Transient Valve Temperature Measurement (TVTM)

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Christoph Beerens and Alexander Mueller
MAHLE International GmbH

Kimm Karrip
MAHLE Engine Components USA, Inc.

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Abstract

As emissions regulations and carbon footprint are more and more demandingly controlled, thermal efficiency of engine components must be optimized. Valve group components have to allow for ever increasing temperatures, endure aggressive condensates or even contribute directly to rising efficiency and emissions demands. Even with integrated and cooled exhaust manifolds, the exhaust valves are meeting full combustion temperatures, especially for stoichiometric combustion.

MAHLE has developed a new technology in order to measure valve temperatures in real time, i.e. Transient Valve Temperature Measurement (TVTM).

This is a complex methodology using thermocouples installed inside of the valves, offering the possibility to run the engine at different conditions, without any functional changes in the valve train system at all. Specifically valve rotation is not affected and thus temperatures all around the valve seat can be captured during rotation. The test is cost effective, using series' components.

With the application of this TVTM testing method, results are supporting the confirmation of design limits, material fatigue, mapping of valve rotation etc. All this is possible across the entire engine operating range, avoiding blind spots in valve temperature measurements. In this paper, a description of the TVTM technique, some typical results and also the benefits in comparison with standard thermometric valve temperature measurements are presented.

Introduction

In modern engines, valve temperatures become more and more critical. New combustion regimes, emissions regulations and increased specific performance create higher exhaust gas temperatures. In order to validate valve strength and material selection, reliable temperature distribution information is required.

In engine development, estimates can be made within the margins of previous experience. Leaving the range of experience often necessitates new information based on measurements.

The traditional method of residual hardness testing with thermometric valves (TMV) allows for only one steady-state combination of engine speed, torque, etc. It may even be uncertain which engine operating condition yields maximum temperatures.

Modern engines thus require a much wider scope of measurements than this single condition, even transients can be critical now with the application of the stoichiometric $\lambda=1$ in a wider range of speed/ BMEP combinations. There is a lot of literature about valve temperature measurement, as can be seen in the references, but MAHLE identified a special list of requirements.

MAHLE thus developed a transient measurement technology without any interference to the valve train mechanics and thermodynamics. All issues with non-symmetric temperature distributions were to be eliminated as well. This can then reliably support thermomechanical FE analyses and hot gas corrosion assessments.

The technical demands identified and solved were:

1. Valves are still allowed to rotate freely
2. More than one sensor per valve
3. Applicability directly underneath the valve seat surface
3. Applicability on solid and hollow valves
4. Applicability of the sensors without causing issues of valve fatigue and cracks
5. Compliance with packaging restrictions due to finger followers, tappets, etc.

Over the past 10 years, MAHLE has developed and refined the system. This has been accomplished by utilizing developments and existing technologies from within other industries, specifically sophisticated mobile phone electronics. This has allowed the development of this measurement technique to take place without the application of any special or single-purpose electronics. However, dedicated software was required in order to utilize the existing electronics and complete our measurement system development.

Method

The method in short consists of the following basic components, depicted in Fig. 1:

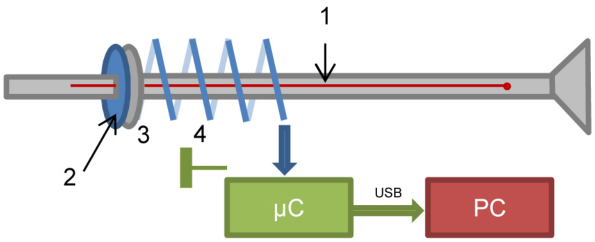

Fig. 1. Set-up of TVTM

- Thermocouples [1] picking up temperatures (2-4 per valve)
- Electronics [2] on the valve spring retainer [3], acquiring the thermocouple's analog voltage and converting it into a digital signal
- Signal and power transmission path along the valve spring [4]
- One single microcontroller collecting digital data from all valves and thermocouples in the engine
- Computer communicating with the microcontroller: Data storage and display

Mechanically the valves are first applied with thermocouples in the required positions and with contacting jumpers on the valve shaft end.

The electronic circuit board (Fig. 2) is then placed on top of the valve spring retainer. It is fixed to the valve stem by a small locking pin through a hole across the valve stem.

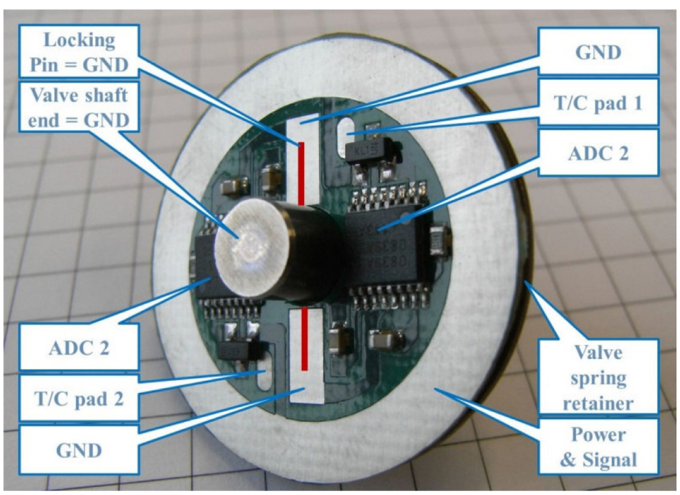

Fig. 2. Circuit board for digitization of thermocouple voltages

A wired connection between the thermocouple leads and the circuit board is established by thin wires. They are connected from a pad on the board to a micro terminal pad on the valve shaft. These pads are positioned near the top end of the valve, but above the valve spring retainer and the board.

