

Double Compression Expansion Engine Concepts: A Path to High Efficiency

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ABSTRACT

Internal combustion engine (ICE) fuel efficiency is a balance between good indicated efficiency and mechanical efficiency. High indicated efficiency is reached with a very diluted air/fuel-mixture and high load resulting in high peak cylinder pressure (PCP). On the other hand, high mechanical efficiency is obtained with very low peak cylinder pressure as the piston rings and bearings can be made with less friction. This paper presents studies of a combustion engine which consists of a two stage compression and expansion cycle. By splitting the engine into two different cycles, high-pressure (HP) and low-pressure (LP) cycles respectively, it is possible to reach high levels of both indicated and mechanical efficiency simultaneously. The HP cycle is designed similar to today's turbo-charged diesel engine but with an even higher boost pressure, resulting in high PCP. To cope with high PCP, the engine needs to be rigid. The usage of higher piston ring tension and larger bearings are examples of measures to cope with higher PCP. These measures will cost in terms of friction. Hence, mechanical efficiency is not as good as other engine concepts with lower PCP. The low-pressure cycle on the other hand, uses a design more similar to current naturally aspirated (NA) spark ignited (SI) engines, but designed for even lower PCP. Because of this, the engine does not need to be as rigidly designed and the overall friction levels will be much lower. By combining these two engine philosophies, a total engine concept with both high indicated and mechanical efficiencies can be achieved. Simulations show net indicated efficiency above 60% and a brake efficiency of 56%.

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INTRODUCTION

Reducing carbon-dioxide emission (CO_2) is one of the most important challenges of today to overcome. A major source of CO_2 -emission comes from the usage of internal combustion engines in vehicles to transport people and goods. This emission is directly proportional to fuel consumption. In order to reduce CO_2 -emissions, European Union legislations state that by 2015, the fleet averaged CO_2 -emissions from a passenger car manufacturer is limited to 130g/km. Reaching 2020 the limitations are even tougher, a fleet average of only 95g/km is allowed. If a manufacturer fails to meet these requirements, the manufacturer has to pay "excess emissions premiums" for every car registered, basically a penalty-tax if the requirements are not fulfilled.

Fuel consumption is even more important for engines used in heavy trucks. These vehicles travel longer annual distances, making fuel cost a significantly larger part of total costs compared to a passenger car. Hence, improvements in fuel economy are highly desired.

Improving engine brake efficiency is vital in order to achieve these requirements. Brake efficiency (η_b), is the function of four parts: *combustion* (η_c), *thermodynamic* (η_t), *gas-exchange* (η_{ge}) and *mechanical* (η_m). All of these efficiencies need to be high in order to reach high brake efficiency. Definitions of these efficiencies are presented in [Figure 1](#). Further information and definitions of the variables used in [Figure 1](#) are presented in [appendix A](#).

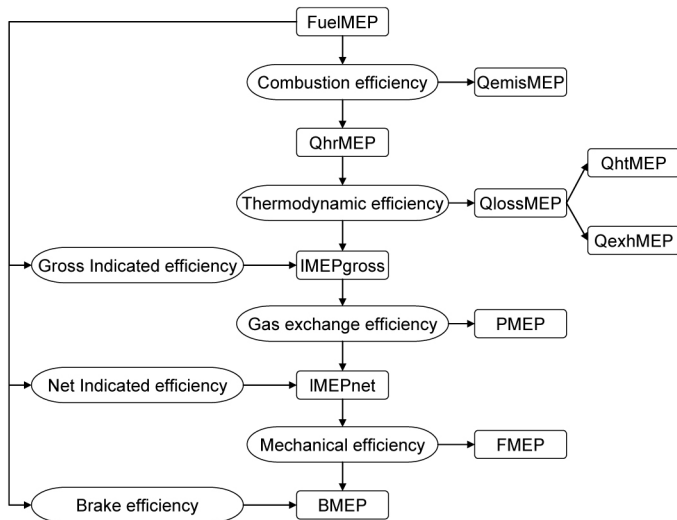


Figure 1. Energy conversion chart from fuel energy to brake work expressed as mean effective pressures (MEP).

