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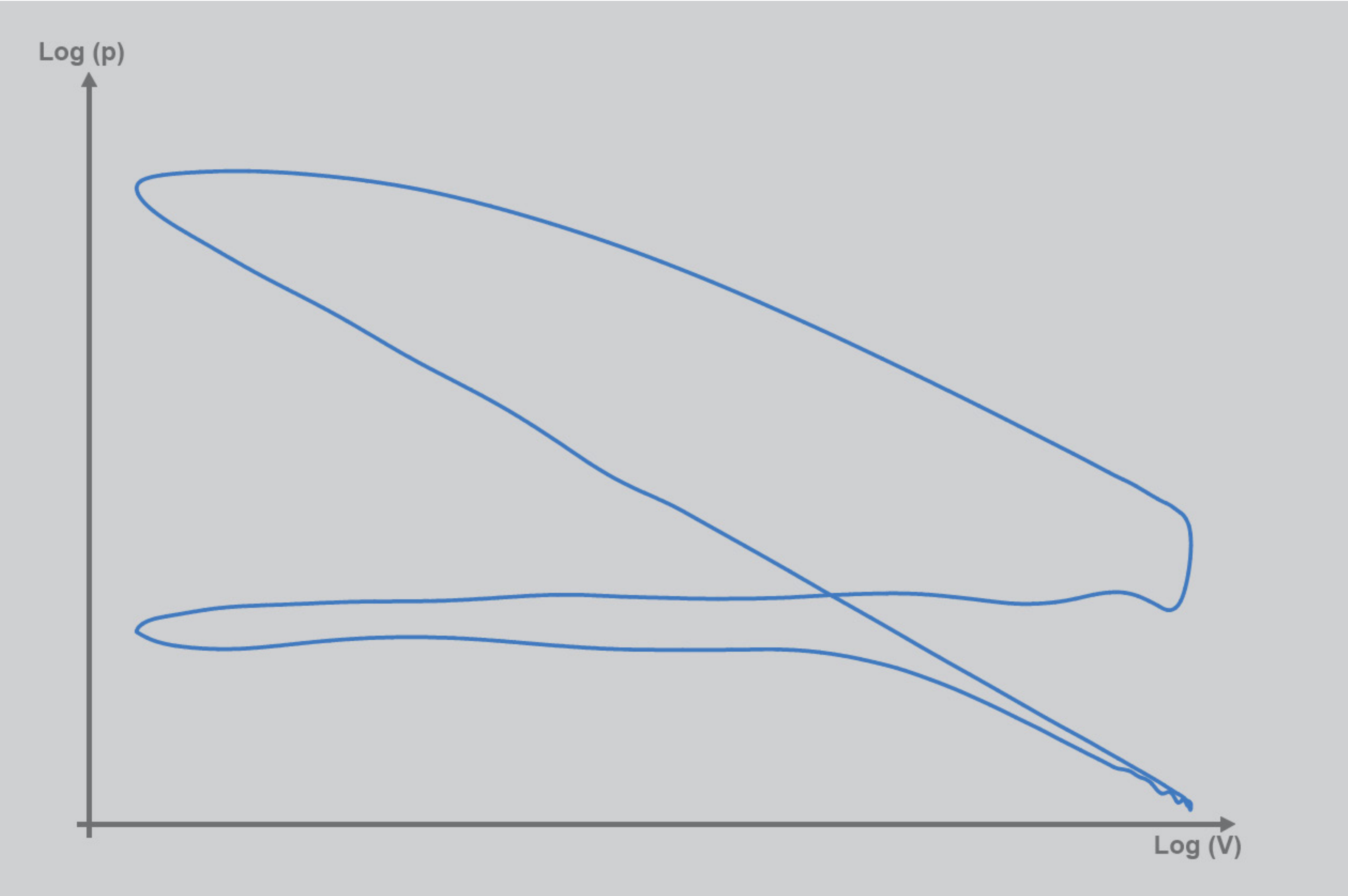

Assessment of the Methods for Dividing Indicated Mean Effective Pressure into High Pressure and Gas Exchange Portions

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Hubert Fußhoeller; FKFS

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Motivation

Indicated mean effective pressure (NMEP) represents a particularly important index value in connection with combustion analysis and combustion engine indication. It describes the work produced due to combustion, and it allows different engines to be compared with one another independently of the displacement. Since NMEP is an internal variable (based on the measured pressure curve), it is independent of friction – unlike the measured torque. On this basis, the friction mean effective pressure FMEP can be calculated from the difference between the brake mean effective pressure BMEP (calculated from the torque) and the NMEP.

