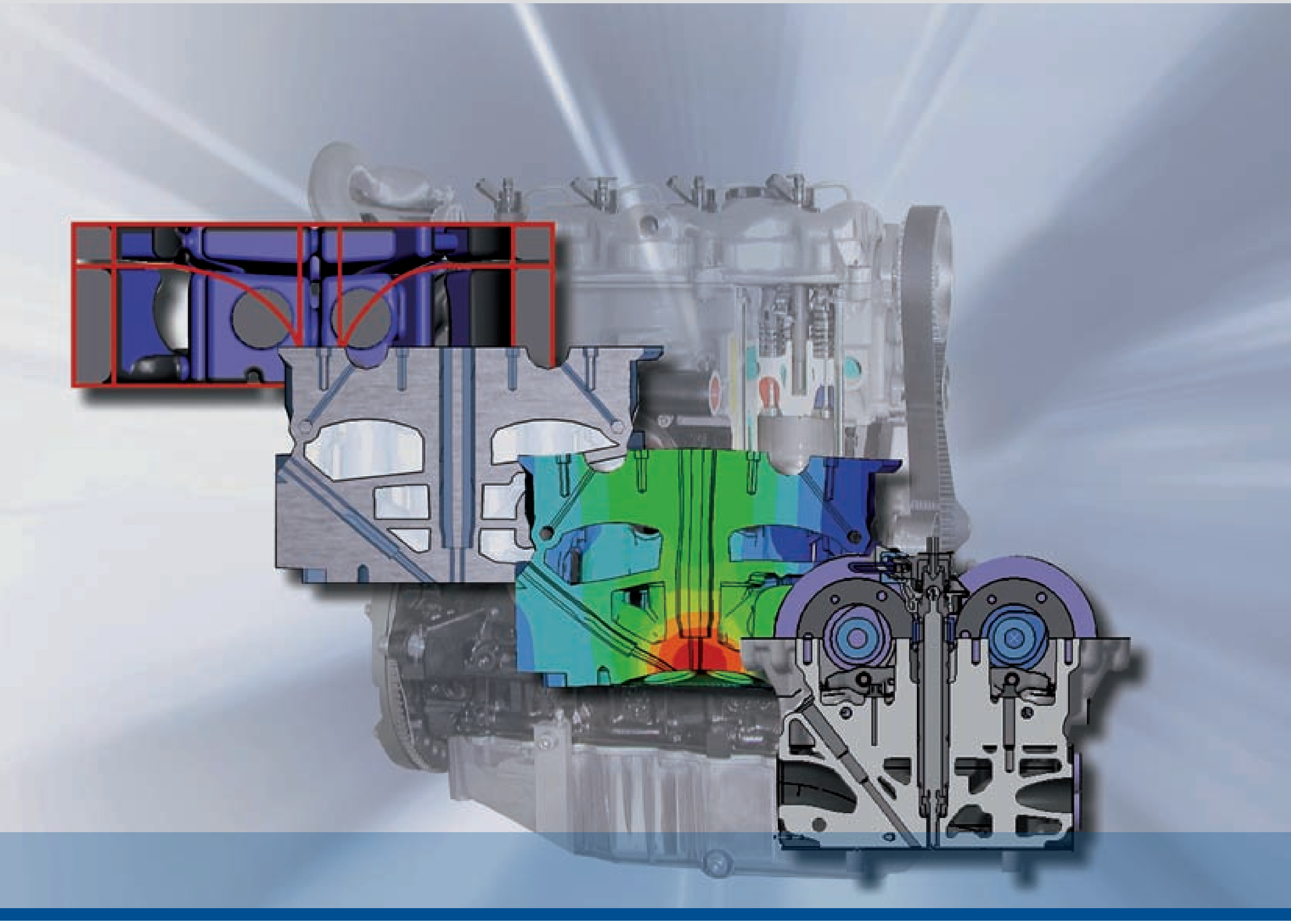

Cylinder Head Concepts for High Peak Firing Pressures

In future, peak combustion pressure and thermal loading of the components will further increase. In addition to the crank case and the crank train components, particularly the design of the cylinder head is affected by this development. In this connection, an important question is how a cylinder head should be designed to meet the higher demands. Therefore, FEV Motorentechnik performed an internal R & D project where various kinds of concepts have been designed and compared with each other.

