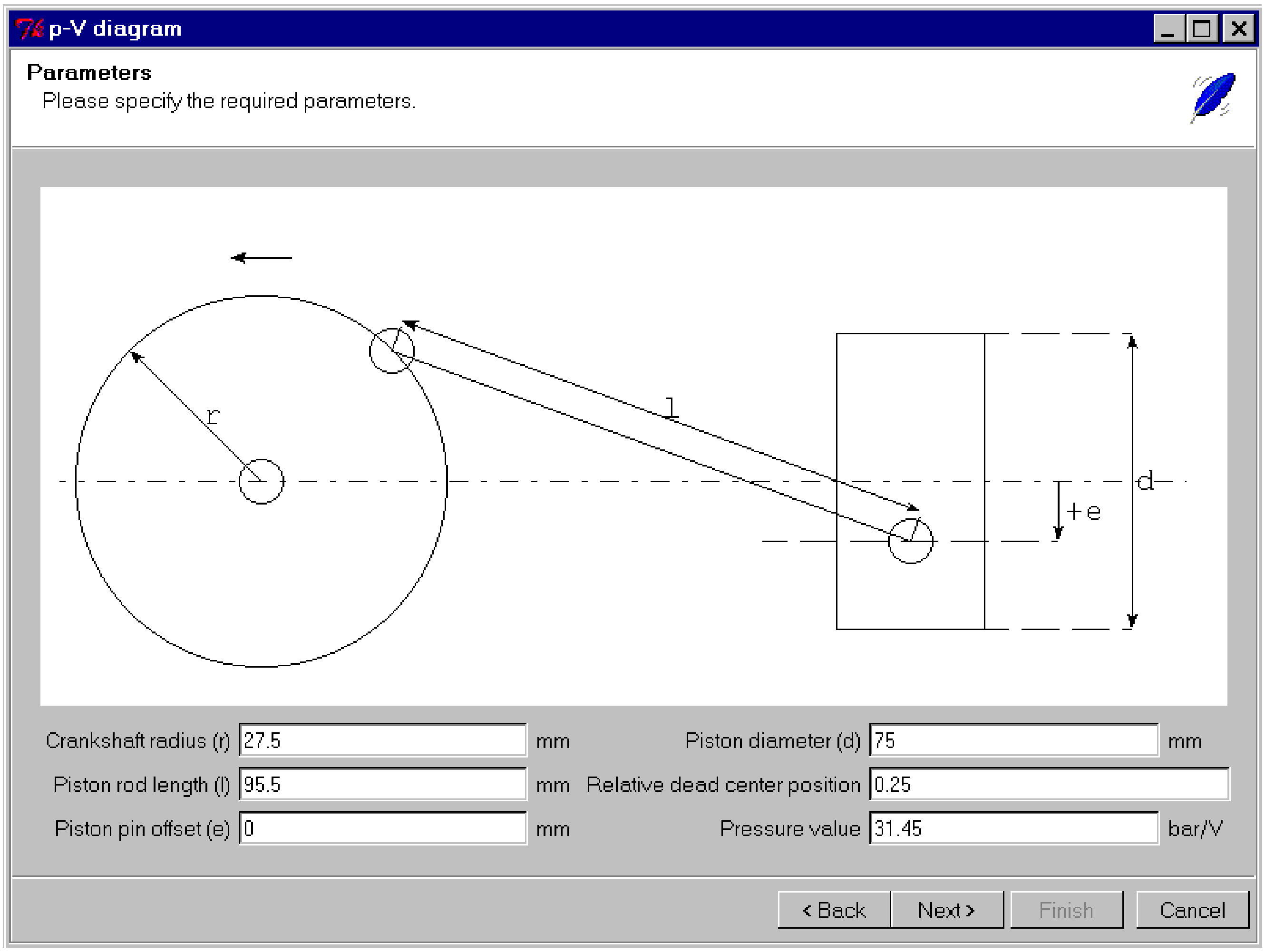
Methods and equipment for measuring the cylinder pressure in piston machines

p-V 1.0 and PicopV 1.0

for determination of p-V-diagrams with DiaW - Diagram for Windows



Picture 1

Application

In piston machines like pumps, compressors, and engines with internal or external combustion with one or more pistons a gas or a fluid is pressing onto the piston(s). When a piston moves, it delivers or consumes mechanical work. Methods and equipment for determination of this work are described in the following.

