

The hot-air engine as a heat engine:
Recording and evaluating the pV diagram with CASSY

Objects of the experiment

- Recording the pV diagram for different heating voltages.
- Determining the mechanical work per revolution from the enclosed area.

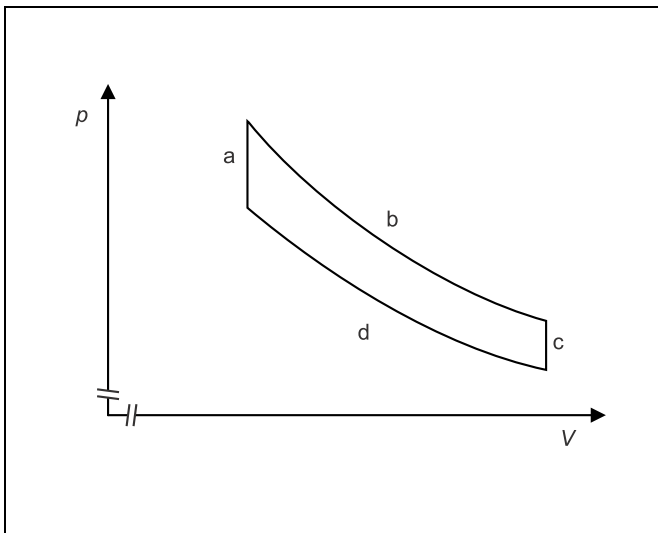


Fig. 1 pV diagram of the Stirling cycle

Principles

The cycle of a heat engine is frequently represented as a closed curve in a pV diagram (p : pressure, V : volume). Here the mechanical work taken from the system is given by the enclosed area:

$$W = -\oint p \cdot dV \quad (I)$$

The cycle of the hot-air engine is often described in an idealised form as a Stirling cycle (see Fig. 1), i. e., a succession of isochoric heating (a), isothermal expansion (b), isochoric cooling (c) and isothermal compression (d). This description, however, is a rough approximation because the working piston moves sinusoidally and therefore an isochoric change of state cannot be expected. In this experiment, the pV diagram is recorded with the computer-assisted data acquisition system CASSY for comparison with the real behaviour of the hot-air engine. A pressure sensor measures the pressure p in the cylinder and a displacement sensor measures the position s of the working piston, from which the volume V is calculated. The measured values are immediately displayed on the monitor in a pV diagram.

Apparatus

1 hot-air engine	388 182
1 U-core with yoke	562 11
1 clamping device	562 12
1 mains coil, 230 V, with 500 turns	562 21
1 extra-low-voltage coil, 50 turns	562 18
1 Sensor-CASSY	524 010
1 CASSY Lab	524 200
1 B box	524 038
1 pressure sensor	529 038
1 multicore cable, 6-pole, 1.5 m long	501 16
1 current supply box	524 031
1 displacement sensor	529 031
1 cord, 10 m	309 48
1 helical spring, 5 N; 0.25 N/cm	352 08

Connection leads

additionally required:

open water vessel (at least 10 l)	
1 submersible pump 12 V	388 181
1 low-voltage power supply	522 16
2 silicone tubings int. dia. 7 × 1.5 mm, 1 m	667 194

or

cooling water feed and runoff

Setup

The experimental setup is illustrated in Fig. 2.

Cooling-water supply:

- Fill at least 10 l of water into the open water vessel, and hang the submersible pump in.
- Connect the output of the submersible pump to the cooling-water inflow of the hot-air engine, and guide the cooling water drain into the water vessel.
- Connect the submersible pump to the low-voltage power supply.

or

- Connect the cooling-water inflow of the hot-air engine to the tap, and guide the cooling-water drain to the runoff.

Connection to CASSY:

- Connect the Sensor-CASSY to the serial input (e.g. COM1) of the computer, and plug the current supply box and the B box in.
- Connect the pressure sensor to the B box via the 6-pole multicore cable.
- Remove the sealing stopper and slide the tubing of the pressure sensor over the tubing shaft at the piston rod.
- Fix the displacement sensor on the base plate of the hot-air engine with two coupling plugs, and connect it to the current supply box.
- Tie the cord to the pin with eye which is connected to the working piston, guide it two times (in order to avoid slip) around the displacement sensor, and tie the other end to the helical spring, which is attached to the eye at the support head, applying a slight tension (in the lower dead centre of the working piston there must already be a tension).

