ABSTRACT

This paper gives an overview of the development work for an aftertreatment system, used in hand held powertools to fulfil the corporate average US Limits.

The paper will start with a description of the annual reductions in US Limits with differences in CARB and EPA legislation and the consequences of the legislation in Europe from 2007 onwards.

There then follows a chapter describing space restrictions in the given muffler leading to a maximum size for the substrate. Tests results are shown, giving an idea of additional measures taken to avoid dangerous temperatures on the muffler surface and of the emitted exhaust gas. The exothermic temperature increase created under service conditions imposes an additional thermal load from the catalyst back towards the engine itself. Therefore, some modifications regarding gas flow and positioning of the catalyst had to be made to find an adequate solution for series production.

Durability tests were conducted, to ensure the proper durability behavior both in emissions and mechanical performance. The temperatures inside the catalyst are also discussed; these are extremely high under the harsh conditions very close to the outlet port of the two-stroke engine. Different designs of Metalit® are investigated with respect to vibration behavior and natural frequencies in order to find a durable and cost-effective solution for series production. A shortlist of powertools that are currently in series production with the catalyst system will be given at the end of the paper.

INTRODUCTION

“Much progress has been achieved in improving the air quality in the US (and Europe) through the successive tightening of the emission standards” [1,2] for the automotive industry. But only a very minor share of the emissions derive from small handheld engines such as chainsaws, trimmers, blowers, brush cutters and other powertools. Even the small engine industry is being forced by new emission legislation to cut down on emissions - sometimes by more than 75% within half a decade.

In the US, a system of averaging and banking of emissions enables the manufacturer of powertools to introduce new low emission technologies to the market in stages. Often new technologies are developed to over-fulfil emission legislation. So a clear technological evolution towards low emission technology is forced. For a small engine manufacturer the US regulations drive R&D-departments to develop the best and most cost-efficient technology to the market, because they do not have to spend capacity onto old products.

The legislation in Europe has confirmed the tightened emission standards of the US legislation with a totally different situation for the small engine manufacturer because there is no system for averaging and banking emissions. Consequently all products have to be within the official emission levels from 2007 onwards. New low emission technologies for the next product generation
have to be developed not in steps (i.e. no learning curve from sequence to sequence, no technological evolution) but everything has to be done in parallel for the European market. This results in higher costs and greater technological risks.

ENGINE TECHNOLOGIES

BASELINE EMISSIONS

Handheld powertools like chainsaws are lightweight heavy-duty engines. Due to the operation in forest conditions, such as cutting branches, cut down trees, etc. there is a need to be able to operate the engine in any position possible. Two-stroke engines run with a fuel/oil mixture and allow for the lubrication of the engine in any position. For this reason and the possible high speeds (up to 16,000 rpm), the lightweight two-stroke engine is the favorite concept for handheld application like chainsaws.

The emissions of the valve-free two-stroke engine are mainly due to scavenging losses caused by filling the cylinder with fresh air/fuel mixture for combustion. To optimize the filling of the cylinder and reduce the scavenging losses, four-channel technology was introduced. The four channels in the cylinder wall optimize the direction and the timing of the cylinder filling. HC-emissions with this technology are typically 145 g/kWh. Two new technologies to improve the dynamics and quality of the cylinder filling are under development. These are the Stratified Scavenging engine, which works on the principle of flushing the exhaust gases with air out of the combustion chamber and the Compression Wave Injection engine (CWI). The CWI works as a „passive injection” engine where only a minor amount of fuel-oil/air mixture is pumped into the crankcase. Most of the fuel is injected in the combustion chamber by a resonator-tube, driven from the reflected pressure pulse of the previous combustion.

Other technologies like Direct Injection (DI) and four-stroke engines are able to meet the emission standards in the smaller engine class 20-50 cc for near future. However, these engine concepts are more expensive, heavier, and problematic to run at very high speed required for chainsaw applications – especially the four-stroke engines. A detailed matrix of different engine technologies is presented by W. Zahn et al [3,4].

DRIVERS FOR AFTERTREATMENT SYSTEMS

Due to the fact that a huge number of different engines has to fulfill the emission standards, catalytic exhaust gas aftertreatment systems are being developed. Existing engines can be used further, which means that product lifetime is increased. Additionally the product is proven to have a high reliability in the market and there is less R&D capacity needed for installing an after treatment system than for engineering a new product. Aftertreatment systems with catalysts are used worldwide in high numbers in two- and threewheelers equipped with two-stroke engines [5,6].