By breaking the indicated mean effective pressure down into high pressure and gas exchange portions, further conclusions can be drawn from the respective sub-index values in various fields of development. However, the methods of arriving at the breakdown may differ greatly. As well as the commonly used BDC-BDC and pV intersection methods, the Witt-Shelby method must also be mentioned in this context. Moreover, because the values differ in all of these methods, the general question arises as to which of them can be described as the 'right' one. Users of combustion analysis should consider this question, especially in the light of the increasing use of fully variable valve trains.

The following sections describe and evaluate the methods just mentioned, and are intended to provide a basis for decisions regarding each individual application case.

Fundamentals

To determine the NMEP from the pressure curve, the process work is divided by the displacement. The work is calculated from the circular integral pdV over the combustion cycle.

$$pmi = \frac{W_{cyc}}{V_d} = \frac{\oint_{cyc} pdV}{V_d}$$

If the NMEP is broken down into high pressure $IMEP_H$ and gas exchange $IMEP_L$, different subvalues are obtained depending on the method used; within one method, however, the same total NMEP is always obtained with all the breakdown variants on summation.

$$NMEP = IMEP_H + IMEP_L$$

The following index values may be adduced for a detailed assessment of the process:

The high pressure efficiency

$$\eta_H = \frac{W_H}{Q_{fuel}}$$

to evaluate the high pressure process, where W_H can be determined through $IMEP_H$, and Q_{fuel} can be determined from the product of the fuel mass and the lower calorific value.

The gas exchange efficiency

$$\eta_L = \frac{\eta_i}{\eta_H} = \frac{W_{cyc}}{W_H} = \frac{NMEP}{IMEP_H} \quad \text{based on} \quad \eta_i = \eta_L \cdot \eta_H$$

or, more usually, the gas exchange work W_L i.e. the size of the gas exchange area in the pV graph, or the gas exchange indicated mean effective pressure $IMEP_L$ to evaluate the gas exchange.

The BDC-BDC Method

The breakdown of NMEP according to the BDC-BDC method corresponds to the classical breakdown into

- compression stroke and expansion stroke
- exhaust stroke and intake stroke

By definition (i.e. not necessarily in reality), the two portions – the high pressure and gas exchange portions – are calculated starting from bottom dead center: on the one hand, over the compression and expansion strokes and on the other, over the exhaust and intake strokes, until bottom dead center is reached again.

The relevant equation to calculate the work is as follows:

$$W_{cyc} = \oint_{cyc} p dV = \int_{H_{BDC-BDC}} p dV + \int_{L_{BDC-BDC}} p dV = W_{H_{BDC}} + W_{L_{BDC}}$$

and hence

$$NMEP = \frac{W_{H_{BDC}} + W_{L_{BDC}}}{V_d} = IMEP_{H_{BDC}} + IMEP_{L_{BDC}}$$

The high pressure work and the gas exchange work both contain the portion labeled as Area C. This is a positive component in the high pressure portion and a negative component in the gas exchange portion. When the high pressure and gas exchange portions are added to obtain the total work or NMEP, the positive and negative components of Area C are eliminated.

Depending on the exhaust or intake timings, this method may lead to erroneous interpretations – for example, of expansion or blowdown losses, or of gas exchange work. This is caused by the problem of attribution to the high pressure or the gas exchange portion rather than by an incorrect calculation.

In engines with variable valve timings, different effects may then be produced during operation; in some cases, this problem may lead to incorrect countermeasures in the combustion process or the calibration of the electronic control unit.

