LIMITS OF INTERNAL COMBUSTION ENGINES EFFICIENCY

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Abstract

List of old and new concepts of ICE thermodynamic improvements considering realistic limits of both mechanical and thermal stress and pollutant emissions, especially new concepts of combustion (HCCI-like), piston motion control, consequences of downsizing, possibilities of waste heat recovery and heat regeneration. Methods of simulation for conceptual optimization in hierarchy of procedures. Importance of transparency for conceptual approach. Computerized T-s diagram. References to methods of higher order of precision using 1-D, Q-D and 3-D models, modularized thermodynamics using GT Suite elements for unconventional engine cycles. Examples of results, considering limits of isochoric-like combustion, high levels of turbocharging, bottoming cycles for waste/heat recovery and heat regeneration assessment. Conclusions for further development.

1. Introduction

The ever increasing fuel prices and focus on exhaust emissions including CO_2 creates an evolution pressure at internal combustion engines (further ICE). Although their concept is rather old, new solutions have been yet found. Moreover, even the known up-to-now not realized solutions are frequently enabled by new technologies, especially using, e.g., mechatronics as sophisticated engine management. The emerging ICE competitors (especially fuel cells as a prime mover or the hybrid solutions of automotive powertrains) are setting the future level of prices, which should be respected during assessment of ICE development possibilities.

The simulation methods of different depth and width are used currently to preliminary conceptual optimization of qualitatively new engine systems (e.g., combustion or waste heat utilization) as well as for parametric optimization for quantitatively new levels (e.g., two-stage turbocharging) - [1], [2], [3], as it was assessed at one of the previous KONES conferences - [4]. The "simple" transparent methods have not lost their importance, however, because they are able to find the utmost limits of specific solutions. If designed properly, they can be surprisingly precise despite the standard meaning of them.

Therefore, the aim of this contribution is to give an insight into thermodynamic base of pros and cons of ICE problem solutions. The topics of powertrain solutions are out of the scope and range of this paper. The well-known state-of-the-art solutions will be skipped, too.

2. Currently Known Solutions

The solutions available can be divided into several categories concerning thermodynamics of a cycle at different temperature levels - Fig. 1.

Advanced **combustion systems** should avoid temperature stratification of lean mixtures (NO_x) and fuel-rich zones of high temperature (soot). They are based on fast compression-ignited premixed flame in lean mixture (HCCI) or on a diffusion flame of low temperature and oxygen present inside the flame envelope (Bunsen's burner principle realized by sufficient lift-off-length, multi-injection or even using Diesel air-assisted injection). Many mixed solutions have been introduced (e.g., controlled auto-ignition in the limited domain of mixture or dual-fuel engine combustion, like HPLI or even HCLI, etc.).

