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ANALYSIS OF POTENTIAL INCREASES IN ENERGY EFFICIENCY FOR PISTON COMBUSTION MACHINES WITH UNCONVENTIONAL GEOMETRY

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Starting with various alternative piston combustion machine (pcm) designs, such as RKM Schapiro piston machines, potential increases in thermodynamic potential based on changed boundary conditions are estimated.

The boundary conditions of conventional pcms define the parameters maximum peak pressure, compression ratio and friction mean effective pressure. Adding a supercharger to a modern conventional pcm determines the charge pressure ratio parameter.

This study estimates changes in thermodynamic potential by varying the boundary conditions affecting machine parameters beyond those defined by conventional pcms.

This was accomplished using SimEngine, a software application for simulating engine thermodynamics. This software has great functionality for simulating unconventional combustion engines and engines equipped with additional thermodynamic components.

1 Scope of Analysis

Modern internal combustion engines have a total of more than 100 years development and optimisation time passed and can surely described as well product – but are they really optimal?

1.1 *RKM Schapiro engine*

There are some innovative alternative designs, such as the RKM Schapiro engine, which may have potential to beat the weaknesses of conventional engine designs. Taking the RKM engine as example, the limitations of maximum peak pressure and sealing can be completely solved. However, due to high peak acceleration forces, the maximum engine speed is limited.

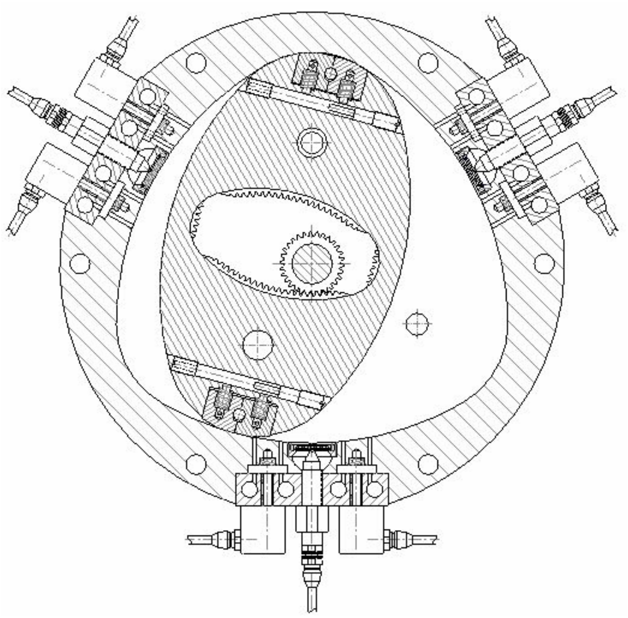

Figure 1: Principle schematic of one of possible 1-axis RKM engines

1.2 *Targets*

The target of this article is to identify thermodynamic potentials if exceeding current boundary conditions. So, this article should not qualify the RKM concept itself. It shall give more an outlook of the potential which can currently not be used.

The parameters, limited by current technology, are maximum peak pressure (pmax); compression ratio (CR) and friction mean effective pressure (fmep).

The following table gives an outlook of the varied parameters:

Parameter	**Current limitation**	**Investigation of up to…**
Maximum peak pressure	~120 bar (Otto) ~200 bar (Diesel)	400 bar
Compression ratio	~20 (Diesel)	50
Break mean effective pressure	~25 bar	100 bar (a.m.a.p.)
Friction mean effective pressure	~0.5 bar	0.1 bar

A second part gives an outlook of application for alternative compressors or expanders. The investigation subject here may be an application as steam expander.

1.3 *Analysis of wasted power*

Based on the principle laws of thermodynamic, the internal efficiency (η_i) of an internal combustion engine is limited by its compression ratio and the isentropic coefficient of the working fluid (air):

$$\eta = 1 - \varepsilon^{1-\kappa},$$

with η efficiency, ε compression, and κ isentropic coefficient, $\kappa > 1$.