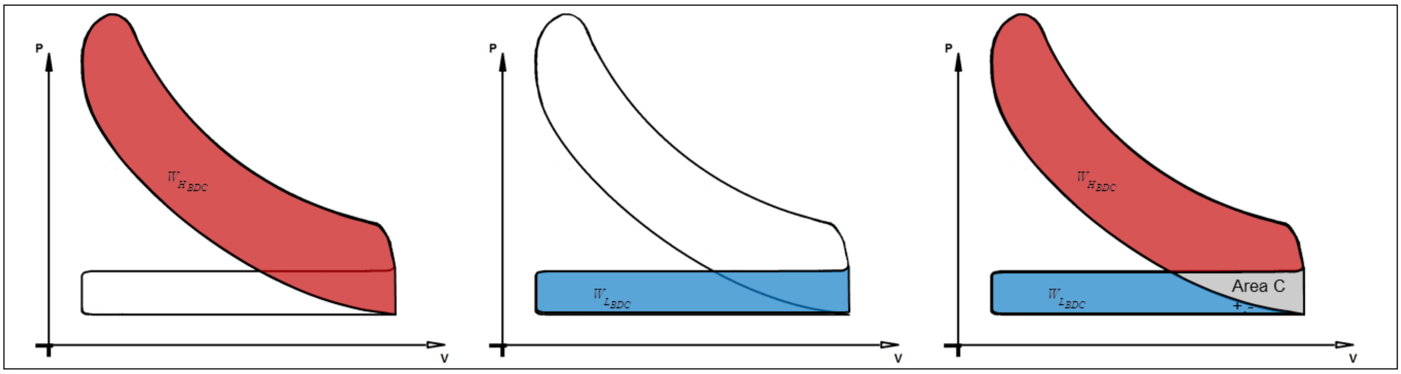

Figure 1: High pressure work, gas exchange work and total work including Area C with the BDC-BDC method (from left to right)

The pV Intersection Point Method

With the intersection point method, the process is broken down into work that can be gained or work that has to be performed, starting from the intersection point between the compression line and the exhaust line.
In terms of thermodynamics, processes that run to the right supply work W^+ whereas work W^- must be performed for processes that run to the left.

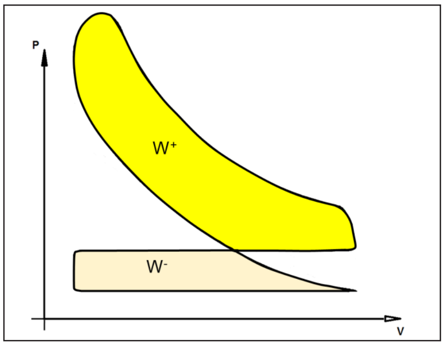

Figure 2: Breakdown of work in terms of thermodynamics into work that can be gained or that must be performed, with the pV intersection point method

There is no breakdown into high pressure or gas exchange portions, nor can a relationship with ideal comparative processes be established.

The work is calculated according to

$$W_i = \oint_{0-720} pdV = \oint_{S-S_H} pdV + \oint_{S-S_L} pdV = W_s^+ + W_s^-$$

from which follows the calculation of the divided mean effective pressures:

$$NMEP = \frac{W_s^+ + W_s^-}{V_d} = IMEP_{H_s} + IMEP_{L_s}$$

The determination of the intersection point required to calculate the divided work proves difficult and/or is not always unambiguous.