During one cycle of operation of a piston machine every piston oscillates one or two times, i. e. it makes 2 or 4 strokes. Motion of the piston varies the volume in the chamber formed by the cylinder and the piston.

In the science of thermodynamics the behavior of a certain constant mass of gas during variation of its volume is described by the p-V diagram showing the pressure as a function of the volume:

$$p = f(V)$$

This function depends on further conditions, especially on the flow of heat into or out of the gas during variation of the volume.

In case the volume of the gas is e. g. decreased (the gas is compressed), the gas absorbs mechanical work.

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In case the gas is compressed and then expanded again to the initial volume, but the pressure is e. g. lower during compression than during the following expansion, the functional curves p = f(V) are different for compression and expansion and form a loop. In this example the gas consumes less work during compression than it delivers during expansion, i. e. there remains a remainder of mechanical work, which the cycle of compression and expansion has delivered after its end to the wall of the chamber enclosing the gas.

The loop formed by the two functional curves p = f(V) describes the cycle of compression and expansion in the assumed example. The area below every of the both functions shows the work consumed or delivered by the gas during the respective compression or expansion. So the difference of both areas, i. e. the area enclosed by the loop, shows the work after the end of the cycle.

Because in a piston machine the piston is during compression and expansion the moving part of the wall enclosing the gas, the piston delivers that work during compression and absorbs that work during expansion, which the p-V diagram shows as areas below the respective functional curves. Therefore the p-V dagram shows by the difference of these both areas, i. e. by the area enclosed by the both functional curves, the mechanical work, which has been delivered or consumed by the piston machine in the measured cylinder during the considered cycle.

In other words:
If the pressure in the cylinder and thus the force pressing onto the piston during one stroke of the piston are different from those during the following stroke,
or more exactly:
if the pressure during two subsequent strokes follows different functions of the piston position,
the piston has absorbed mechanical work from the pressure medium gas or fluid or it has delivered mechanical work at the end of one cycle consisting of the both strokes.

In case of a 2-stroke process the p-V diagram consists of two functional curves forming one loop; in case of a 4-stroke process there are four functional curves forming two loops.

However, the p-V - diagram only describes the thermodynamic behavior of a gas as long, as the mass of gas in the considered volume remains constant, i. e. the cylinder is is closed.

Therefore the p-V - diagram cannot show during the change of gas in a combustion engine or in case of a pump working with a practically incompressible fluid the volume displaced by the pressure medium, but only the piston position.

The same applies to an internal combustion engine, if it does not aspirate the ready mixture of fuel and combustion air, but the fuel is injected later after beginning of compression of the combustion air.

In practice the cylinder pressure is determined as a function of the piston position:

$$p = f(s \text{ proportional } \Delta V)$$

Variation of the piston position multiplied by the area of the piston is the variation of the volume.
Accordingly the area enclosed by the functional curves p = f(s) multiplied by the piston area is the work delivered or consumed by the cycle described by the curves.

On the other hand pressure multiplied by the area of the piston is the force pressing onto the piston.

For simplification a diagram with functional curves for p = f(s proportional ΔV) is called „p-V diagram“, too.

In the past and partly still today the cylinder pressure depending on the piston position is measured on slowly running piston machines with directly accessible piston position by x-y recorders directly actuated by the motion of the piston and by the pressure. These recorders are called „engine indicators“, the diagram produced by these recorders is called „indicator diagram“, and the quantities effective at the piston are called accordingly „indicated pressure“, „indicated power or performance“, and „indicated work“.

Several reasons do no more allow application of mechanical engine indicators in most of all cases:

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Movements of the pistons and pressure variations are too fast. Moreover the frequency of pressure variations has increased much more than the frequency of piston motion, because the internal combustion can produce pressure oscillation of high frequency („knocking“).

The diagram drawn on a paper by the engine indicator is not well suited for automatic data processing.

Today most of all machines with pistons transform the oscillation of the pistons into rotation of a crank shaft, but the pistons themselves are only seldom accessible directly during operation.

Because of the above reasons an equipment of today for production of the p-V-diagram is different from the mainly historical engine indicator as follows:

The pressure is measured by a piezo-electric pressure sensor.

Instead of the position of the piston the angular position of the crankshaft is measured by an incremental pick-up (resolver) with sufficiently high resolution.

It is usual to trigger the memorization of the measured value of pressure with every step or every n-th step of the resolver.