The costs for a catalytic aftertreatment system including catalyst, thermal insulation, thermal stable gaskets and new exhaust flow geometry can be calculated. The most cost-effective emission solution for the market can therefore be determined. The system is modular, meaning the extra cost for a catalytic muffler can be avoided in countries without emission standards.

Figure 2: Typical raw emission levels for different engine technologies

![Figure 2: Typical raw emission levels for different engine technologies](image)

On a voluntarily base Stihl started to offer a chainsaw with an optional catalyst in 1989 (Fig.3).

BASIC INVESTIGATIONS

ADOPTION OF CATALYST SYSTEM ON HEAVY-DUTY CHAINSAWS

To fulfil the market demands and the tough time schedule imposed by emission-legislation, additional basic investigations were also carried out. With the high
number of different engines, a basic knowledge of catalytic exhaust gas aftertreatment has been built up. The task was divided into basic questions: What do the emission dynamics of exhaust gases look like at the inlet of the catalyst, especially the variation of unburned hydrocarbon over crank angle? What is the flow distribution at the catalyst? What are the resulting temperatures created by the conversion? What vibration levels are applied to the catalyst? Of course, not all these questions could be answered with regard to every engine. Therefore, a large chainsaw with a 76.5 cc / 4.4kW engine was chosen to represent a “worst case” scenario for this basic evaluation (Fig.4).

Figure 4: Muffler of a heavy duty chainsaw

FAST FID EVALUATION

The most severe thermal load for catalytic converters is based on the high HC emission levels and excess air. For this reason an actual chainsaw for heavy-duty application was investigated in terms of its dynamic HC emissions.

FLOW DISTRIBUTION

To minimize the thermal-mechanical loads an optimized flow distribution for the catalytic converter is the engineering target. To verify the flow distribution, early prototype samples were taken to evaluate the flow pattern. Fig. 6 gives an example for a standard test set-up for two-stroke engines. The inlet flow condition into the muffler influences the flow distribution in a significant way. Therefore the airflow is directed through the cylinder with the piston positioned in a way that inlet and outlet ports are open at the same time. This takes the actual inlet flow condition into account.
The target is to avoid flow concentration as well as high flow close to the mantle. Figure 7 shows the result of the investigation described above and represents one result during the optimization process. A substrate with a dia. of 45 mm was investigated here and the uniformity index $\gamma$ (also referred to as UI) was calculated to be 0.894.

$$\gamma = 1 - \frac{\sigma}{2}$$  \hspace{1cm} (1)

$$\sigma = \frac{\sum_{i=1}^{n} \omega_i}{n}$$ \hspace{1cm} (2)

$$\omega_i = \frac{\sqrt{(w_i - \bar{w})^2}}{w}$$ \hspace{1cm} (3)

$$\bar{w} = \frac{\sum_{i=1}^{n} w_i}{n}$$ \hspace{1cm} (4)

The view corresponds to the upside-down orientation of cylinder head in Fig. 6. Further improvements in flow distribution can be achieved by design changes upstream of the substrate or an additional spoiler.

CFD CALCULATION

Computational Fluid Dynamics is a valuable tool for optimizing flow inside mufflers. Compared to experiments CFD is moderate with regard to cost and time demands and this enables the virtual testing of large numbers of different muffler designs. The simulation is not thought to replace testing but the experiments can be used for model tuning and improvement. With a well-tuned model it is possible to pre-select the most promising muffler configurations allowing a more efficient use of the testing resources available. Figure 8 shows the predicted (left) as well as the measured (right) velocity distribution on the downstream face of the converter for an arbitrary configuration. The simulation was performed using the commercial CFD-Code FLUENT. In order to enable a direct comparison, geometry, volume flow and temperature boundary conditions of the simulation were chosen according to the experimental set-up (Fig. 6).

As can be clearly seen areas of high and low velocity are well represented by the simulation. The catalyst flow shown is not optimized since the flow distribution is relatively uneven with high velocities occurring along the casing. With a value of UI = 0.83 the calculated uniformity index is lower than the measured one of UI = 0.89. However, it was possible to correctly predict the relative change of UI caused for example by different designs upstream of the substrate.
TEMPERATURE PROFILE EVALUATION

The introduction of a catalytic converter in an existing application influences the gas exchange of the engine. Therefore new calibration is required and a validation and limitation of the maximum temperatures due to exothermal reactions in the catalyst is necessary to guarantee a low deterioration factor and to ensure mechanical durability over lifetime.

![Temperature Distribution](image)

Figure 9: Temperature distribution acquired in the reference load cycle.