For the concept presented in this paper, pumping losses are defined as the losses that occur from only the gas exchange-phase in the LP cylinder, since this is actually where the real gas exchange (pushing out expanded gases and inducing fresh ambient air) happens. The gas exchange in the HP cylinder is more like a work transfer from the LP cylinder to the HP cylinder.

OTHER SPLIT-CYCLE ENGINE CONCEPTS OF TODAY

The concept presented in this paper is considered as a split-cycle concept. It is not the first though, it began already in 1897 when Rudolf Diesel himself tried to construct the “series XIV-engine” which would be the ultimate in thermal efficiency [1]. This concept consists of two conventional combustion cylinders which feed the combusted gases into a larger expansion cylinder. The engine was constructed and tested but the results obtained were not as Diesel expected. Due to massive heat losses, the thermodynamic efficiency of this engine was very poor. A more recent split-cycle concept is the Compact Compression Ignition (CCI) engine [2]. It uses 3 different types of cylinders, an intake cylinder, a combustion cylinder and an exhaust cylinder. Simulations performed concludes that the CCI engine has an efficiency advantage due to the reduced wall surface area in the combustion cylinder. Heat transfer losses will thus be reduced compared to a conventional engine, but no absolute numbers have been presented yet. The Scuderi engine is another split-cycle concept [3]. This concept uses 2 different cylinders, a compressor cylinder and an expander cylinder. They are slightly separated in phasing and the displacements of the cylinders are quite similarly sized, compared to other split-cycle concepts. So far the Scuderi engine have presented a brake specific fuel consumption (BSFC) of slightly below 240 g/(kW*h) [4]. Assuming a fuel lower heating value of 44 MJ/kg, this will translate into a brake efficiency of 34.1%. Also Ricardo has presented a split-cycle concept called “CryoPower”

where a recuperator and isothermal compression are applied [5]. The recuperator is used to transfer heat from the exhaust gases into the compressed air before combustion. Simulations performed by Ricardo predicts a thermal efficiency of 60%, which is very high. No experimental results have been presented so far though.

OBJECTIVES

In this paper, simulation results for a Double Compression Expansion Engine (DCEE) concept are presented. The aim of the simulations is to establish a first idea of what can be achieved in terms of efficiency and any design challenges to be anticipated. The main target is to reach high brake efficiency and exhaust emissions have not been considered. Exhaust emissions is an important aspect to consider, but today there is a multitude of existing exhaust after treatment systems and it is anticipated that one or several of these solutions can be used in conjunction with the presented concept to pass emission legislations.

Differences between DCEE and Other Split-Cycle Concepts Presented

Although several split-cycle concepts have been presented in the past but all of them are in some way different from the DCEE concept. The numbers of cylinders is e.g. different compared to Diesel's XIV engine. Diesel's engine used 2 combustion cylinders in conjunction with a low-pressure cylinder. The DCEE concept has only one combustion cylinder and one low-pressure cylinder. The CCI concept uses 3 different cylinders, compressor, combustor and expander cylinders respectively. Also the cylinder phasing is not the same between CCI and DCEE. The two different pistons in the DCEE concept are 180 crank angle degrees (CAD) apart, i.e. the first piston is at TDC when the other one is at BDC. With the CCI concept the adjacent cylinders are not at the opposite dead centers simultaneously. The Scuderi concept also has 2 different cylinders as the DCEE, but does not utilize a dual stage compression and expansion process, which is used with the DCEE concept. Thus, the obtained in-cylinder pressures will differ substantially between the concepts. The DCEE concept lacks both the recuperator and the isothermal compression present in the Ricardo engine.