The entire unit of valve spring/valve spring retainer/electronics board additionally has to be electrically insulated on two ends. On one side insulation is established against the cylinder head via an insulating lower valve spring disk, on the other side by a plastic conical sleeve against the cotters, Fig. 3. This unit then can transmit power to the boards and digital signals in both directions simultaneously. The electrical contacts established across the valve springs are safe due to their relatively high pre-stress.

The IC which converts the thermocouple analog voltage into digital data is in contact with the valve spring on the signal side. It utilizes the valve stem to valve guide, cam follower and seat insert contacts as ground terminal, all in parallel.

Digital data then is further transferred from the valve spring out of the engine to a microcontroller. Via USB connection finally thermocouple data are transmitted to a PC for online storage and display.

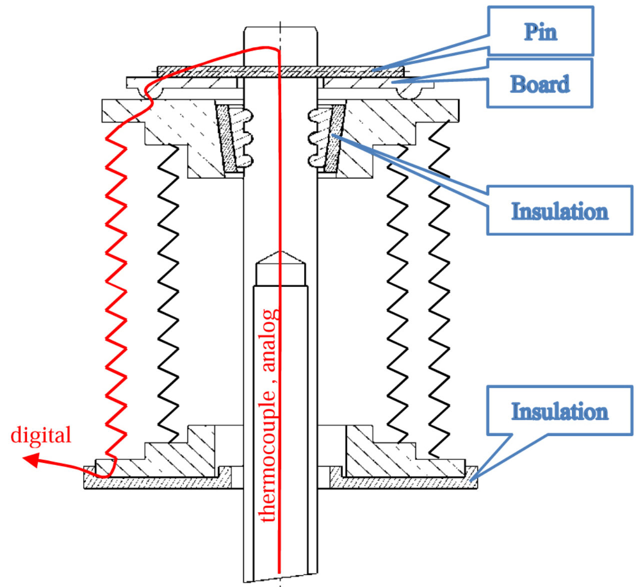

Fig. 3. Mechanical setup of TVTM, signal path in red

Placement of the thermocouples depends on the actual measurement objectives. Some typical examples (Fig. 4):

- Underneath the valve seat: Valve rotation, gradients
- Valve shaft: Temperature levels for fatigue
- Valve fillet: Temperature levels for fatigue
- Valve front: Wall temperatures, knocking issues

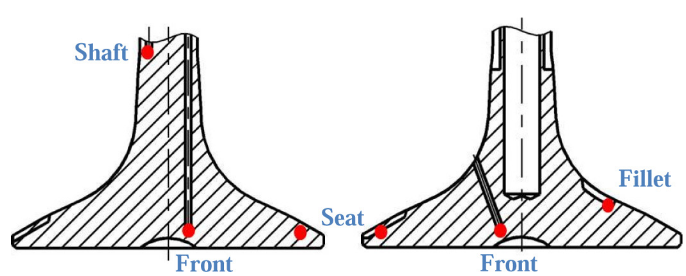

Fig. 4. Typical thermocouple positions for TVTM

Application: Solid and Hollow Valve Selection

An obvious TVTM application is the comparison of solid vs. hollow (=sodium-filled) valves. Solid valves have a long history of surviving well during engine operation. However beyond certain limits, more sophisticated and higher cost hollow valves are required. This limit is more and more often encountered due to the current developmental push for increased engine specific output.

The actual selection task is commercially important in order to base the decision for more expensive hollow valves on facts rather than guesswork only.

Using the top-rated version of an engine, one now can measure at all representative power ratings and identify the limiting power rating for solid valves, beyond which solid valves have to be exchanged by hollow valves. The application in Fig. 5 is a gasoline turbocharged engine with a power density of about 80 kW/liter.

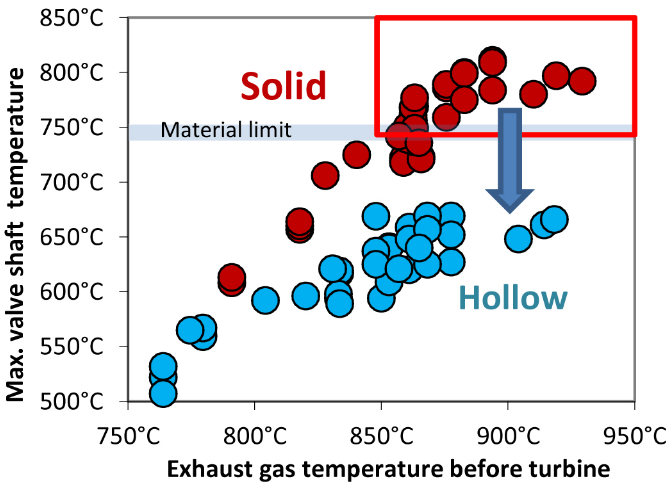

Fig. 5. Temperature measurements of solid vs. hollow valves

All the identified critical ratings of the engine (those in the red quadrant) will now either have to be equipped with sodium-cooled hollow valves or even an upgraded valve head material.