For this reason a special load cycle had been developed on the basis of which new application are tested. Fig. 9 shows the axial and radial temperature distribution in this specific cycle for a substrate with 45mm diameter. In this case the maximum temperature achieved is approximately 1,050 °C in the center of the matrix, (dark blue graph). It decreases in axial direction (purple and black graphs). The temperatures in the matrix close to the mantle lie within a range of 930 °C to 990 °C depending on its position (light blue, yellow, green and white graphs). The corresponding temperature on the outer side of the mantle is about a maximum of 810 °C.

VIBRATION EVALUATION

Beside the thermal loads mechanical vibration can also have negative influence on substrate durability. To know the extent of vibration loads on the substrate they have to be evaluated under operating condition. Since the substrate itself is covered by the exhaust gas guiding muffler housing a contact free measurement procedure has to be chosen. In this case a Laser Scanning Vibrometer was taken which allows vibration evaluation under hot conditions, however only in one direction. Fig. 10 shows the test set-up to carry out vibration measurement on a Stihl chainsaw MS 460, which is already equipped with a catalytic converter system. Engine speed in this test was approx. 14,000 rpm. This is the worst case condition in term of vibration loads, since they include the maximum mass forces of the piston.

![Test Set-Up](image)

Figure 10: Test set up for vibration evaluation

The focus of this measurement was put on the level of vibration as well as on the frequencies occurring. The results, Fig. 11, show that the maximum vibration levels are approximate 50g RMS in radial direction.

Typically $\delta = 4-5$ is calculated for those applications.

$$\delta = \frac{X_{peak}}{X_{RMS}}$$

Based on equation (5) the max. level is about 200 – 250 g peak.
Figure 11: RMS vibration level in radial direction

Figure 12: Frequency response @ the substrate

Fig. 12 indicates that the significant vibration response is limited to 2,500 Hz. The main frequency is located at 236 Hz which correlates with the first engine order.

NATURAL FREQUENCY EVALUATION

The frequency figures, which have been evaluated above have to be compared with the first natural frequencies from the matrix. A superposition of one of the significant response frequencies from the substrate with the first natural frequency of the matrix would lead to severe mechanical tensions since the matrix itself has relatively low system damping.

The natural frequency of the matrix and the mantle can be determined by using a Scanning Laser Vibrometer (SLV). This procedure allows to investigate surfaces with regard to their modal properties. Fig. 13 shows the 1st up to the 4th matrix/mantle modes. A combined matrix/mantle mode is described by synchronous movement of matrix and mantle. These modes do not contribute to matrix mantle failure since they do not generate mechanical stresses of any note between matrix and mantle.

Figure 13: Combined matrix/mantle modes

In comparison to the combined matrix / mantle modes, matrix modes, if they occur in the actual frequency range, have an essential influence on the matrix mantle joint. A large number of prototype Metalit® substrates with variations in diameter, cell density, foil thickness and winding type were investigated. In Fig. 14 the influence of the substrate diameter on the 1st matrix mode is shown. The design of the substrates in this comparison was kept constant with respect to length of 25 mm, cell density of 400 cpsi with 110 µm foil thickness and SM winding type of the matrix.

Figure 14: Frequencies of first matrix mode vs. substrate diameter

It can be seen that the 1st matrix mode has a sufficient safety margin to the actual frequency range of the application. Furthermore it is evident, the smaller the diameter the higher the frequency of the first matrix mode.
CURRENT SERIES PRODUCTS

The experience from the basic work carried out with the chain saw and the detailed understanding of the catalyst situation has lead to the development of new mufflers. The standard muffler for blowers and trimmers equipped with a Metalit® is shown in Fig. 15.

![Figure 15: Cross section of a production muffler with catalyst for blowers and trimmers](image)

The catalyst is positioned below the outlet port of the engine and covered at its entrance by a shield to generate more homogeneous gas flow through the catalyst. Additionally the shield prevents the oil film on the piston skirt from cooking after engine stop by reducing the direct heat radiation from the hot catalyst. This functional design brought a significant reduction in catalyst deterioration (no hot spots) and an increase in engine lifetime (better protection of the oil film on the piston).

CONCLUSION

Many calculations and experiments have to be performed in order to develop a durable exhaust gas aftertreatment system that performs well with regard to emissions. In mass production the system has to meet the demands of emission legislation and life span of the OEM. Understanding of influences that treat the system under harsh conditions, could be worked out. This know-how will flow into further developments, to further reduce the emission levels of handheld powertools using a cost-effective and lightweight system.

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REFERENCES

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

RMS Root Mean Square
δ Standard Deviation
X_peak Max. peak acceleration
X_RMS Max. RMS acceleration
γ Uniformity Index (UI)

Average velocity

Measured velocity

SLV Scanning Laser Vibrometer