Power supply:

- Mount the cylinder head cap with filament (mind the mark, see instruction sheet of the hot-air engine).
- Turn the flywheel, and check the sealing of the hot-air engine; if necessary slide the tubing of the pressure sensor further on the tubing shaft.
- Set up the dismantlable transformer, and connect the 12-V output to the connector sockets of the cylinder head cap.

Setting CassY Lab:

- Call the CASSY Lab software, and click “Update Setup” in the register “CASSY” of the dialog window “Settings”.
- Click the display of the B box, and select the following settings:
Measurement quantity: “Relative Pressure pB1 (2000 hPa)”
Measuring range: “–2000 hPa ... 2000 hPa”
- Click the display of the current supply box, and select the following settings:
Measurement quantity “Path sA1”
Measuring range: “0 cm ... 15 cm”
- Remove the spring from the eye, and loosen the cord.
- Turn the displacement sensor until approx. sA1 = 7.5 cm is displayed, and attach the spring with the cord to the eye again.

Safety notes

The hot-air engine operated as a heat engine is not self-starting and stops, e.g., after a power failure. Blocking the piston rods and the crankshaft, too, can cause a standstill of the engine. In the case of a standstill, the heat supplied to the cylinder head is not reduced at a sufficient rate.

- Read the instruction sheet of the hot-air engine.
- Do not heat the cylinder head continuously when the engine lies idle.
- Do not leave the hot-air engine unsupervised during operation.
- In the case of a standstill, switch the electric heating off immediately.
- Protect the piston rods and the crankshaft against unauthorized access by putting on the grille.

The glass components of the hot-air engine must not be exposed to excess thermal load.

- Do not operate the hot-air engine without cooling water, and check whether the cooling-water circulation is flawless.
- Do not allow the temperature of the cooling water to exceed 30 °C when the water enters the cooling circuit.
- Heat the filament up to high temperatures (yellow heat) only when the engine runs fast, and do not maintain high temperatures in continuous operation.

Attention: the cylinder-head cap and the connector sockets become very hot during long intervals at maximum calorific power.

- Mount the grille of the cylinder.
- Allow the hot-air engine to cool down before removing the connecting cables or before exchanging the cylinder-head cap.