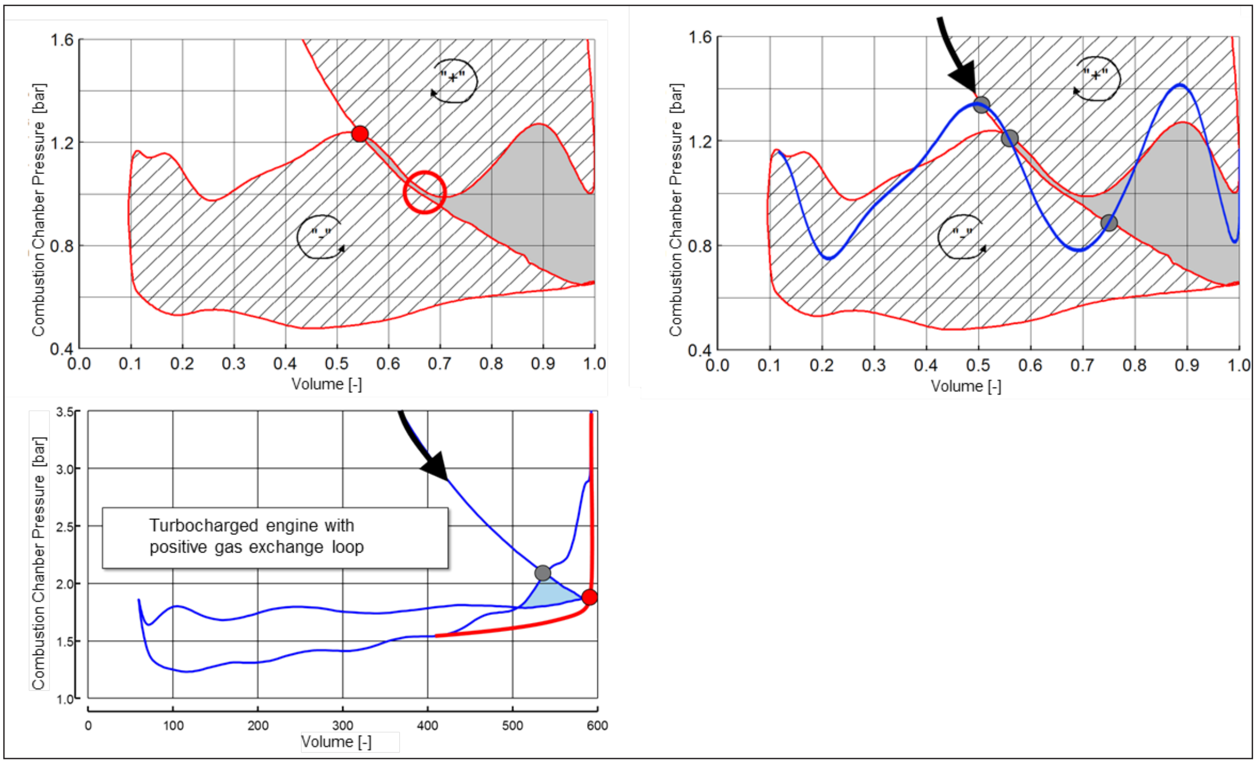

Figure 3: Unambiguous and multiple intersection finding

Figure 3 shows, on the left, the gas exchange and parts of the high pressure for a typical partial load operating point. The red dot indicates the intersection point that is to be found. The intersection point that is found is unambiguous for the pressure curve shown. However, it can be seen that a critical point with a 'near' intersection point can be found along the compression line, in the direction of increasing volume. With only a slight change in the pressure curve during the exhaust phase, this could lead to the finding of a different intersection point. To illustrate this clearly, a critical profile for the exhaust phase is superimposed in blue in Figure 3, on the right. A somewhat larger pressure oscillation amplitude in the exhaust phase produces three possible intersection points. The directional dependency of the intersection point that is found is also clearly recognizable. In this case, it has proven appropriate to perform the search from TDC towards BDC along the compression line.

This makes it possible to ensure the smallest possible variation width for the intersection points that are found. As can be seen in Figure 3 (bottom), further problems may occur in the case of supercharged engines with a positive gas exchange loop. In the profile shown in blue, the question arises as to how the small area shaded in light blue should be evaluated. Is it positive or negative work? Should the first or second intersection point be chosen? For profiles with a purely positive gas exchange cycle (marked in red), it makes sense to find the intersection at BDC, although the BDC limit position can cause difficulties with the finding algorithm. Ideally, there is a transition here from the intersection point method to the BDC-BDC method.

With this method too, in case of variable timings, phenomena that really should be ascribed to the gas exchange may be assigned to the high pressure portion in certain cases, and vice-versa. This could also lead to misinterpretations, depending on the engine's operating mode.

The Witt/Shelby Method

The Witt/Shelby method allows good comparability of different processes, even in case of timing variation processes such as close of exhaust or intake valve. The method can also be used to show two-stroke processes.

The name of the Witt/Shelby method is derived from the 1999 dissertation by Dr. Andreas Witt and SAE Paper 2004-01-1262 by Michael H. Shelby, Robert Stein and Christopher C. Warren dating from 2004.

The Witt/Shelby method is based on an extension of the BDC-BDC method. It allows a full breakdown of the process into the high pressure and gas exchange portions. According to Witt/Shelby, the high pressure portion comprises all combustion-related components, and the gas exchange-related components (like the expansion losses) are fully extracted. It is therefore easy to identify a deterioration in combustion, caused for example by diminishing swirl or delayed combustion. This method also enables good evaluation of processes that are otherwise difficult to interpret, such as early close of intake valve or late close of intake valve.

The fundamental basis of this method is the extrapolation of the pressure curves, based on the polytropic equation:

$$p \cdot V^n = const$$

Different methods can be used for this purpose, based either on logarithmic pressure curves or on the differentiated form of the polytropic change of state equation. In either case, the objective is to determine the ideal pressure curve. The work from open/close timing to BDC can then be calculated.

1. Numerical integration over the section points of the ideal pressure curve
2. Calculation with the equation to calculate the work along one isentrope

$$W = \frac{p_1 \cdot V_1}{n-1} \cdot \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

3. Formation of the numerical integral of the real curve
4. Forming the differential area supplies the incremental compression work (ICW) or the expansion work W_{Exp}

The work designated here as ICW describes the reduced area in the high pressure cycle in relation to the standard process, in case of late close of intake valve.