It can easily be seen, that an improvement of the compression ratio directly leads to a higher efficiency. The isentropic coefficient of combustion gases is dependent from λ, the relative air/fuel ratio, which is much better for lean mixtures than for rich mixtures.

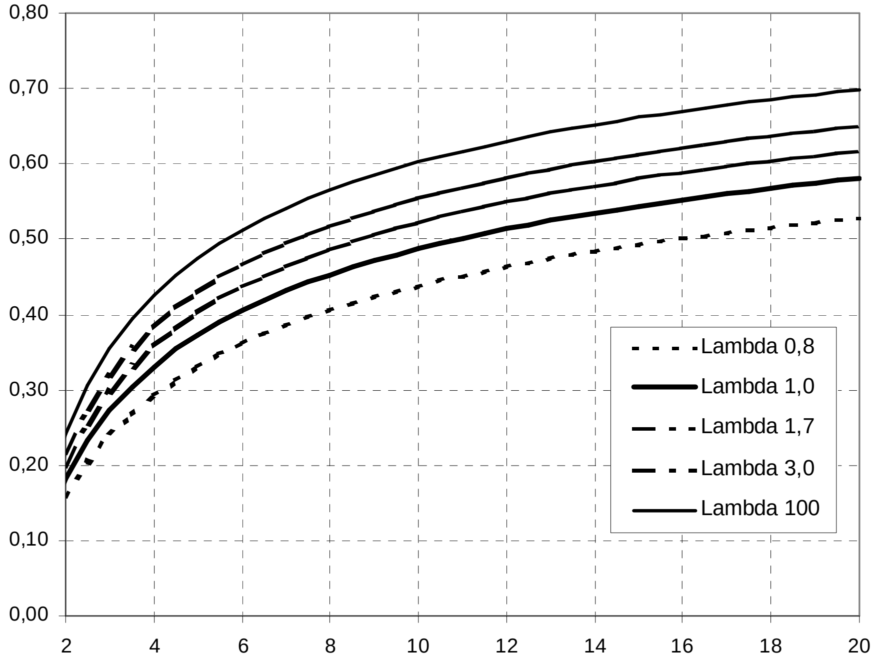

Figure 2: Thermodynamic efficiency potential depending on compression ratio and λ = A/F ratio

However, the compression ratio of Otto engines is limited by knocking behaviour of the gasoline fuels. It is also not possible to operate an Otto engine very lean, so its basic thermodynamic potential seems to be exhausted.

Diesel engines already have a high compression ratio of ~ 20 and also operate with lean mixture. This is the reason for there higher efficiency. However, only a few Diesel engines have higher compression ratios due to the limiting increasing maximum pressure and increasing friction due to heavier engine design. The current resulting effective efficiency (η_e) is in the range of 40%.

1.4 *Gasoline applications and Miller principle*

For gasoline applications, there is one principle available, which can avoid knocking while increasing the compression ratio: The Miller principle. Hereby the valve timing is trimmed in a way that the compression is lower than the expansion ratio. A geometrical compression ratio of 13..15 can be reached without knocking, but it is necessary to boost the engine to achieve an acceptable specific power. This principle is used in some modern block heat and power plants and raises their efficiency a few percent.

However, knocking is phenomenon, which is caused by high temperatures and pressures. The high temperatures can be avoided by decreasing the geometrical compression ratio.

If the engine power output should stay constant, it is necessary to boost the engine and cool the charge air down to an ambient temperature like level. So, the temperature at end of compression (relevant for knocking) can kept cool, but the pressure is kept nearly constant. This limits the efficiency gain by the Miller principle.

1.5 *Diesel applications*

Modern Diesel engines are limited mainly by two factors: a) The fuel evaporation and b) The maximum cylinder pressure.

Bad fuel evaporation causes big droplets, which leads to high soot emissions on the one hand and NO_x emissions on the other hand, caused by locally high combustion temperatures. Avoiding that unwanted emissions leads to more lean combustion, which costs power, this trade-off can be optimized with increasing fuel pressure levels of up to 2000 bar.