This state of the art has disadvantages:

1. The position of the piston must be calculated from the angular position of the crankshaft.
2. Coupling a resolver to the crankshaft is expensive and can be difficult.
3. The sampling rate of memorization is proportional to rotary speed of the machine. This is non-favourable for studying oscillations of which the frequency does not depend on the rotary speed of the machine, because if a certain number of measurements per revolution is specified, the sampling rate can become too low in relation to the frequency of the interesting oscillation in the lower speed range of the machine.

Indicator control and user’s programs „p-V“ and „PicopV“

Disadvantage no. 1 is no more really important thanks to automatic data processing. Also the user’s programs „p-V“ and „PicopV“ described herein transform the memorized function p = f(angle φ) into the function p = f(s proportional ΔV) and calculate the indicated work. For this purpose the user can input the necessary data about geometry and cylinder pressure measuring chain (see picture 1).

Furthermore the automatic output of the results of „p-V“ resp. „PicopV“ to the user’s program „DiaW - Diagram for Windows“ offers to the user comfortable possibilities of presentation on the screen and of editing a printed report (see pictures 2 and 3).

The disadvantages no. 2 and 3 are avoided by a combination of the indicator control with the user’s programs „p-V“ respectively „PicopV“.

These combinations allow to use a much more coarse division of the rotation, normally the toothing of the flywheel, instead of a resolver. Provided a sufficiently high sampling rate and an adequate capacity of memory this method requires no compromise concerning accuracy.

Instead of the resolver two simple pick-ups are sufficient, one sensing an index mark indicating the upper dead center of the crank drive and the other normally sensing the toothing of the flywheel.

However, if desired or necessary, also a usual resolver instead of the two sensors can be used and connected to the indicator control.

The data acquisition equipment can be selected according to the requirements from the available storage oscilloscopes and data acquisition equipment for PCs.

The p-V-diagram shown in picture 2 is for example based on a data acquisition by a storage oscilloscope with low capacity of memory and low resolution of the measured values.

Generally an oscilloscope, which can optionally show the analog measured value directly on the screen or memorize it digitally and display the memorized value, has the advantage, that the user can check in the direct analog mode, whether pressure oscillations can be not memorized or falsified because of a too low sampling rate. Of course it is possible to use for this control purpose an analog oscilloscope connected parallel to the inputs of a PC based digital data acquisition equipment.

Contrary to picture 2 the p-V-diagram shown in picture 3 is based on a memorization by a PC with data acquisition equipment with high capacity of memory and high resolution of the measured values.

The PC user's software „p-V“ forms a p-V diagram from a PC file containing measured values of the pressure and information about the rotary position of the crankshaft (this information is produced by the indicator control during data acquisition), and calculates the work delivered or consumed by the working cycle represented by the p-V - diagram.

So this program can evaluate data already memorized during an earlier measurement. Such an evaluation can also be done additionally to different traditional methods without automatic data processing and can thus be part of an exercise. Therefore a demonstration equipment including „p-V“ is recommended for technical training, because students can recognize separate steps of data processing and partly they can do these steps by themselves.

At the time „p-V“ is available in a version processing data files of the storage oscilloscope contained in the scope of delivery.

The report in picture 2 is produced with „p-V“ basing on measured values memorized in such a storage oscilloscope and then transferred to a PC.

Different from „p-V“ the PC user's software “PicopV“ controls continuously together with the indicator control acquisition of data for inividual working cycles, forms from them p-V diagrams, evaluates the latter and calculates an average of indicated work of the evaluated working cycles. This average is important with respect to the differences between the individual working cycles even at constant load of a combustion engine.

„PicopV“ displays graphically for the evaluated working cycles:
    versus time signals for the pressure and information belonging to about the rotary crankshaft position,
    the p-V diagram belonging to,
    and the alteration of the indicated work of the evaluated cycles.

