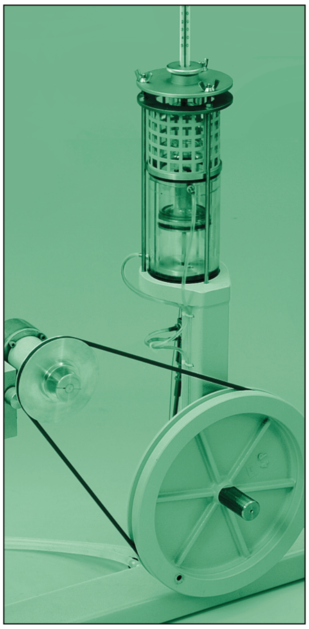
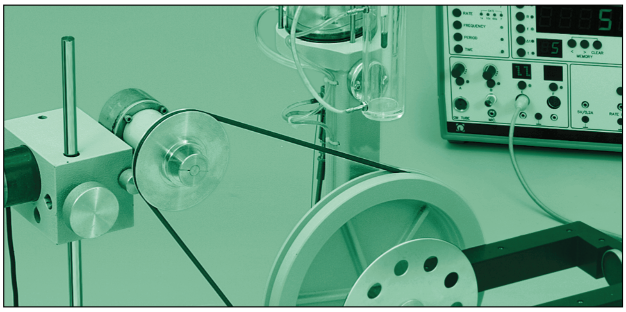
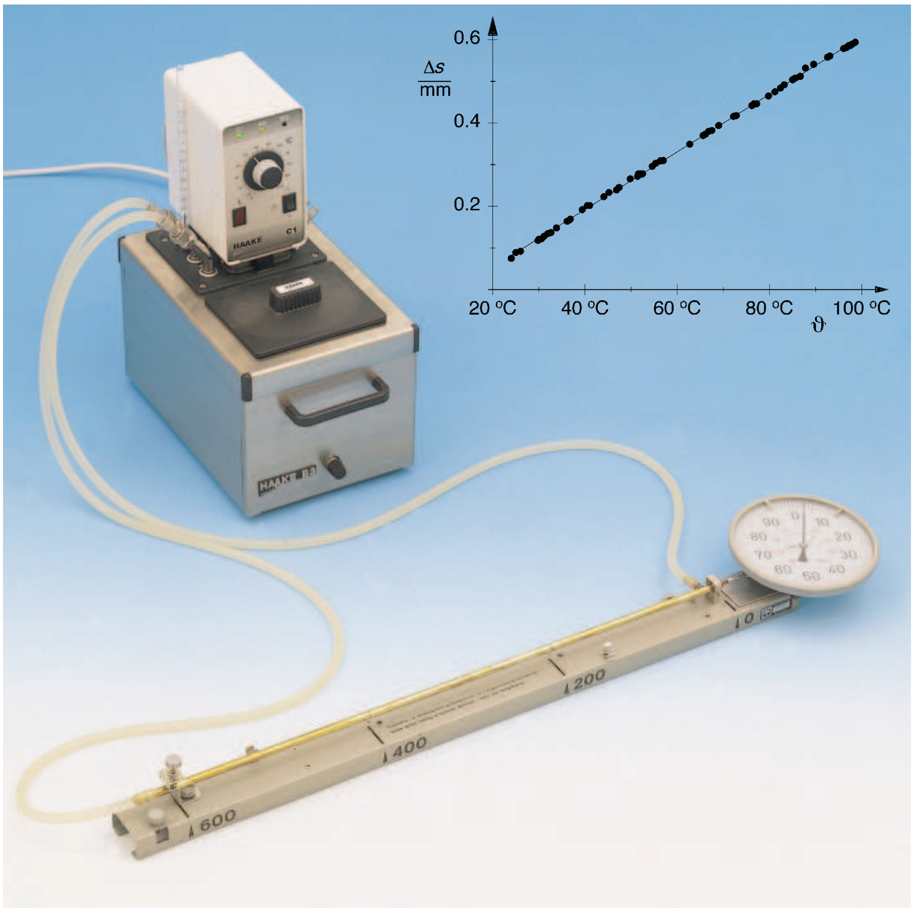




P2

Heat

P2 Heat



Measuring the longitudinal expansion of solid bodies as a function of temperature (P 2.1.1.3)

P 2.1.1

Thermal expansion of solid bodies

P 2.1.1.1 Thermal expansion of solid bodies – measuring using STM equipment

P 2.1.1.2 Thermal expansion of solid bodies – measuring using the expansion apparatus

P 2.1.1.3 Measuring the longitudinal expansion of solid bodies as a function of temperature