EFFICIENCIES OF EXISTING ENGINES

Today, the most commonly used engines in vehicles are based on the four-stroke cycle, either spark ignited (SI) or compression ignited (CI). Both of these have some similarities but also major differences in terms of efficiency.

Naturally-Aspirated (NA) SI Engine

The NA SI-gasoline engine, uses a spark to ignite a homogenous air/fuel-mixture to start the combustion. Since the air/fuel-mixture is pushed into the crevice volumes by the flame, some of the fuel will

not be consumed during the combustion process. This leads to combustion losses and combustion efficiency tends to range somewhere between 95 and 98% [6].

The SI engine uses a low compression ratio, which is needed to avoid knock. The low compression ratio will adversely affect thermodynamic efficiency, being only around 35% in engines of today [6]. With a well-designed and optimized intake and exhaust system, gas exchange efficiency at high loads can be up to 98% [6]. However, this is only valid if the engine is operating at high load or unthrottled. At part load a throttle will be needed to restrict the amount of air into the cylinder to maintain a required stoichiometric air/fuel mixture. This will cause pumping losses and gas exchange efficiency will suffer. Usage of stratified direct injection technology and variable valve timing-systems can drastically reduce these losses and improve the gas exchange efficiency. The low compression ratio in conjunction with relatively slow combustion results in relatively low peak cylinder pressure. Thus, the engine can be mechanically designed for lower peak pressure, which is a benefit in terms of friction. Figure 2 presents a FMEP graph for a naturally aspirated SI engine from 2004 and a range of FMEP for contemporary SI engines as shown by the grey area [7]. As an example, the red curve in Figure 2 indicates that a FMEP-value of 0.3 bar is reached at an engine speed of 2300 rpm. This engine was able to produce 11.7 bar brake mean effective pressure (BMEP) (560Nm of torque with an engine displacement of 6 liters gives a specific torque of 93 Nm/liter) at this engine speed, which translates into a mechanical efficiency of around 97%.

Typical efficiency-values for the NA SI engine are presented Table 1

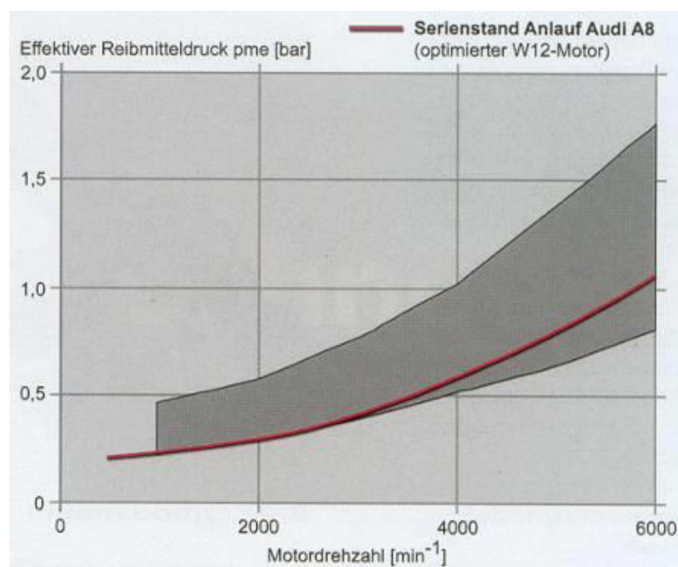


Figure 2. Friction mean effective pressure [bar] as function of engine speed [rpm] [7]. Red line indicates FMEP for the low friction SI engine discussed in this paper and dark grey area represents an interval in FMEP for existing naturally aspirated SI engines.

Table 1. Typical efficiency levels obtained in current NA SI and turbocharged CI engines.