If the previous TMV method was used to characterize these valve temperatures, a separate installation of thermometric valves as well as a separate engine test would need to be performed for each power rating shown. Taking into consideration that each test would need to be run for a minimum of 2 hours at each power rating, as well as the time required to remove the cylinder head and install new thermometric valves each time, this would be an expensive and time consuming endeavour.

Application: Gradients of Temperatures

Thermal gradients around the valve seat due to uneven cooling of the cylinder head are natural to all IC engines.

In Fig. 6 the typical temperature distribution of relatively hot and cold zones is indicated by the red and blue rings on the cylinder's flame deck. Differences in temperature around circumference of the valve seat insert generate a tangential temperature gradient along the valve seat as well. This can be picked up by a thermocouple in the valve seat traveling along the valve seat insert together with the rotating valve.

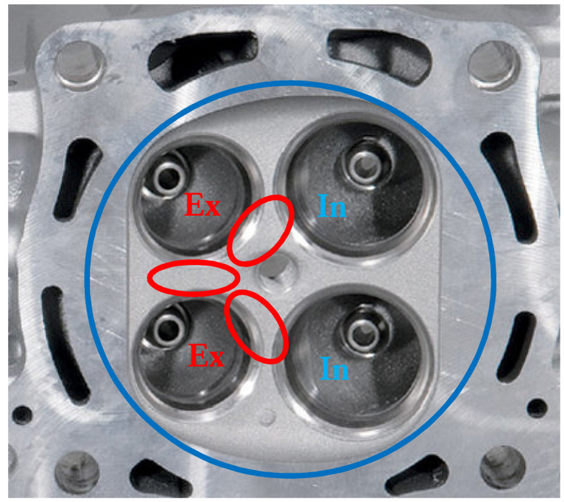

Fig. 6. Hot (**red**) and cold (**blue**) areas on the cylinder head side

There is a point where the amount of asymmetry is becoming critical, naturally.

Two types of problems may then occur:

1. Radial valve seat cracks due to thermomechanical fatigue (at gradients >180K typically), see Fig. 7
2. Unilateral wear of the valve seat insert

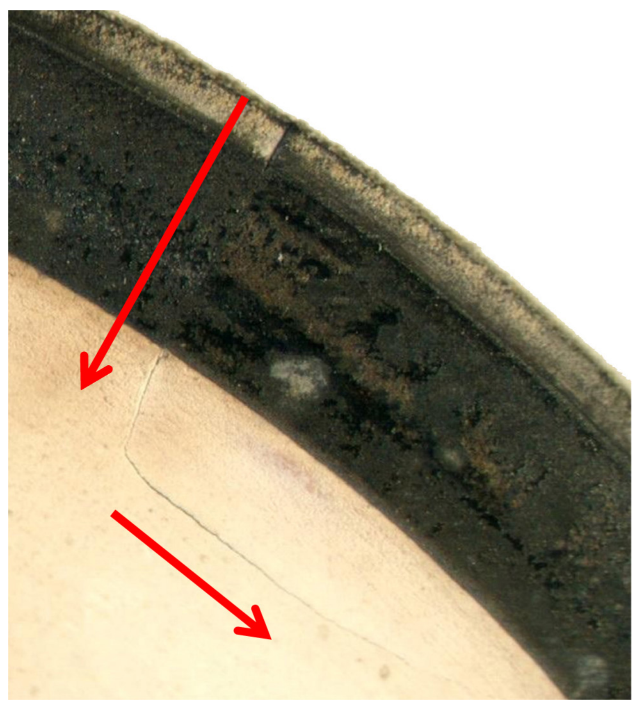

Fig. 7. Typical valve seat crack: radial, then tangential growth

By application of the TVTM on rotating valves one now can see the non-uniform distribution of temperatures around the circumference, (Fig. 8). Each periodic pattern represents a full valve rotation, rotation speed and temperature levels are clearly variable and documented by TVTM (result is from a 121 HD Diesel engine).

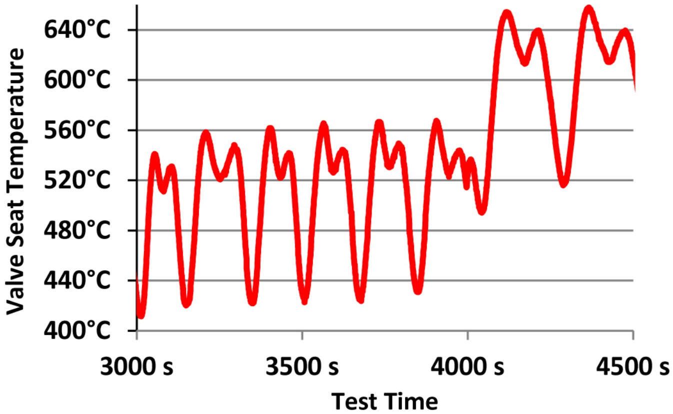

Fig. 8. Transient temperatures underneath a valve seat face

Minimum temperatures are always located next to the cylinder liner, where cooling is excellent. Maximum temperatures are located in valve bridge areas or near injectors, where there is much poorer cooling. An engine speed reduction occurred during the example in Fig. 8, at about 3900s. This always results in lower valve rotation speed instantaneously. The actual level of temperatures is primarily depending on BMEPs though, not on engine speed. Thus with engine speed decreased and power increased, valve temperatures were raised.