Cat. No.	Description	P 2.1.1.1	P 2.1.1.2	P 2.1.1.3
381 331	Pointer for linear expansion	1		
381 332	Al-tube, l = 22 cm, d = 8 mm	1		
381 333	Fe-tube, l = 44 cm, d = 8 mm	1		
340 82	Dual scale	1		
314 04	Support clip, for plugging in	2		
301 21	Stand base MF	2		
301 27	Stand rod, 50 cm, 10 mm dia.	2		
301 26	Stand rod, 25 cm, 10 mm dia.	1		
301 25	Clamping block MF	2		
301 09	Bosshead S	2		
666 555	Universal Bunsen clamp S	1		
664 248	Erlenmeyer flask, 50 ml	1		
200 69304	Rubber stopper with hole	1		
665 226	Connector, straight, 6 .... 8 mm dia.	1		
667 194	Tubing, silicone, int. dia. 7 mm/1.5 mm, 1 m	1	1	2
664 183	Petri dish, 100 x 20 mm	1		
311 78	Tape measure, 1.5 m / 1 mm	1		
303 22	Alcohol burner, metal	1		
381 341	Expansion apparatus		1	1
361 15	Dial gauge		1	1
381 36	Holder for dial gauge		1	1
382 34	Thermometer, -10 to +110 °C		1	1
303 28	Steam generator, 550 W/230 V		1	
664 185	Petri dish, 150 x 25 mm		1	
666 768	Circulation thermostat 30 ... 100 °C			1
666 7703	Pump set			1

The relationship between the length s and the temperature ϑ of a liquid is approximately linear:

$$s = s_0 \cdot (1 + \alpha \cdot \vartheta)$$

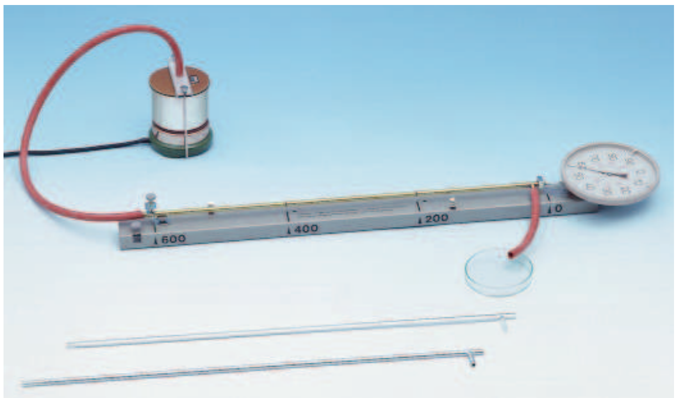
s_0: length at 0°C, ϑ: temperature in °C

The linear expansion coefficient α is determined by the material of the solid body. We can conduct measurements on this topic using e.g. thin tubes through which hot water or steam flows.

In the first experiment, steam is channeled through different tube samples. The thermal expansion is measured in a simple arrangement, and the dependency on the material is demonstrated.

The second experiment measures the increase in length of various tube samples between room temperature and steam temperature using the expansion apparatus. The effective length s_0 of each tube can be defined as 200, 400 or 600 mm.

In the final experiment, a circulation thermostat is used to heat the water, which flows through various tube samples. The expansion apparatus measures the change in the lengths of the tubes as a function of the temperature ϑ (cf. diagram).


Thermal expansion of solid bodies – measuring using the expansion apparatus (P 2.1.1.2)

P 2.1.2

Thermal expansion of liquids

P 2.1.2.1 Determining the volumetric expansion coefficient of liquids

Determining the volumetric expansion coefficient of liquids (P 2.1.2.1 b)

In general, liquids expands more than solids when heated. The relationship between the Volume V and the temperature ϑ of a liquid is approximately linear here:

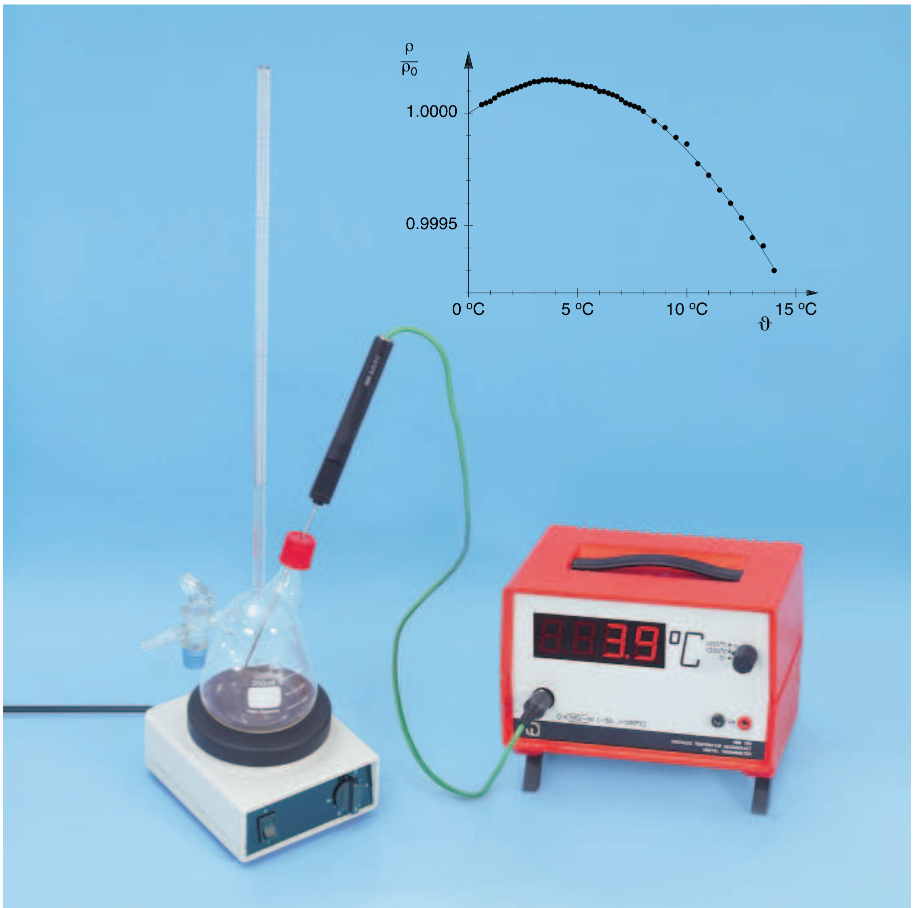
$$V = V_0 \cdot (1 + \gamma \cdot \vartheta)$$