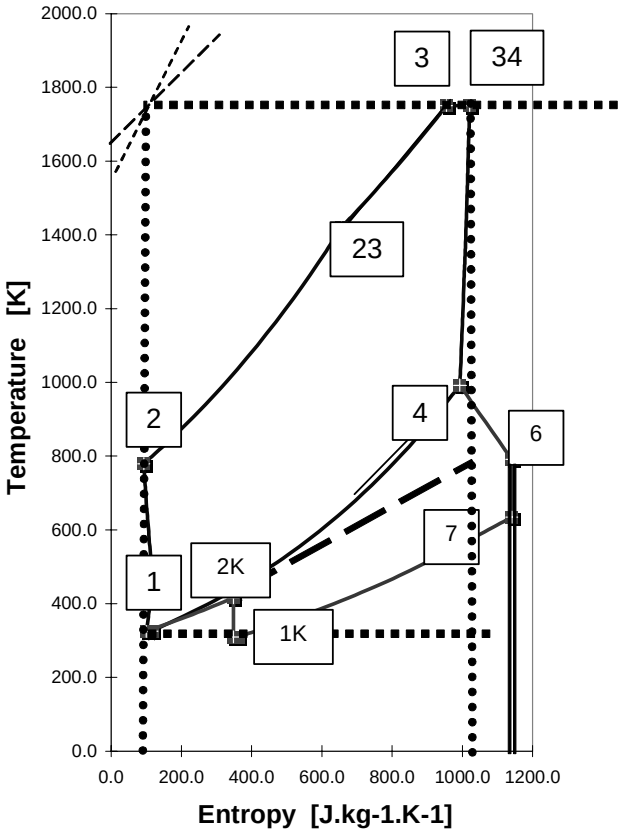

Fig. 1. T-s diagram of a turbocharged ICE

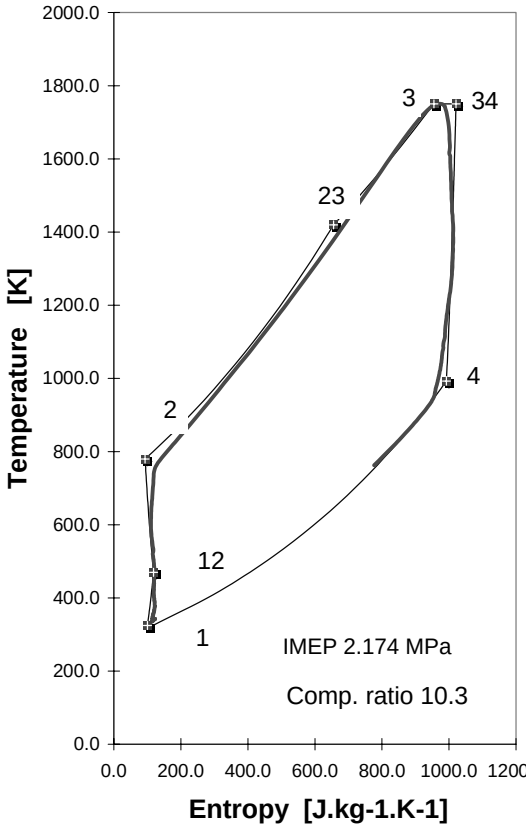

Fig. 2. Real and idealized cycles of an ICE

Alternative synthetic fuels of defined properties and oxygenated ones (e.g., based on biomass) or hydrogen can be used to support these aims. Nevertheless, the contradictory demands concerning temperature, density of fuel supply in terms of b.m.e.p., combustion efficiency (especially HC formation) and engine design limit - maximum pressure - are clear at these advanced combustion systems.

Some problems can be coped with if **internal heat regeneration** is employed, using porous ceramics. It may substitute the need for high compression ratio increasing the temperature before combustion starts by the heat accumulated from hot burnt gas during the previous cycle. The systems inspired by Stirling engine are rather complicated to be mature for the use. The heat accumulated in thermally isolated walls and its uncontrolled (and improper) transfer to a gas in a cylinder **cut definitely** the success of **adiabatic engines**, on the other hand.

The power density of ICE can be increased by **supercharging, using exhaust turbine** as a mover for it. It gives as a side effect the substantial relative decrease of heat and mechanical losses, enhancing ICE efficiency. Extrapolation of today's experience to very high boost

pressures causes unexpected aftermath, however. It concerns **two-stage turbocharging**, as well. The same is valid for the simplest waste heat recovery, using **turbo-compounding**. If combustion is controlled to low temperature more waste heat at low temperature level is produced or even unused combustibles are burnt in an oxidation catalyst. Then **bottoming cycles** using steam may be of value.

All these advanced measures need a **precise control and closed-loop variability** of almost all ICE parameters used in past with constant setting only (valve variable actuation, variable compression ratio, massive EGR control, fast thermal control of inlet air, etc., but even the highest variability of a piston movement using linear electric machine may be concerned). Mechatronic solutions enable the engine to cope with these demands but the resulting transmission efficiency between piston work and engine output must be evaluated correctly, considering, e.g., the poor regenerating capabilities of electromechanical systems with controlled reciprocating movement.