1 Introduction

The development of modern diesel engines is characterized by combined increases in specific power and torque, **Figure 1**. In passenger car applications, engines with specific values of 75 kW/l and more than 200 Nm/l are already in series production, and engines with higher specific values are under development. Naturally, all other engine characteristics have to be improved simultaneously as well. Because of the great importance in public discussion today, the reduction of fuel consumption and the connected CO_2 emission have to be considered. But all other characteristics such as low emissions, costs, reliability, NHV behavior, or comfort are also very important for the success of advanced engines.

One of the development work measures is to increase the peak combustion pressure and thermal loading of the component. In addition to the crank case and the crank train components, particularly the design of the cylinder head is affected by this development.

In this connection, an important question is how a cylinder head should be designed to meet the higher demands. To answer this question, FEV Motorentechnik performed an internal R & D project where various kinds of concepts have been designed and compared with each other. The objective was to identify cylinder head architectures that best meet the specified requirements under the more stringent boundary conditions.

The concept comparisons were supported by intensive FEM structural analysis. In particular, the designer is searching for a procedure to find good design solutions at a very early stage of the design process when the CAD models are not yet finalized in each and every detail. Such an early solution helps minimize effort and costs.

2 Design Concepts

The increasing peak pressure and thermal loading lead to higher mechanical loads of modern cylinder heads, **Figure 2**. These loads include the following:

- Increased operating forces as a product of projected combustion chamber area and peak firing pressure. The higher pressure will be more important with larger cylinder bore diameters.
- Increased bolt forces of the cylinder head bolts, which have to ensure sufficient compression of the cylinder head gasket when applying higher peak firing pressures.
- Increased thermal stress and deformations as a result of higher temperature gradients inside the head. The temperature gradient will be higher, because the local temperatures at the combustion chamber side are increasing more than at the cooled side due to the higher heat flow.

To continue to achieve a functional, high-quality, robust, production-oriented, and economical solution even under the tightened boundary conditions, appropriate design measures are required to compensate for the higher loads that are required:

- In principle, increasing the overall structural stiffness by additional walls or ribs or an optimization of their location or dimension
- fundamental increase of the material stiffness
- utilization of material with a higher Young's modulus
- achieving a homogeneous distribution of the stiffness and avoiding high gradients
- optimization of all fillet radii
- stiffening of hollow areas with structures that can carry forces without having a negative impact on cooling
- utilization of structures that reduce the bending of the flame deck under gas pressure

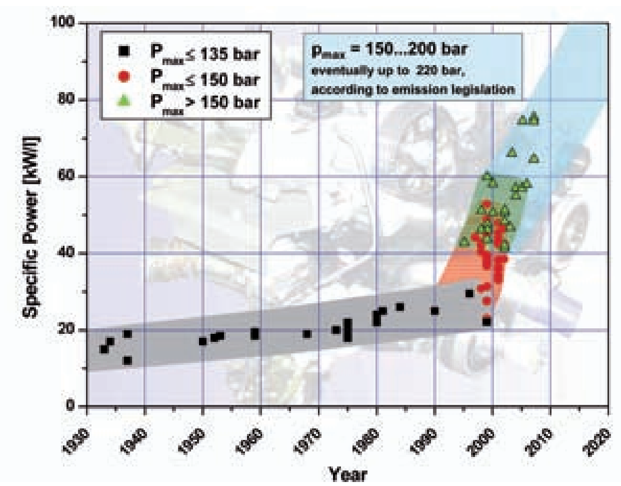

Figure 1: Development of specific performances and peak pressures of passenger car diesel engines