High Pressure IMEP According to Witt/Shelby $IMEP_{Hw/s}$
In order to avoid attribution of the gas exchange-related losses after opening of the exhaust valve to the high pressure portion, the expansion losses W_{Exp} are calculated according to the method described above, and are added to the high pressure work as per the BDC-BDC method.

Division by the working volume produces the high pressure NMEP according to Witt/Shelby for the standard process without ICW:

$$IMEP_{H_{W/S}} = \frac{W_{H_{BDC}} + W_{Exp}}{V_d}$$

If necessary, as for example in the case of late close of intake valve, the incremental compression work must also be taken into account. In order to calculate the ICW, it is also necessary to extrapolate the pressure curve from BDC until close of intake valve, with the help of the method previously described. This is followed by integration and then formation of the differential in relation to the numerical integral of the real pressure curve (from BDC to close of intake valve). It should be noted that the exponents must be calculated specifically, because they differ between expansion and compression.

As illustrated in Figure 4, the high pressure IMEP is then obtained from

$$IMEP_{H_{W/S}} = \frac{W_{H_{BDC}} + W_{Exp} + W_{ICW}}{V_d}$$

Gas Exchange IMEP According to Witt/Shelby

Likewise for the gas exchange portion of the IMEP according to Witt/Shelby, account must be taken not only of the expansion losses but also of the ICW in case of late intake valve close.

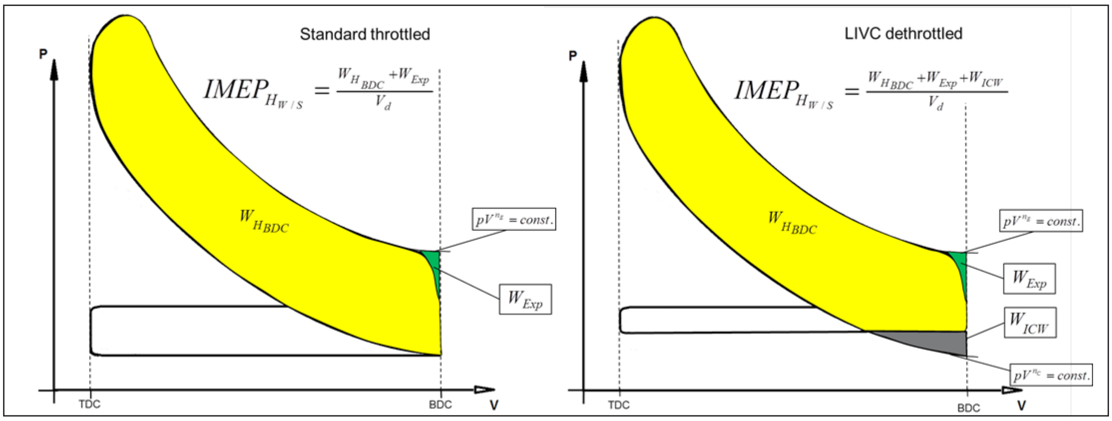

Figure 4: High pressure portion according to Witt/Shelby for the standard process, and with late intake valve close

The expansion losses and the ICW should be added as negative here in relation to the gas exchange work according to the BDC-BDC method.

$$IMEP_{L_{W/S}} = \frac{W_{L_{BDC}} - W_{ICW} - W_{EXP}}{V_d}$$

The graphic representation of the relationships for the gas exchange portion in case of late intake valve close is shown on the left in Figure 5.

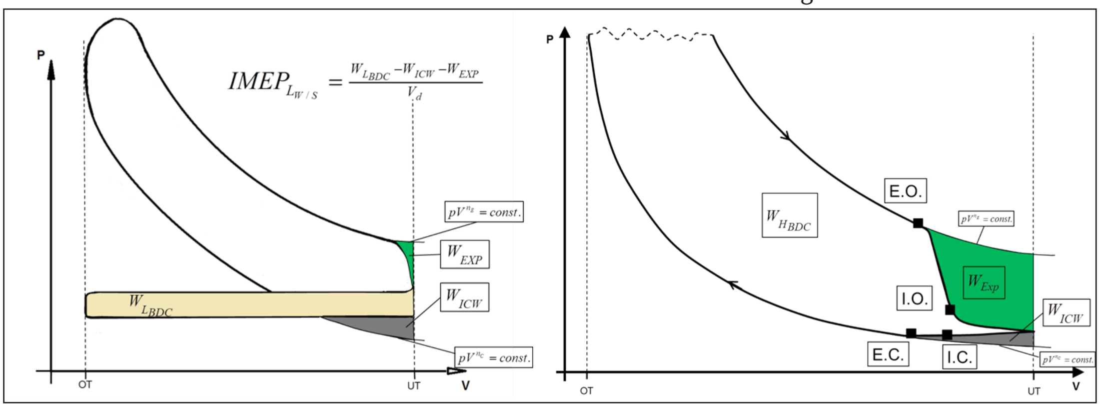

Figure 5: Gas exchange portion according to Witt/Shelby in case of late intake valve close and evaluation of the 2-stroke process