3. Assessment Tools

T-s diagram belongs to old but useful means of conceptual assessment if properly used as an analytic device - Fig. 1. It was computerized considering the changes of heat capacities with temperature and gas composition for this reason - [5] and the results of higher-level simulations (1-D) are presented in this form, as well. If heat losses are accounted for the precision of idealized cycle is surprising - Fig. 2. The main advantage of T-s diagram is immediate evaluation of strong and weak properties of every solution concerning heat supply and removal or internal heat regeneration. If cycle specific work is kept constant, the highest efficiency is reached if the "entropy dimension" of a cycle is minimum one - Fig. 1. There are two limits of T-s use, which should be respected. It is necessary to distinguish between reversible or irreversible changes. Secondly - especially in the case of super/turbocharging, the comparison of cycles with different initial gas density is not possible by graphic appearance of the cycle itself but using numerical results only for absolute, not specific work. The former issue is applicable for turbocharger cycle, as well: starting with irreversible expansion in exhaust valve (4-6 in Fig. 1) all changes in a real turbocharger (4-6-7-1K-2K) does not set bounds for real work of a cycle. On the other hand, this "lost" work gives an idea, how much work could be recovered by ideal expansion (at entropy of point 4) to atmospheric pressure 1K-7. The exhaust loss itself is represented between isochoric change 1-4 and isobar 1-2K. Going further to use the bottom right corner to the surroundings temperature should need extraordinary complicated isothermal compression or coupled steam cycle with condensation.

Heat supply should be realized quickly - in terms of cylinder volume change, with low local temperatures and without over-heating of already burnt layers (e.g., by compression of increasing pressure) to limit NO_x formation and to reach high cycle efficiency. It limits the maximum temperature 3-34 and forces to use the highest maximum pressure possible (23-3) and the highest possible compression ratio (specific volume 1-4 divided by 2-23). The aim should be to use in a maximum way the upper left corner of Carnot cycle.

Similar simple tool was created for simulation of a turbocharger operation - [6]. It uses an algebraic model based on integral representation of high-pressure cycle and exhaust process (conservation of mass and energy) and realistic efficiencies of a turbine and a compressor together with 1-D based assessment of pressure pulsation influence.

More precise results are of course obtained using 1-D and 3-D simulation. It is extremely important that advanced 1-D models are structurized to modular form, which enables the researcher to simulate very unconventional cycles - [7], [14].

4. Examples or Results

4.1. HCCI-like Combustion

The idealized cycle with limited maximum pressure, temperature and given compression ratio was used to find what efficiency can be reached by nearly isochoric heat supply. The indicated mean effective pressure was set to 1.5 MPa (only), maximum temperature to 1 700 K. The air excess was changed to find the value providing the IMEP at different values of a boost pressure. Simultaneously, the isochoric heat supply was cut if the maximum pressure was reached and the isobaric heat supply was finished if the maximum temperature was obtained. The rest of heat was supplied at constant temperature (see the scheme in Fig. 1 or 2). An efficient iterative method was developed for this purpose.

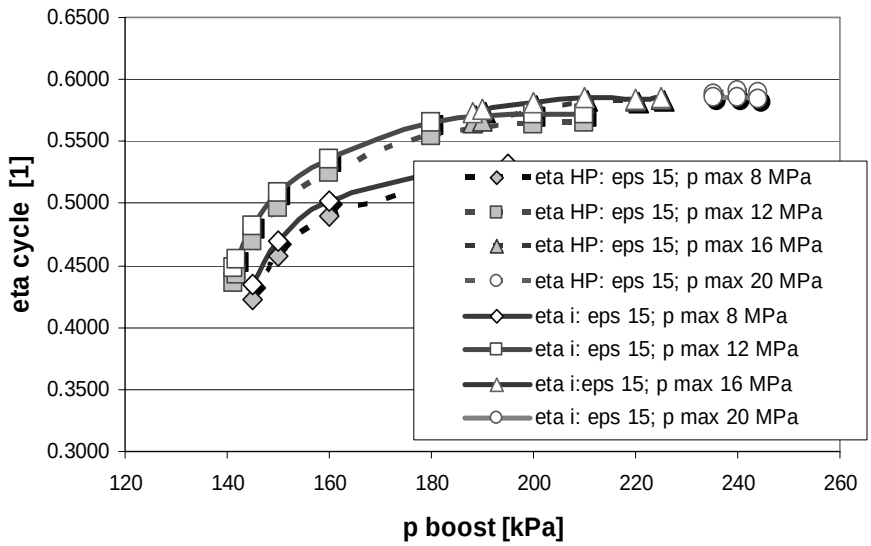

Fig. 3. Cycle efficiency without cooling losses for high pressure part (HP) and the whole cycle (eta i) including turbocharger losses

