

Fuel Economy Benefits for Commercial Diesel Engines with Waste Heat Recovery

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ABSTRACT

In the near future engine emitted carbon dioxides (CO_2) are going to be limited for all vehicle categories with respect to the Green House Gases (GHG) norms. To tackle this challenge, new concepts need to be developed. For this reason waste heat recovery (WHR) is a promising research field.

For commercial vehicles the first phase of CO_2 emission legislation will be introduced in the USA in 2014 and will be further tightened towards 2030. Besides the US, CO_2 emission legislation for commercial engines will also be introduced in Europe in the near future. The demanded CO_2 reduction calls for a better fuel economy which is also of interest for the end user, specifically for the owners of heavy duty diesel vehicles with high mileages. To meet these future legislation objectives, a waste heat recovery system is a beneficial solution of recovering wasted energies from different heat sources in the engine. Specifically the considerable amount of exergy in the exhaust gas, which results from its high temperature and mass flow, has a large recovery potential. By utilizing a waste heat recovery system a portion of this exergy can be converted into an effective power form, which then will be used as entire engine power output. The major challenge ahead is the recovery of the wasted exhaust energy with the maximum possible system efficiency.

In this paper different technologies for waste heat recovery systems will be discussed and most feasible applications for the heavy duty and industrial engines will be shown. Furthermore an application of an Organic Rankine Cycle (ORC) as waste heat recovery system for commercial vehicles will be introduced. Additionally, an adequate working fluid and system layout, which are considered for thermodynamic calculations, will be in focus. The second major part of this paper will be the simulation work. In addition to the presentation of the simulation tools and system layouts, results for the fuel saving potential of a specific ORC application will be given.

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INTRODUCTION

In the past, engine development was mainly focused on emission reduction due to increasingly stringent emission limits. Current engine development is, however, primarily spurred on by the total-cost-of-ownership (TCO) as well as CO_2 emission reduction. The TCO is largely determined by fuel costs; therefore a fuel consumption reduction is of significant engineering interest. Another motivation for the CO_2 emissions reduction is the introduction of legislative CO_2 limits for commercial vehicle, which is currently introduced in the USA and it is being debated in Europe. For CO_2 reduction several technologies can be realized. Among them are combustion optimization, innovative exhaust aftertreatment components and concepts, new engine control concepts, hybridization as well as WHR [1].

Engine technologies are being upgraded towards 2025-2030 to achieve the post global warming legislations. The global warming demands to reduce the CO_2 gases produced from industries and mobile vehicles. This upcoming legislation encourages for higher engine's Brake Thermal Efficiency (BTE) which impacts on engine technology. The following upgraded engine technology for a heavy duty diesel engine might be considered to optimize engine BTE which leads to the reduction of CO_2 emission [2]:

- Maximizing peak firing pressure
- Optimizing boosting system
- Optimizing injection pressure and injection rate and shape
- Improving engine's pumping losses

- Improving engine's total friction
- High efficiency aftertreatment systems
- Efficient EGR system (for EGR engines)
- Smooth and precise engine calibration
- High accuracy sensors and controls

The engine technologies themselves, however, can upgrade the BTE of a state-of-the-art Euro VI engine up to maximum of 10-12%. The upcoming legislation for improving BTE or CO₂ emission of the heavy duty vehicles is anticipated to lie between 15-20% for the first trials. Achieving such a challenging level of engine BTE requires further extra integrated technologies.

In addition to the improvement of the engine on average only 42-46% of the energy input given by the fuel is converted into usable engine power (Figure 1). Recuperating some of the thermal losses will be a powerful method to cope with future legislations. Particularly the considerable amount of exergy in the exhaust gas, which results from its high temperature and mass flow, has a large recovery potential. By utilizing an ORC system as waste heat recovery a portion of this exergy can be converted into an effective power form which then will be used as entire system power output. The major challenge ahead is to recover the wasted exhaust energy with the maximum possible system efficiency. ORC systems for future heavy duty applications will have two possible exhaust gas heat sources: Tailpipe and Exhaust Gas Recirculation (EGR). Optimizing such a system within its given boundary conditions will be the most challenging part when talking about waste heat recovery in mobile applications, because such a system highly depends on [3]:

- Type of WHR system
- Efficiency of the WHR system
- Negative impacts of WHR on engine fuel economy (weight, back pressure, controls, ...)
- Investment and payback time (Break-Even point)

