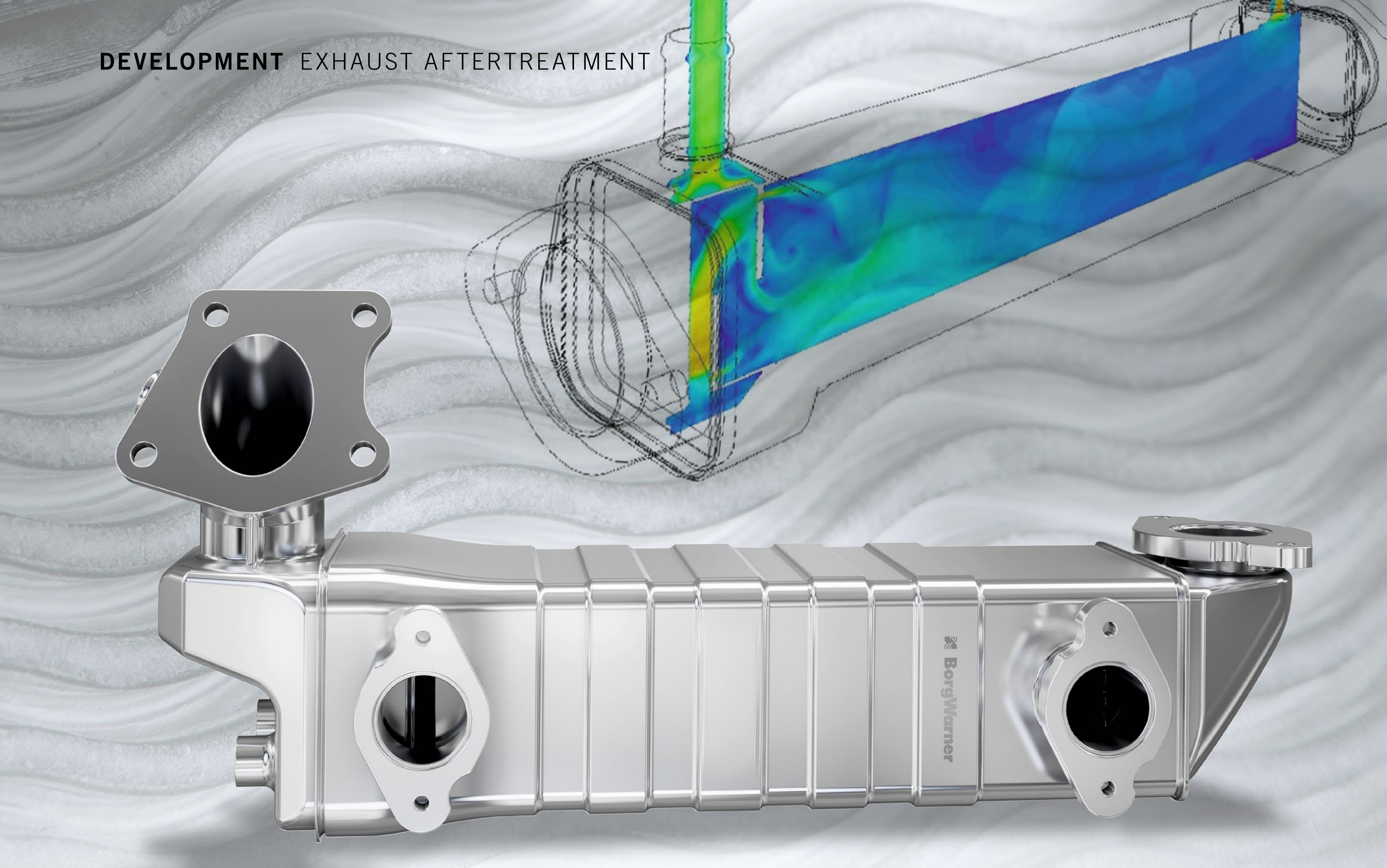

Exhaust Gas Recirculation Coolers for Commercial Vehicles Engines from 4 to 9 l Displacement

The increasingly lower emission limits for CO_2 and NO_x require higher exhaust gas recirculation rates at higher exhaust gas temperatures. BorgWarner has therefore developed a new generation of floating box exhaust gas recirculation coolers that offer reliable protection against boiling as well as thermal fatigue.