The example of theoretical indicated efficiency for different maximum pressure at compression ratio 15 is shown at Fig. 3 - [8]. The cooling loss was not taken into account therefore other 6% points should be deduced from the resulting theoretical efficiency for it. In the case of low boost pressure, where air excess had to be low to achieve the IMEP, the heat supply is far from being isochoric. It is clear from Fig. 4, where the necessary air excess and the relative value of isochoric heat supply is shown. Only in the case of maximum pressure of 16 MPa and especially at 20 MPa some HCCI-like combustion takes place. The efficiency is due to it quite high even after being corrected to cooling loss.

The difference between artificially closed cycle with high-pressure part only (HP) and the complete cycle shows the recovery of exhaust pressure energy via a turbocharger to the engine crankshaft. Typically it is positive at low boost pressure. If pressure increases, the recovery becomes a loss (e.g., see for boost pressure higher than 220 kPa). It shows transparently the basic weak points of HCCI at higher loads: the need for very high level of turbocharging at low energy contents in exhaust and extremely high combustion pressures. It requires very efficient turbocharging system (see below) and it limits possibilities of turbocompounding due to lack of usable enthalpy flow in exhaust gas. The maximum temperature remains, nevertheless, quite low. The trend is the same at different compression ratio the higher ones being slightly more favorable as far as efficiency is concerned.

Advanced simulations of HCCI chemistry and its transient control are presented in [9].

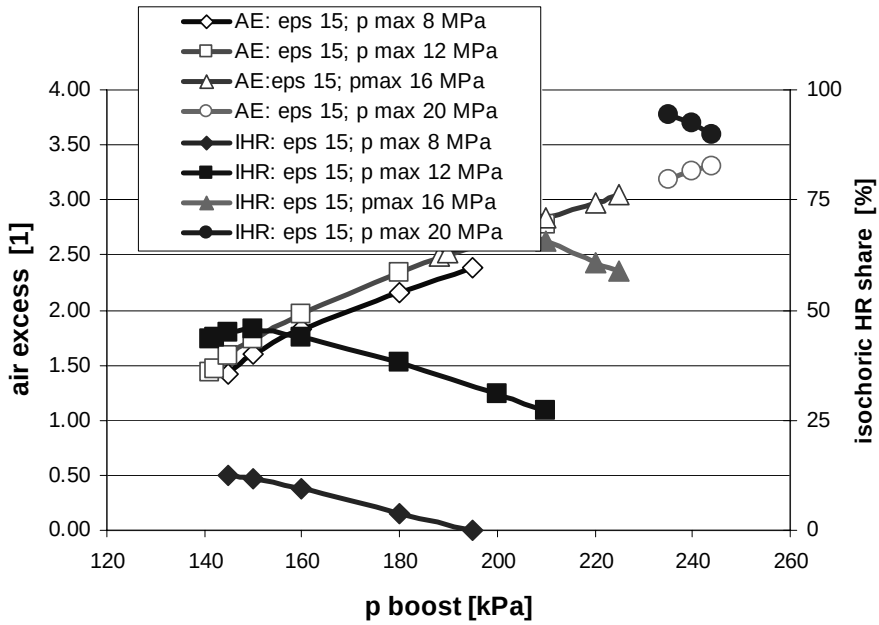

Fig. 4. Air excess and share of isochoric heat supply for different limits of maximum pressure and variable boost pressure

4.2. Variability of Engine Parameters

An extreme example of totally changed piston movement using a linear electric machine is presented in terms of efficiency at Fig. 5. It continues the analysis of isochoric heat supply advantages from the other point of view. Q-D simulation was used for it assuming a realistic heat release pattern but a long-time piston staying-out near to a TDC. The inertia forces were not taken into account for this preliminary feasibility study – [10]. The contribution of this extreme change is surprisingly low and efficient only at high engine speeds otherwise the heat transfer to walls destroys the positive effect of heat supply pattern. The asymmetry of compression and expansion of different duration is not acceptable at all. This way does not seem to be feasible.