Analysis of 2-Stroke Processes with Witt/Shelby
The Witt/Shelby method also allows unambiguous analysis of 2-stroke processes. Here too, the expansion losses and the incremental compression work are calculated with the help of the polytropic extension of the real pressure curve. Figure 5 shows the 2-stroke process on the right, and the analysis according to Witt/Shelby.

Real Examples and Differences between the Methods

In the next section, the three methods for breaking down the NMEP are compared to one another with the help of two examples, in order to illustrate their advantages and drawbacks, and also to clarify how suitable these methods are for use in analysis.

Example 1:
1 600 rpm, NMEP = 3 bar; exhaust timing variation

The first example is an operating point at 1 600 rpm, NMEP = 3 bar with a residual gas variation due to late adjustment of the exhaust camshaft. The residual gas content increases due to the concomitant enlargement of the valve overlap in the gas exchange TDC.

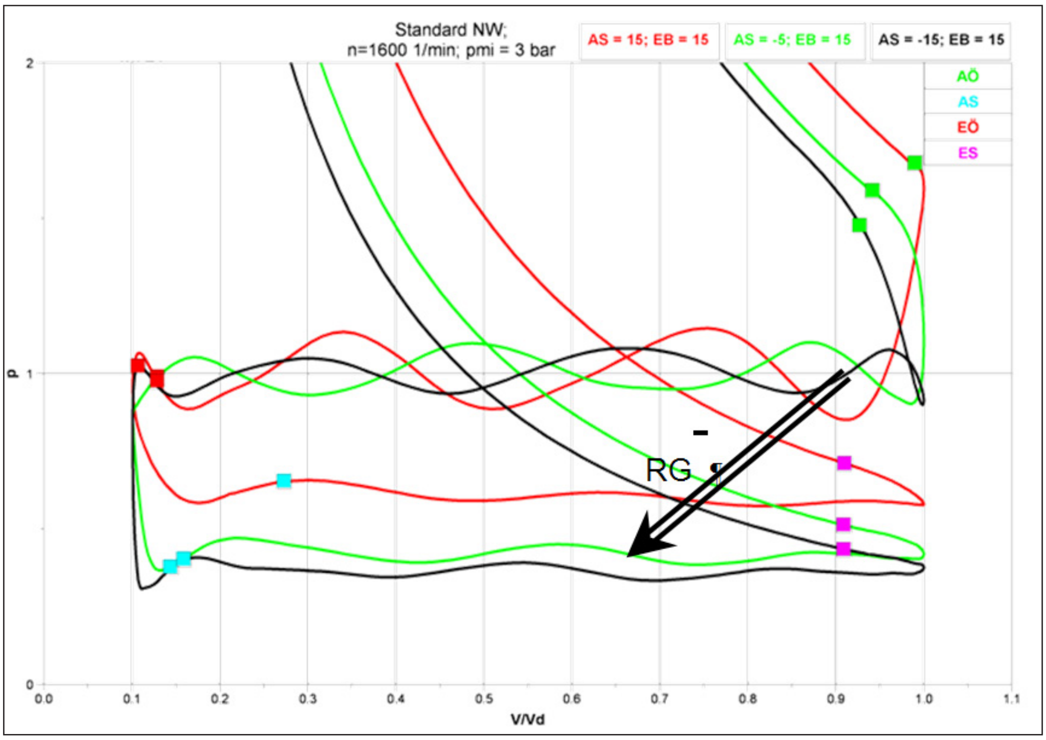

Figure 6: Dethrottling due to residual gas variation over exhaust camshaft phasing

Figure 6 shows the P-V graph for three different exhaust timings.

The graph clearly shows the increase in pressure during the intake phase as the residual gas content increases. For the same load, the increase in residual gas requires the opening of throttle valve and, consequently, an increase in pressure during dethrottling.

The decrease in expansion losses with the late adjustment of the exhaust camshaft can also be seen clearly. But in case of a very late adjustment (red line AS/EC = 15), an increase in blowdown losses can also be observed.

The following table compares the three methods discussed and their effects.