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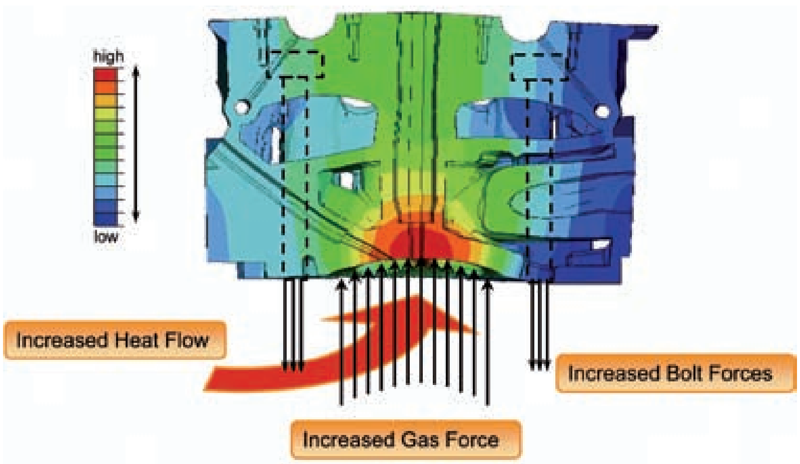

Figure 2: Cylinder head loads due to increased peak pressures and heat

- the need for the structure to expand should not be restricted to avoid excessive strains
- realization of good cooling by an appropriate form of the water jacket. At the same time, a sufficient coolant flow and velocity must be ensured, in particular at hot spots.
- utilization of material with higher thermal conductivity.

The incorporation of the listed measures into the head design cannot be realized without any compromises, since the different cylinder head design elements such as gas exchange channels, injector, glow plug, water jackets, valves, valve trains, camshafts, oil ducts, and seals have to be accommodated in a limited installation space. Simultaneously, the requirements regarding low weight and all casting or production-related boundary conditions have to be met. **Figure 3** depicts concepts analyzed at FEV where the described design measures have been implemented.

In accordance with Figure 3, the concepts that have been devised can be subdivided based on the materials that were used into the categories aluminum alloys, iron alloys, and aluminum/iron hybrids. Since the focus of the design studies has been on future, high-speed direct injection diesel engines for passenger car applications, an aluminum cylinder head concept with 4 valves per cylinder and a single-core water jacket can be regarded as the concept that is currently being manufactured most often in series production and thus as the appropriate starting point (No. 1 in the overview in Figure 3).

To increase the component strength, the first option is to change the material, i.e. to use a material with a higher Young's modulus. The first choice with regard to mass production capability would be the utilization of the grey cast iron (GJL), which is most frequently used today, or, for even higher strength requirements, compacted graphite iron (GJV). Compared to an aluminum design, the utilization of cast iron would initially have the advantage for the design engineer to decrease the wall thickness at many locations inside the head due to the higher Young's modulus, even considering the higher mechanical component loads (No. 7 in Figure 3).

Since the higher strength of cast iron is only needed in a few areas in the cylinder head, other solutions can be used in which the aluminum is substituted locally in only these critical areas by iron materials.

The result is a hybrid design, in which the bottom part of the head including the water jacket that is directly exposed to high pressure and high heat will be made from gray cast iron (GJL) or compacted graphite iron (GJV). To limit the weight increase, the upper part of the head will still be made from aluminum (No. 10 in Figure 3).

An alternative concept, utilizing aluminum and other materials such as GJV (CGI) is created when an insert that stiffens the structure is directly cast in the surrounding aluminum. This approach, however, is only helpful, if the materials used have a similar expansion rate. If not, internal stresses are created during cooling of the casting, which means that such a concept will not be feasible (No. 8 and 9 in Figure 3).