	NA SI engine	Turbocharged CI engine (Heavy duty)
Combustion efficiency	95-98% [6]	99.9% [8]
Thermodynamic efficiency	35% [6]	50% [9]
Gas exchange efficiency	98% [6]	104% [6]
Mechanical efficiency	97% [7]	94% [9]
Brake efficiency	32-33% ¹	44% [9]

Turbo-Charged Compression-Ignited (CI) Engine

CI engines use a leaner than stoichiometric air/fuel-mixture and fuel is directly injected into the cylinder. A leaner than stoichiometric air/fuel-mixtures ensures a sufficient amount of oxygen to oxidize all injected fuel. Also direct injection prevents fuel from being trapped in crevice volumes. Hence, combustion losses are very small and combustion efficiency is normally above 98% and can even reach 99.9% [8].

Unlike the SI engine, knock is not a concern with the CI engine. Higher compression ratios can thus be used and thermodynamic efficiency improves. Current heavy duty truck engines deliver around 50% thermodynamic efficiency [9]. This is not the highest thermodynamic efficiency of production engines of today though.

Current boosted two-stroke ship engines are able to produce 55% thermodynamic efficiency [10]. However, it is not appropriate to implement this engine type in vehicles on land due to excessive weight and space requirements.

With carefully designed intake and exhaust systems, gas exchange efficiency can reach as high as 104% for a turbocharged engine [6]. This means exhaust backpressure is lower than intake boost pressure, giving a positive work contribution on the crankshaft. However, the operating range when this occurs is quite limited. Outside the optimal conditions for the turbine and compressor designs, gas exchange efficiency could drop well below 100%. By using a variable geometry turbine (VGT) turbocharger, widening of the optimal operating range can be achieved, although it is still limited.

1. The brake efficiency calculated for the SI engine is the multiple of all the cited part efficiencies.

High compression ratio together with high boost operation will cause very high PCP for the CI engine. Current heavy-duty engines operate with a PCP around 200 bar [11]. To cope with this high pressure, the engine mechanical parts need to be rigid, causing high FMEP levels. An FMEP of 1.2 bar is typical with 200 bar peak pressure. This is four times higher than for the SI engine previously discussed. To reach the same mechanical efficiency as the SI engine, the load has to be multiplied by four. This means a CI engine needs to operate at a BMEP level of $4 \times 11.7 \text{ bar} = 46.8 \text{ bar}$ to obtain the same mechanical efficiency as the NA SI engine. This load level is beyond the capabilities of current engines. For reference, a 13-liter engine presented in 2013, had a BMEP capability of 24.2 bar (13 liter displacement delivering 2508Nm of torque) [12]. This is only slightly more than half of the 46.8 bar BMEP needed and the mechanical efficiency (94%) is thus worse compared to the SI engine.

In total, brake efficiency for current engines used in heavy trucks are around the 44% mark [9]. The right column in Table 1 presents typical efficiency values obtained in a turbo-charged CI engines.

High Efficiency Engine Concepts

Over the years, a lot of research has been performed to improve efficiency. Figure 3 presents a comparison of typical efficiency-values obtained with existing engines but also research engine concepts published.

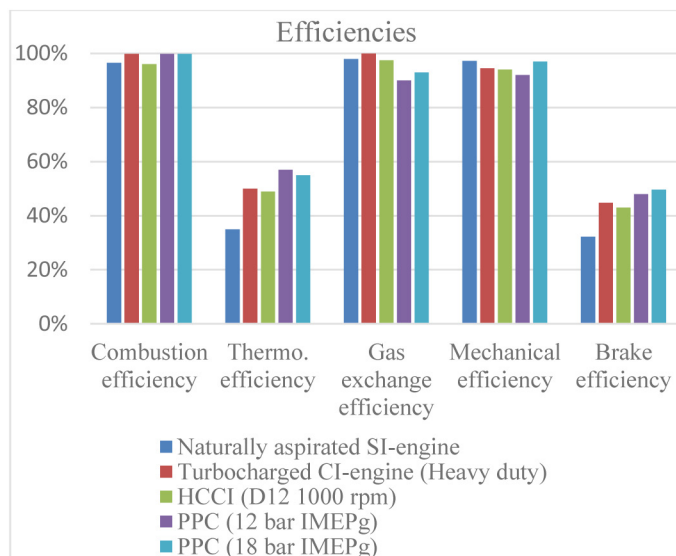


Figure 3. Part efficiencies obtained in current and research engine concepts.