Rotation direction may start clockwise at about 4000 rpm for light vehicle engines, in some engines stopping at 6000 rpm and reversing rotation beyond 6250 rpm then.

The peak-peak differences (about 120K in Fig. 8) now can be measured at different engine speeds and loads, simultaneously yielding also the absolute level of temperatures, rotational speed depending on engine speed etc. This allows an insight into the behaviour of the valves which is inaccessible by the "classical" TMV-measurements using residual hardness in steady-state only.

As a note: Important information about a valve train is whether there is any valve rotation at all in realistic speed/load combinations. A lack of valve rotation can, again, induce severe unilateral valve seat/valve seat insert wear problems. In the end, valve torching will restrict engine life simply because the valves do not rotate.

Naturally TMV-valves under rotation are also annealed within the transient temperature field as seen above in Fig. 8. There is no calibration procedure for such an annealing process. One may say that the standard TMV is completely unreliable when applied on the valve seat area due to rotation of the valves. Only by blocking the valves against rotation the TMV results become completely reliable, especially in the valve seat area. But then different sections of the TMV valves have different temperature distributions. In the evaluation this has to be taken into account and requires a lot more considerations and efforts.

In some cases also the valve shaft has a non-negligible uneven temperature distribution in circumference (up to 40K). Valve rotation creates the same TMV problem there. In the engine, quite a lot of valve bending and thus misalignment in between valve seat and valve seat insert is induced by this "bimetallic" bending effect. This can further induce wear problems.

Valve rotation speeds can be rather slow, in Fig. 8 about 200s/360°. During the test, one thus has to wait quite some time before deciding that there actually is no rotation of the valves. On sports car engines rotation speeds up to 6 rpm (i.e. 10s/360°) were measured, at extremely high engine speeds. Then there was nearly no waiting period at all required for that observation. In order to record the situation properly it is good practice to record at least one full valve rotation, better even two.

Remark: Valve *spring* rotation is not a safe indicator for valve rotations. The valve may still be stationary, as circumferentially there are only surface pressure contacts in the valve group, no form-fits.

Application: Transient Engine Load Changes

Engine transient operation was identified as being crucial to emissions (RDE "real driving emissions" and others). Fuel enrichment applied here can make the catalytic converter inefficient; oil mist can be drawn into the combustion chamber, etc.

Former static fuel enrichment strategies for cooling of components may no longer be acceptable, especially in transients. Hence for short-term transients, stoichiometric combustion is very attractive.

Using the TVTM method, there now is an insight into the valve's temperature transients during demanding combustion regimes. For short-terms transients, higher temperatures can be permissible for the valves. There are absolute limits for instantaneous temperature-induced damage in the valves, though, as material properties deteriorate with increased temperatures beyond anything reasonable. Immediate failure may occur after only a few of these transient cycles. A reasonable number of these extreme transient events has to be survived in order to get a safe calibration. TVTM is a means to achieve further progress here.

This is ongoing work, as the short-term fatigue and oxidation properties for valve steels at much higher temperatures than recently observed are not available yet. This approach may become more important in the near future.

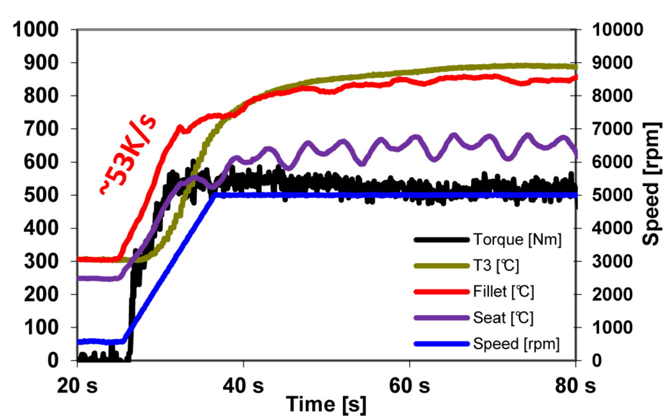

Fig. 9. Transient response of valve temperatures to a load step

One example of a rapid load change is plotted here in Fig. 9: An engine speed and load change from 600 rpm idle to 5000 rpm full load within 11 seconds was performed here. Full load was stabilized even before full speed after about 6 seconds. Valve fillet temperature increased at about 53K/s at the start of the transient. The valve seat temperature gradient was less steep, valve rotation started immediately, which is typical at 5000 rpm.

Hence here the time-period of safe valve operation for up to 750°C can extend to at least 15 seconds. For a smaller load change this period can be further extended as well as with more precise high-temperature material data. TVTM will now help in finding the proper calibration for stoichiometric short-term transients easily.

MAHLE EvoTherm® Valve

The development trends of recent years towards higher specific engine output have led to the gas exchange valves being subjected to increasing thermal loads. The component temperatures at the exhaust valve are already above 800°C in many cases. This is a challenge even for high-strength valve materials.

Also knock limit and low-speed pre-ignition additionally present substantial obstacles to the optimization of fuel consumption in gasoline downsizing engines. These phenomena are critical for the further development of CO_2-optimized gasoline engines.

Due to this fact, combustion optimization by thermal management of the valves also gains an increasing importance.

