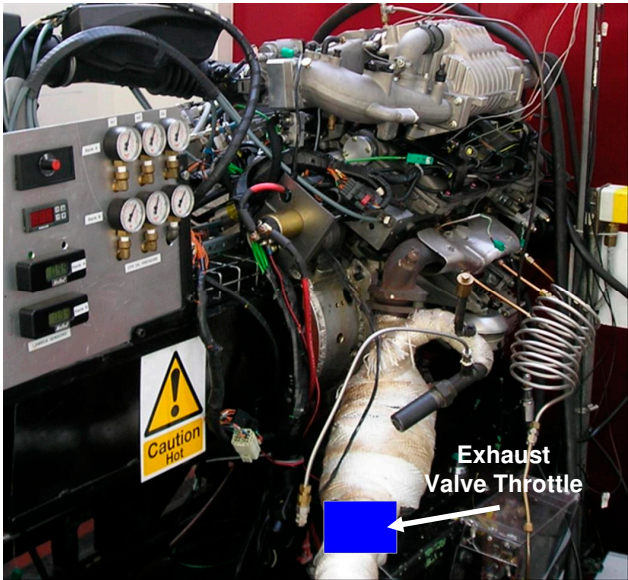


Figure 2. Location of Exhaust valve throttle - right bank.

### WAVE CODE - MOODELLING TOOLS

The 1-D numerical study was applied to extend information about gas dynamics process taking place inside engine manifolds and their influence on engine operation characteristics for four different NVO values and with restricted flow.

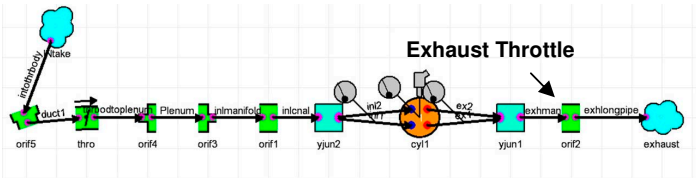


Figure 3. Single Cylinder Engine-Wave Model

| Exhaust manif.  | Inlet manifold  |
|-----------------|-----------------|
| Exhaust port    | Inlet port      |
| Length L=40mm   | Length L=55mm   |
| Diameter D=28mm | Diameter D=35mm |
| Port Junction   | Port Junction   |
| L=30mm          | L=46mm          |
| D=38 mm         | D=35 mm         |
| Exhaust pipe    | InMOP500 CA     |
| L=3m            | L=200mm         |
| D=38mm          | D=45mm          |

Table 3. Single Cylinder Engine - Dimensions.