The other limiting factor, the maximum cylinder pressure is given by the engine geometry. If a high engine power output is wanted, either the compression ratio has to be decreased or late injection timing has to be applied, both costs efficiency.

By that reason, the Diesel engine was identified as the engine with the highest thermodynamic potential, given by new engine geometries.

2 Simulation results

All following Simulations were calculated with SimEngine, the thermodynamic simulation software, which has great functionality for internal combustion engines with advanced thermodynamic functionality. As one example, the software can handle numerous of real gas media, a behaviour which is important especially at high pressures. Furthermore, that software can also handle steam processes with different media in a combined simulation environment with internal combustion engines.

2.1 *Base Parameters*

Starting from a well optimised series engine, several modifications have been calculated. Most of these modifications are not applicable at an engine with standard geometry, either due to the compression ratio or due to the maximum cylinder pressure.

The base engine has en effective efficiency (η_e) of approx. 42.2%, which is an actual best reference case for passenger car Diesel engines. All simulations are based on 1500 rpm engine speed and 95°C water and oil temperature.

2.2 *Injection Timing*

The first variation loop is the injection timing. Starting from the base case, the injection timing was modified in direction early. Observed was the indicated an effective efficiency as well as the maximum peak pressure.

As first result, it can be seen, that the maximum peak pressure increases dramatically with the injection timing, while the indicated mean effective pressure (imep) stays nearly constant.

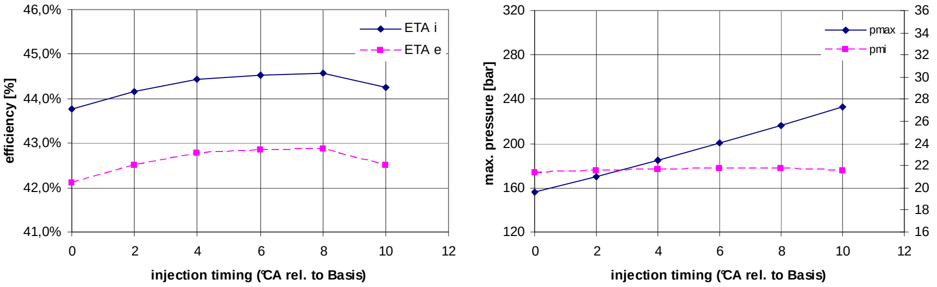

Figure 3: Effect of injection timing

As moving the injection timing in early position, efficiency first raises, but at too early injection timings, the efficiency drops due to increasing wall heat transfer. A reasonable value for the injection timing is 4° crank angle (CA) earlier than the base scenario, which leads to ~0.5% efficiency gain. This value is used as base value for the following variations.

2.3 *Variation of compression ratio*

As it was expected as the main responsible parameter for the engine efficiency, raising the compression ratio should show high potential for increasing the engine efficiency.

A variation calculated from 16 to 35 showed, that primary the maximum cylinder pressure raises up to 284 bar at the highest compression ratio. The indicated mean effective pressure (imep) stays here nearly constant, too.

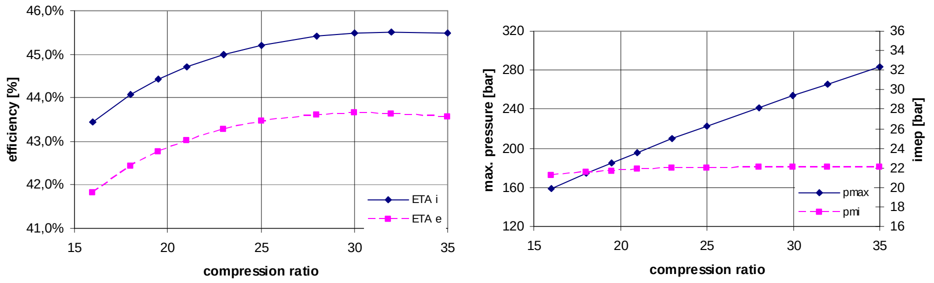

Figure 4: Effect of compression ratio

The efficiency gain is great in the region between 16 and 25. Higher compression values seem to have no additional benefit. Just in Fig. 2 can be seen, that the compression ratio gain gets more flat for higher values. Due to increasing wall heat transfer losses, there is a maximum somewhere between 28 and 32.

