

Closed-Loop Combustion Control for a 6-Cylinder Port-Injected Natural-gas Engine

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ABSTRACT

High EGR rates combined with turbocharging has been identified as a promising way to increase the maximum load and efficiency of heavy duty spark ignition engines. With stoichiometric conditions a three way catalyst can be used which means that regulated emissions can be kept at very low levels. Obtaining reliable spark ignition is difficult however with high pressure and dilution. There will be a limit to the amount of EGR that can be tolerated for each operating point. Open loop operation based on steady state maps is difficult since there is substantial dynamics both from the turbocharger and from the wall heat interaction. The proposed approach applies standard closed loop lambda control for controlling the overall air/fuel ratio for a heavy duty 6-cylinder port injected natural gas engine. A closed loop load control is also applied for keeping the load at a constant level when using EGR. Furthermore, cylinder pressure based dilution limit control is applied on the EGR in order to keep the coefficient of variation at the desired level of 5%. This way confirms that the EGR ratio is kept at its maximum stable level all times. Pumping losses decrease due to the further opening of the throttle, thereby the gas exchange efficiency improves and since the regulator keeps track of the changes the engine all the time operates in a stable region. Our findings show that excellent steady-state performance can be achieved using closed loop combustion control for keeping the EGR level at the highest level while the stability level is still good enough.

INTRODUCTION

Recently, environmental improvement (CO₂, NO_x and ozone reduction) and energy issues have become more and more important as worldwide concerns. Natural gas consisting of highly methane (90%) is a good alternative fuel to improve these problems because of its plentiful availability and clean burning characteristics. Heavy duty spark ignited (SI) natural gas engines could be operated with two approaches viz. lean operation and stoichiometric operation. Recent work at the department

of energy sciences at Lund University has showed better result by stoichiometric operation [1] since stoichiometric operation with a three way catalyst results in very low emissions while keeping efficiency in a reasonable level. Stoichiometric operation with high EGR rates combined with turbocharging has been identified as a promising way to get the following advantages:

- Better fuel economy than pure stoichiometric operation since [2]:
 - **Reduced throttling losses (at low/part loads):** The addition of inert exhaust gas into the intake system means that for a given power output, the throttle plate must be opened further, resulting in increased inlet manifold pressure and reduced throttling losses.
 - **Reduced heat rejection:** Lowered peak combustion temperatures not only reduce NO_x formation, it also reduces the loss of thermal energy to combustion chamber surfaces, leaving more available for conversion to mechanical work during the expansion stroke.
 - **Reduced chemical dissociation:** The lower peak temperatures result in more of the released energy remaining as sensible energy near TDC, rather than being bound up (early in the expansion stroke) in the dissociation of combustion products. This effect is relatively minor compared to the first two.
- Lower emissions than lean burn operation because of using 3-way catalyst
- Decreasing knock tendency

These advantages results in increasing the maximum load and efficiency of heavy duty spark ignition engines.

Many researchers have been dedicated to extend the limit of dilution burn operation in order to improve fuel efficiency, as well as reducing exhaust gas emission from the spark ignition engine. The dilution limit is imposed by increased cyclic variation of the combustion intensity that reduces the drivability and the effect is usually quantified through the coefficient of variation (COV) of the indicated mean effective pressure (IMEP) analysis [2-4]. So there will be a limit to the amount of EGR that can be tolerated for each operating point. As the unburned mixture in a spark ignited engine is diluted with EGR (or even excess air), the flame development period, the duration of burning phase and the cyclic variation in combustion process will increase and if the combustion passes the dilution limit then the operation becomes rough and unstable. It is found that drivability problems tend to occur when COVimep values exceed about 5%; therefore any values above this represents combustion variability that is unacceptably high.

The factors that have been found to influence cycle to cycle variation are:

1. Variation in gas motion in the cylinder during combustion
2. The variation in the amounts of EGR (internal and external), fuel and air each cycle
3. The variation in mixture composition within the cylinder each cycle. This effect is especially pronounced near the spark plug due to the variations in mixing between air, fuel and internal and external EGR.

Since the engine is operating in steady-state mode and with highest amount of EGR, the variations are mostly because of the third reason.

The objective of this work is to develop a tool for mapping the best positions of the throttle and EGR valve in different loads and speeds where the engine has the lowest pumping losses and COV of IMEP is still below 5%. For developing this tool three different regulators have been designed. A standard closed loop lambda control for controlling the overall air/fuel ratio and a standard closed loop load control were developed. Furthermore, cylinder pressure based lean limit control is applied in order to keep the COVimep at the desired level of 5%.

EXPERIMENTAL SETUP & CONTROL METHOD

This section will cover the information about the experimental engine and the modifications, the engine control system, measurements system, gas data, developed regulators and the explanations of the performed experiment.

THE ENGINE & MODIFICATIONS

The experimental engine was originally a diesel engine from Volvo which is converted to a natural gas engine see table 1 for specification. The engine is equipped with short route cooled EGR system and also turbocharger with wastegate.

Number of Cylinder	6
Displacement	9,4 Liter
Bore	120 mm
Stroke	138 mm
Compression ratio	10,5 :1
Fuel	Natural gas

Table 1: Specification of the engine

Following modifications were performed on the engine:

- **Multi-Port injection System:** Originally the engine has single point injection, with four injectors at the fuel injector assembly. The gas pressure is approximately 10 bar. The test bench engine is supplied with natural gas at 4.6 bar, so the port injection system is equipped with 12 injectors (2 per cylinder) to be able to cover the whole load range, see Figure 1.