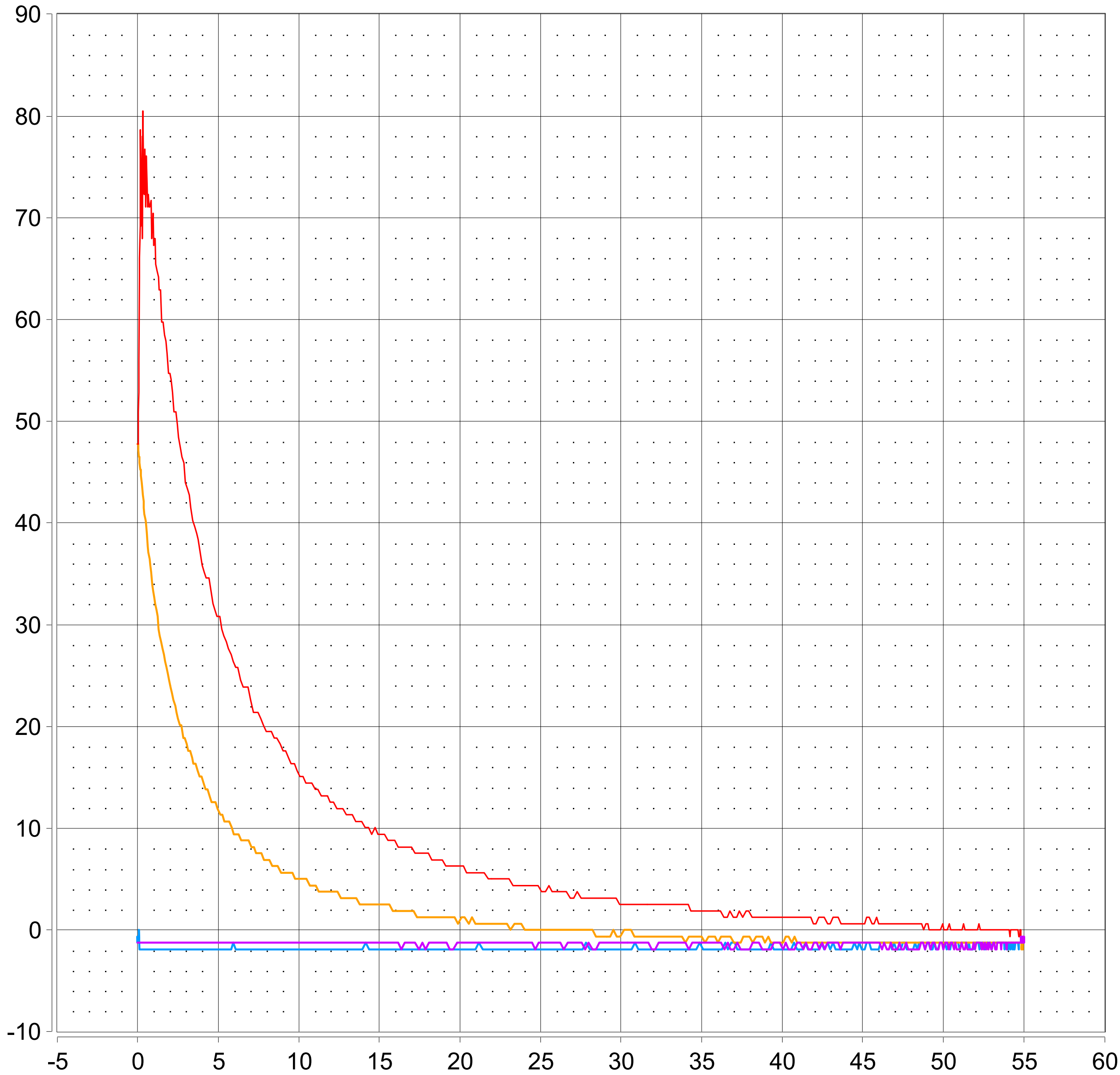
The repeating frequency of acquisition and evaluation of working cycles by „PicopV“ depends on the capacity of the PC.

Thanks to these functions „PicopV“ is not restricted to application in technical training, but allows time-effective execution and documentation of tests.

At the time „PicopV“ is available in a version controlling the data acquisition equipment with high sampling rate, high memory capacity and high measuring resolution contained in the scope of delivery, which is to be connected to a PC.

The report in picture 3 is produced with „PicopV“.

Versions 1.0 of „p-V“ and „PicopV“ are suitable for one cylinder of a four stroke piston machine with simple crankshaft, even with piston pin offset. Other versions are available with delay.



