Heat

Thermodynamic cycle
Hot-air engine: quantitative experiments

LD
Physics
Leaflets

P2.6.2.2

Determining the efficiency of the hot-air engine as a heat engine

Objects of the experiments

- Measuring the heat Q_2 transferred to the cooling water during one revolution.
- Measuring the mechanical work W per revolution.
- Determining the efficiency η of the hot-air engine.

Principles

During one revolution, a hot-air engine takes the heat quantity Q_1 from a reservoir, generates the mechanical work W and transfers the heat Q_2 to a second reservoir. If there are no thermal losses, the inner energy of the system has the same value at the beginning and at the end, and we have

$$Q_1 = Q_2 + W \tag{I}$$

The hot-air engine does not exhibit this ideal behaviour as it is optimized for educational purposes. Transparent parts of the engine make it possible to observe the components during operation and there is no thermal insulation of the cylinder head. A considerable part of the supplied electric energy is “lost” due to heat conduction and heat radiation. This means

$$Q_1 > Q_2 + W \tag{II}$$

The efficiency of a heat engine is usually defined as the ratio

$$\eta = \frac{W}{Q_1} \tag{III}$$

In the case of the hot-air engine, however, it makes more sense to regard the ratio

$$\eta = \frac{W}{Q_2 + W} \tag{IV}$$

as the efficiency.

The heat Q_2 is transferred to the cooling water of the hot-air engine and manifests itself an increase in temperature of the water. However, such an increase in temperature is also caused by frictional losses W_R of the hot-air engine at least as far as friction of the piston in the cylinder in concerned (see P2.6.2.1). These frictional losses have to be taken into account as mechanical work in an energy balance and therefore they have to be added to the mechanical work transmitted to the flywheel.

In the experiment, a Prony brake exerts a torque N on the crankshaft of the hot-air engine (see Fig. 1). The Prony brake decelerates the hot-air engine to a rotational speed f. Then

$$W' = 2\pi \cdot N \tag{V}$$

is the mechanical work transmitted to the crankshaft, and

$$W = W' + W_R \tag{VI}$$

is the total mechanical work per revolution.

The power P transferred to the cooling water is determined from the change in temperature $\Delta\vartheta$:

$$P = c \cdot \rho \cdot \frac{\Delta V}{\Delta t} \cdot \Delta\vartheta \tag{VII}$$

$c = 4.185\ \mathrm{J\,g^{-1}\,K^{-1}}$: specific heat capacity of water,
$\rho = 1\ \mathrm{g\,cm^{-3}}$: density of water
$\frac{\Delta V}{\Delta t}$: volume flow rate of the cooling water

From this we obtain the heat

$$Q'_2 = \frac{P}{f} \tag{VIII}$$

which is transferred to the cooling water, and the heat

$$Q_2 = Q'_2 - W_R \tag{IX}$$

which goes back to the thermodynamic cycle.

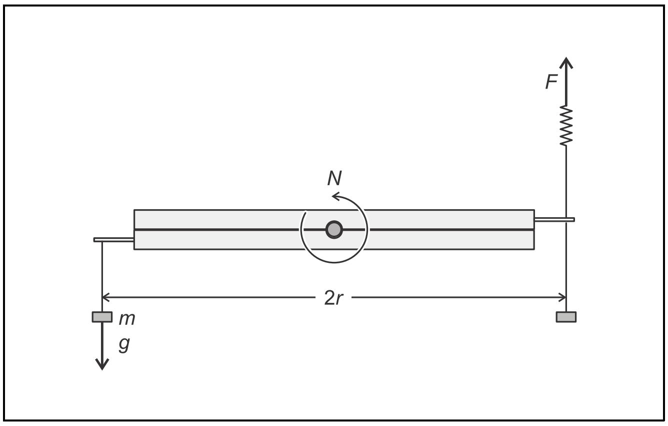


Fig. 1 *Prony* brake for generating a decelerating torque $N = (F + m \cdot g) \cdot r$