Due to increasing peak pressure, the friction mean effective pressure also increases with higher compression ratios, so that the effective efficiency maximum is reaches earlier then the indicated efficiency maximum.

A reasonable maximum value for the compression ratio has been set to ~26.

2.4 *A/F ratio variation*

The next variation with high potential, read at Fig. 2, is the A/F ratio. A more lean mixture has more N_2 and O_2 components and less CO_2 and H_2O components in its combustion gas, which leads to a higher isentropic coefficient. An additional beneficial effect is the lower peak temperature, which may lead to less heat transfer losses.

Of course, with a more lean mixture, the indicated mean effective pressure drops. This effect would smooth the simulation results and make them not comparable. To avoid this issue, the boost pressure was modified, so that the imep was constant at 21.7 bar.

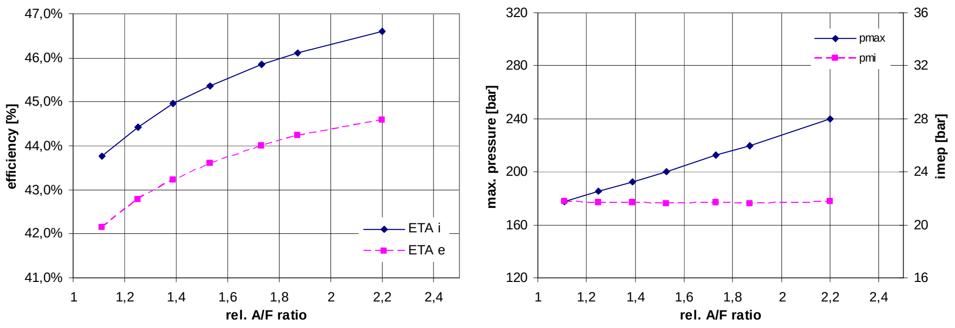

Figure 5: Variation of rel. A/F ratio with constant imep by raising charge air pressure

Similar to all other variations, the maximum cylinder pressure also increases with more lean mixture. In this case, it is caused by the higher absolute gas mass due to the increasing boost pressure.

The efficiency gain by lean mixture is enormous. There is a span width of 3%-points in total, while varying the relative A/F ration from 1.11 to 2.2.

Unfortunately, the extreme lean simulation points are not realistic. The exhaust gas temperature and enthalpy drops, so that there is not enough energy to drive the turbocharger, which has to boost an even higher pressure. The leanest possible rel. A/F ratio is in the range of ~1.6.

2.5 *Charge Air pressure*

The last potential can be seen in raising the maximum charge air pressure. There are three motivation factors for raising the charge air pressure.

1) While the indicated mean effective pressure gets higher, the friction mean effective pressure of the engine stays nearly constant or increases slowly. As result, the mechanical efficiency gets better.
2) The energy density increases faster than the losses by wall heat transfer and pumping losses.
3) Considering also part load operation, a part load operating point can be still in the charged area. The efficiency characteristic becomes more flat.

Due to possible cross-effects with A/F ration and compression ratio, we calculated several variations of the charge air pressure, based on compression ratio 19.5 and 26, and relative A/F ratio 1.25 and 1.6.