Combustion, gas exchange and mechanical efficiencies are above the 90% bracket for all the presented concepts. Thermodynamic efficiency on the other hand is significantly less, 57% at best with the PPC research engine [13]. Hence, in order to improve brake efficiency significantly, the greatest potential is in improving the thermodynamic efficiency.

Thermodynamic efficiency is determined by two factors, exhaust losses (Q_{exh}MEP) and heat transfer losses (Q_{ht}MEP), see Figure 1. Exhaust losses occur when not fully expanded exhaust gases are expelled into the exhaust manifold. With the Atkinson cycle, the effective expansion ratio is greater than the effective compression ratio, which makes it possible to extract more useful work for a given fuel input [14]. However, the relative heat transfer and friction losses increase since the effective displacement is reduced while heat transfer and friction losses remain the same. The gain in thermodynamic efficiency therefore is partly lost and the net gain in brake efficiency is not very large. Adopting a low heat rejection strategy (LHR), heat transfer losses are reduced. However as Johnsson et al. found out, the decreased heat transfer losses caused an almost equal increase in exhaust losses [15]. Overexpansion is therefore needed to improve thermodynamic efficiency. In 2009, theoretical studies of a six-stroke engine concept were made [16]. The six-stroke concept consists of a conventional four-stroke cycle, but with a two-stroke heat recovery cycle added. A substantial increase of work could be extracted with a given fuel amount, but no experimental results have been presented so far.

Low temperature combustion (LTC) concepts are a way to improve thermodynamic efficiency. In 2006, experimental work done by Hyvönen et al. for a Homogenous Charge Compression Ignition (HCCI) engine reached a thermodynamic efficiency of 49% [17]. However, due to poor combustion, gas exchange and mechanical efficiencies, brake efficiency reached merely 43%, which is not better compared to a current CI engine. In 2009, Manente conducted experiments in a Scania D12-engine with Partially Premixed Combustion (PPC) [13]. A thermodynamic efficiency of 57% was reached, which is around 10 percentage points better than CI engines of today. Low in-cylinder heat transfer and low exhaust losses were the keys for obtaining this level of efficiency. A brake efficiency of 48% was estimated. This is only 4 percentage points higher than a CI engine, although thermodynamic efficiency improved by 10 percentage points. This can be explained by the limited load level (12 bar IMEP_g) obtained, pumping and friction losses thus become a bigger fraction of the total fuel input. In an effort to reach higher brake efficiency, experiments were later done with a lowered compression ratio to 14.3:1 (instead of 17.1:1) [18]. This enabled the engine to run at higher engine loads, thus improving gas exchange and mechanical efficiencies. The lowered compression ratio slightly reduced the thermodynamic efficiency though (reduced to 55%), and the estimated brake efficiency reached 49.7%.

In 2013, Tunér performed simulations which compared CI and PPC engines [19]. The conclusion was that gross indicated efficiency (combustion and thermodynamic efficiencies multiplied) was drastically improved from 46.7% with CI to 54.1% with PPC. This was mainly due to halved in-cylinder heat transfer losses, while pumping losses were more than three times bigger. CFD studies comparing heat transfer losses in a CI and a PPC engine were performed by Fridriksson [20]. The studies revealed that gas temperatures close to wall surfaces tend to be between 400 and 500 K

lower with PPC than with a conventional CI engine. Hence, the near wall temperature gradient is lower which results in significantly lower heat transfer losses.