Apparatus

1 hot-air engine	388 182
1 accessories for hot-air engine	388 221
1 U-core with yoke	562 11
1 clamping device	562 12
1 mains coil with 500 turns	562 21
1 extra-low-voltage coil, 50 turns	562 18
1 multimeter METRAmax 2	531 100
1 multimeter METRAmax 3	531 712
1 set of 12 weights, 50 g each	342 61
1 precision dynamometer, 1.0 N	314 141
1 counter P	575 45
1 slot sensor, infra-red	337 46
1 transformer, 6 V~,12 V~/30 VA	562 73
1 adapter cable, 4-pole, 1.5 m long	501 18
1 thermometer, –10° to + 40 °C	382 36
1 plastic beaker, 1000 ml	590 06
1 stopclock II, 60 s/30 min	313 17
2 stand bases, V-shape, 20 cm	300 02
1 stand rod, 25 cm	300 41
1 stand rod, 47 cm	300 42
1 stand rod, right-angled	300 51
2 Leybold multiclamps	301 011

connection leads (partly with 2.5 mm^2 cross section)

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.

Temperature measurement in the cooling water:

- Remove the GL14 screwing from the cooling-water outlet of the cylinder head, and mount the temperature adapter **(a)** from the accessories for hot-air engine (see instruction sheet 388 221).
- Insert the thermometer, –10° to + 40 °C, in the temperature adapter, and clamp it with the GL 18 screwing.

Cooling-water supply:

- Fill at least 10 l of water into the open water vessel, and immerse the submersible pump in it.
- 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.

Power supply:

- Mount the cylinder-head cap with filament (heed the mark, see instruction sheet of the hot-air engine).
- Turn the flywheel, and check the packing of the hot-air engine; if necessary, close the hose nozzle for the pressure sensor with a stopper.
- Set up the detachable transformer, and connect the 12-V output to the 4-mm sockets of the cylinder-head cap together with a voltmeter and an ammeter (measuring range 10 A).

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 und 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 educed at a sufficient rate.

- Mind 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.