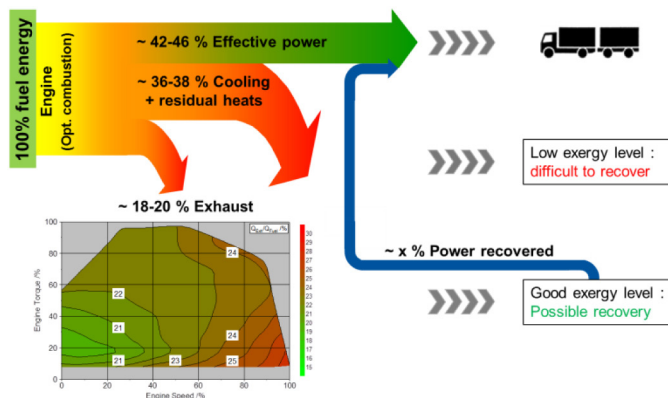


Fig. 1. Energy losses for state-of-the-art Heavy Duty engines

Considering the above mentioned items, applying a waste heat recovery system is mandatory to achieve the maximum BTE. In fact, only an efficient, optimized and low cost system can balance the legislator, manufacturer and consumer requirements.

POTENTIAL WASTE HEAT RECOVERY APPLICATIONS

Alongside the Organic Rankine Cycle also the Turbocompound and the Thermoelectric Generator (TEG) are potential waste heat recovery applications, which can be used in mobile machinery (Figure 2). The following explanations will introduce these technologies and rank them according to their recovering potential, advantages and disadvantages:

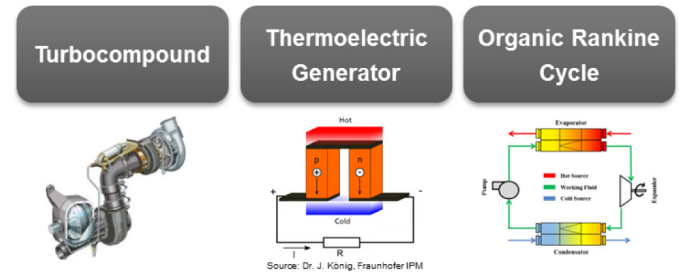


Fig. 2. Potential waste heat recovery applications

A Turbocompound is an additional turbine downstream the turbocharger. The exergy of the exhaust, which would be lost via the exhaust pipe, is recovered by this turbine and converted into extra power; therefore it leads to higher power output of the system or a reduction in fuel consumption. The disadvantage of the Turbocompound is the negative impact on the engines backpressure for non-optimal operating points. The power gained by the turbine can either be mechanically connected to the crankshaft or used electrically via a generator. The mechanical coupling requires a reduction gear drive, which increases the complexity and costs of the system. The electrical coupling has the advantage that the turbine speed is independent from the engine speed. On the other hand the additionally needed generator has a negative effect on costs and packaging [4]. The main disadvantage and in some cases also an exclusion criterion is the lower exhaust gas temperature after the second turbine which impacts the aftertreatment system.

By applying a temperature difference to a TEG an electric current is generated. In mobile applications the heat source usually is the exhaust and the heat sink is the coolant of the vehicle cooling system. In presence of a temperature difference the P- and N-type load carriers of a semi conductive material diffuse from the hot to the cold side until equilibrium is reached. This phenomenon is called *Seebeck Effect*. Various thermoelectric materials can be rated with the so called ZT-Value. This value is a material property: the higher the ZT-Value the higher the efficiency [5]. The electrical power gained by the TEG can be used to support the onboard power systems and so reduce the fuel consumption. The main advantage of this technology is that it does not include any moving parts. Also the packaging demand is very low compared to an ORC or Turbocompound with generator, which makes this technology attractive for passenger cars. The main disadvantage is the cooling demand, due to the fact that the available voltage depends on the heat flow into the TEG module and therefore a permanent effective

cooling besides the high temperature exhaust gas mass flow is mandatory to reach a noticeable power output. TEG materials currently available do not reach high ZT-Values and are still under development, which results in a low power density. Due to this fact TEGs cannot reach the benefits of an ORC or Turbocompound.

