Hard working but not exhausted

Reducing emissions from diesel engines

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As more and more ships sail around the globe, China, in particular, is experiencing a huge increase in shipping traffic. Leading engine builders in China use ABB turbocharging solutions in marine, power and locomotive applications. With ever-tightening fuel efficiency and emissions requirements, China's shipbuilding and shipping industries look to ABB to strengthen their competitiveness.

Large engine development has always been closely connected with the development of the exhaust gas turbocharger. Every advance in compressor pressure ratio over the years has brought with it a new opportunity to improve engine performance by increasing the mean effective pressure.

At the same time, indications that a turbocharger generation is reaching its performance limits have also often been seen as a signal to investigate another possibility – multistage turbocharging.

Two-stage turbocharging gets a boost

In spite of strong initial interest, very few of the early studies ever actually got as far as an industrial application. The 1990s saw this situation change. There were two main reasons: Firstly, engine development increasingly was being driven by emissions regulations – air pressure ratios were required that went beyond those needed just to increase the power output. Secondly, turbocharger technology had advanced so much that multistage turbocharging could now be given more serious thought. Recent years have seen the first commercial applications of two-stage turbocharging. However, these are restricted to automotive and high-speed industrial engines, which at the present time have to meet far stricter emissions requirements than the larger engines. Tougher emissions legislation for large engines is nonetheless now in force, and even more stringent regulations are in the pipeline.

The efficiency conundrum

The usual approach when studying engine processes is to assume an ideal cycle and perfect air. However, the efficiency curves obtained in this way can be misleading. Under such ideal conditions we could expect to see thermal efficiencies of 68 to 70 percent being achieved with today's most advanced engines. Nevertheless, an efficiency of 50 percent is considered to be very good. The difference suggests that there is considerable development potential. So why isn't the efficiency higher?

A look at the losses shows the main cause to be the gas properties (mainly because the specific heat varies with the temperature). Changing the engine's design has no effect at all on these. The heat losses are the second most important losses, but neither can these be reduced much by changing the engine's design. Both, however, are strongly dependent on the maximum cycle temperature.

ABB's studies show that the traditional "high temperature" approach to improving engine efficiency needs to be reconsidered. Also, high maximum cycle temperatures are known to promote NO_x formation in modern engines, and NO_x reduction is a key environmental target. How, then, can engine efficiency be increased without making the emissions worse?

Miller timing

One way to do this is to reduce the temperature at the start of the engine cycle, for example with the help of Miller timing. In the Miller cycle, the combustion air is compressed to a much higher pressure than is needed to fill the cylinder for the desired air/fuel ratio. Closure of the inlet valve is timed so that just the right amount of air is sucked into the cylinders. The charge air thus expands, resulting in a lower temperature at the beginning of the cycle.

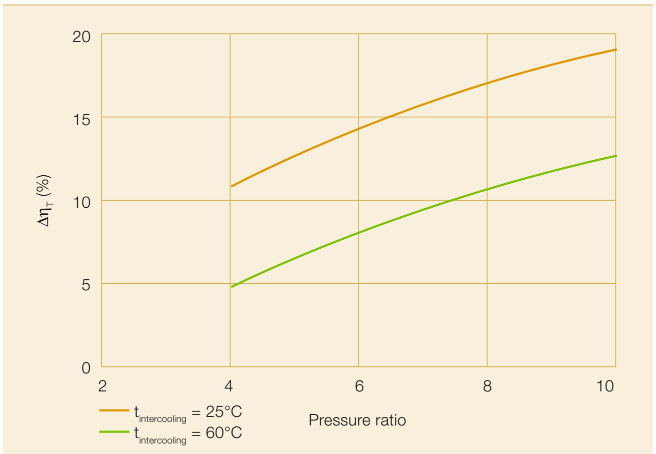
The remarkable improvement achieved with the Miller cycle is greater at low firing pressures. The required maximum pressure for 60 percent efficiency is about 80 bar lower with a Miller engine than for a conventional engine (190 versus 270 bar). Thus, with the Miller cycle very good efficiencies are possible at relatively low firing pressures. NO_x emissions are reduced at the same time thanks to the lower combustion temperature. It can be deduced from this that Miller timing allows, for the same efficiency, an increase in output without having to raise the maximum cylinder pressure, making it feasible to extend the design life span of a given four-stroke IC engine.

The potential benefits for gas engines are even greater. While these engines inherently produce less NO_x, the maximum cycle temperature tends to limit the mean effective pressure and efficiency because of the "knock" effect. Since the Miller cycle allows much lower combustion temperatures, the compression ratios, firing pressures and mean effective pressures could all be higher, considerably narrowing the output and efficiency gap between gas and diesel engines.