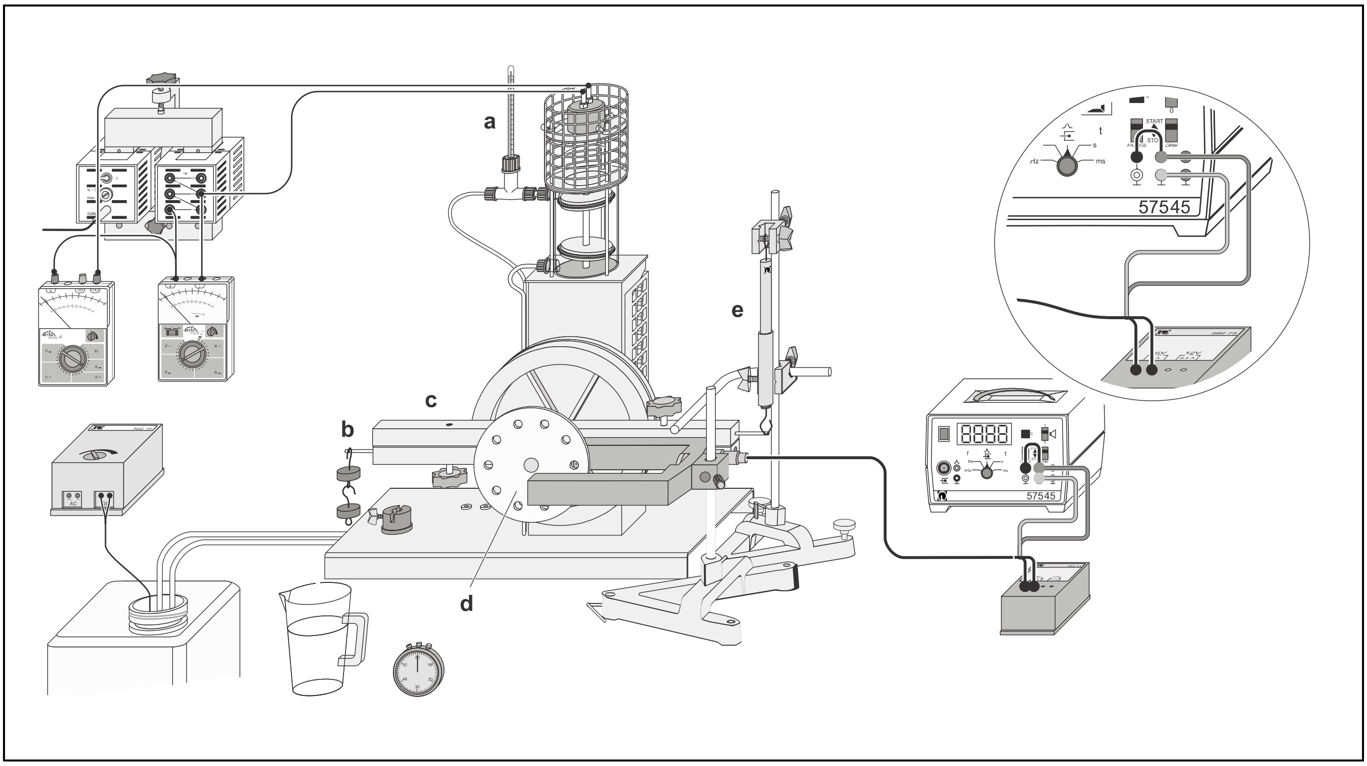


Fig. 2 Experimental setup for determining the efficiency of the hot-air engine operated as a heat engine

Frequency measurement:

- Attach the disc with holes **(d)** from the accessories for hot-air engine to the crankshaft.
- Mount the slot sensor in a stand base, 20 cm, and align it with a hole of the perforated disc, the disc being at rest.
- With the 4-pole adapter cable connect the slot sensor to the 6-V output of the transformer (power supply, black plugs) and to the start input of the counter P (frequency measurement, red and grey plug).
- Drag the start input to the stop input, set the switch to “f”, and switch the counter P on.

Measuring the cooling-water throughput:

- Have the plastic beaker and the stopclock ready.

Carrying out the experiment

a) No-load operation

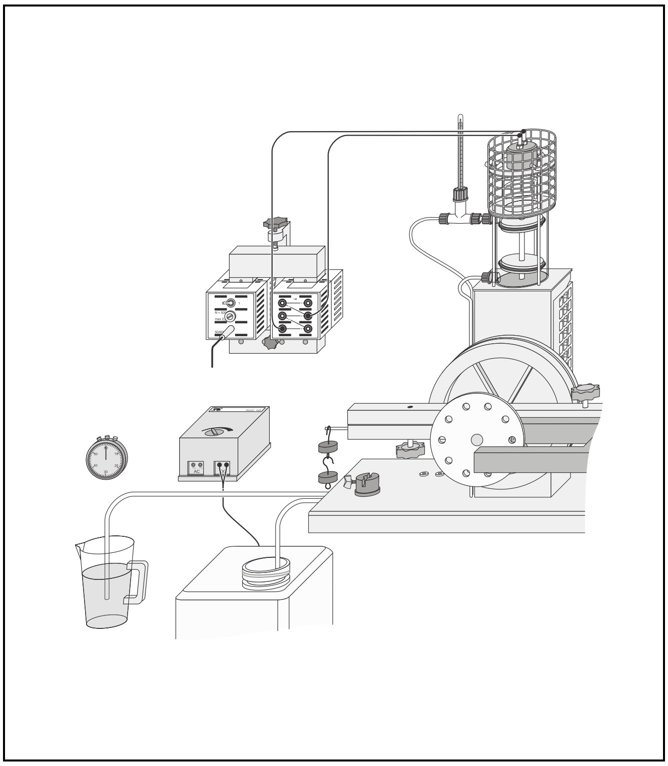
first:

- 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.
- Put the end of the outlet tubing into the plastic beaker, and determine the volume throughput ΔV of the cooling water per time interval Δt (see Fig. 3).
- Measure the temperature ϑ of the water running out every 2 minutes, and wait until the development of the temperature can be uniquely extrapolated.

then:

- Switch the demountable transformer on with an output voltage U = 12 V.

Fig. 3 Determining the volume throughput ΔV per time unit Δt



As soon as the filament is red-hot:

- Start the hot-air engine by turning the flywheel clockwise.

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

- Switch the detachable transformer off, and check the setup.

As soon as the hot-air engine operates autonomously:

- Reduce the heating voltage to U = 8 V.

- Measure the rotational speed f of the hot-air engine, and take it down.

  The rotational speed of the engine is obtained from the measured frequency and the number of holes in the perforated disc.
- Continue measuring the temperature ϑ of the cooling water every 2 minutes, observe the increase in temperature, and wait until the temperature has reached its maximum value.

next:

- Switch the detachable transformer off , and continue observing the development of the temperature.
- Determine the temperature change $\Delta\vartheta$ of the cooling water, record it.