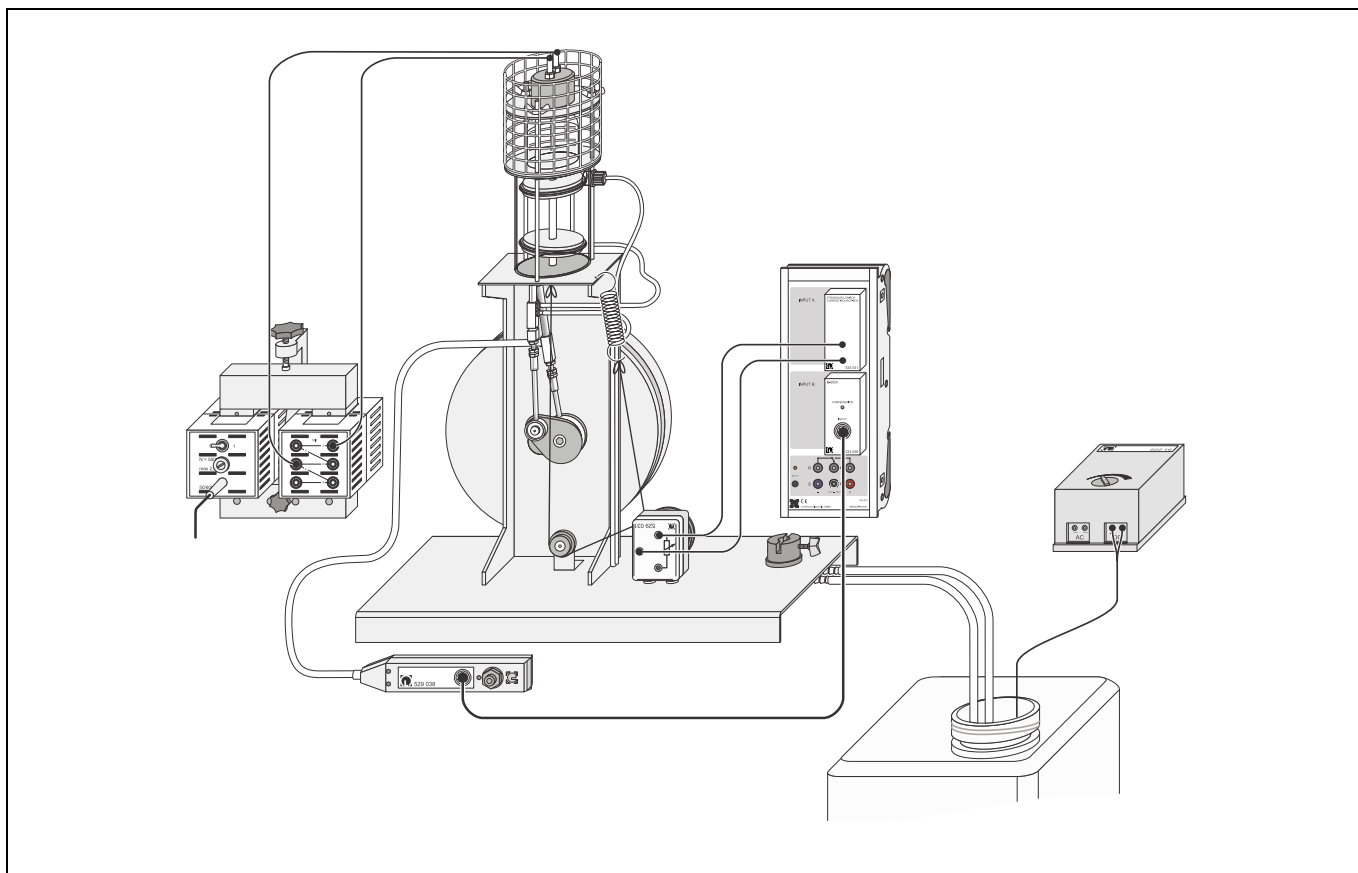


Fig. 2 Experimental setup for recording the pV diagram of the hot-air engine with CASSY, shown without grille of the holder

- Next turn the flywheel by hand and check whether the positions of the working piston are always in the selected measuring range.
- Determine the path s_0 that corresponds to the smallest volume V_0 (upper dead centre of the working piston).
- Introduce a new quantity in the register "Parameter/Formula/FFT" of the dialog window "Settings":
Quantity: Volume, Symbol: V , Unit: cm^3
Formula: $(sA1 - s_0) \cdot 28.3 + 195$ (insert numerical value of s_0).
- Select in the register "Display" of the dialog window "Settings":
x-axis: V , y-axis: $pB1$


Carrying out the experiment

- Switch the cooling-water supply on (for this, set, e.g., the low-voltage power supply to position 2), check the circulation, and wait until the water runs back through the outlet tubing.
- Tap a heating voltage of 10 V, switch the mains coil on, and observe the filament.

As soon as the filament has reached red heat:

- Start the hot-air engine by clockwise rotation of the flywheel.

If the hot-air engine does not get started despite several trials:

- Switch the mains coil off, and check the setup.
- Wait until the operation of the hot-air engine has stabilised.
- Select the following measuring parameters: "Automatic Recording", "Interval: 1 ms", "Number: 250"
- Start the measurement with the button  or the key F9, and record the pV diagram.
- Enhance the heating voltage U step by step up to 16 V, and record the pV diagram each time.
- Set the measuring parameter "Number" to 500, and repeat the recording with the heating voltages 8 and 6 V.

Measuring example and evaluation

Fig. 3 shows the pV diagram recorded at the heating voltage $U = 10\text{ V}$. The course of the curve deviates considerably from the Stirling cycle. This deviation is not surprising at all if the time behaviour of the pressure and the volume shown in Fig. 4 is considered. The volume exhibits a sinusoidal behaviour, i. e., the change of state is not isochoric in any instant.

Tab. 1: Mechanical work $W(10^4\text{ hPa cm}^3 = 1\text{ J})$ per revolution as a function of the heating voltage U

$\frac{U}{V}$	$\frac{W}{J}$
6	1.2
8	1.5
10	1.9
12	2.3
14	2.6
16	2.9

Determining the mechanical work W per revolution :

- Click the diagram with the right mouse button.
- Select the menu item "Calculate Integral \rightarrow Peak Area", and drag the mouse pointer along the measuring curve with the left mouse button held down until the whole cycle is displayed in a colour.