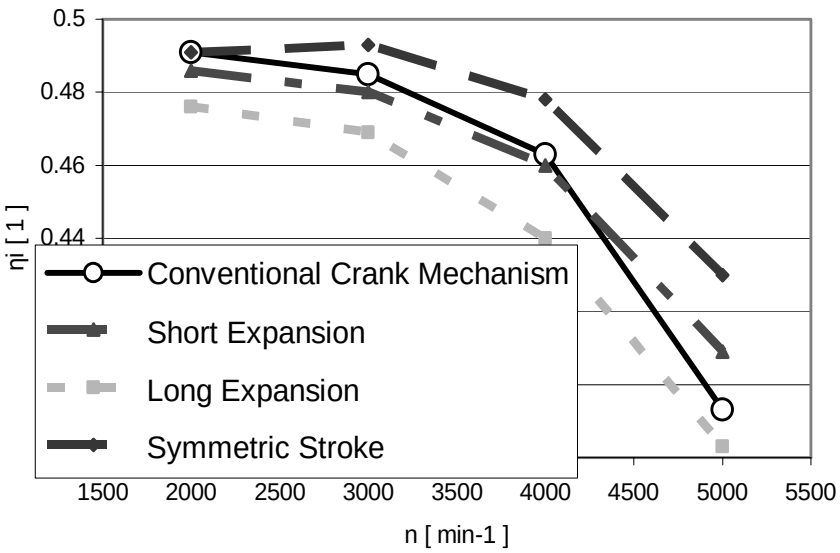

Fig. 5. Cycle efficiency for trapezoidal pattern of piston motion with interruptions at TDC and BDC

The results of VVT and VVA concepts are well-known and will not be mentioned here as well as the change of compression ratio during operation. Common rail injection systems of

multiple injections belong to this chapter, as well.

4.3. Charge Exchange and Turbocharging

Turbocharging will be accepted soon even for car SI engines. It down-sizes engines and losses, as well, especially those that are not dependent on the load. Otherwise, the use of high boost pressure needs not only to employ a turbocharger of high overall efficiency – [11] - but also to reach low pressure losses in outer low-pressure piping. It demonstrates Fig. 6 where the turbocharger power equilibrium pressure-ratio patterns for compressor and turbine are plotted in the coordinates of a compressor map. Although the difference between turbine and compressor pressure ratios (at exhaust temperature of 900 K and TC efficiency 50%) is reasonable, applying commonly used pressure losses at a diesel particle filter (30 kPa at the full power), the resulting boost pressure in comparison with turbine inlet backpressure gives quite pessimistic picture.

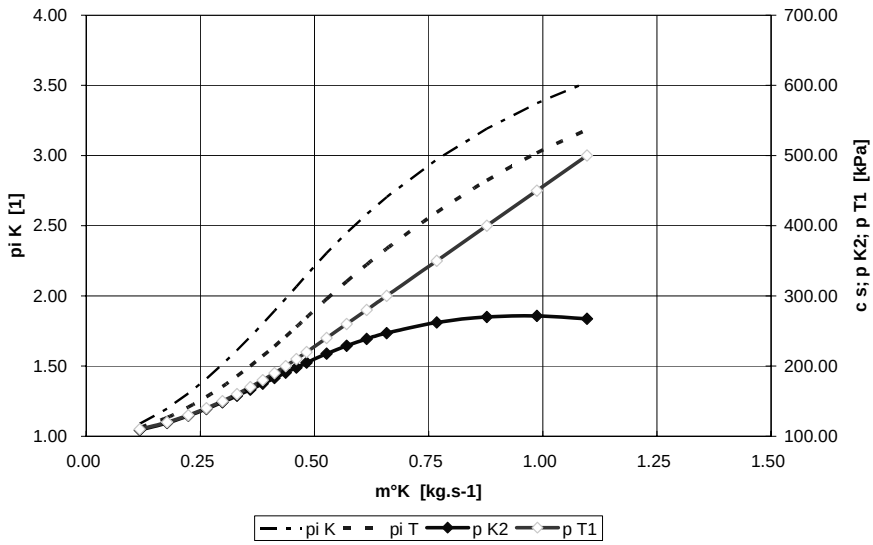

Fig. 6. Dependence of power-balanced compressor and turbine pressure ratio for certain turbine lay-out at given temperature of exhaust gas upstream a turbine. Flow-rate dependence on pressures upstream turbine and downstream compressor explains the demand on low-loss exhaust aftertreatment facilities