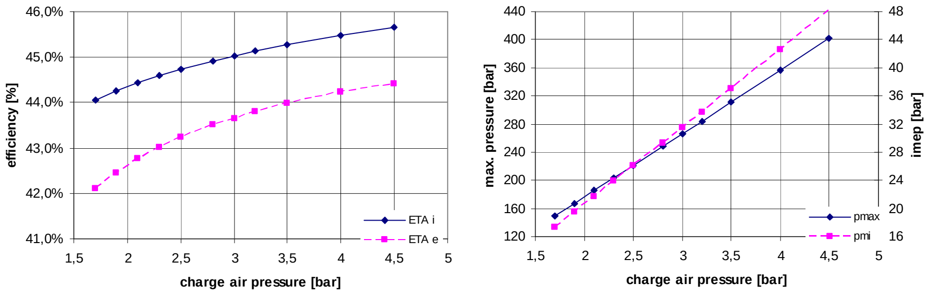

Figure 6: Variation of boost pressure at CR = 19.5 and rel. A/F ratio = 1.25

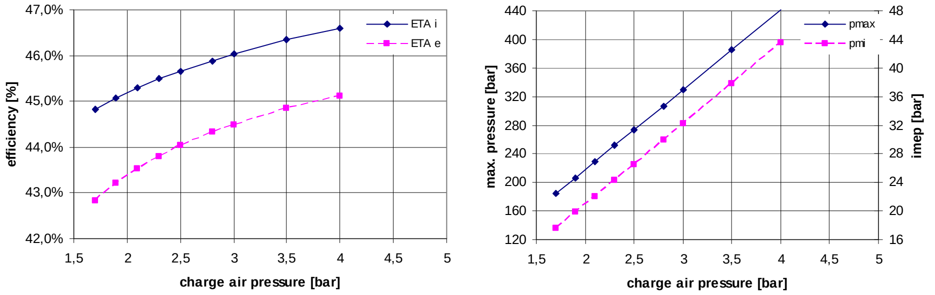

Figure 7: Variation of boost pressure at CR = 26 and rel. A/F ratio = 1.25

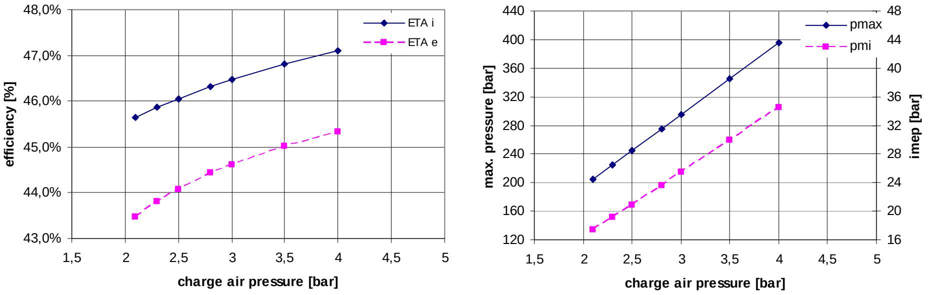

Figure 8: Variation of boost pressure at CR = 26 and rel. A/F ratio = 1.6

If we limit the maximum cylinder pressure to 400 bar, as result can be seen, that highest potential in imep is given by the base case with CR=19.5 and rel. A/F ratio of 1.25. Here the imep value reaches over 48.2 bar, while indicated and effective efficiency raise to 45.6% and 44.4%.

The highest efficiency can be reached with higher CR and more lean mixture. In that extreme scenario with CR = 26 and rel. A/F ratio = 1.6, the efficiency raises up to 47.1% and 45.3%. However the power density does not reach such high values, the imep is limited to 34.4 bar here.

2.6 *Friction*

Until today, it is not possible to give an exact estimation of the friction mean effective pressure of alternative crank drives. However, the potential can be estimated, if the indicated efficiency is used as upper border line.

3 Conclusion

As one can see, there is still some thermodynamic potential left in internal combustion engines, which can not be used formerly due to limitations in maximum cylinder pressure. The simulation results showed potential of up to 47.1% in indicated efficiency and 45.3% in effective efficiency. This is a further potential of 3% absolute or 7% relative. Additionally, there is some potential with friction-reduced crank drives.

Abbreviations

Effective efficiency	η_e , ETA e
Indicated efficiency	η_i , ETA i
indicated mean effective pressure	imep
break mean effective pressure	bmep
friction mean effective pressure	fmep
Crank angle	CA
Compression ratio	CR

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RKM GbR Website: www.rkm-schapiro.org.