Heat

Thermodynamic cycle
Hot-air engine: quantitative experiments

Frictional losses in the hot-air engine (calorific determination)

Objects of the experiments

■ Measuring the warming of the cooling water due to the friction of the hot-air engine's piston.

■ Determining the frictional work of the hot-air engine's piston per revolution.

Principles

Operated as a heat-engine, the hot-air engine takes the heat quantity Q_1 per revolution from a reservoir 1, generates the mechanical work W and transfers the difference

$$Q_2 = Q_1 - W \qquad\qquad\qquad (I)$$

to a reservoir 2. If the hot-air engine is operated as a refrigerator, the mechanical work W is supplied from outside, the sense of rotation being the same. In this case, too, a heat quantity Q_1 is taken from reservoir 1, and a heat quantity Q_2 is transferred to reservoir 2.

In both cases, losses occur which enter the energy balance of the hot-air engine. For example, a certain amount of mechanical energy (frictional work) per revolution is expended on friction of the piston in the cylinder and on bearing friction and thereby transformed into thermal energy (heat). The frictional work of the piston in the cylinder can be determined quantitatively as it causes warming of the cooling water. Bearing friction escapes this measurement.

In the experiment, the frictional work of the piston is determined by measuring the temperature increase $\Delta\vartheta$ in the cooling water while the hot-air engine is driven with an electric motor, the cylinder head being open. The power transferred to the cooling water is

$$P = c \cdot \rho \cdot \frac{\Delta V}{\Delta t} \cdot \Delta\vartheta \qquad\qquad (II)$$

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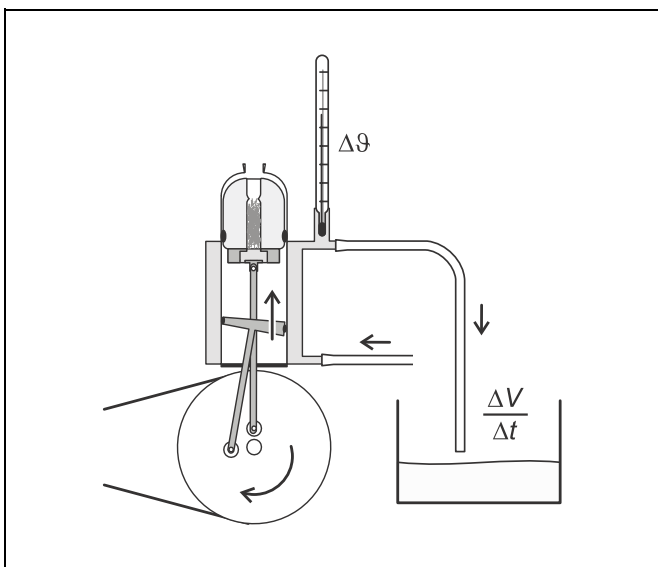$\rho = 1$ g cm^{-3}: density of water
$\dfrac{\Delta V}{\Delta t}$: volume throughput of the cooling water

The searched-for frictional work per revolution is calculated from this as follows:

$$W_R = \frac{P}{f} \qquad\qquad\qquad (III).$$

f: rotational speed of the hot-air engine

Calorific determination of the frictional losses in the hot-air engine

Apparatus

1 hot-air engine	388 182
1 accessories for hot-air engine	388 221
1 thermometer, −10° to + 40 °C	382 36
1 experiment motor	347 35
1 control unit for experiment motor	347 36
1 counter P	575 45
1 forked light barrier, 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 connection lead, 25 cm, red	500 411
1 plastic beaker, 1000 ml	590 06
1 stopclock II, 60s/30 min	313 17
1 stand base, V-shape, 20 cm	300 02
2 stand rods, 25 cm	300 41

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 inlet and outlet

Safety notes

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

■ Mind the instruction sheet of the hot-air engine.

■ 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.

Setup

The experimental setup is illustrated in Fig. 1.

Temperature measurement:

– Remove the GL14 screwing from the cooling-water outlet of the cylinder head, and mount the temperature adapter **(c)** from the accessories for hot-air engine (see instruction sheet 388 221).

– Insert the thermometer 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 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.

– If necessary, loosen the GL screwing for a short time, allow the water to rise a bit in the glass tube, and fasten the GL screwing.

Setting up and operating the hot-air engine:

– Remove the cylinder-head cap (see instruction sheet of the hot-air engine).

– If necessary, close the hose nozzle for the pressure sensor with a stopper.

– Mount the electric motor, and connect it to the control unit.

– Put the driving belt on the flywheel and the driving disc, and tighten it by slewing the electric motor.

Measuring the frequency:

– Attach the disc with holes from the accessories for hot-air engine to the crankshaft.

– Mount the forked light barrier on the stand material, and align it with a hole of the standing disc with holes.