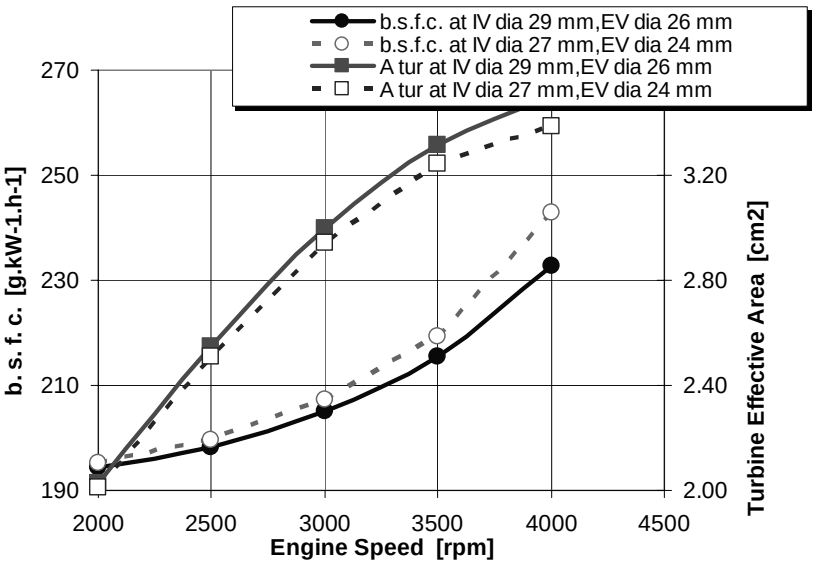

Fig. 7. Engine efficiency with different size of valves [12]

Using turbocharging, the valves can be of decreased dimensions without major penalty in b.s.f.c. and other parameters. It is important for design of CI engines with complicated

injectors as well as for SI engines using DI stratified mixture concepts – Fig. 7. Dynamic features of turbocharged engines require mastering the turbo-lag by introduction of advanced predictive control of an engine. It is based on simulation of unsteady operation - [13].

4.4. Waste Heat Recovery, Turbocompounding, and Bottoming Steam Cycles

Despite very high efficiency of reciprocating engines, the exhaust process forms a source of losses due to limited expansion ratio (see Fig. 1) and pressure differences at non-stationary process. The heat rejected during exhaust process or just before it might be stored in accumulator and used for the next cycle before heat supply by combustion starts. This principle has been proven at Stirling engines. There are many design obstacles to do it at an ICE. Nevertheless, this way enables the designer to decrease a compression ratio if temperature reached by heat release from an accumulator is comparable to that achieved by high compression. Fig. 8 compares cycles with the same limiting pressure and temperature for the same efficiency with the use of more intensive heat regeneration at low compression ratio. The scheme of regeneration ifs not ideal because of the loss of temperature level during charging the accumulator (34-344) and releasing heat from it (12-2) but it gives a good potential to do it quick enough. The whole concept requires detailed simulation based on specific code – [14].