In order to find a technical solution for the current challenges MAHLE has developed a new technology based on conventional hollow valves with cylindrical bores: An extended hollow cavity is produced in the valve head with just one additional process: electrochemical machining (Fig. 10). This enlarged internal surface achieves better liquid sodium cooling, dissipating the heat during engine operation even better.

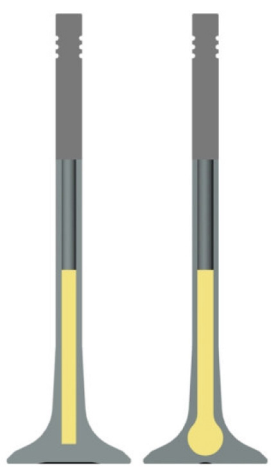

Fig. 10. Typical hollow (left) vs. MAHLE EvoTherm® (right) valves

The idea behind this product is to decrease the overall valve temperature in order to increase the operating limits. Also a decrease in the valve plate surface temperature has a positive influence on valve-induced knocking behaviour.

Measurement of the reduction of surface temperatures for EvoTherm® valves in comparison to conventional hollow valves used to be performed with the well-known method of thermometric valves (TMV). The example in Fig. 11 is from a turbocharged downsizing engine with a specific power density above 130 kW/L. The EvoTherm® valve surfaces towards the combustion chamber are cooler as a result (reduction of approx. 30 to 50K). This is shifting the knock limit and thus enables an earlier ignition angle in the calibration of the gasoline engine, yielding CO_2-savings. Also valve temperatures are reduced in the areas of both valve fillet and valve stem with up to 70K (Fig. 11), improving fatigue strength.

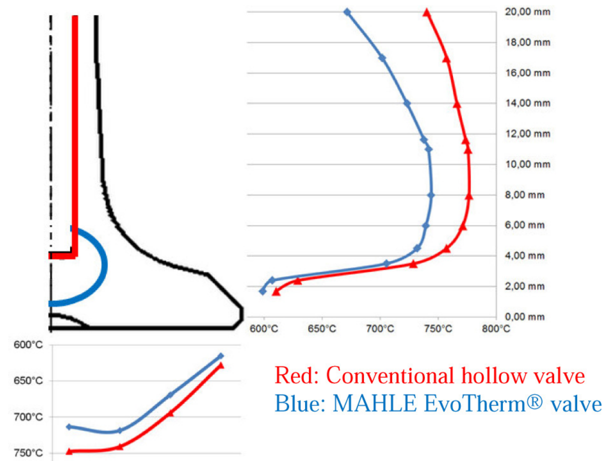

Fig. 11. Surface temperatures on an exhaust hollow and MAHLE EvoTherm® valve

Here in only one engine condition and no valve rotation at all temperatures were measured. Lots of blind spots still exist, especially for new engine developments, where one cannot rely on experience only anymore.

To get a better understanding of the thermal behaviour of the EvoTherm® valve the transient valve temperature measurement is and will be a very important tool.

Following are some examples that demonstrate the necessity of a transient temperature measurement in order to better understand and develop new valve types, especially sodium-cooled valves. The method is applied in fired engine tests, as simulation results for the complex shaker-cooling are still rather more like a research topic than reliable quantified results.

Blind spots also now can be completely eliminated by running a back-to-back engine test with the different valve types in all engine conditions relevant for real world engine operation

Example: MAHLE EvoTherm® Valves, Gradients

The first example is about an analysis of the temperature distribution around valve seat circumference. A standard (solid) valve was first running in the fired 131 HD engine, then a hollow EvoTherm® valve with Sodium cooling afterwards.

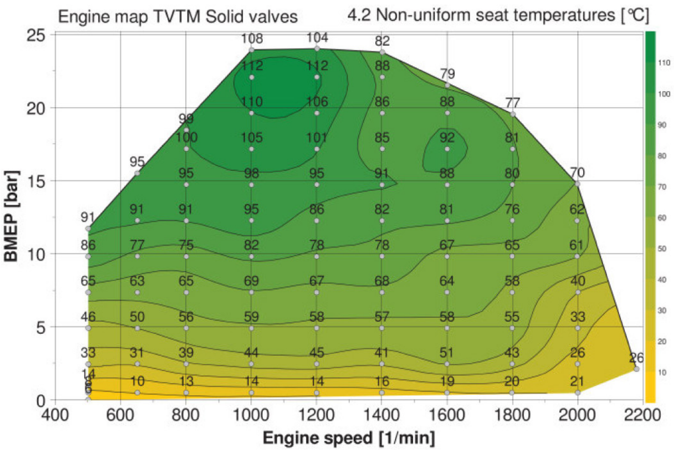

Fig. 12. Non-uniform valve seat temperatures, solid valve

The solid valve (Fig. 12) has a relatively large variation of temperatures around circumference of the valve seat face. This behaviour will typically create problems, such as seen in Fig. 7.

In contrast the EvoTherm® valve (Fig. 13) has a completely different behaviour, as maximum temperature variation around the valve seat location now is only 34K, where the solid valve had 112K. Obviously the pear-shaped cavity behaves quite differently in contrast to the standard cylindrical cavity, which only lowers temperatures in valve centre and shaft. The completely new temperature management of the EvoTherm® valve is now detectable, due to TVTM measurements.