Conclusions of Efficiencies in Current Engines

From the discussion made in the previous sections, turbocharged CI engines do in general have a higher brake efficiency compared to SI engines. This is mainly due to improved thermodynamic efficiency as the CI engine is not limited by knock. With a LTC concept, even higher levels of thermodynamic efficiency can be obtained. Unfortunately, the gain in thermodynamic efficiency is not fully converted into improved brake efficiency. The limited load range obtained with LTC concepts adversely affects gas-exchange and mechanical efficiencies. Naturally aspirated SI engines on the other hand can obtain very good mechanical efficiency, but suffer from poor thermodynamic efficiency.

It is obvious that each of the mentioned engine concepts has its strengths and weaknesses efficiency-wise. If all of the strengths could be combined into a single engine concept, further improvements in brake efficiency improvements could be achieved.

THE DOUBLE COMPRESSION EXPANSION ENGINE (DCEE) CONCEPT

The DCEE concept is a split cycle concept (SCC), where the cycle is split into a low pressure (LP) and a high pressure (HP) cycle. Fuel injection and combustion will occur in the HP cycle. Also, the compression and expansion strokes are performed in dual stages, once in each cycle. The main parts in the two different cycles are the high pressure cylinder (HP cylinder) for the HP cycle and the low pressure cylinder (LP cylinder) for the LP cycle respectively. Figure 4 presents an overall concept layout for the DCEE concept.

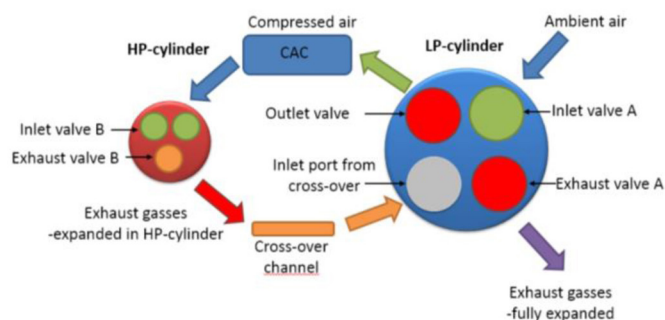


Figure 4. System layout of the DCEE concept.

The LP cylinder has two main purposes. The first one is to induct ambient air, perform a first stage compression and transfer it to the HP cylinder. The second one is to perform second stage expansion of the gas from the HP cylinder. Since the gas from the HP cylinder has already been expanded once, the PCP will be significantly lower in the LP cylinder. Hence, the LP cylinder can have a mechanical design similar to the one of a naturally aspirated SI engine. A big benefit is very low friction. For reference, the previously mentioned SI engine

can obtain a FMEP of only 0.3 bar at 2300 rpm. The LP cylinder will be operated at even lower pressures, meaning FMEP should become even lower.

The LP cylinder head contains three valves with different purposes and an inlet port for the incoming exhaust gases from the HP cylinder. A conventional engine with a 4 valves per cylinder design only needs valves with two different purposes, hence two physical valves can be used for each purpose. The DCEE concept will thus have an effective flow area that is only half of the flow area attained in a conventional 4 valves per cylinder head. Pumping losses is expected to be greater which the simulation results later will confirm.

The HP cylinder is designed more similar to current boosted CI engines, but charged with an even higher boost level. Current engines seldom use a boost pressure in excess of 4 bar absolute pressure. The boost pressure in the DCEE concept is predicted to be in the range of 7 to 16 bar. The LP cylinder will provide the required boost pressure by performing a compression stroke. This is possible since the LP cylinder has a displacement which is 6-12 times greater than the displacement of the HP cylinder.

With the high boost levels used, very high load level can be obtained. At the same time, PCP will also be high. High PCP can partly be compensated by a relatively low compression ratio used in the HP cylinder. A first approximation is to allow 300 bar PCP. Due to the high PCP encountered, the engine needs to be designed for this. For example high tension piston rings and large bearings will be needed and these measures will cause greater friction losses. However, due to the very high load levels attained, mechanical efficiency will still be at acceptable levels.

