Modeling of a heavy duty diesel engine to ease complex optimization decisions

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Introduction

Engine optimization becomes more difficult every day, more and more limits regarding emissions of noxious components have to be met. Considering heavy duty marine engines such as the 6DZC from ABC (Table 1) there are several important instances: IMO III reduces NO_x by 75% from 2021[1], EPA reduces NO_x by 70% from 2016 [2]. Therefore very complex systems are implemented, which each have multiple calibration or working parameters. Some are fixed, some can change depending on engine load and speed. An example of a fixed parameter is compression ratio, it can only be changed while building the engine. Other fixed parameters include: choice of injection nozzle (#holes, ⌀hole), bore, stroke, etc. Exhaust gas recirculation (EGR) is a parameter that can be changed continuously during operation of the engine. Typically there are other parameters present: Variable Valve Timing, injection timing, injection duration, injection pressure, secondary injection, wastegate setting(s), etc. Ideally these parameters are configured in a way that the engine emits very little harmful components and fuel consumption is very low.

Cylinder configuration	6 in line
Bore [mm]	256
Stroke [mm]	310
Rated power [kW]	1326
Rated speed [rpm]	1000

Table 1: ABC 6DZC engine

The most straightforward approach would be to test every parameter combination, record emission components and fuel consumption and choose the optimal parameter combination. This has to be repeated for every speed and load of the engine, which results in an engine map. This method becomes more and more expensive, both in time as in fuel consumption because every additional operating parameter increases the amount of tests exponentially.

This is why engine simulation becomes inevitable [3]. Accurate engine simulation is able to exclude regions of parameter values that are clearly infeasible and can give a good indication where engine tests are more interesting.

Building an engine model

A distinction between two different sub-domains can be made, using respectively open or closed valves. When one of the valves is open, a gas dynamics model is used to to calculate cylinder filling and gas composition. When intake and exhaust valves are closed compression, combustion and expansion are modeled. A commercial [4] one-dimensional fluid dynamics code is used as the gas dynamics model because calculation is very fast in comparison to CFD simulation. This provides boundary conditions for the combustion model.

The gas dynamics model is built out of different components: pipes, bends, flow splits, coolers, compressors, valves, etc. For each component the physical properties such as diameter, radius of bend,... are defined. Flow splits are more difficult to model in one dimension, and calibration is necessary. The same holds for valves and compressors, these are too complex to model in 1D and require some calibration and/or measurement data.

Combustion is currently modeled by using the DIPulse model [5]. Based on in-cylinder conditions, provided by the gas dynamics model, and injection rate.

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It models every injection event as a pulse entraining unburned and burned gases. The strict separation between the two sub-domains allows for separate and accurate calibration.

Basic engine measurements are necessary: power, fuel consumption, air flow rate, pressures, temperature at various locations and essentially intake, exhaust and in-cylinder pressure traces. These measurements are used to calculate the heat release rate in the cylinder for the test points. Then, a simulation without combustion calculation is run, the calculated heat release rate is used instead. This allows calibration of all flow related parameters, resulting in accurate volumetric efficiency (V_e) which means that the boundary conditions in the cylinder can be accurately predicted for every operating point.

The combustion model is not running yet, but the measured heat release rates are already available which should be the target for the combustion model. The combustion model can be calibrated by trying to approximate the measured heat release rate.

Evaluation of the model

Currently the model is able to accurately reproduce the gas dynamics, power and fuel consumption of the engine. In figure 1 the volumetric efficiency, referenced to atmospheric conditions, from the measurement is compared to the simulation for several operating points. It can be concluded that the model can accurately predict the gas dynamics. Power and brake-specific fuel consumption are predicted within the same range.

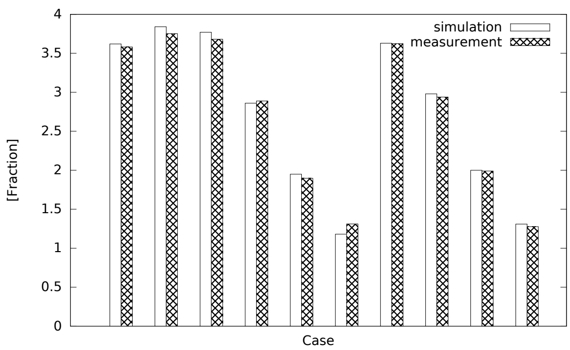

Figure 1: Volumetric efficiency comparison.

The amount of emission of NO_x is one of the key results of the simulation, every legislative organization limits this harmful component strongly. This is calculated using the in-cylinder temperature (based on the predictive model) and the extended Zeldovich mechanism [6], using standard reaction rate constants. In figure 2 the relative NO_x emission from the model is compared to measurements for the same operating points. It can clearly be seen this step needs further attention. Some trends are visible in both the measurement and the simulation, which allows some qualitative conclusions from simulation. Quantitative conclusions will only be possible after a thorough adjustment of the model regarding NO_x emissions.

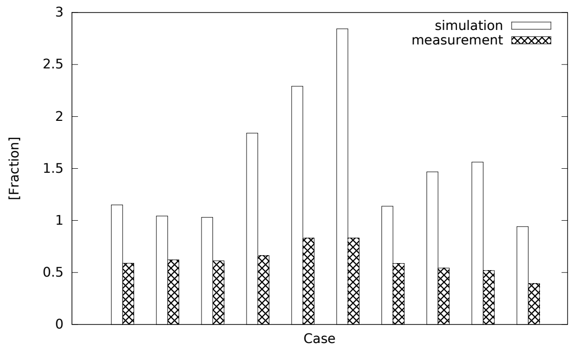

Figure 2: NO_x emission comparison.

Conclusion

The current approach shows great prospects regarding heavy duty engine simulation. Many tests could be avoided, lowering costs and speeding up the development process. It is however clear that two calibration stages are not sufficient to accurately predict NO_x. Additional work has to be done in order to address this issue.

Acknowledgments

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