Figure 1: Multi-Port Fuel Injection

- **Mouthpieces:** in order to prevent cross breathing of natural gas between cylinders, six mouthpieces were designed to pass the gas flow in the same direction as the cylinders, see figure 2.

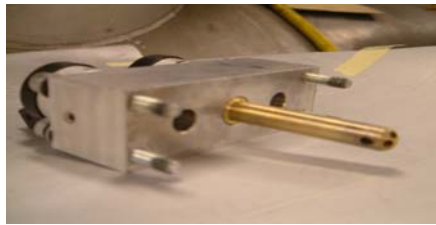


Figure 2: Injector Mouthpiece

ENGINE CONTROL SYSTEM

A master PC based on GNU/Linux operating system is used as a control system. This communicates with three cylinder-control-modules (CCM) for cylinder-individual control of ignition and fuel injection via CAN communication, see figure 3. Crank and cam information are used to synchronize the CCMs with the crank rotation.

Flexible controller implementation is achieved using Simulink and C-code is generated using the automatic code generation tool of Real Time Workshop. The C-code is then compiled to an executable program which communicates with the main control program. The controllers used for this experiment are lambda, load and EGR controller which determine the offset amount of fuel, air and EGR. The controllers can be activated from Graphical User Interface (GUI).

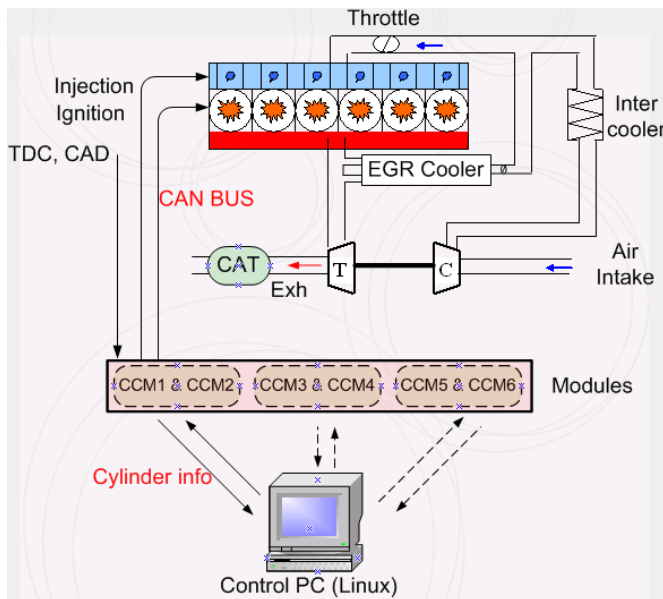


Figure 3: The Engine and its control system

MEASUREMENT SYSTEMS

Each cylinder head is equipped with a piezo electric pressure transducer, Kistler 7061B to monitor cylinders pressures for heat release calculations. Cylinder pressure data is sampled by a Microstar 5400A data acquisition processor. EGR was calculated by measuring CO₂ at inlet and exhaust. Emissions (HC, CO, NO, NO₂, NO_x, CO₂, O₂) are measured before and

after catalyst. Also, temperatures at inlet/exhaust, pressures at inlet/exhaust, fuel and air flow, lambda, torque and engine speed have been measured.

GAS DATA

The composition of the natural gas, which varies slightly over time, is shown in Table 2. The lower heating value is 48,4 MJ/kg.

Composition	%	Structure
Methane	89,84	CH ₄
Ethane	5,82	C ₂ H ₆
Propane	2,33	C ₃ H ₈
I-Butane	0,38	C ₄ H ₁₀
N-Butane	0,52	C ₄ H ₁₀
I-Pentane	0,11	C ₅ H ₁₂
N-Pentane	0,07	C ₅ H ₁₂
Hexane	0,05	C ₆ H ₁₄
Nitrogen	0,27	N ₂
CO ₂	0,6	CO ₂

Table 2: The natural gas composition

CONTROL METHOD

As mentioned before the objective of this work is to develop a tool for mapping the best positions of the throttle and EGR valve in different loads and speeds where the engine has the lowest pumping losses and COV_{imep} is still below 5%. For developing this tool different regulators were needed. Three different regulators were designed for controlling overall air / fuel ratio, load and EGR level, see Figure 4. Bumpless transfer and Anti-Windup algorithm were applied during the design of the regulators.

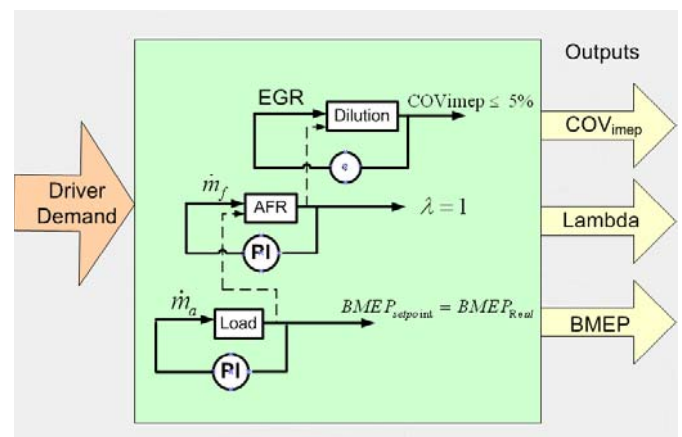


Figure 4: Closed-Loop Combustion Control

CLOSED LOOP LAMBDA CONTROL

Closed loop lambda control evaluates the signals from the broadband lambda sensor. The sensor measures the oxygen content in the exhaust gas and thus provides information about the mixture composition. The