V_0: volume at 0°C, ϑ: temperature in °C

When determining the volumetric expansion coefficient γ, it must be remembered that the vessel in which the liquid is heated also expands.

In this experiment, the volumetric expansion coefficients of water and methanol are determined using a volume dilatometer made of glass. An attached riser tube with a known cross-section is used to measure the change in volume. i. e. the change in volume is determined from the rise height of the liquid.

Cat. No.	Description	P 2.1.2.1 (a)	P 2.1.2.1 (b)	P 2.1.2.1 (c)
382 15	Dilatometer, 50 ml	1	1	1
382 34	Thermometer, -10° to + 110 °C	1		
666 193	Temperature sensor NiCr-Ni		1	
666 190	Digital thermometer with 1 input		1	
315 05	School and laboratory balance 311, 311 g	1	1	1
666 767	Hot plate, 150 mm dia., 1500 W	1	1	1
664 104	Beaker, 400 ml, ss., hard glass	1	1	1
300 02	Stand base, V-shape, 20 cm	1	1	1
300 42	Stand rod, 47 cm	1	1	1
301 01	Leybold multiclamp	2	2	2
666 555	Universal clamp, 0...80 mm dia.	2	2	2
671 9720	Ethanol, fully denatured, 1 l	1	1	1
524 009	Mobile-CASSY			1
524 0673	NiCr-Ni Adapter S			1
529 676	NiCr-Ni temperatrue sensor 1.5 mm			1



Investigating the density maximum of water (P 2.1.3.1 b)

P 2.1.3

Thermal anomaly of water

P 2.1.3.1 Investigating the density maximum of water

Cat. No.	Description	P 2.1.3.1 (a)	P 2.1.3.1 (b)	P 2.1.3.1 (c)
667 505	Device for demonstrating the anomaly of water	1	1	1
382 36	Thermometer, -10° to + 40 °C	1		
666 190	Digital thermometer with 1 input		1	
666 193	Temperature sensor NiCr-Ni		1	
666 845	Magnetic stirrer, 0...2000 rpm	1	1	1
664 195	Glass tank, 300 x 200 x 150 mm	1	1	1
665 008	Funnel, 50 mm dia., plastic	1	1	1
307 66	Rubber tubing, i. d. 8 mm	1	1	1
300 02	Stand base, V-shape, 20 cm	1	1	1
300 42	Stand rod, 47 cm	1	1	1
301 01	Leybold multiclamp	1	1	1
301 10	Clamp with ring	1	1	1
666 555	Universal Bunsen clamp S	1	1	1
524 009	Mobile-CASSY			1
524 0673	NiCr-Ni Adapter S			1
529 676	NiCr-Ni temperatrue sensor 1.5 mm			1

When heated from a starting temperature of 0 °C, water demonstrates a critical anomaly: it has a negative volumetric expansion coefficient up to 4 °C, i.e. it contracts when heated. After reaching zero at 4 °C, the volumetric expansion coefficient takes on a positive value. As the density corresponds to the reciprocal of the volume of a quantity of matter, water has a density maximum at 4 °C.

This experiment verifies the density maximum of water by measuring the expansion in a vessel with riser tube. Starting at room temperature, the complete setup is cooled in a constantly stirred water bath to about 1 °C, or alternatively allowed to gradually reach the ambient temperature after cooling in an ice chest or refrigerator. The rise height h is measured as a function of the temperature ϑ. As the change in volume is very slight in relation to the total volume V_0, we obtain the density

$$\rho(\vartheta) = \rho(0\ °\mathrm{C}) \cdot \left(1 - \frac{A}{V_0} \cdot h(\vartheta)\right)$$

A: cross-section of riser tube

P 2.2.1

Thermal conduction

P 2.2.1.1 Determining the heat conductivity of building materials using the single-plate method

P 2.2.1.2 Determining the heat conductivity of building materials with the aid of a reference material of known thermal conductivity

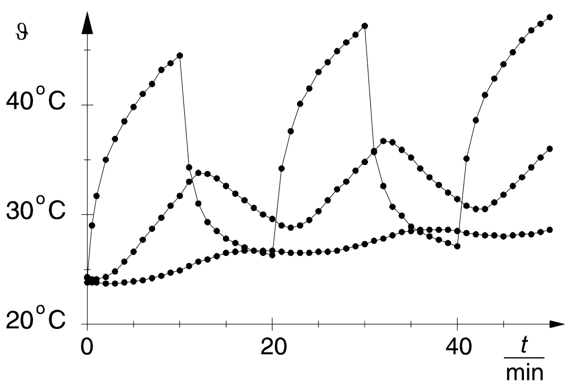
P 2.2.1.3 Damping of temperature variations using multi-layer walls