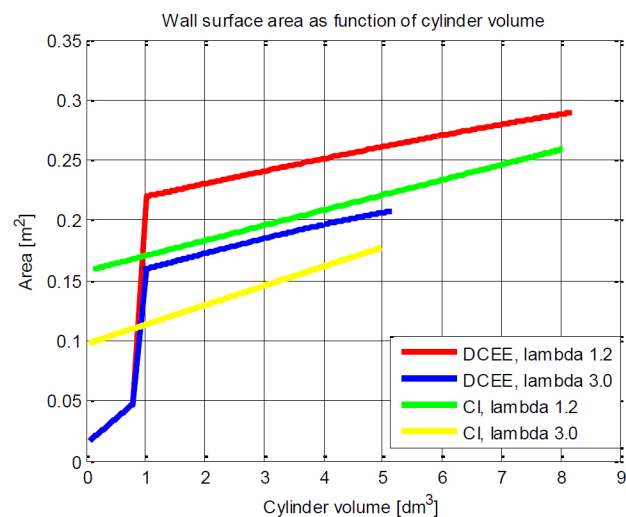


Figure 5. Wall surface area as function of cylinder volume. Geometry is the same as used in the simulation models.

Figure 5 presents an effective in-cylinder wall surface area comparison between the DCEE and conventional concepts. Figure 6 presents a comparison between the DCEE and conventional concepts regarding area/volume ratio. As previously mentioned, the DCEE concept performs expansion in two stages. The first stage takes place in the HP cylinder and the second stage in the LP cylinder. The conventional cycle on the other hand performs only one expansion stage.

single cylinder. In-cylinder temperatures will be highest at the beginning of the expansion and monotonically decrease with expansion. Hence, a decreased wall surface area will be a benefit and reduces heat transfer losses. This is achieved with the DCEE concept, where the early stages of expansion are performed in the HP cylinder with small wall surface area and much better area/volume ratio.

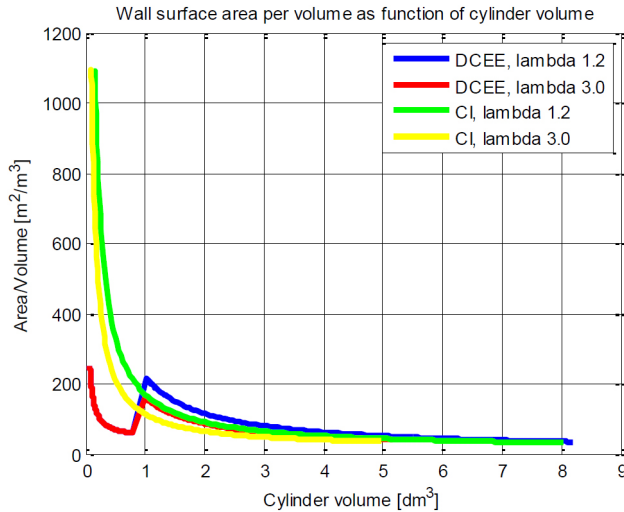


Figure 6. Wall surface area to cylinder volume ratio as function of cylinder volume. Geometry is same as used in the simulation models.

Figure 7 below shows the in-cylinder pressure trace for the DCEE concept, while Figure 8 and Figure 9 presents the PV diagrams for the HP and LP cylinders respectively.

At 0 CAD in Figure 7, the second stage compression is initiated in the HP cylinder and a compression pressure of 250 bar is attained at 180 CAD. At the same time, the LP cylinder does its intake stroke and inducts ambient air. At 180 CAD, combustion has been started in the HP cylinder and continues with the first stage expansion. By adjusting combustion phasing, PCP is kept close to 300 bar. The LP cylinder will at the same time perform the first stage compression. When a desired boost pressure has been reached, the compressed air is transferred to the charge-air-cooler unit. When enough compressed air has been transferred, a recompression process starts. The purpose is to equalize the pressure in the LP cylinder and the HP cylinder since they will be interconnected at 360 CAD. The charge-air-cooler has two functions. The first function is to cool down the compressed air when a close to stoichiometric ($\lambda=1.2$) air-fuel mixture is used. The second function is to store the compressed air until the inlet valve for the HP cylinder opens at 540 CAD in Figure 7. The volume of this unit is 30 liters.