– With the 4-pole adapter cable connect the forked light barrier 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 green 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.
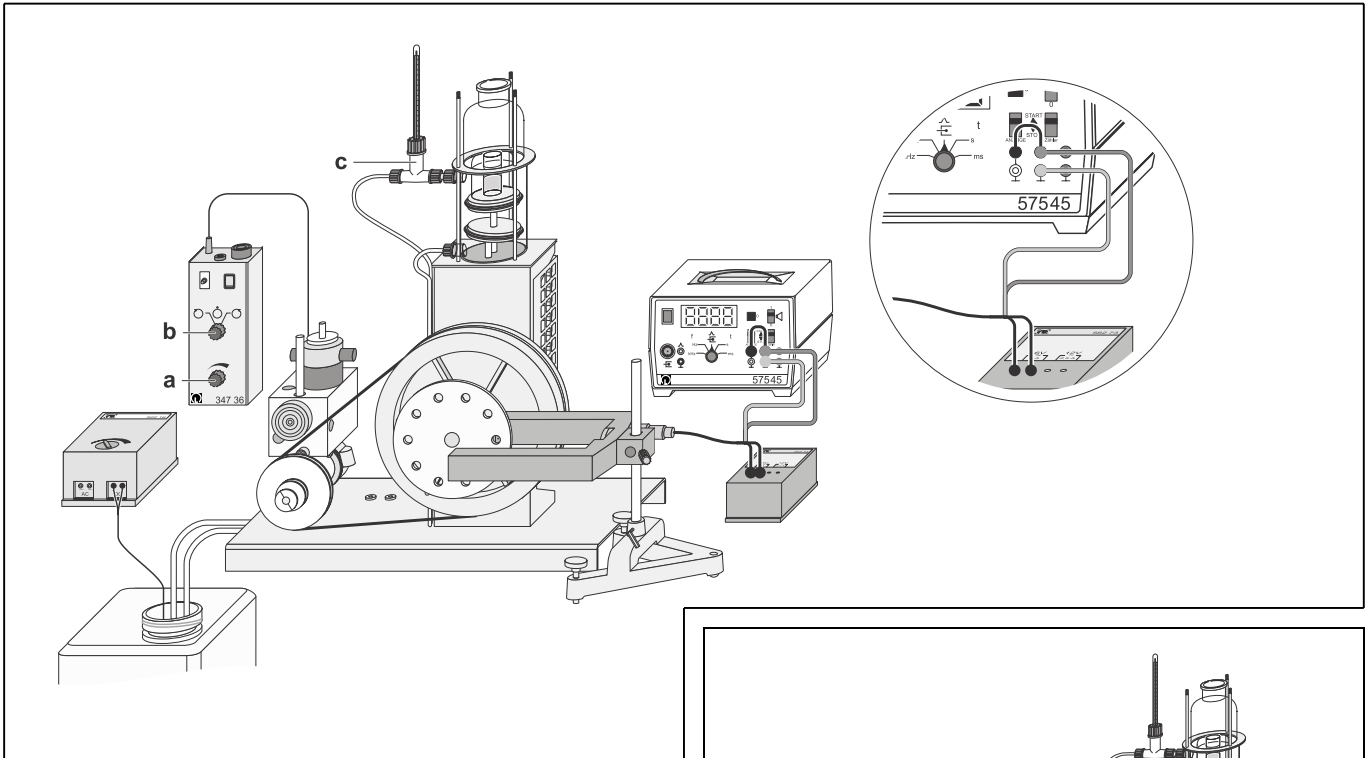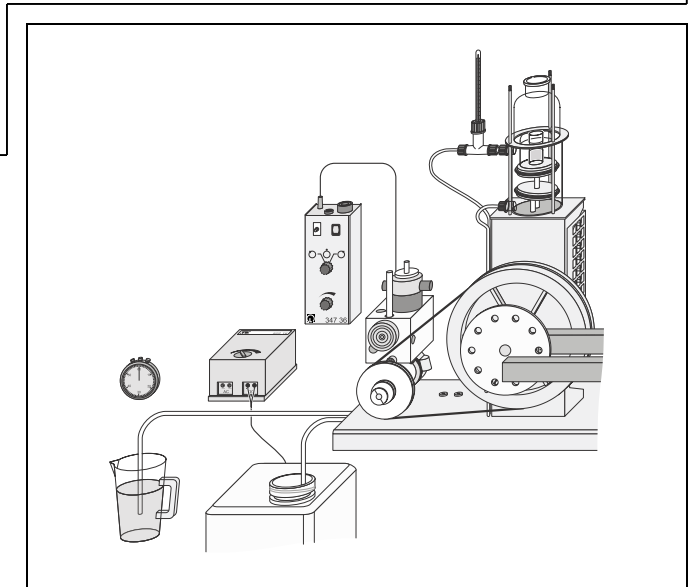
Fig. 1   Experimental setup for the calorific determination of the
         frictional losses in the hot-air engine

Fig. 2   Determining the volume throughput ΔV per time unit Δt

Carrying out the experiment

–   Set the direction switch **(b)** to the middle position (stand-
    still), set the speed adjusting knob **(a)** to the middle posi-
    tion, and switch the control unit on.