Determining the heat conductivity of building materials with the aid of a reference material of known thermal conductivity (P 2.2.1.2)

In the equilibrium state, the heat flow through a plate with the cross-section area A and the thickness d depends on the temperature difference $\vartheta_2 - \vartheta_1$ between the front and rear sides and on the thermal conductivity λ of the plate material:

$$\frac{\Delta Q}{\Delta t} = \lambda \cdot A \cdot \frac{\vartheta_2 - \vartheta_1}{d}$$

The object of the first two experiments is to determine the thermal conductivity of building materials. In these experiments, sheets of building materials are placed in the heating chamber and their front surfaces are heated. The temperatures ϑ_1 and ϑ_2 are measured using measuring sensors. The heat flow is determined either from the electrical power of the hot plate or by measuring the temperature using a reference material with known thermal conductivity λ_0 which is pressed against the sheet of the respective building material from behind.

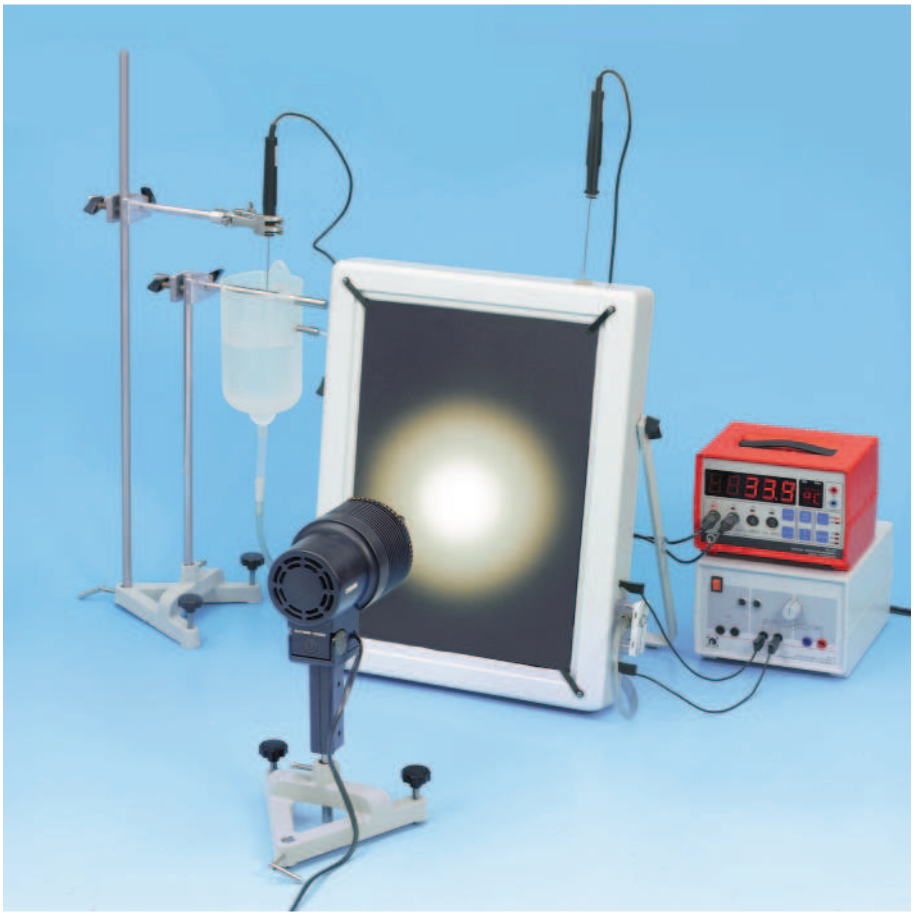


Temperature variations in multi-layer walls (P 2.2.1.3)

Cat. No.	Description	P 2.2.1.1	P 2.2.1.2	P 2.2.1.3
389 29	Calorimetric chamber	1	1	1
389 30	Set of building materials for calorimetric chamber	1	1	1
521 25	Transformer 2....12 V	1	1	1
666 198	Digital temperature controller and indicator	1		
666 190	Digital thermometer with 1 input	1*		
666 209	Digital thermometer with 4 inputs		1	1
666 193	Temperature sensor NiCr-Ni	2	3	3
531 120	Ammeter, AC, $I < 2$ A, e.g. Multimeter LDanalog 20	1		
531 120	Voltmeter, AC, $U < 12$ V, e.g. Multimeter LDanalog 20	1		
313 17	Stopclock II, 60 s/30 min	1		1
450 64	Halogen lamp housing, 12 V, 50/100 W			1
450 63	Halogen lamp, 12 V/100 W			1
300 11	Saddle base			1
501 33	Connecting lead, 100 cm, black, Ø 2,5 mm^2	3	2	2
501 46	Pair of cables, 100 cm, red and blue	1		

* *alternatively:* digital thermometer with 4 inputs (666 209)

The final experiment demonstrates the damping of temperature variations by means of two-layer walls. The temperature changes between day and night are simulated by repeatedly switching a lamp directed at the outside surface of the wall on and off. This produces a temperature “wave” which penetrates the wall; the wall in turn damps the amplitude of this wave. This experiment measures the temperatures ϑ_A on the outer surface, ϑ_Z between the two layers and ϑ_I on the inside as a function of time.