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Exhaust Gas Recirculation (EGR) is an emission control technology that reduces NO_X formation for most types of diesel engines and reduces CO_2 emissions in gasoline applications [1]. This is accomplished by recirculating a portion of the engine's exhaust gas back to the engine cylinders. The recirculated exhaust gas is mixed with intake air and introduced into the cylinder for combustion. EGR is able to reduce peak temperatures in the combustion chamber and lower the engine's NO_X production. Recent emissions standards have become more restrictive in terms of CO_2 and NO_x reduction. This has been translated into higher EGR rates at higher exhaust gas temperatures for much longer lifetimes. As a result, thermal fatigue and boiling have become critical for the new generation of EGR coolers, not only for the most demanding heavy-duty commercial vehicle applications, but also for medium- and light-duty applications including passenger cars.

CO_2 emissions restrictions have pushed manufacturers to reduce coolant pump consumption, so that now both the coolant system flow and pressure are being reduced. This has a direct impact on increasing thermal stress and the boiling level for EGR coolers and requires the use of novel tools to redesign these components to ensure the best performance against heavy boiling [2] and thermal fatigue [3, 4].

TYPES OF EGR COOLERS

There are several design options for EGR coolers depending on the usage, available packaging and reliability requirements. Hybrid tube monoblock EGR coolers are the most simple and compact solution for many applications, and especially for passenger cars and light-duty commercial vehicles. Monoblock coolers have no decoupling elements, so the inner core is rigidly fixed to the outer case, leading to higher thermal stress. Coolant-wise, distribution can rarely be improved because the coolant inlet port position and orientation is fixed by the engine manufacturer, limiting protection against heavy boiling.

At the other end of the scale is the demanding heavy-duty commercial vehicle market, where reliability targets and lifetime requirements are particularly challenging. These vehicles usually have engines beyond 9 l of displacement, where packaging restrictions are not as strict, making it possible to add decoupling elements for increased thermal fatigue durability. That is the case for the compact floating core EGR cooler developed by BorgWarner [5], which features a water-cooled, flexible thermal damper directly integrated in the inner core.

For medium-duty applications with engines in the 4 to 9 l displacement range, packaging limitations may not allow the use of a compact floating core cooler, while the monoblock design is insufficient due to thermal fatigue and boiling limitations. For these cases, BorgWarner has developed the Floating Box (FBox) EGR cooler, which presents the next generation of floating core coolers, **FIGURE 1**. These coolers are compact in design and offer high thermo-mechanical robustness. FBox is a new component with two main functions, **FIGURE 2**. On one hand, the flexible feature works as a thermo-mechanical decoupler, where the inlet gas box/diffuser expansion is not transferred directly to the inner core and the outer case. The inner tube's longitudinal thermal expansion is less restricted for reducing inner core thermal stress. On the other hand, FBox creates a coolant manifold around the hot-side header. This allows notable improvement of coolant distribution in the cooler inlet side, since the manifold redistributes the coolant as needed. This enhances thermal fatigue robustness, while also reducing the boiling risk under low coolant flow conditions. The inlet gas side gas box/diffuser is the component that reaches the highest temperatures because it is not usually cooled. As the FBox decouples the inlet gasbox thermal expansion from the inner core, it reduces not only the impact of the thermal expansion on the hot-side header and the inner core, but also the impact of the thermal transients.

Coolant fluid enters the inner core through a calibrated window that is placed right next to the header. More than one window can be used so coolant distribution optimization is very flexible. The window size and position can be adjusted by a Computational Fluid Dynamics (CFD) simulation to provide the best trade-off between thermal robustness and coolant side pressure drop.