–   Switch the cooling-water supply on (for this, set, e.g., the
    low-voltage power supply to position 2), check the circula-
    tion, and wait until the water runs back through the outlet
    tubing.

–   Measure the temperature of the water running out every 2
    minutes, and wait until the development of the temperature
    can be uniquely extrapolated.

–   Set the direction switch to clockwise running of the hot-air
    engine, and measure the rotational speed of the hot-air
    engine.

    The rotational speed of the engine is obtained from the
    measured frequency and the number of holes in the per-
    forated disc.

–   Continue measuring the temperature of the water running
    out every 2 minutes, observe the temperature increase, and
    wait until the development of the temperature can be
    uniquely extrapolated.

–   When the temperature has reached its maximum value,
    switch the clockwise running of the engine off, continue
    measuring the temperature of the cooling water every 2
    minutes until the development of the temperature can be
    uniquely extrapolated.

–   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. 2).

–   Vary the rotational speed with the speed adjusting knob **(a)**,
    and repeat the measurement.

Measuring example

Volume throughput of the cooling water: 420 cm^3 in 5 min

Table 1: Temperature of the cooling water measured in time
intervals of 2 minutes (the electric motor was switched on after
10 minutes and switched off after 32 minutes). Rotational
speed: $f = 1.6$ s^{-1}

$\dfrac{t}{\text{min}}$	$\dfrac{\vartheta}{°\text{C}}$	$\dfrac{t}{\text{min}}$	$\dfrac{\vartheta}{°\text{C}}$
0	21.8	24	22.1
2	21.7	26	22.2
4	21.6	28	22.2
6	21.55	30	22.2
8	21.5	32	22.2
10	21.5	34	22.1
12	21.6	36	22.0
14	21.8	38	21.8
16	21.9	40	21.6
18	22.0	42	21.6
20	22.0	44	21.5
22	22.1	46	21.5

Table 2: Temperature changes $\Delta\vartheta$ of the cooling water measured for different rotational speeds f of the hot-air engine.

$\dfrac{f}{s^{-1}}$	$\dfrac{\Delta\vartheta}{°C}$
1.1	0.6
1.6	0.7
2.2	0.4
2.7	0.5
3.4	0.6

Table 3: Values of the frictional work per revolution W_R determined in dependence on the rotational speed f.

$\dfrac{f}{s^{-1}}$	$\dfrac{W_R}{J}$
1.1	3.2
1.6	2.6
2.2	1.1
2.7	1.1
3.4	1.0

Evaluation

Fig. 3 is an example of a plot showing the development of the temperature of the cooling water while the water is heated by the friction of the piston at the rotational speed $f = 1.6\ s^{-1}$ (see Table 1). From the figure one reads the temperature change $\Delta\vartheta = 0.7\ °C$.

The volume throughput is

$$\frac{\Delta V}{\Delta t} = \frac{420\ cm^3}{300\ s} = 1.4\ \frac{cm^3}{s}$$

According to Eqs. (II) and (III), the power transferred to the cooling water is $P = 4.1\ W$, and the frictional work per revolution thus is $W_R = 2.6\ J$.

In Table 3, the corresponding values are compiled. They are obtained from the temperature changes for different rotational speeds f given in Table 2. Fig. 4 is a plot of theses values.

Results

Part of the work of the hot-air engine operated as a heat-engine is transformed into heat due to frictional work and then transferred to the cooling water. The frictional work per revolution depends on the rotational speed of the hot-air engine.

Fig. 3   Development of the temperature of the cooling water while the water is heated by the friction of the piston in the cylinder. Rotational speed: $f = 1{,}6\ s^{-1}$
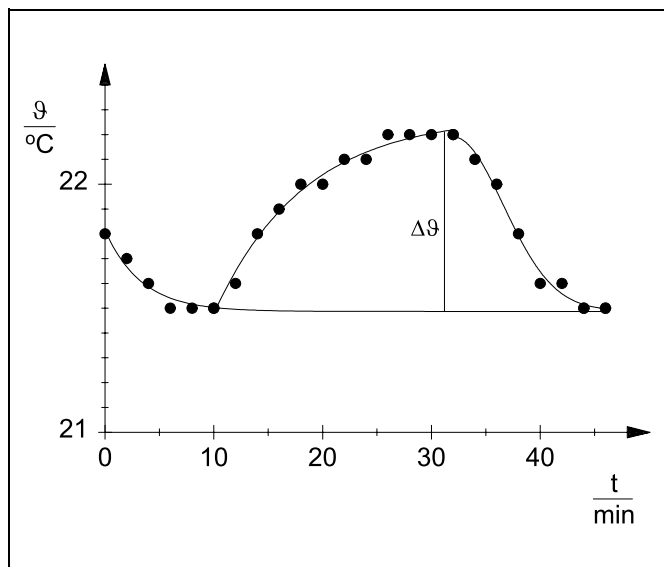

Fig. 4   Frictional work W_R per revolution as a function of the rotational speed f on the hot-air engine