Remark:

If the volume of the available cooling water is too small, the temperature of the vessel will also rise. The measured temperature change $\Delta\vartheta$ has then to be corrected correspondingly.

- Repeat the measurement at the heating voltages U = 10 V, 12 V and 14 V.

b) Operation with Prony brake:

first:

- Put the two parts of the Prony brake **(c)** on the crankshaft of the hot-air engine, slightly fasten the knurled screws, and align the brake horizontally.
- Mount the stand rod, 47 cm, in a stand base, 20 cm, and attach the right-angled stand rod.
- Attach the precision dynamometer 1.0 N **(e)** to the stand rod with a Leybold multiclamp, fasten it to the “right” eye of the Prony brake, and set the zero of the dynamometer.

next:

Remark:

The mechanical load must not lead to a standstill of the engine. In case of a standstill, immediately restart the engine by hand, or switch the heating off.

- Adjust the desired frictional force by screwing the two parts of the Prony brake together.
- In order to balance the frictional force, suspend a 50-g weight **(b)** from the left end.
- Operate the hot-air engine at the heating voltage U = 14 V, and observe how the temperature of the cooling water develops.
- Read the force F from the precision dynamometer.

  Decelerating torque: $N = (F + m \cdot g) \cdot 0.25$ m
- Determine the increase in temperature of the cooling water.

- Enhance the frictional force of the Prony brake, and repeat the measurement.

Measuring example

Volume throughput of the cooling water: 780 cm^3 in 5 min

$$\frac{\Delta V}{\Delta t} = \frac{780\ \text{cm}^3}{300\ \text{s}} = 2.6\ \frac{\text{cm}^3}{\text{s}}$$

a) No-load operation:

Table 1: Measured values for no-load operation.

$\frac{U}{\text{V}}$	$\frac{I}{\text{A}}$	$\frac{f}{\text{s}^{-1}}$	$\frac{\Delta\vartheta}{°\text{C}}$
8	7.6	1.6	3.3
10	9.4	4.2	5.3
12	>10	6.0	7.7
14	>10	7.4	10.0

b) Operation with Prony brake:

Table 2: Measured values for operation with Prony brake (heating voltage U = 14 V)

$\frac{f}{\text{s}^{-1}}$	$\frac{\Delta\vartheta}{°\text{C}}$	$\frac{m}{50\ \text{g}}$ *	$\frac{F}{\text{N}}$ *
6.0	8.6	1	0.13
5.3	8.2	1	0.33
4.2	6.6	2	0.10

* decelerating torque: $N = (F + m \cdot g) \cdot 0.25$ m

Evaluation and results

In Table 3, the data calculated from the measured values are listed as functions on the heating voltage U and the decelerating torque N: the rotational speed f of the hot-air engine achieved in each case, the frictional work W_R of the piston (taken from experiment P2.6.1.1), the heat Q_2 transferred to the cooling water by the thermodynamic cycle during one revolution (calculated according to (VII)-(IX)) and the total mechanical work W (calculated according to (V) and (VI) performed during one revolution.

From the last two quantities, the efficiency η is obtained according to (IV) (see Table 4). Figs. 4–6 are plots of f as a function of U and N respectively, and of Q and W as functions of f.

Table 3:

$\frac{U}{\mathrm{V}}$	$\frac{N}{\mathrm{N \cdot m}}$	$\frac{f}{\mathrm{s}^{-1}}$	$\frac{W_R}{\mathrm{J}}$	$\frac{W}{\mathrm{J}}$	$\frac{Q_2}{\mathrm{J}}$
8	0	1.6	2.6	2.6	19.8
10	0	4.2	1.0	1.0	12.7
12	0	6.0	1.0	1.0	13.0
14	0	7.4	1.0	1.0	13.7
14	0.16	6.0	1.0	2.0	14.6
14	0.21	5.3	1.0	2.3	15.8
14	0.27	4.2	1.0	2.7	16.1

Table 4:

$\frac{U}{\mathrm{V}}$	$\frac{N}{\mathrm{N \cdot m}}$	$\frac{f}{\mathrm{s}^{-1}}$	η
8	0	1.6	0.12
10	0	4.2	0.07
12	0	6.0	0.08
14	0	7.4	0.07
14	0.16	6.0	0.12
14	0.21	5.3	0.13
14	0.27	4.2	0.14