Determining the efficiency of a solar collector as a function of the throughput volume of water (P 2.2.2.1)

P 2.2.2
Solar collector

P 2.2.2.1 Determining the efficiency of a solar collector as a function of the throughput volume of water

P 2.2.2.2 Determining the efficiency of a solar collector as a function of the thermal insulation

Cat. No.	Description	P 2.2.2.1-2 (a)	P 2.2.2.1-2 (b)
389 50	Solar collector	1	1
579 220	STE water pump 10 V	1	1
450 70	Flood light lamp, 1000 W	1	1
521 35	Variable extra-low voltage transformer S	1	1
666 209	Digital thermometer with 4 inputs	1	
666 193	Temperature sensor NiCr-Ni	2	
524 009	Mobile-CASSY		1
524 0673	NiCr-Ni Adapter S		1
529 676	NiCr-Ni temperature sensor 1.5 mm		2
311 77	Steel tape measure, 2 m	1	1
313 17	Stopclock II, 60 s/30 min	1	1
300 02	Stand base, V-shape, 20 cm	2	2
300 41	Stand rod, 25 cm	1	1
300 42	Stand rod, 47 cm	1	1
300 43	Stand rod, 75 cm	1	1
301 01	Leybold multiclamp	3	3
666 555	Universal clamp, 0...80 mm dia.	1	1
590 06	Plastic beaker, 1000 ml	1	1
604 431	Silicone tubing, i.d. 5 mm	1	1
604 432	Silicone tubing, i.d. 6 mm	1	1
604 434	Silicone tubing, i.d. 8 mm	1	1
665 226	Connector, straight, 6/8 mm	1	1
501 46	Pair of cables, 100 cm, red and blue	1	1

A solar collector absorbs radiant energy to heat the water flowing through it. When the collector is warmer than its surroundings, it loses heat to its surroundings through radiation, convection and heat conductivity. These losses reduce the efficiency

$$\eta = \frac{\Delta Q}{\Delta E}$$

i.e. the ratio of the emitted heat quantity ΔQ to the absorbed radiant energy ΔE.

In both experiments, the heat quantity ΔQ emitted per unit of time is determined from the increase in the temperature of the water flowing through the apparatus, and the radiant energy absorbed per unit of time is estimated on the basis of the power of the lamp and its distance from the absorber. The throughput volume of the water and the heat insulation of the solar collector are varied in the course of the experiment.

P 2.3.1

Mixing temperatures

P 2.3.1.1 Measuring the temperature of a mixture of hot and cold water

Measuring the temperature of a mixture of hot and cold water (P 2.3.1.1 a)

When cold water with the temperature ϑ_1 is mixed with warm or hot water having the temperature ϑ_2, an exchange of heat takes place until all the water reaches the same temperature. If no heat is lost to the surroundings, we can formulate the following for the mixing temperature:

$$\vartheta_m = \frac{m_1}{m_1 + m_2} \vartheta_1 + \frac{m_2}{m_1 + m_2} \vartheta_2$$

m_1, m_2: mass of cold and warm water respectively

Thus the mixing temperature ϑ_m is equivalent to a weighted mean value of the two temperatures ϑ_1 and ϑ_2.

The use of the Dewar flask in this experiment essentially prevents the loss of heat to the surroundings. This vessel has a double wall; the intermediate space is evacuated and the interior surface is mirrored. The water is stirred thoroughly to ensure a complete exchange of heat. This experiment measures the mixing temperature ϑ_m for different values for ϑ_1, ϑ_2, m_1, and m_2.

Cat.No.	Description	P 2.3.1.1 (a)	P 2.3.1.1 (b)	P 2.3.1.1 (c)
386 48	Dewar vessel	1	1	1
384 161	Lid for Dewar vessel	1	1	1
382 34	Thermometer, -10° to + 110 °C	1		
666 193	Temperature sensor NiCr-Ni		1	
666 190	Digital thermometer with 1 input		1	
315 23	School and laboratory balance 610 tare, 610 g	1	1	1
313 07	Stopclock I, 30 s/15 min	1	1	1
666 767	Hot plate, 150 mm dia., 1500 W	1	1	1
664 104	Beaker, 400 ml, ss, hard glass	2	2	2
524 009	Mobile-CASSY			1
524 0673	NiCr-Ni Adapter S			1
529 676	NiCr-Ni temperatrue sensor 1.5 mm			1

Determining the specific heat capacity of solids (P 2.3.2.1 a)

P 2.3.2

Heat capacities

P 2.3.2.1 Determining the specific heat capacity of solids

Cat. No.	Description	P 2.3.2.1 (a)	P 2.3.2.1 (b)	P 2.3.2.1 (c)
386 48	Dewar vessel	1	1	1
384 161	Lid for Dewar vessel	1	1	1
384 34	Heating apparatus	1	1	1
384 35	Copper shot, 200 g	1	1	1
384 36	Glass shot, 100 g	1	1	1
315 76	Lead shot, 200 g	1	1	1
303 28	Steam generator, 550 W/230 V	1	1	1
382 34	Thermometer, -10° to + 110 °C	1		
666 190	Digital thermometer with 1 input		1	
666 193	Temperature sensor NiCr-Ni		1	
315 23	School and laboratory balance 610 tare, 610 g	1	1	1
300 02	Stand base, V-shape, 20 cm	1	1	1
300 42	Stand rod, 47 cm	1	1	1
301 01	Leybold multiclamp	1	1	1
666 555	Universal Bunsen clamp S	1	1	1
667 614	Heat-protective gloves, pair; length: 290 mm	1	1	1
664 104	Beaker, 400 ml, ss, hard glass	1	1	1
667 194	Silicone tubing, i. d. 7 x 1.5 mm, 1 m	1	1	1
524 009	Mobile-CASSY			1
524 0673	NiCr-Ni Adapter S			1
529 676	NiCr-Ni temperatrue sensor 1.5 mm			1