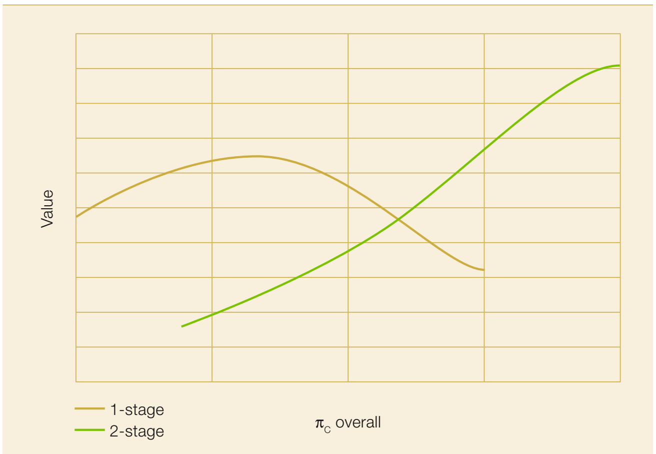
Challenges for the engine designer

All of the above considerations are based on a theoretical Miller process. To achieve the mentioned results, however, the turbocharging system would have to deliver air pressures twice as high as those achieved today. Engine builders, too, would have to address certain issues. For example,

1 Turbocharging efficiency gain with intercooling



2 Trade-off between single- and two-stage turbocharging



the turbocharging system as a whole would have to be redesigned for much higher pressures and forces and the valve train system would need to be improved and controlled. It would also be necessary to look deeper into the issue of "cold" combustion and to develop new overall engine control strategies.

but the diagram will always look very similar. Because of this degree of uncertainty it would seem to be more reasonable to take one big step rather than lots of smaller ones, not least because of the repeated new investment – for both the turbo-charger manufacturer and engine builder – that these would entail.

What about the turbocharging process?
In the idealized Miller cycle, the overall turbocharging efficiency is assumed to be 70 percent. This, however, would require a turbocharger efficiency of about 80 percent at a pressure ratio of between 8 and 10. A turbocharger able to deliver this does not exist, of course, and it is difficult to imagine that one will ever be produced commercially.

A two-stage system with intercooling would, however, allow figures close to these. The relationship between very high pressure ratios and high turbocharging efficiency is important here. Intercooling is key since, by allowing an approximation of isothermal compression, it improves the air compression process and consequently reduces the required compression energy. The efficiency gain depends on the intercooling temperature and on the overall pressure ratio 1.

Intercooling, though, is not the only reason for the higher efficiency with two-stage turbocharging. Another can be found on the gas side: The expansion energy available for the two turbines is higher than with a single stage, because the losses in the high-pressure stage increase the energy at the low-stage inlet; also, the efficiencies of the compressor and turbine can be generally higher due to the lower specific loading. It is also expected that the bearing friction losses and the boundary layer losses will both be lower.

Another important point is that at higher pressure ratios smaller turbine areas are required even with higher turbocharging efficiencies. Starting with a moderate pressure ratio, the effective turbine area increases with every power increase; this means that at part load the available pressure ratio decreases. Based on past experience, it could be presumed that high-pressure turbocharging will therefore result in even worse part-load behaviour. However, that is not the case. At least the boost pressure at part load will be higher than it is at present.

From single-stage to two-stage
Although the switch from single- to two-stage high-pressure turbocharging is a major move, the argument for change and a considerable increase in pressure ratio is strengthened by the following considerations:

- Two relatively small turbochargers can be used since the turbine area is the controlling factor and decreases with an increasing pressure ratio.
- Intercooling results in a considerable increase in turbocharging efficiency; this benefit grows as the pressure ratio increases.
- System matching is generally not restricted by the map width and design conditions.
- Two-stage turbocharging offers good control flexibility.
- Reliability and durability are generally better because of the moderate pressure ratio at each step.
- Smaller turbochargers exhibit better acceleration and vibration behaviour.

The trade-off between single- and two-stage turbocharging can be simply deduced from qualitative value versus pressure ratio diagram in 2.

The point at which the two systems are equal in value does of course depend on how the value is defined,

High-pressure turbocharging's potential
Investigations carried out by ABB show that high-pressure turbocharging has wide-ranging potential for future engine development by enabling higher power densities, higher efficiencies and lower emissions. Used with the Miller cycle, for example, it promises a very favourable shift in the trade-off between efficiency and NO_x emissions. By keeping the air-to-fuel ratio at a satisfactory level, it could also allow better exploitation of exhaust gas recirculation's potential for NO_x reduction.

Based on the results of first tests with two-stage turbocharging on a real engine it can be said that a considerable amount of development is still necessary, both with regard to the turbocharging system and the engine. In view of this, it therefore seems reasonable to fully exploit the limits of single-stage turbocharging as the next development step towards lower emissions.

At the same time it can be said that major progress in high-pressure turbocharging, and especially two-stage turbocharging, could have very significant benefits – for the engine builder by providing more freedom to explore his engines' full design potential, for the end-user by reducing fuel consumption, and for the environment by lowering NO_x and CO_x emissions.

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