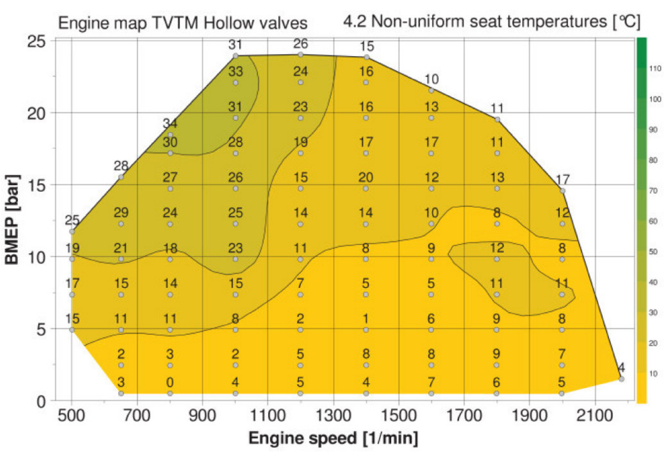

Fig. 13. Non-uniform valve seat temperatures, EvoTherm® valve

A standard TMV-test could not in any way be reasonably carried out yielding this type of results.

Application: Valve Temperature Distribution in a HD NG Engine

In a second example, the behaviour of valves for a heavy-duty gas engine was investigated. Solid valves, being the standard still in the HD world, were identified as critical components for SI gas operation, amongst others. Thus the back-to-back test with solid and hollow valves was performed here in order to investigate the thermal efficiency or effectiveness of sodium-cooled hollow valves for this HD-SI application. Fillet temperatures are plotted as this is a fatigue-related topic.

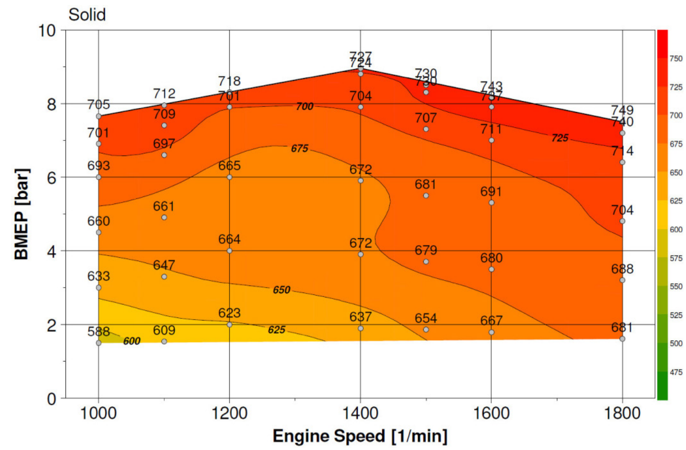

Fig. 14. Solid valve for HD natural gas engine

The typical result for valves in a NG engine is maximum temperatures occurring at peak power in the high engine speed range, Fig. 14. With NG there is no fuel enrichment in order to protect components, thus temperatures are always rising with engine speed, where with gasoline engines fuel enrichment limits temperature increase. Due to a lower specific power output of the HD application, the result is still within an acceptable range, but approaching the limits.

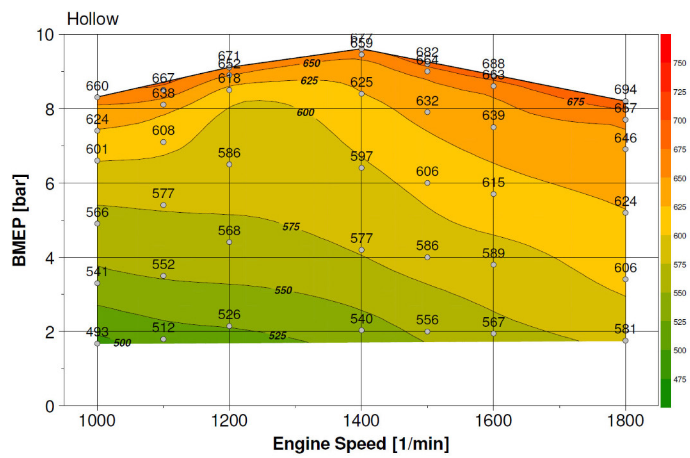

Fig. 15. Hollow valve for HD natural gas engine

In contrast to the solid valve, temperatures for Sodium-cooled hollow valves (Fig. 15: Hollow valve for HD natural gas engine) are lowered effectively, even at low engine speeds.

As only the valve dynamics is driving the shaker-cooling effect, it is reassuring to see that Sodium cooling here is effective already at low engine speeds. The design of this valve group seems to be fine. Common design errors made in valve groups are a mismatched placing of cooling jacket height and sodium-filled cavity height. Heat flux then cannot take the short route, vastly cutting down cooling effectivity.

The same applies to a lack of lubrication oil inside of the valve guide. The oil film transports the heat from the valve stem to the valve guide much better than a mere air-filled gap. The air gap can be caused by excessive backpressure blowing the oil out of the valve guide. Double-lipped valve stem seals can help against this phenomenon.

The plot of the differences of solid vs. hollow exhaust valves (Fig. 16) documents the good overall cooling capability of the hollow valve in this NG application. By the application of sodium-filled valves the margin of specific power application in NG engines therefore can be shifted much higher.