When a body is heated or cooled, the absorbed heat capacity ΔQ is proportional to the change in temperature $\Delta\vartheta$ and to the mass *m* of the body:

$$\Delta Q = c \cdot m \cdot \Delta\vartheta$$

The proportionality factor *c*, the specific heat capacity of the body, is a quantity which depends on the respective material.

To determine the specific heat capacity, various materials in particle form are weighed, heated in steam to the temperature ϑ_1 and poured into a weighed-out quantity of water with the temperature ϑ_2. After careful stirring, heat exchange ensures that the particles and the water have the same temperature ϑ_m. The heat quantity released by the particles:

$$\Delta Q_1 = c_1 \cdot m_1 \cdot (\vartheta_1 \cdot \vartheta_m)$$

m_1: mass of particles

c_1: specific heat capacity of particles

is equal to the heat quantity absorbed by the water

$$\Delta Q_2 = c_2 \cdot m_2 \cdot (\vartheta_m \cdot \vartheta_2)$$

m_2: mass of water

The specific heat capacity of water c_2 is assumed as a given. The temperature ϑ_1 corresponds to the temperature of the steam. Therefore, the specific heat quantity c_1 can be calculated from the measurement quantities ϑ_2, ϑ_m, m_1 and m_2 .

P 2.3.3

Conversion of mechanical energy

P 2.3.3.1 Converting mechanical energy into heat energy – recording and evaluating measured values manually

P 2.3.3.2 Converting mechanical energy into heat energy – recording and evaluating measured values with CASSY

Converting mechanical energy into heat energy – recording and evaluating measured values manually (P 2.3.3.1)

Energy is a fundamental quantity of physics. This is because the various forms of energy can be converted from one to another and are thus equivalent to each other, and because the total energy is conserved in the case of conversion in a closed system.

These two experiments show the equivalence of mechanical and heat energy. A hand crank is used to turn various calorimeter vessels on their own axes, and friction on a nylon belt causes them to become warmer. The friction force is equivalent to the weight *G* of a suspended weight. For *n* turns of the calorimeter, the mechanical work is thus

$$W_n = G \cdot n \cdot \pi \cdot d$$

d: diameter of calorimeter

This results in an increase in the temperature of the calorimeter which corresponds to the specific heat capacity

$$Q_n = m \cdot c \cdot (\vartheta_n - \vartheta_0),$$

c: specific heat capacity, *m*: weight,
ϑ_n: temperature after *n* turns

To confirm the relationship

$$Q_n = W_n$$

the two quantities are plotted together in a diagram. In the first experiment, the measurement is conducted and evaluated manually point by point. The second experiment takes advantage of the computer-assisted measuring system CASSY.

Cat. No.	Description	P 2.3.3.1 (a)	P 2.3.3.1 (b)	P 2.3.3.1 (c)	P 2.3.3.2
388 00	Equivalent of heat, basic apparatus	1	1	1	1
388 01	Water calorimeter	1	1	1	1
388 02	Copper-block calorimeter with heating coil	1	1	1	1
388 03	Aluminum-block calorimeter with heating	1	1	1	1
388 04	Large aluminum-block calorimeter with heating coil	1	1	1	1
388 05	Thermometer for calorimeters	1			
388 24	Weight with hook, 5 kg	1	1	1	1
666 190	Digital thermometer with 1 input		1		
666 193	Temperature sensor NiCr-Ni		1		
524 010USB	Sensor CASSY				1
337 46	Forked light barrier, infra-red				1
524 0673	NiCr-Ni Adapter S			1	1
524 074	Timer S				1
501 16	Multicore cable, 6-pole, 1.5 m long				1
524 200	CASSY Lab				1
300 02	Stand base, V-shape, 20 cm				1
300 40	Stand rod, 10 cm				1
300 41	Stand rod, 25 cm		1	1	1
301 07	Simple bench clamp		1	1	1
301 11	Clamp with jaw clamp		1	1	1
	additionally required: 1 PC with Windows 95/NT or higher				1
524 009	Mobile-CASSY			1	
529 676	NiCr-Ni temperatrue sensor 1.5 mm			1	1

Converting electrical into heat energy - measuring with the joule and wattmeter (P 2.3.4.2)