Intermediate baffles are often used for improving coolant-side distribution along the cooler. In the case of FBox coolers, they can be placed directly inside the FBox, which helps in the manufacturing process while also allowing use of single-piece tubular outer cases. Coolant-side velocities achieved with the FBox are much higher than those in a monoblock EGR cooler – especially at the hot gas side flange face where the boiling risk is particularly high.

COOLING OPTIMIZATION

One of the most interesting characteristics of the FBox is that coolant velocities

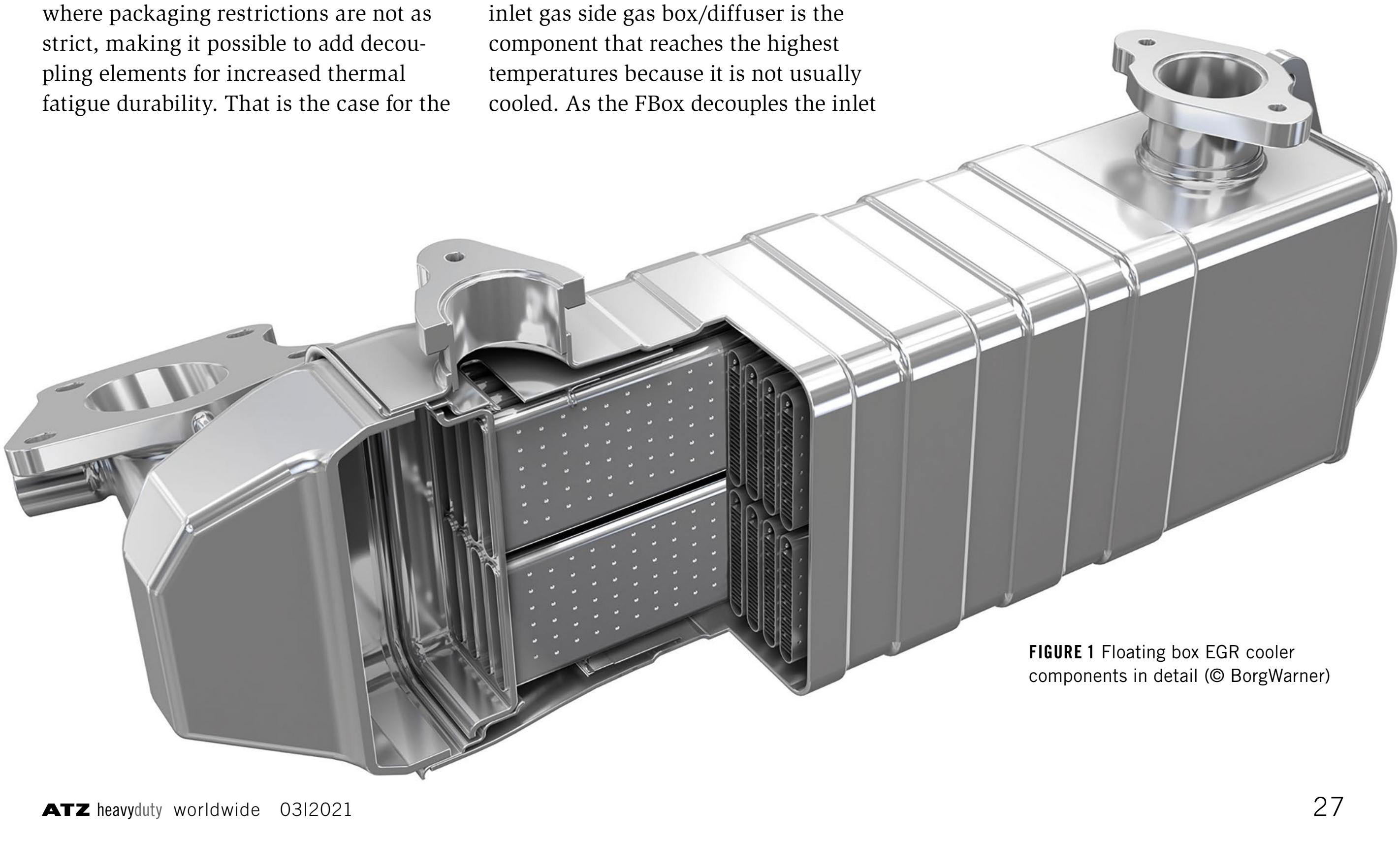

FIGURE 1 Floating box EGR cooler components in detail (© BorgWarner)