10.851/2 gb   Picture 2
Diesel engine

p-V diagram

Crankshaft radius: 27.5 mm
Piston rod length: 95.5 mm
Piston pin offset: 0 mm
Piston diameter: 75 mm
Pressure value: 31.45 bar/V
Relative dead center position: 0.25

Work: 150.7 J

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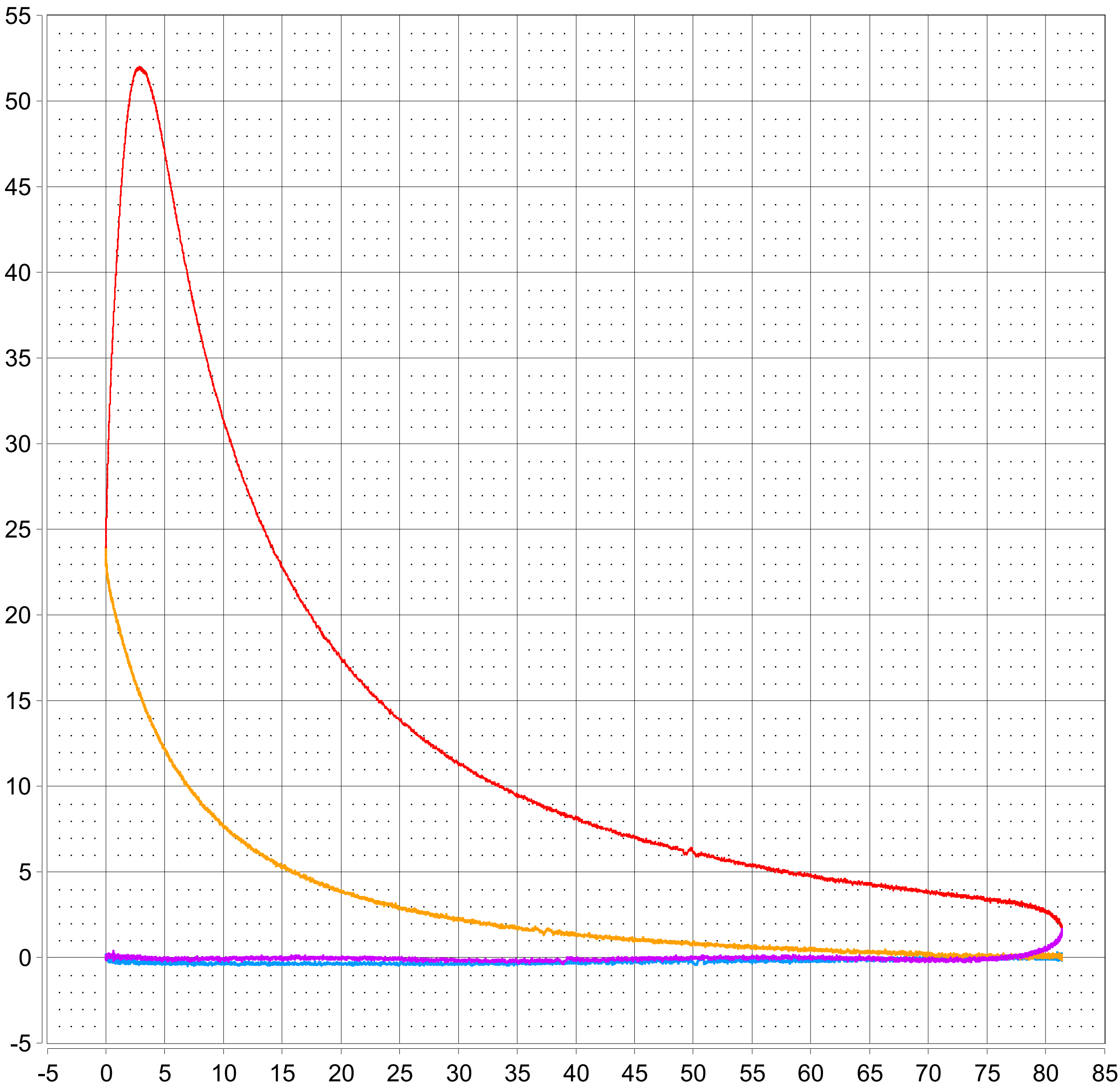
10851b2a X: s/mm Piston position
1: p/bar aspiration
2: p/bar compression
3: p/bar combustion
4: p/bar exhaust



10.851/2 gb   Picture 3
Spark ignition engine

p-V diagram

Crankshaft radius: 40.7 mm
Piston rod length: 137.0 mm
Piston pin offset: 0.0 mm
Piston diameter: 79.0 mm
Pressure value: 29.94 bar/V
Relative dead center position: 0.5683

Computed Work (this measurement): : 406.6 J
Average Work (last 47 measurements): 402.1 J

10851b3
10851b3 X: s/mm Piston position
1: p/bar aspiration
2: p/bar compression
3: p/bar combustion
4: p/bar exhaust