P 2.3.4

Conversion of electrical energy

Cat. No.	Description	P 2.3.4.1 (a)	P 2.3.4.1 (b)	P 2.3.4.1 (c)	P 2.3.4.2 (a)	P 2.3.4.2 (b)	P 2.3.4.2 (c)	P 2.3.4.3
384 20	Electric calorimeter attachment	1	1	1				
386 48	Dewar vessel calorimeter with base	1	1	1				
388 02	Copper-block calorimeter with heating coil				1	1	1	1
388 03	Aluminum-block calorimeter with heating				1	1	1	1
388 04	Large aluminum-block calorimeter with heating coil				1	1	1	1
388 06	Pair of connecting cables				1	1	1	1
521 35	Voltage source, 0 … 12 V, e. g. Variable extra-low voltage transformer S	1	1	1	1	1	1	1
382 34	Thermometer, -10° to + 110 °C	1						
388 05	Thermometer for calorimeters				1			
666 190	Digital thermometer with 1 input		1			1		
666 193	Temperature sensor NiCr-Ni		1			1		
531 120	Voltmeter, AC, $U < 12$ V, e.g. Multimeter LDanalog 20	1	1	1				
531 130	Ammeter, $I < 6$ A, e.g. Multimeter LDanalog 30	1	1	1				
313 07	Stopclock I, 30s/15min	1	1	1				
664 103	Beaker, 250 ml, ss, hard glass	1	1	1				
665 755	Graduated cylinder, 250 ml: 2	1	1	1				
501 28	Connecting lead, Ø 2.5 mm^2, 50 cm, black	3	3	3				
501 45	Pair of cables, 50 cm, red and blue	1	1	1	1	1	1	3
531 831	Joule and wattmeter				1	1	1	
524 009	Mobile-CASSY			1			1	
524 0673	NiCr-Ni Adapter S			1			1	1
529 676	NiCr-Ni temperatrue sensor 1.5 mm			1			1	1
524 010USB	Sensor-CASSY							1
524 200	CASSY- Lab							1
	additionally required: 1 PC with Windows 95/NT or higher							1

Just like mechanical energy, electrical energy can also be converted into heat. We can use e.g. a calorimeter vessel with a wire winding to which a voltage is connected to demonstrate this fact. When a current flows through the wire, Joule heat is generated and heats the calorimeter.

The supplied electrical energy

$$W(t) = U \cdot I \cdot t$$

is determined in the first experiment by measuring the voltage U, the current I and the time t, and in the second experiment measured directly using the joule and wattmeter. This results in a change in the temperature of the calorimeter which corresponds to the specific heat capacity

$$Q(t) = m \cdot c \cdot (\vartheta(t) - \vartheta(0)),$$

c: specific heat capacity, m: mass,
$\vartheta(t)$: temperature at time t

To confirm the equivalence

$$Q(t) = W(t)$$

the two quantities are plotted together in a diagram.

P 2.4.1

Melting heat and evaporation heat

P 2.4.1.1 Determining the specific evaporation heat of water

P 2.4.1.2 Determining the specific melting heat of ice

Determining the specific evaporation heat of water (P 2.4.1.1)

When a substance is heated at a constant pressure, its temperature generally increases. When that substance undergoes a phase transition, however, the temperature does not increase even when more heat is added, as the heat is required for the phase transition. As soon as the phase transition is complete, the temperature once more increases with the additional heat supplied. Thus, for example, the specific evaporation heat Q_V per unit of mass is required for evaporating water, and the specific melting heat Q_S per unit of mass is required for melting ice.

To determine the specific evaporation heat Q_v of water, pure steam is fed into the calorimeter in the first experiment, in which cold water is heated to the mixing temperature ϑ_m. The steam condenses to water and gives off heat in the process; the condensed water is cooled to the mixing temperature. The experiment measures the starting temperature ϑ_2 and the mass m_2 of the cold water, the mixing temperature ϑ_m and the total mass

$$m = m_1 + m_2$$

By comparing the amount of heat given off and absorbed, we can derive the equation

$$Q_V = \frac{m_1 \cdot c \cdot (\vartheta_m - \vartheta_1) + m_2 \cdot c \cdot (\vartheta_m - \vartheta_2)}{m_1} .$$

$\vartheta_1 \approx 100$ °C, c: specific heat capacity of water

In the second experiment, pure ice is filled in a calorimeter, where it cools water to the mixing temperature ϑ_m, in order to determine the specific melting heat. The ice absorbs the melting heat and melts into water, which warms to the mixing temperature. Analogously to the first experiment, we can say for the specific melting heat:

$$Q_S = \frac{m_1 \cdot c \cdot (\vartheta_m - \vartheta_1) + m_2 \cdot c \cdot (\vartheta_m - \vartheta_2)}{m_1} .$$

$\vartheta_1 = 0$ °C

Cat. No.	Description	P 2.4.1.1 (a)	P 2.4.1.1 (b)	P 2.4.1.1 (c)	P 2.4.1.2 (a)	P 2.4.1.2 (b)	P 2.4.1.2 (c)
386 48	Dewar vessel	1	1	1	1	1	1
384 17	Water separator	1	1	1			
303 28	Steam generator, 550 W/230 V	1	1	1			
303 25	Immersion heater				1	1	1
382 34	Thermometer, -10° to + 110 °C	1			1		
666 190	Digital thermometer with 1 input		1			1	
666 193	Temperature sensor NiCr-Ni		1			1	
315 23	School and laboratory balance 610 Tara, 610 g	1	1	1	1	1	1
300 02	Stand base, V-shape, 20 cm	1	1	1			
300 42	Stand rod, 47 cm	1	1	1			
301 01	Leybold multiclamp	2	2	2			
666 555	Universal Bunsen clamp S	2	2	2			
664 104	Beaker, 400 ml, ss, hard glass	1	1	1	1	1	1
667 194	Silicone tubing, int. dia. 7 x 1.5 mm, 1 m	1	1	1			
590 06	Plastic beaker, 1000 ml				1	1	1
524 009	Mobile-CASSY			1			1
524 0673	NiCr-Ni Adapter S			1			1
529 676	NiCr-Ni temperatrue sensor 1.5 mm			1			1