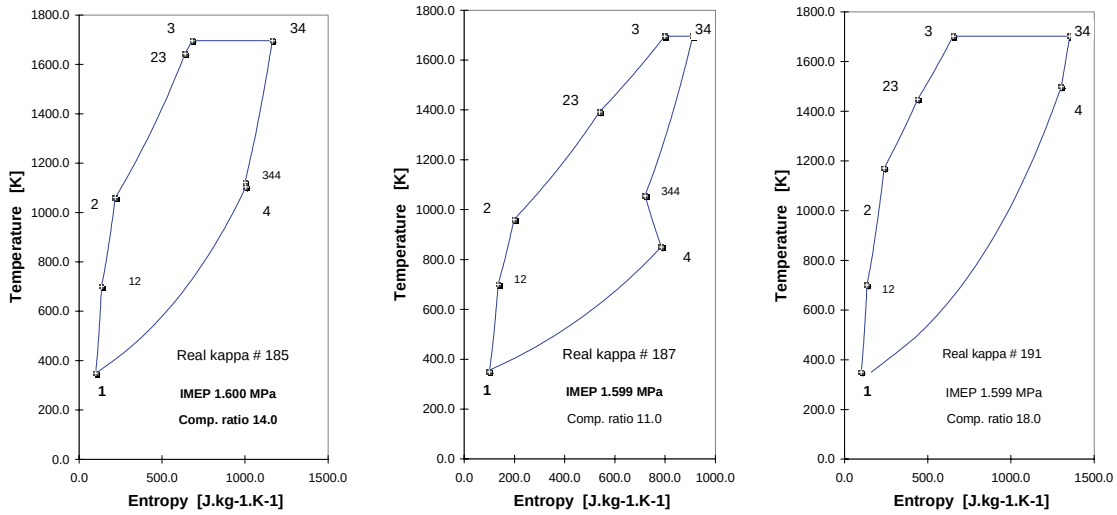

Fig. 8. Engine cycles using heat regeneration between 34-344 and 12-2. Cycles have the same efficiency despite changes in compression ratio

Turbocompounding pays back some lost energy from exhaust. It was analyzed many times before. If costs are not a limiting factor the steam cycle offers quite high potential of more effective waste heat use. An example of detailed simulation of a steam engine using IAPWS steam water data and Q-D model with heat transfer in a vane volumetric steam engine is presented at Fig. 9 - [15]. It increases the efficiency of a turbocharged lean mixture gas engine by some 5% points, which might be worthwhile after the fuel prices are at much higher level.

5. Conclusions

The brief description of some ways to increase engine efficiency by other 3-5 % points has been introduced. It should use fast combustion at low temperature combined with efficient downsizing and turbocharging with properly designed low-pressure accessories, possibly with waste heat in-cylinder and external recoveries. The engine had to withstand

extremely high pressures. The control system based on predictive concept must use closed-loop facilities to achieve stable low temperature operation. Simulation tools developed recently offer a worthwhile tool to master this complicated task. The cost effectiveness remains open and depends on the fuel price trends in future.

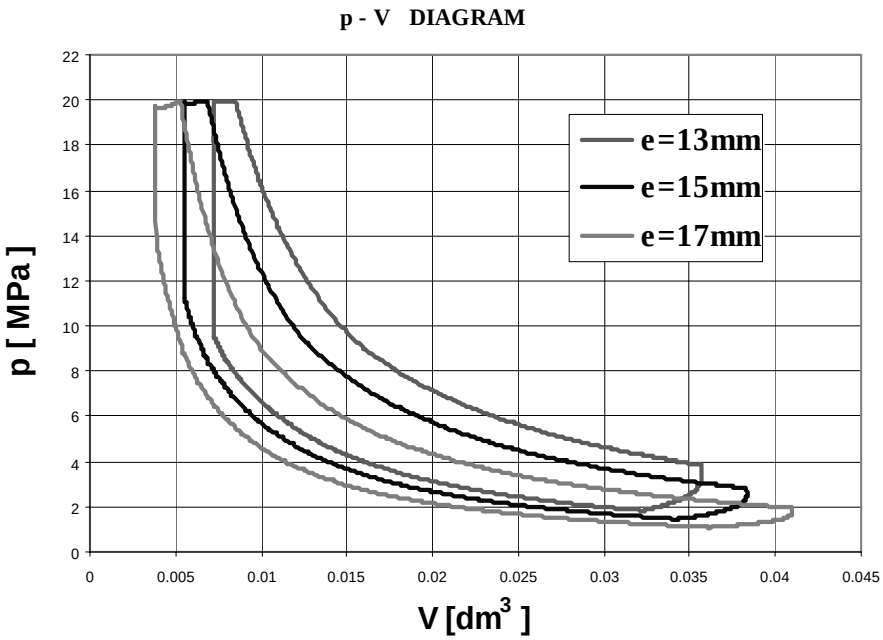

Fig. 9. A simulated pressure diagram of a high pressure steam engine of rotational type

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