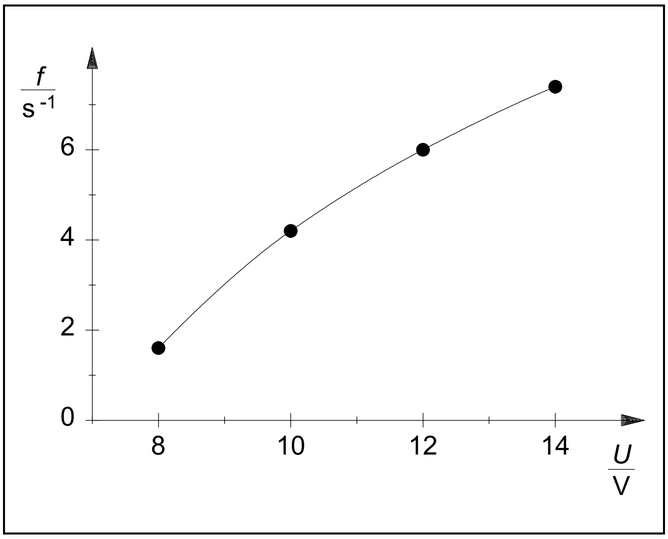


Fig. 4 Rotational speed f of the hot-air engine in no-load operation as a function of the heating voltage U.

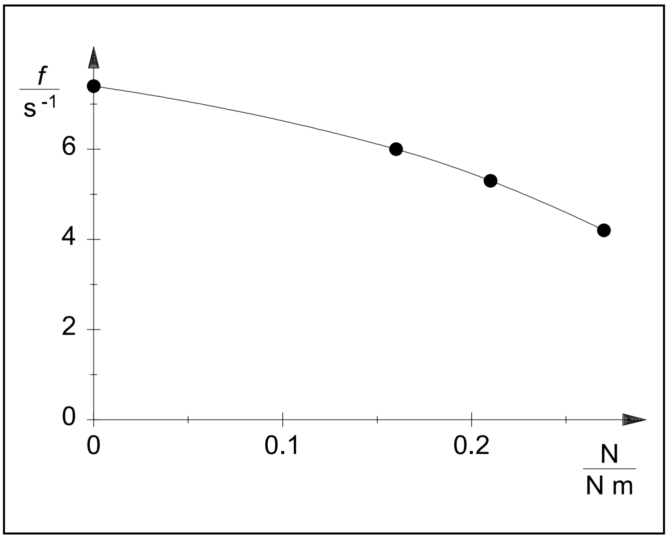


Fig. 5 Rotational speed f of the hot-air engine as a function of the decelerating torque N (at the heating voltage U = 14 V).

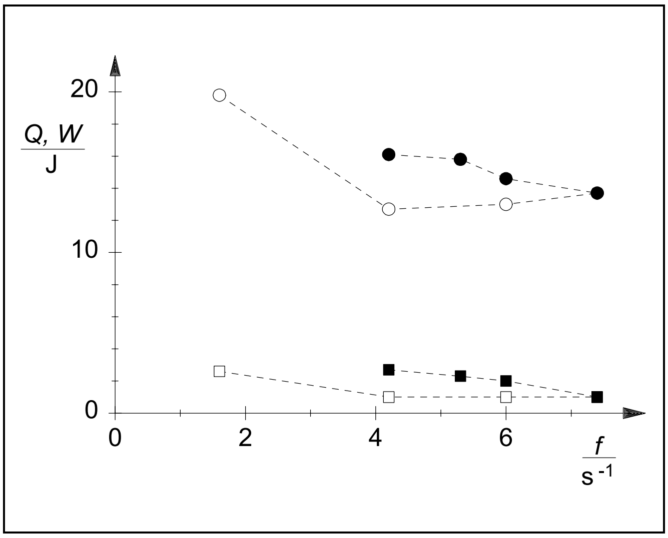


Fig. 6 The quantities Q_2 and W as functions of the rotational speed f
● : heat Q_2 in decelerated operation
○ : heat Q_2 in no-load operation
■ : mechanical work W in decelerated operation
□ : mechanical work W in no-load operation