The most successful-looking concept for passenger car diesel engines is the stiffening by additional structures made from aluminum. Examples for this are an intermediate deck, **Figure 4** and No. 2 in Figure 3, which divides the water jacket horizontally, local ribbing (No. 3 in Figure 3), one rib in longitudinal engine direction (No. 5 in Figure 3), or the reinforcement of the flame deck (No. 4 in Figure 3). These solutions can be implemented without any serious weight penalty compared to the base format, and they therefore avoid the biggest drawback of all of the iron variants.

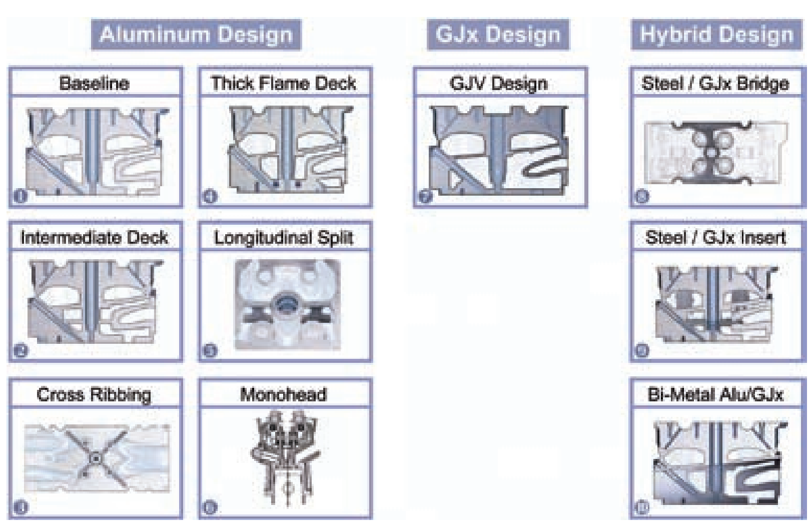

Figure 3: Cylinder head concepts for high PFP

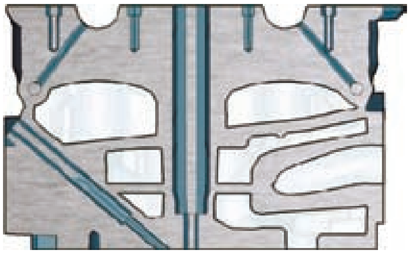

Figure 4: Intermediate deck

Naturally, cooling must be ensured in each case. Ribbing in the area of the water jacket is therefore fitted with suitable openings. A strongly reinforced flame deck is cooled down through additional coolant bores.

Compared to the baseline cylinder head, all investigated variants need more effort in at least one or several fabrication steps. Measures reinforcing the structure through additional ribbing, reducing deformation, or increasing specific coolant flow, typically increase the complexity of the core package and the casting process of the component (intermediate deck, longitudinal ribs or transversal ribs), or machining (coolant flow drilling in the flame deck). The complexity will increase even more through the implementation of concepts that utilize inserts made from higher-strength materials (hybrid concepts). The entire component process from preparing the casting model and machining to the disposal of the component at the end of the life cycle, during which the two materials must be separated again using a reliable process, must be geared towards the combination of different base materials. It can also be expected that component-specific casting process development will be necessary.

Finally, a monoblock concept (No. 6 in Figure 3) is also an interesting variant for engines with high peak firing pressures. The monoblock may be more easily realized today with the now available modern fabrication processes. In addition to some technical advantages, such as the deletion of the cylinder head gasket and bolting as well as the favorable design of the coolant jacket, there are still the well-known disadvantages of such a complex component. Inherent in the design are for example the slightly smaller valve seat ring diameters or the required adaptation of the machining and assembly equipment in an existing series production environment.

3 Concept Evaluation by Simulation

As for other structural components, the evaluation of the cylinder head design is done by numerical simulation based on Finite Element Analysis (FEA) as well as Computational Fluid Dynamics (CFD). These technologies allow to predict the properties of components as early as in the development stage prior to the first prototype and evaluate possibly required design changes accordingly.