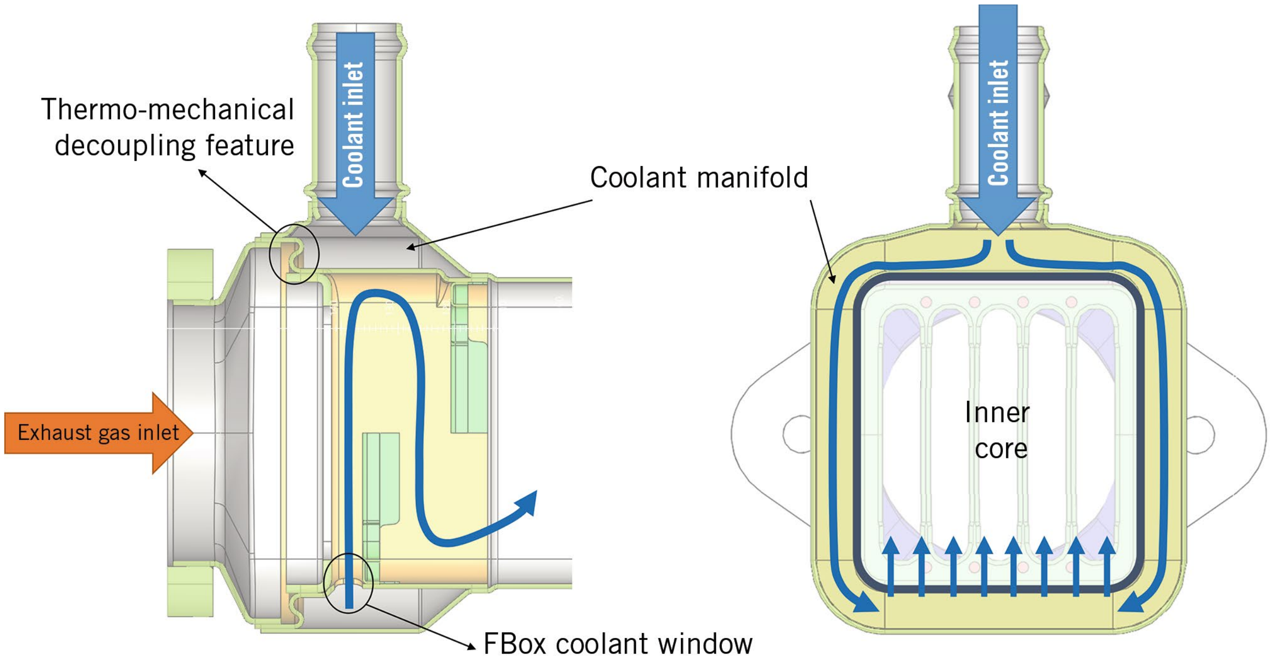

FIGURE 2 FBox cooler special features (© BorgWarner)

can easily be optimized through a CFD simulation. BorgWarner has developed a simulation procedure for this purpose that examines dozens of different cases in order to find the Pareto frontier in terms of coolant-side pressure drop and hot-side header maximum temperature. The simulation model is pre-processed to handle several design modifications such as the coolant window location, window cross-section or the intermediate baffles geometry and position. With this approach, choosing the optimum design is assured by taking into consideration the maximum coolant side pressure drop allowed, **FIGURE 3**. Another important advantage is that the FBox design provides lower header temperatures for the same coolant-side pressure drop than the equivalent monoblock cooler.