		Witt/Shelby			BDC-BDC			pV Intersection		
CAM Shaft Position	Residual Gas	$\eta_{H_{W/S}}$	$IMEP_{L_{W/S}}$	$IMEP_{H_{W/S}}$	$\eta_{H_{BDC}}$	$IMEP_{L_{BDC}}$	$IMEP_{H_{BDC}}$	η_{H_S}	$IMEP_{L_S}$	$IMEP_{H_S}$
AS = –15 EB = 15	15 %	37,54	–0,630	3,63	37,45	–0,620	3,62	35,21	–0,404	3,404
AS = –5 EB = 15	19 %	37,38	–0,581	3,581	37,36	–0,579	3,579	35,45	–0,397	3,397
AS = 15 EB = 15	35 %	35,65	–0,400	3,4	35,64	–0,398	3,398	34,68	–0,307	3,307

Table 1: Comparison of the methods Witt/Shelby, BDC-BDC and pV intersection

All the methods tend to show a deterioration in high pressure efficiency as the residual gas content increases. However, this is less pronounced with the intersection method. In all variants, the reduction in the amount of the gas exchange IMEP can be observed as the residual gas content (and hence the dethrottling) increases.

A comparison of high pressure efficiency between the methods shows virtually no difference between the Witt/Shelby method and the BDC-BDC method. A small difference occurs only in the case of early 'exhaust valve open' timing. This is caused because the expansion losses are excluded from the calculation in the Witt/Shelby method. However, very major differences are recorded in relation to the intersection point method.

The same trend is also evident in the gas exchange IMEP. A consideration of the percentage improvement in the gas exchange IMEP due to dethrottling over the residual gas increase shows the largest improvement with the Witt/Shelby method (because expansion losses are included), but this differs only slightly from the BDC-BDC method. Considerably smaller improvements occur with the intersection point method.

$$\%IMEP_{L_{W/S}} = 36{,}5\ \%,$$

$$\%IMEP_{L_{UT}} = 35{,}8\ \%,$$

$$\%IMEP_{L_S} = 24\ \%$$

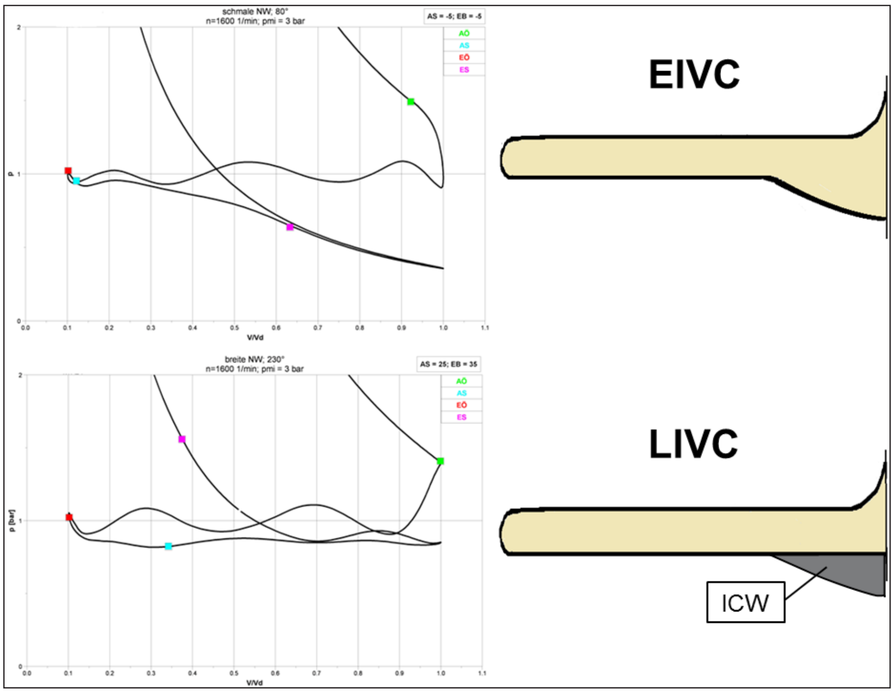

Figure 7: Dethrottling due to early intake valve close (EIVC) and lateintake valve close (LIVC)

Example 2:
1 600 rpm, NMEP = 3 bar; dethrottling due to early intake valve close or late intake valve

In addition to dethrottling due to the increase in residual gas described in the previous example, this example focuses on dethrottling due to an early or late close of the intake valve. In this case, an attempt is made to maintain approximately the same content of residual gas in order to avoid cross-influences. Figure 7 shows the pV graphs (real and schematic) for both dethrottling processes.