The Organic Rankine Cycle differs from the traditional Rankine Cycle by the use of the working fluid. The Rankine Cycle uses water whereas the ORC uses a high molecular mass organic fluid. The working principle is the same as that of the Rankine cycle and can be seen in Figure 3:

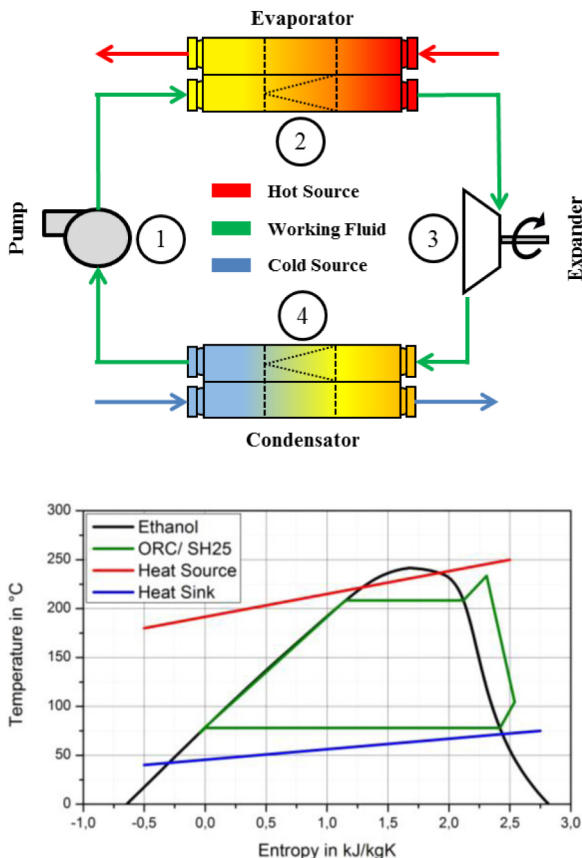


Fig. 3. ORC process description

The working fluid is pressurized in a liquid phase (1) and is routed to the evaporator (2) where it passes the three zones: pre-heating (liquid), evaporating (two-phase), superheating (vapor). The superheated fluid in vapor state is expanded in the expander to a low pressure level (3) and will be finally re-condensated to liquid state (4). The ideal cycle follows an isentropic pumping, isobaric evaporation, isentropic expansion and isobaric condensation. The real cycle has a lower efficiency due to irreversibility: isentropic and volumetric efficiency of the expander and pump and the effectiveness of the heat exchangers [6]. The net efficiency of the ORC cycle can be defined as:

$$\eta_{ORC} = \frac{W_{expander} - W_{pump}}{Q_{source}}$$

(1)

The cycle performance can be influenced by the high and low pressure levels and the temperature levels after evaporator and condenser. The boundary conditions must be chosen carefully according to working fluid and component requirements. The process theory is well known and a state-of-the-art technology for power plants. The challenges for mobile applications are the packaging and the additional cooling demand, therefore the ORC must be integrated into the vehicle cooling system, which raises the amount of boundary conditions. Except for a few disadvantages of such an ORC system like packaging, safety requirements, additional components and cooling demand as well as increased control and maintenance effort, the advantages are convincing. The integration as a retrofit solution is possible, because the system operates without active control of the combustion engine. When compared to the two aforementioned technologies the ORC has a much higher power output and is a well proven technology. The ORC is the most promising technology for waste heat recovery in commercial vehicles. The following sections cover various ORC research fields and demonstrate the interactions between thermodynamics, fluids, components, simulation and costs to show the huge potential of this technology.

WORKING FLUIDS FOR ORC SYSTEM

An optimal ORC process strongly depends on the selected working fluid. The choice can be based on thermodynamic or economic criteria. To find the most promising one from a huge amount of potential fluids each has to be evaluated carefully. Various approaches for selecting the ideal working fluid can be found in the literature, the most common is the two step approach [7]: During the first step a fluid is chosen and an optimization of the process variables follows in the second step. The process variables of the cycle and the thermo physical properties of the working fluid are directly dependent on each other, which leads to the main disadvantage of this procedure: the negligence of specific cycle parameters and fluid trade-offs. For this reason new approaches which integrate the selection of the working fluid directly into the design process came up. Key process parameters are optimized in the presence of a fluid represented by PC-SAFT in one holistic framework [7]. Future investigations should follow the idea of a coupled optimization to find the best working fluid for the ORC process; nevertheless the two step approach is also a good method to evaluate fluids for special applications and will be presented in this paper with the following comments.