Coolant fluid velocities near the hot header are very high and can be adjusted simply by means of window height, **FIGURE 4**. This is notable since the majority of the EGR coolers coolant velocity maps depend primarily on the inlet port cross-section, inlet port location and coolant flow values, which are not controllable by the EGR cooler manufacturer. This is not the case with the FBox since coolant velocity depends mainly on the features that are inside the EGR cooler, where coolant distribution can be optimized easily.

Boiling in EGR coolers is a complex topic, with bubble generation, motion and degassing being critical for ensuring good performance and durability [2]. The majority of the EGR coolers manufactured today show a certain level of boiling from increasing thermal loads, so one of the goals is also to ensure effective bubble degassing. In parallel-flow configuration, the most robust solution would be to have the inlet port located in the bottom side of the EGR cooler, so coolant would exit with the bubbles. This is not always possible, but the FBox allows the inlet port to be placed in any of the four faces of the cooler. In counter-flow configuration the worst case possible would be to have the outlet coolant port in the bottom side, which would trap the bubbles and lead to vapor accumulation inside the cooler and failure. With the FBox this can be also avoided, as the coolant window would be located in the top to ensure complete degassing so the bubbles would collapse inside the manifold

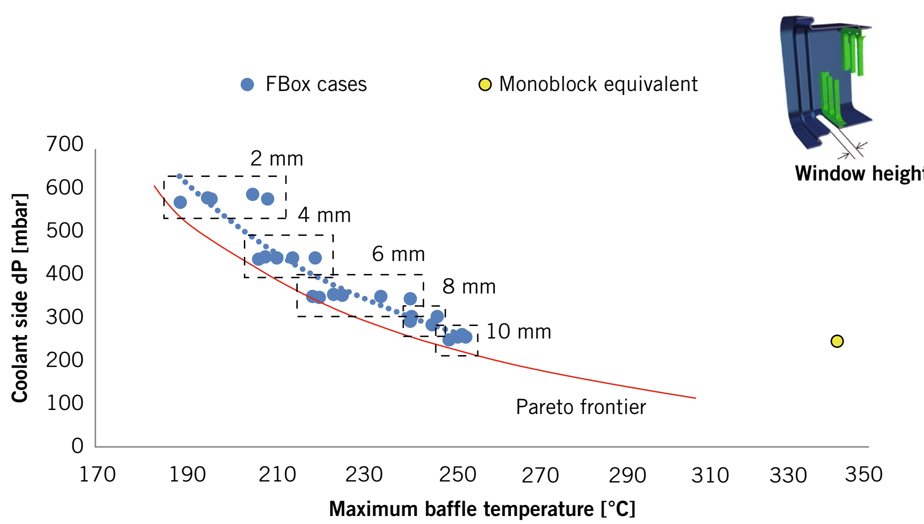

FIGURE 3 Coolant CFD optimization example (© BorgWarner)