A complete cylinder head analysis primarily consists of:

- Cylinder head CFD analysis of the gas exchange process
- CFD analysis of the coolant fluid
- nonlinear FEA of the structural mechanics for stress and durability prediction either due to cylinder pressure load (high cycle fatigue, HCF) and due to thermal distortion (low cycle fatigue, LCF)
- linear FEA structural dynamics to evaluate structure-borne noise levels.

To fully evaluate fully detailed cylinder heads regarding peak cylinder pressure resistance, HCF safety is definitely the right parameter. The influence of the different temperature levels and distributions and their relevant impact on the material properties need to be considered for this type of analysis. The HCF safety factors are typically calculated using FEA. After completion of the FEA computation considering the entire load profile, the three-dimensional component stresses are determined as mean and amplitude values at each location on the structure in the most critical section. Finally, the durability analysis is applied using all significant influence factors. The final result is the distribution of safety factors on the structure.

To compare the different cylinder head concepts shown in previous Section 2 with respect to their cylinder peak pressure resistance, which is the subject of this article, the evaluation of a normalized component stiffness is used to begin with. This ensures that a comparison between the concepts themselves is made and the influence of local details is not overestimated. High structural stiffness definitely means a good base for the later detailed design work achieving high durability, sealing functionality, and good NHV behavior.

3.1 Assessment of Component Temperature

Under stationary conditions, the heat transferred into the cylinder head is being dissipated again by the cooling system, which means that the heat flow between gas and component equal the heat flow between component and cooling medium. Assuming constant heat transfer conditions, the temperature difference between coolant temperature and component temperature is increased with increasing heat flow from the combustion chamber to the cylinder head material. Since more heat is brought into the component with larger specific engine power, the component temperature is directly coupled to the specific engine power, assuming that the cool-

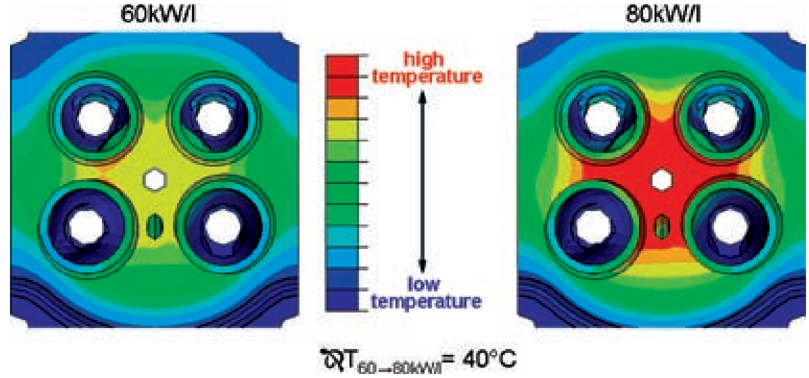

Figure 5: Calculated temperature distribution in the flame deck (aluminum baseline for different specific engine power)

ing liquid will have almost constant temperature. The following investigations are applied for two different heat flow magnitudes such that the evaluation of the concepts also pays attention against the backdrop of increasing specific engine power. **Figure 5** shows the exact temperature distribution at the bottom plate of the aluminum baseline design for a specific engine power of 60 kW/l and 80 kW/l. The principal temperature distribution is similar. However, the variant with 80 kW/l shows an overall higher temperature level as expected.

As expected, the overall temperature level for the aluminum variants is almost constant. We will take a closer look at the absolute maximum temperatures later on. **Figure 6** shows the same evaluation for the CGI variant with intermediate deck.

The overall temperature level is, as expected, significantly larger for the CGI variant due to the lower thermal conductivity of the material. The qualitative temperature distribution is also quite different for the two variants. While the temperature level for the aluminum variant is almost constant on a high level throughout large areas of the flame deck, the CGI variant shows local „hot-spots" between the valve openings, such that the temperature gradient are considerably higher for this variant. What is also interesting is that the temperature with increasing specific engine power increases not only absolutely, but also relatively.