As the ORC cycle performance strongly depends on the system boundary conditions (pressure and temperature levels) with a wide spread of different requirements, no ideal working fluid is available which covers all of these requirements. For this reason fluid candidates are selected by holistically defined criteria. Considerable criteria for the selection of a working fluid are shown in Figure 4:

Each given criterion has its own specific and vehicle-relevant limitations. Very important physical properties are the melting point, the boiling temperature and the ignition point. The melting point was chosen to be under -40°C which ensures that the fluid is always liquid, also in winter conditions so that no additional heating is

required. The best overall system output will be reached if the critical temperature of the working fluid is close to the temperature of the waste heat source [8]. In power plant applications the Rankine Cycle is a well-known technology for recovering wasted heat. Talking about the traditional Rankine Cycle implies the usage of water as working fluid. For stationary applications with their high waste heat temperatures and mass flows, water is the optimal fluid, because its thermodynamic properties fit best to the plant boundary conditions. For medium heat sources, as given in mobile applications, organic fluids with their low boiling points show more advantages than water. For having the highest system output the selected working fluid boiling temperature should be in a feasible range according to the given boundary conditions. The ignition point can also be related to the safety requirements, because a high ignition point reduces the risk of ignition under expected conditions. Besides the important vehicle-relevant limitations, physical properties like the critical temperature and pressure, a low heat capacity, high thermal conductivity and a high enthalpy of evaporation have a major effect on the optimization of the ORC efficiency. The Global Warming Potential (GWP) and the Ozone Depletion Potential (ODP) are safety criteria as well and must be as low as possible when using them for mobile applications. Worldwide (*Hazard and Precautionary Statements*) and European (*Risk and Safety Statements*) legislative limitations should be taken into account when clarifying issues about toxicity and harmful effects, flammability and explosiveness as well as environmental impacts for mobile machinery. The decomposition temperature of the working fluid should be at a feasible level so that long term use is guaranteed. The chemical properties of a fluid are also important when talking about material compatibility; both a feasible decomposition temperature and material compatibility have an influence on maintenance costs. Besides the physical and chemical properties of a fluid the market acceptance plays a major role when choosing between fluids, so it is expedient to take economic issues like availability, cost per liter, and cost for certification and challenges for new production chains into account as well. All these requirements lead to a pre-selection list of candidate working fluids.

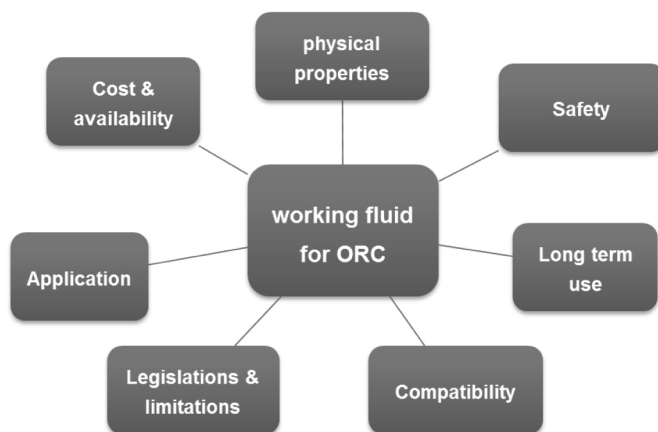


Fig. 4. Selection criteria for ORC fluids

FEV GmbH and the Institute of Combustion Engines of the RWTH Aachen University (VKA) benchmarked a wide range of potential fluids with respect to the aforementioned criteria. A pre-calculation and further assessment leads to five promising candidates given in Figure 5 [3]:

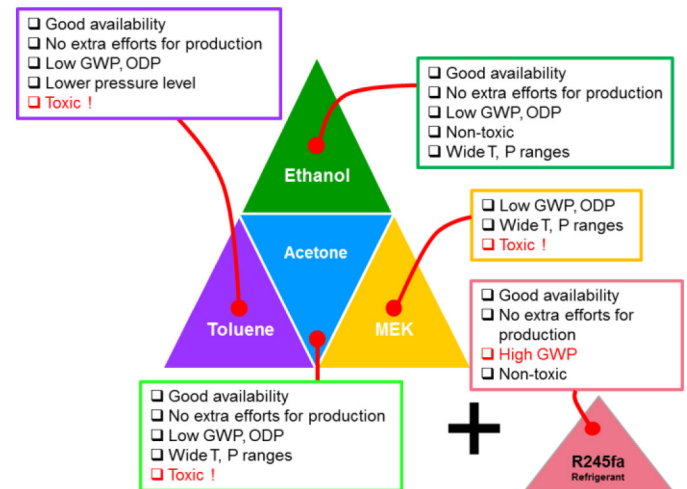


Fig. 5. ORC fluid candidates after assessment

Good availability, low GWP and ODP, non-toxicity, feasible critical temperatures and pressures make ethanol the most promising fluid. Acetone and MEK are neglected because of their toxicity. The refrigerant R245fa is a well-known fluid and is in use for low heat source ORC, like geothermal or solar applications. For this reason R245fa will be taken into account for further investigations, although the GWP has a high value, which normally is an exclusion criterion. Toluene has very promising physical properties and although it is very toxic it was taken into account for further investigations. Further studies are being done with ethanol, toluene and R245fa to find the best ORC fluid for mobile applications. Following an intensive thermodynamic research was done; all three fluids were simulated with an ORC simulation model with the commercial software GT-Suite®.

In Figure 6 all three fluids were plotted with water as reference fluid:

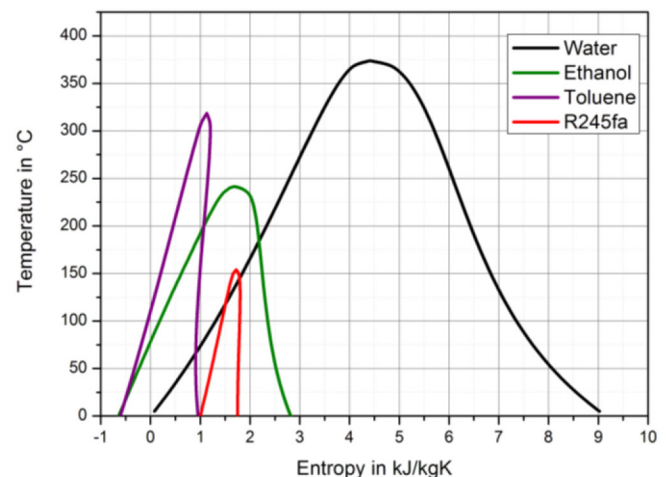


Fig. 6. T-s diagram of potential ORC fluids

According to the slope of their saturation curves ORC fluids can be classified as wet, isentropic and dry fluids - negative, infinite, positive slope. One main driver for the decision for or against a fluid type is

the expander. For example wet fluids cannot be used with a turbine expander. Water is a wet fluid; the positive slope has a negative effect on the turbine expander if the expansion ends in the two phase region. The droplet formation can destroy the turbine blades. This can only be avoided with extensive superheating or multiple stage expanders, which is not feasible for mobile applications. To cope with this problem displacement type expanders are a better choice because they are able to work in the two phase region too. To be securing that according to the customer's choice both types of expanders can be used, isentropic (or nearly isentropic) fluids like ethanol were considered to be the best choices for ORC working fluids [8]. Practically no superheating is needed to avoid ending the expansion phase in the two phase region. A major advantage of dry fluids and their positive slope is on the one that no superheating is needed and on the other hand that there is a potential heat left after expansion, which can be used to internally preheat the ORC fluid. This will have a positive effect on the cycle efficiency, because reaching the same cycle power output less source heat is required. A more detailed discussion regarding the expander choice will be given in the chapter "ORC system components for mobile application".

To achieve a good power output at the expansion machine a high pressure ratio is favorable. The high pressure side is limited by the critical temperature (fluid property) and waste heat temperature (system architecture). A very important system criterion is the ability to cool the refrigerant. As the condensing heat has to be fully compensated by the vehicle cooling system a feasible minimum temperature after the condenser has to be defined - in this paper 60°C. Figure 7 shows the three fluids represented by their saturation curves:

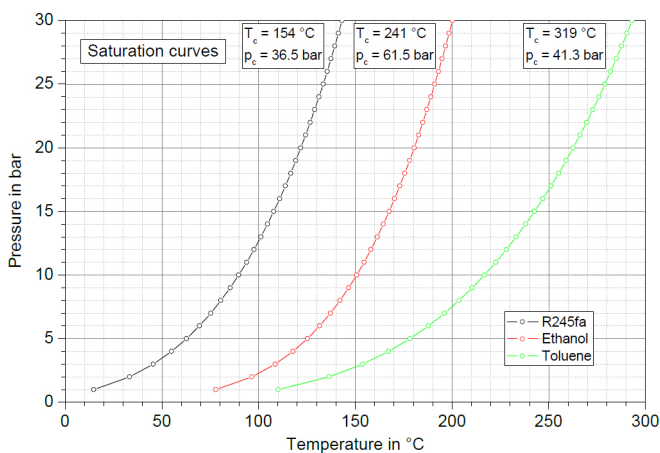


Fig. 7. Fluid saturation curves

When taking a low pressure of 1 bar into account it is noticeable that the temperatures of ethanol and toluene are high enough to be cooled down by the vehicle cooling system. R245fa has a temperature of nearly 14°C at 1 bar which can only be cooled down under a small range of ambient conditions. The following Figures 8, 9, 10 represent the theoretically isentropic process efficiency for ethanol, toluene and R245fa when expanding to a pressure level which corresponds to 60°C fluid temperature:

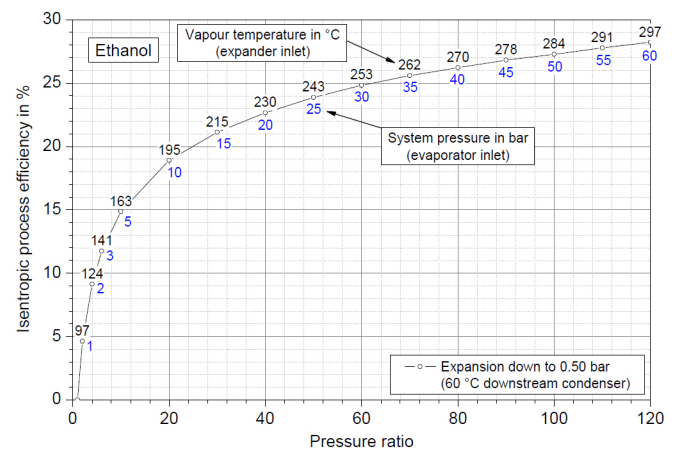


Fig. 8. Ethanol - Theoretical isentropic process efficiency

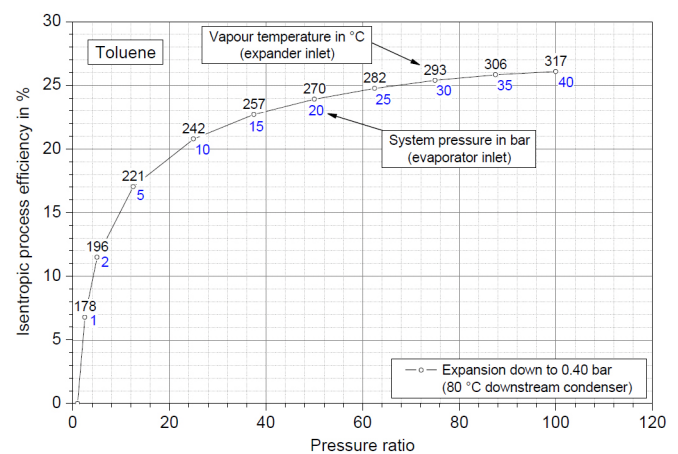


Fig. 9. Toluene - Theoretical isentropic process efficiency

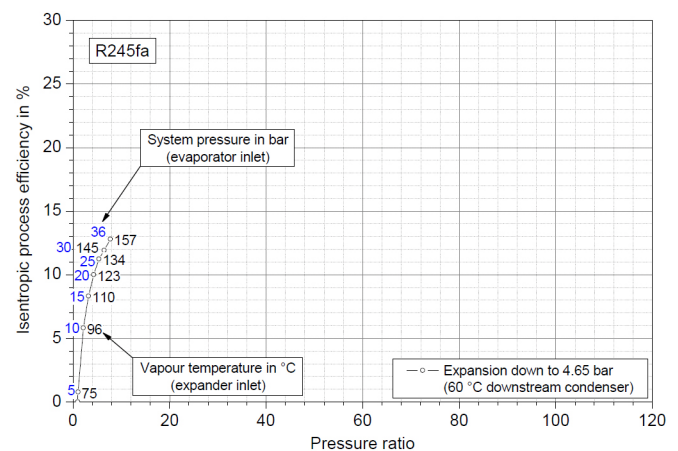


Fig. 10. R245fa - Theoretical isentropic process efficiency

At 60°C fluid temperature downstream the condenser ethanol reaches a low side pressure level of 0.5 bars. Because of the sub-ambient low side pressure level high pressure ratios can be reached and result in a maximum cycle efficiency of 28%. For Toluene the low side temperature is set to 80°C because this already reduces the pressure