At 360 CAD, the LP and HP cylinders are connected when the HP cylinder exhaust valve is opened. From this moment, the HP cylinder will perform its exhaust stroke while the LP cylinder will perform the second stage expansion. A net expansion will be obtained due to the larger displacement of the LP cylinder compared to the HP cylinder.

At 540 CAD, the HP cylinder starts its intake stroke, inducing compressed air that has been momentarily stored in the charge-air-cooler unit. The LP cylinder performs its exhaust stroke where the previously second stage expanded gases are pushed out into the exhaust manifold. This stroke finishes at 720 CAD and a new cycle begins over again.

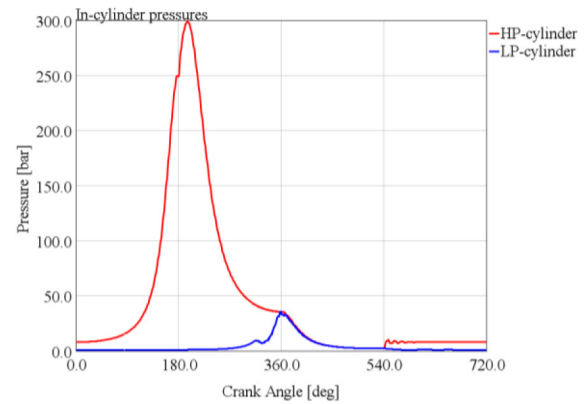


Figure 7. Pressure traces for the DCEE concept.

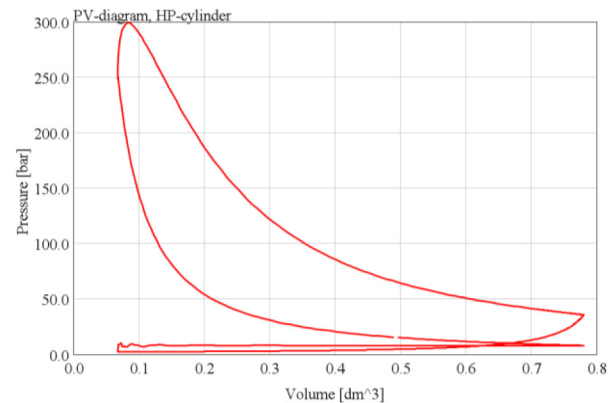


Figure 8. PV diagram for the HP cylinder.

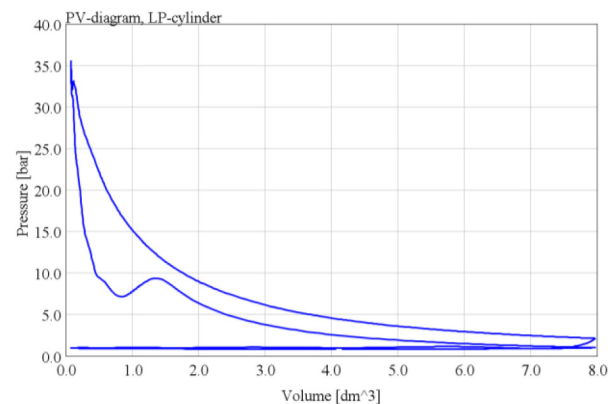


Figure 9. PV diagram for the LP cylinder.

SIMULATION SETUP

A 1D-simulation of the DCEE concept has been made in GT-power [21]. A simulation model layout of the concept is presented in Figure 10.