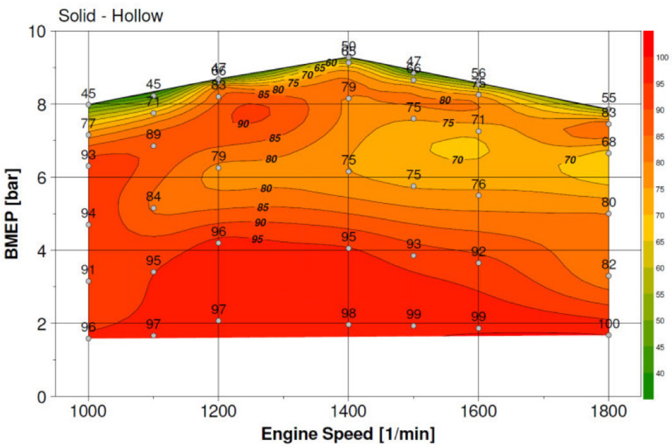

Fig. 16. Temperature potential, solid minus hollow valves

TMV 2.0

In spite of all benefits of the TRANSIENT valve temperature measurements, there are limitations as well.

One field, where the classical TMV can deliver more information than TVTM, is for simulation calibrations of high spatial resolution. In the past, this was performed along the surface of the components, resulting in absolute temperatures only, Fig 17 (and Fig. 11).

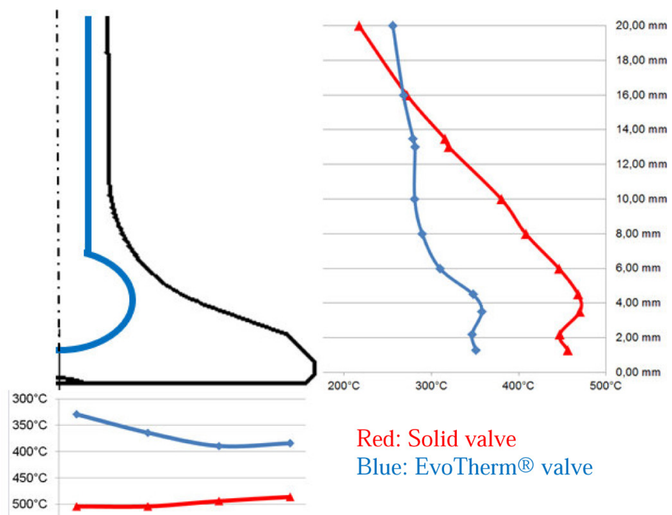

Fig. 17. Classical TMV-results, temperatures along the surfaces

While the TVTM method is still limited to 2-4 thermocouples per valve, the classical TMV method was performed using just a line of points, delivering the outer surface temperature distribution only.

Our new approach is the application of a fine 2D-mesh of hardness measurement points in cross-sections of the valve head e.g. This usually results in thousands of points covering the entire cross-section of the valve, Fig. . The first improvement here is a gain of accuracy, as the systematic hardness testing error is smoothed out and eliminated due to the "oversampling" with a lot more points than previously. (This applies to the calibration curve measurements as well!)

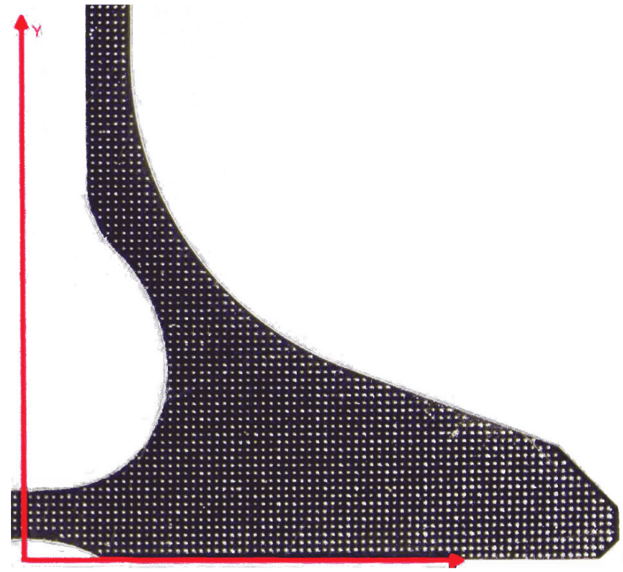

Fig. 18. Hardness indentation pattern for TMV (0.2×0.2 mm²)

Even heat fluxes now can be derived from the temperature fields as in Fig. 8. This can be achieved via generation of the thermal gradients directly within a spreadsheet. The static heat flux equation only is applied in a spreadsheet, with heat conductivity λ being the only material property required:

$$\dot{q} = -\lambda \cdot \mathrm{grad(T)}$$

An example temperature distribution is displayed in Fig. 19, where the cooling effect (i.e. heat flux) of the sodium-filled cavity in a hollow valve is clearly visible due to said gradients.

The steepness of these surfaces represents heat flux density and direction. This method can rightly be called the "MAHLE heat flux measurement valve".

Second benefit of this TMV 2.0 method is the direct applicability of the derived temperature field onto a finite element model for simulations of fatigue levels and oxidation temperatures. There are no thermal boundary conditions needed anymore! Even on the inside of the valve in the Sodium-filled cavity, which is otherwise very difficult to model, the solution is correct. Thermal equilibrium for the entire valve is intrinsically solved exactly without any iterations or trial and error!

Side note: The same applies to oil-cooled steel pistons, where thermal boundary conditions are made obsolete as well. The oil cooling gallery, just like the sodium-filled cavity in valves, is thermodynamically complex as well. Measured temperature fields and heat fluxes are a major step forward for reliable FEA piston simulation results, replacing guesswork for pistons and valves likewise.