Starting from 60 kW/l for both designs, the aluminum structure shows 15 % higher maximum temperatures, whereas the CGI variant has a temperature increase of 22 % in the hottest spots of the flame deck.

Figure 7 shows the comparison of the peak temperatures for all investigated variants, relative to their baseline variant at 60 kW/l. The influence of the geometric design itself on the peak temperature is around 5 %, as the change of materials to CGI leads to a temperature increase of about 60 %. Increasing the specific engine power has the same results for all aluminum variants (increase of peak temperatures by 15 %), while the CGI design reacts significantly more sensitive as discussed above.

Those results consequently raise the question of the absolute temperature limit of the two considered materials. The answers differ considerably depending on the source of literature. However, it is certain that two things need to be avoided: Modifications of the material's inner physical structure by thermal overload and decrease of structural strength below the level of locally occurring stresses. While the stresses are definitely depending on the entire mechanical load spectrum, they may be more critical for the CGI design due to the larger temperature gradients. On the other hand, the CGI design has a larger margin regarding the thermal destruction of the material in the example shown here:

In general, a maximum temperature of 400 °C for iron material melting at about 1500 °C should be less critical than a maximum temperature of 250 °C for the aluminum material melting at 660 °C.

However, considering the higher thermo mechanical load on the CGI variant due to higher temperature gradients and in particular the higher sensitivity regarding specific engine power, the aluminum variants appear to be at least equally suited for the demands for the next engine generations.

3.2 Evaluation of Component Stiffness

Figure 8 shows the calculated component stiffness for the different variants. While the different aluminum variants show advantages with regard to stiffness compared to the baseline design, the CGI variant shows no improvement in this area, but has an about 6 % lower stiffness. The reason for this is that, due to material-specific design, the aluminum variant shows a considerably higher geometrical stiffness. As a result, the material-dependent Young's modulus influence on the stiffness is overcompensated. This effect is also reflected in the component masses: The mass increase of the CGI intermediate deck design compared to the aluminum baseline is

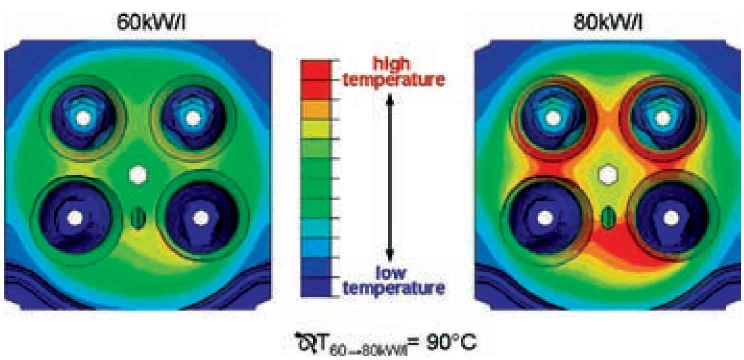

Figure 6: Calculated temperature distribution in the flame deck of the CGI design with intermediate deck for different specific engine power

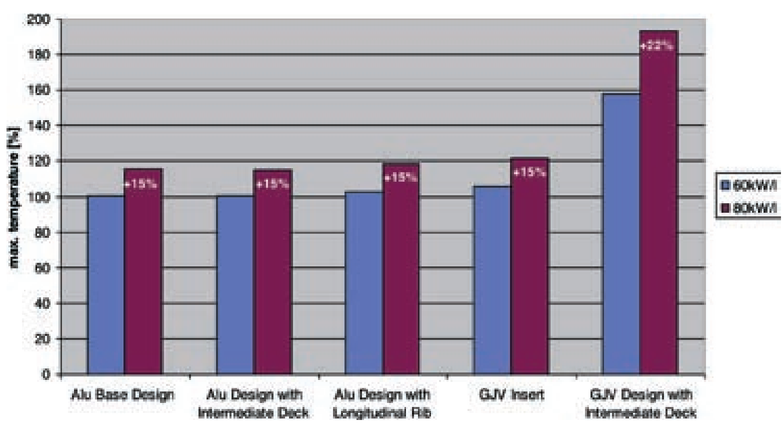

Figure 7: Calculated maximum temperatures in the flame deck for different specific engine power