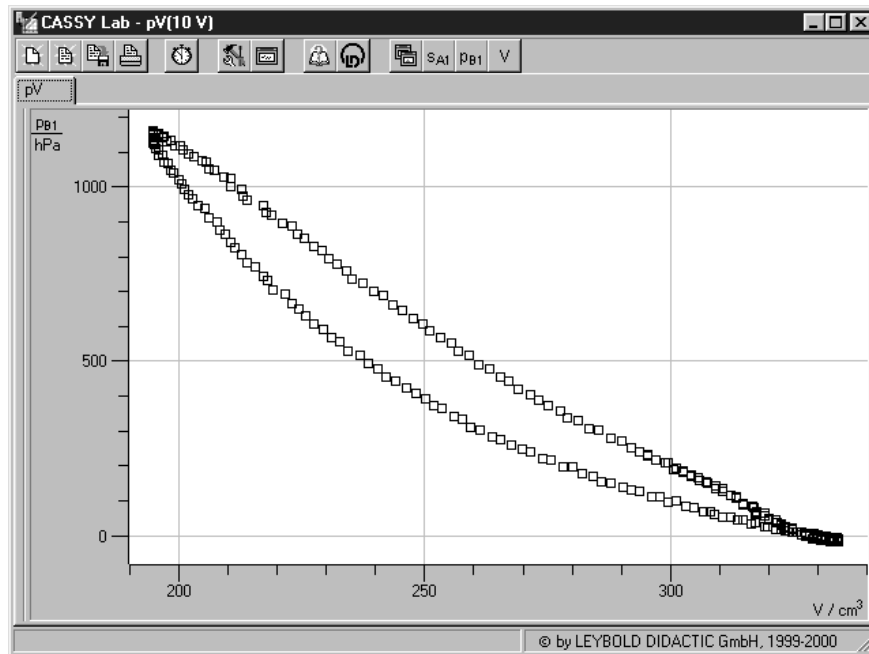


Fig. 3 pV diagram of the hot-air engine at $U = 10\text{ V}$

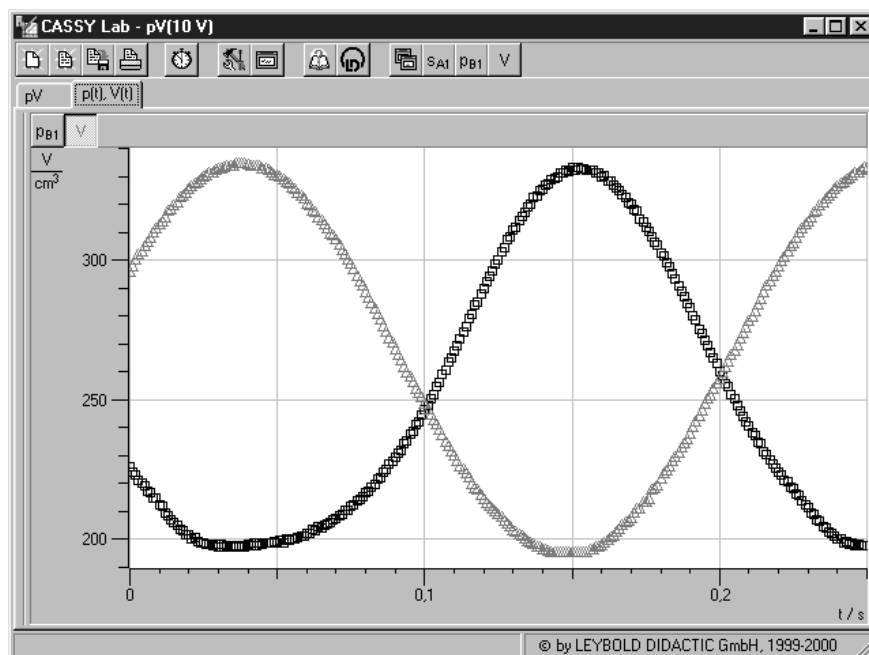


Fig. 4 Relative pressure p and volume V as functions of the time t at $U = 10\text{ V}$.