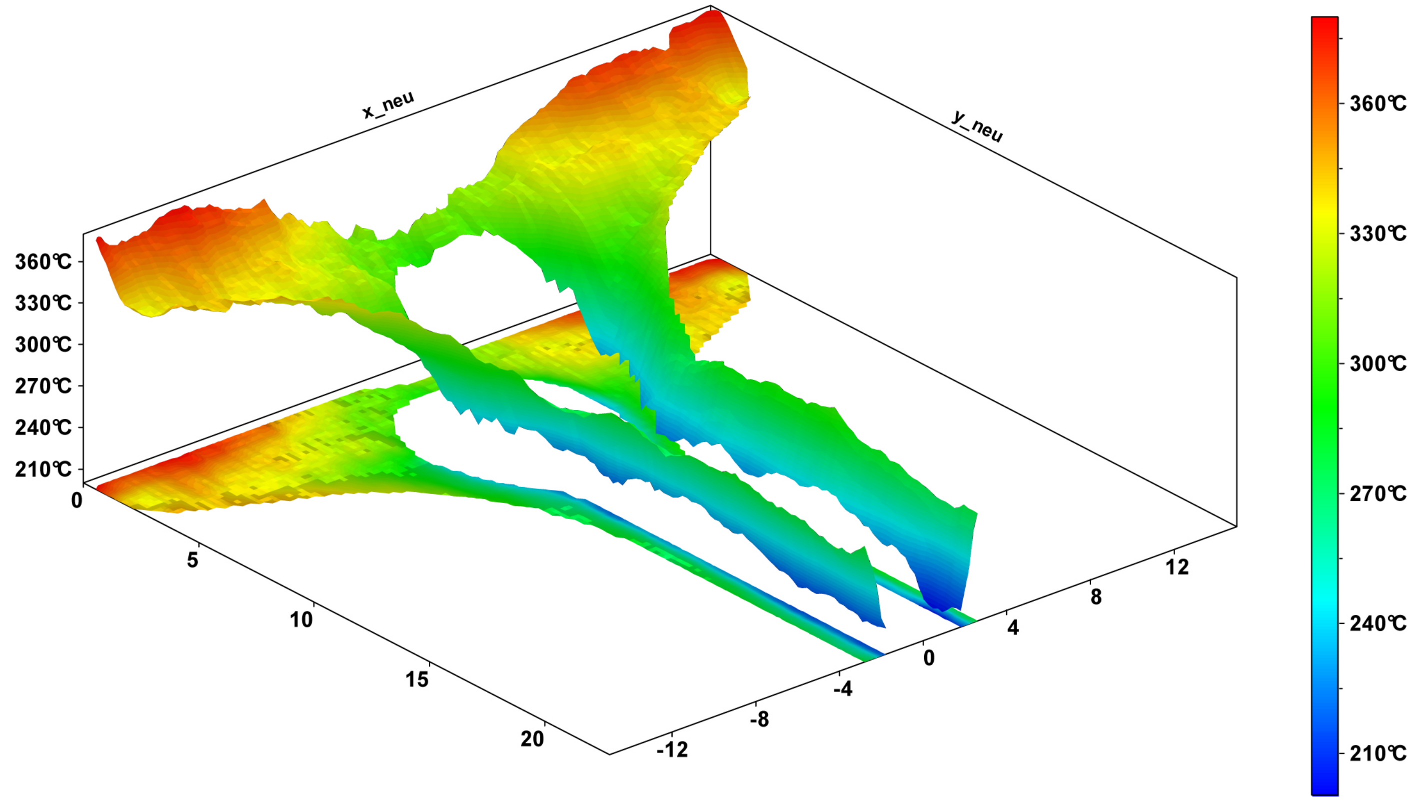

Fig. 19. Temperatures for an EvoTherm® valve (2D cross-section)

Important notice: The effort of creating TMV 2.0 results is not different to the "classical" TMV, as the process of doing hardness measurements in a fine pattern is fully automated, running overnight without any user interference. Prerequisite is only the automated hardness measurement machine, typically required for surface hardening quality monitoring.

Summary/Conclusions

A transient valve temperature measurement technology has been developed by MAHLE and was presented here. Its specific usage is the ability to cover the full range of engine operating conditions. Up to 4 thermocouples can be applied to a single valve. Thus previously existing blind spots in valve development are eliminated. Formerly a single static TMV measurement was usually the only valve temperature information available. The majority of engine operating conditions were blind spots then. TVTM has proven to also document valve rotations.

The addition of an enhanced TMV 2.0 steady-state method to the TVTM creates a valuable toolkit for valve analysis and simulation. Entire temperature fields and heat fluxes now can directly be measured. These results also can be applied to FE models without further modifications, completely eliminating the necessity of complex thermal boundary conditions.

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Contact Information

Dr. Christoph Beerens
MAHLE GmbH
Pragstrasse 26-46
D-70376 Stuttgart
christoph.beerens@mahle.com
+49 711 501 13206

Abbreviations

TVTM - transient valve temperature measurement

TMV - thermometric valve (residual hardness measurement)

SI - spark-ignited

HD - heavy-duty

NG - natural gas

LSPI - low-speed pre-ignition

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