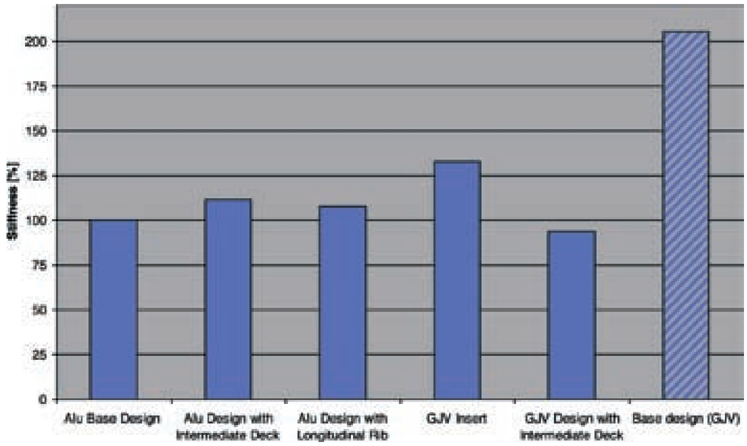

Figure 8: Comparison of structural stiffness of different concepts

only 80 %, although the material density is more than twice as high. As expected, a pure material substitution of the base line variant to CGI would lead, as shown in column six, to an increase in stiffness by slightly more than 100 %, which reflects the ratio of the material's Young's moduli. However, this consideration is merely theoretical, since the resulting design would make no practical sense regarding functionality and casting feasibility.

The design of the CGI variant with intermediate deck has thinner walls, such that the stiffness is comparable to the baseline variant. Very much simplified, the component stresses may therefore be proportional to the Young's moduli, considering that stresses would equal the Young's modulus times deformation $\sigma=\varepsilon\cdot E$. Following this estimation, the CGI stresses would be about factor two higher than the expected stresses of the baseline aluminum variant.

Considering the fatigue strength under alternating bending of both materials for the temperatures in the usually most critical areas as calculated in Section 3, their ratio (CGI temperature divided by aluminum temperature) is also about 2.

This estimation leads to the conclusion that the component safety factors may roughly be in the same range. However, this kind of estimation is very general and neglects a number of influencing factors such that it cannot substitute a detailed HCF analysis of the completely designed and structurally optimized component.

With almost 30 % increase in stiffness, the aluminum design with CGI insert shows the greatest stiffness. However, a safety evaluation of the stiffness and the elasticity module as described above is not possible for this kind of hybrid material solution.

Using the previously described estimation method, both aluminum variants "intermediate deck" and „longitudinal rib" show a significant potential regarding the increase of HCF safety as their stiffness is increased by approximately 10 %.

3.3 Evaluation of Safety Factors

The variants designed in detailed are finally evaluated using a complete HCF safety analysis. **Figure 9** shows the comparison of the safety factors of the aluminum baseline design both with the aluminum intermediate deck solution as well as with the CGI intermediate deck design.

While the minimum safety factors for both aluminum designs are found in the same region, the CGI design shows the weakest points in a different area. With respect to the generic differences in the material concepts, this is not surprising and confirms that an estimation of the component stiffness may only be understood as a first step to obtain a rough idea of the safety factors, especially if concepts based on completely different materials are investigated. The final result confirms this as well. As expected, the minimum safety factors are in the same range, but the minimum safety factor for the CGI intermediate deck solution of 1.7 shows a significantly larger safety margin for the investigated load spectrum than the baseline aluminum solution with a safety factor of 1.3. The aluminum intermediate deck design roughly matches the expectations from the estimation in Section 3.2, ending up with an improvement of the minimum safety factor of 1.4.