If we consider the work according to the intersection point method for the gas exchange, i.e. the effective area from intersection point to intersection point, its size would appear at first glance to be approximately the same. However, as shown schematically on the right, the gas exchange work according to the BDC-BDC method differs greatly from early intake valve close to late intake valve. The major difference is that the ICW is not taken into account in the case of late intake valve close. Minor differences may also occur due to the consideration of expansion losses with the Witt/Shelby method and early intake valve close.

As the following table shows, the residual gas content is virtually identical between the two processes, with 26% for early intake valve close and 24% for late intake valve close. This means that further dethrottling takes place over the limitation of the air mass in the cylinder, due to the control of the effective volume via the valve timings.

With the intersection point method, on the other hand, identical high pressure efficiencies are recorded. However, these are considerably lower as compared to the Witt/Shelby method. The high pressure efficiency according to the Witt/Shelby method is approximately the same for early intake valve close and late intake valve close. The error with the BDC-BDC method can be compensated by correcting the ICW and the expansion losses.

Possibilities for Using the Methods

A consideration of the three methods for breaking down the NMEP shows that each of them has advantages as well as drawbacks. These advantages and drawbacks are summarized again by way of conclusion.

Variant 1: BDC-BDC
The main advantage of the BDC-BDC method is that it offers a simple way of determining the index values. For normal throttled operation, the process can also be assessed with good accuracy in this case. Furthermore, supercharged engines can be evaluated easily. Errors due to multiple intersection points are irrelevant here. It is also simple to make a comparison with theoretical comparative processes, because these are also structured between the BDC to BDC limits. However, an uncritical evaluation of processes cannot be undertaken with the BDC-BDC method. It is not possible to compare dethrottling processes on the basis of variable valve timings.

		Witt/Shelby			BDC-BDC			pV Intersection		
	Residual Gas	$\eta_{H_{W/S}}$	$IMEP_{L_{W/S}}$	$IMEP_{H_{W/S}}$	$\eta_{H_{BDC}}$	$IMEP_{L_{BDC}}$	$IMEP_{H_{BDC}}$	η_{H_S}	$IMEP_{L_S}$	$IMEP_{H_S}$
EIVC	26	36,8	–0,273	3,273	36,8	–0,270	3,270	34,4	–0,063	3,063
LIVC	24	36,5	–0,264	3,264	32,5	–0,168	3,168	34,4	–0,096	3,096

Table 2: Comparison of the methods Witt/Shelby, BDC-BDC and pV intersection, related to EIVC and LIVC

The anticipated, substantially worse high pressure efficiency for late intake valve close with the BDC-BDC method is clearly visible. An analysis of combustion that may have deteriorated due to mixture inhomogeneities, diminishing swirl, a changed 50% MFB (mass fraction burnt) or recondensation is difficult, impossible or not meaningful here.

A comparison of the two processes (early intake valve close and late intake valve close) shows this clearly. A comparative assessment of combustion leads to false conclusions. Likewise, dethrottling depths cannot be compared to one another for different timings.

Variant 2: Intersection Point Method
The intersection point method is very suitable for a fast comparison of processes. A direct comparison of processes with early or late intake valve close is also possible.
However, absolute values cannot be considered. Also, it is not possible to transfer the high pressure portion into comparative processes. With the intersection point method, it proves difficult to determine the intersection point in relation to the search direction and oscillations in the pressure curve. Very different intersection points may be found even in case of small changes in the pressure curve. Noisy signals may also lead sporadically to variable intersection points.

Assessment in case of supercharged engines also proves to be critical. In the borderline case, with a completely positive gas exchange cycle, this method transitions into the BDC-BDC method here. The question of attribution arises in case of alternating gas exchange cycles (e.g. those which start out negative and then become positive), since multiple different intersection points occur in such cases.

Variant 3: Witt/Shelby Method
From the thermodynamic viewpoint, Witt/Shelby is the best method. It produces a clean breakdown into the gas exchange and high pressure portions. It is possible to make a direct comparison of the high pressure portion with the ideal comparative process. Regardless of variable valve timings, combustion-related effects can be read directly from the high pressure efficiency, with no influences due to changed timings. Analysis of 2-stroke processes is also possible.

The disadvantage of this method is that it is only available on the basis of valve timings at present. However, it does seem possible to implement online determination of approximate timings from the pressure curve. But also, as an alternative in cases where timings are available online, they could be taken as the basis for the calculation.

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