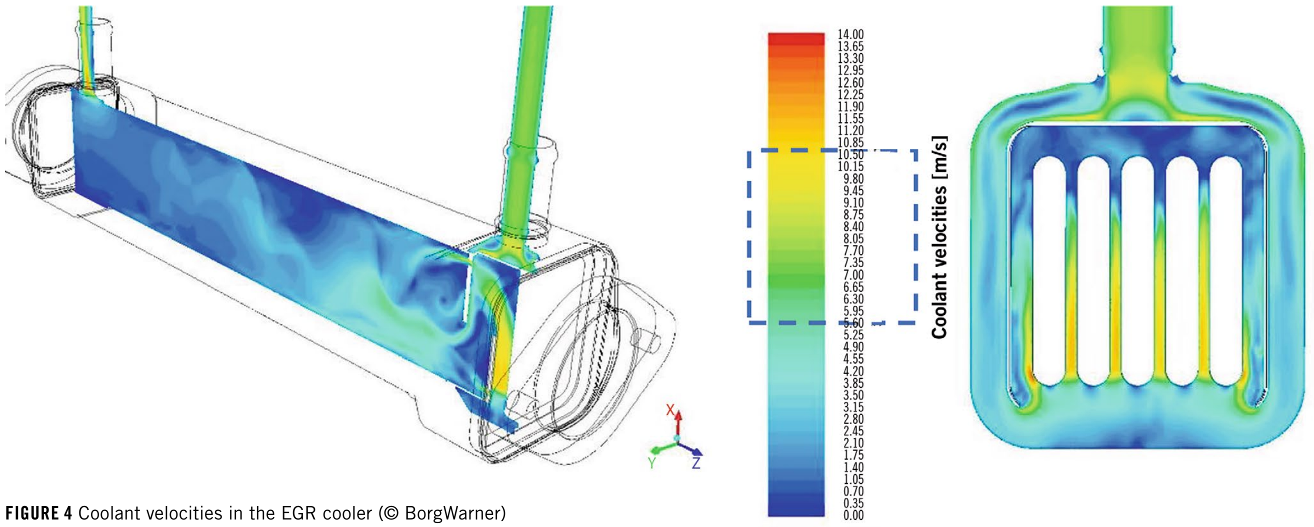

FIGURE 4 Coolant velocities in the EGR cooler (© BorgWarner)

and coolant fluid could exit through the coolant spigot located at any position.

THERMAL DURABILITY

Medium size commercial vehicle engines have a lifetime requirement in the range of 8000 to 12,000 h or 1 million km. In general, these requirements are translated into intermediate thermal fatigue tests [3]. A cooler with a compact floating core would widely meet these targets, but the extra length needed for adding the inner damper is often not available due to packaging restrictions. Monoblock design is normally the only option, but the thermal fatigue durability may be not enough for guaranteeing the reliability level expected. FBox coolers are designed to achieve the required durability for medium-size engines when a compact floating core is not necessary, or not possible, due to packaging restrictions and where the monoblock design does not meet the target. They fill a gap with the current technologies available in the market because their durability is enough for the majority of cases while having a similar compactness to monoblock coolers. Total length is the same as the equivalent monoblock, which is the best compromise between efficiency, pressure drop and cost.

Thermal fatigue durability has been checked with passenger car type coolers manufactured with austenitic stainless steel and with commercial vehicle type coolers manufactured with ferritic stainless steel, **FIGURE 5**. FBox shows much higher durability than the equivalent monoblock EGR cooler in both cases, with between three and eleven times longer life than the equivalent monoblock EGR cooler.

SUMMARY

Specially developed for the commercial vehicle medium-duty market, FBox coolers offer a good compromise between compactness and thermal robustness. The coolers can be tailored for specific requirements in terms of performance and durability, which allows for high flexibility and ability to provide the optimum technical solution in each case.

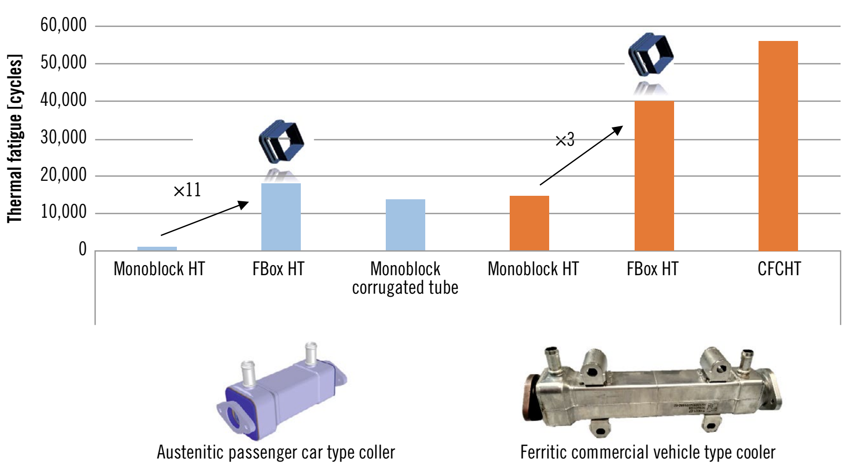

FIGURE 5 Durability against thermal fatigue for different cooler designs in comparison (Hybrid Tube: HT) (© BorgWarner)

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