All three concepts are thus rated durable, while the GCI intermediate deck shows the largest potential regarding peak firing pressure increase, provided that the specific engine power and therefore also the heat flow rate will be approximately the same. With a significant increase in engine power, the aluminum intermediate deck variant would be first choice with regard to peak firing pressure compatibility.

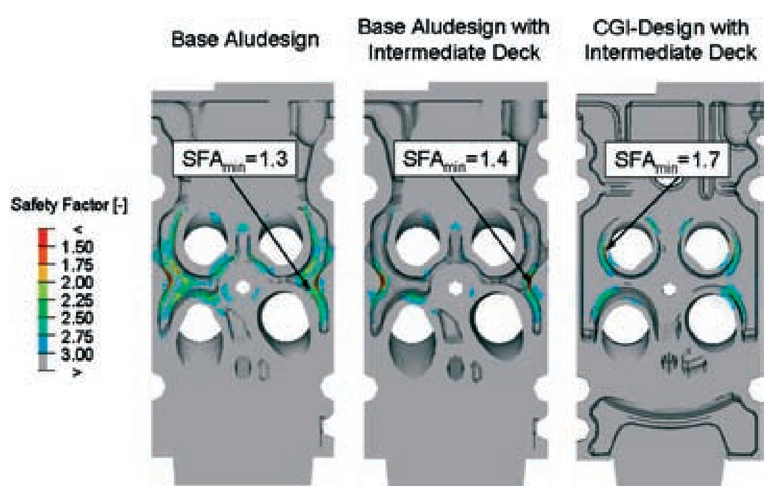

Figure 9: Comparison of HCF safety factors for detailed variants

Table: Evaluation matrix

Variant	HCF	Stiffness	Weight	Costs	Design / Fabrication	Acceptance	Summarized Accessment
Base Concept	o	o	o	o	o	o	function limited regarding high PFP
Intermediate Deck	+	+	o	o	-	o	improved function with only moderate issues
GJV Concept	++	o	--	+	o	--	function limited regarding high specific power

4 Evaluation

The **Table** depicts a summarized assessment of the described concepts. The aluminum cylinder head with the intermediate deck demonstrates the best compromise among all characteristics. Compared to the basic concept, the stiffness and the HCF safety are increased as well. This concept offers good conditions to realize higher peak firing pressures and specific outputs. The disadvantages or a more complex casting can be controlled with only relatively minor extra costs.

Higher HCF safety factors can also be achieved with GCI variants. However, the disadvantage with regard to weight and the limited suitability for very high specific outputs make these kind of concepts less recommendable for the use in passenger cars.

Despite their high stiffness, concepts with GJx inserts are not recommended, because disadvantages regarding costs and casting process can not be avoided.

5 Conclusion

The increasing peak firing pressures of diesel engines and the resulting challenges for the design of cylinder heads can‘t be discussed apart from the increasing specific power and the associated thermal loads.

Considering all influencing factors, aluminum cylinder heads incorporating an intermediate deck as a structural measure are a recommendable solution.

In general, aluminum alloys show a higher potential regarding increased specific engine power than iron materials. The potential of conventional aluminum concepts regarding peak pressure suitability lies in the region of 200 bar. The described intermediate deck and other structural measures allow an additional increase.

Regarding the peak firing pressure increase, CGI offers a high potential. Compared to aluminum, the potential to increase the specific power is lower. Because of the high weight, iron cylinder heads will not play an important role in passenger car applications.

Theoretically, hybrid structures, which combine the strong points of both materials, could represent a suitable solution in the future. However, it is questionable whether these kinds of concepts can be realized, as many fabrication problems have not yet been solved.

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