Recording the vapor pressure curve of water up to 50 bar (P 2.4.2.2)

P 2.4.2

Measuring vapor pressure

P 2.4.2.1 Recording the vapor pressure curve of water up to 1 bar
CASSY-S

P 2.4.2.2 Recording the vapor pressure curve of water up to 50 bar

Cat. No.	Description	P 2.4.2.1	P 2.4.2.2
664 315	Double-necked round-bottom flask, 250 ml, ST 19/26, GL 18	1	
665 305	Core/threads ST 19/26, with GL 18	1	
667 186	Vacuum rubber tubing, int. dia. 8 x 5 mm, 1 m	1	
665 255	Stopcock, 3-way valve, with ST stopcock, 8 mm dia., T-shape	1	
378 031	Small flange DN 16 KF with hose nozzle	1	
378 045	Centering ring DN 16 KF	1	
378 050	Clamping ring DN 10/16 KF	1	
378 701	High-vacuum grease	1	
524 010USB	Sensor CASSY	1	
524 200	CASSY Lab	1	
309 00 335	Rod 10 x 225 mm with thread M6	1	
501 11	Extension cable, 15-pole	1	
524 0673	NiCr-Ni Adapter S	1	
524 065	Absolute pressure sensor S, 0...1500 hPa	1	
666 1261	Quick gas- and liquid sensor, Type K	1	
300 02	Stand base, V-shape, 20 cm	1	
300 43	Stand rod, 75 cm	1	
666 555	Universal clamp, 0 ... 80 mm dia.	1	
301 01	Leybold multiclamp	3	1
302 68	Ring with stem	1	1
666 685	Wire gauze, 160 x 160 mm	1	1
666 711	Butane gas burner, gas and air regulation	1	1
666 712	Butane cartridges 200g, set of 3	1	1
667 614	Heat protective gloves, pair	1	1
385 16	High-pressure steam boiler		1
664 109	Beaker, 25 ml, ss, hard glass		1
300 01	Stand base, V-shape, 28 cm		1
300 41	Stand rod, 25 cm		1
667 613	Safety goggles for wearing over glasses		1
	additionally required: PC with Windows 95/NT or higher	1	

The vapor pressure p of a liquid-vapor mixture in a closed system depends on the temperature T. Above the critical temperature, the vapor pressure is undefined. The substance is gaseous and cannot be liquefied no matter how high the pressure. The increase in the vapor-pressure curve $p(T)$ is determined by several factors, including the molar evaporation heat q_v of the substance:

$$T \cdot \frac{dp}{dT} = \frac{q_v}{v_1 - v_2} \quad \text{(Clausius-Clapeyron)}$$

T: absolute temperature
v_1: molar volume of vapor
v_2: molar volume of liquid

As we can generally ignore v_2 and q_v hardly varies with T, we can derive a good approximation from the law of ideal gases:

$$\ln p = \ln p_0 - \frac{q_v}{R \cdot T}$$

In the first experiment, the vapor pressure curve of water below the normal boiling point is recorded with the computer-assisted measuring system CASSY. The water is placed in a glass vessel, which was sealed beforehand while the water was boiling at standard pressure. The vapor pressure p is measured as a function of the temperature T when cooling and subsequently heating the system, respectively.

The high-pressure steam apparatus is used in the second experiment for measuring pressures of up to 50 bar. The vapor pressure can be read directly from the manometer of this device. A thermometer supplies the corresponding temperature. The measured values are recorded and evaluated manually point by point.

P 2.4.3

Critical temperature

P 2.4.3.1 Investigating a liquid-vapor mixture at the critical point

Investigating a liquid-vapor mixture at the critical point (P 2.4.3.1)

The critical point of a real gas is defined by the critical pressure p_c, the critical density ρ_c and the critical temperature T_c. Below the critical temperature, the substance is gaseous for a sufficiently great molar volume – it is termed a vapor – and is liquid at a sufficiently small molar volume. Between these extremes, a liquid-vapor mix exists, in which the vapor component increases with the molar volume. As liquid and vapor have different densities, they are separated in a gravitational field. As the temperature rises, the density of the liquid decreases and that of the vapor increases, until finally at the critical temperature both densities have the value of the critical density. Liquid and vapor mix completely, and the phase boundary disappears. Above the critical temperature, the substance is gaseous, regardless of the molar volume.

This experiment investigates the behavior of sulfur hexafluoride (SF_6) close to the critical temperature. The critical temperature of this substance is T_c = 318.7 K and the critical pressure is p_c = 37.6 bar. The substance is enclosed in a pressure chamber designed so that hot water or steam can flow through the mantle. The dissolution of the phase boundary between liquid and gas while heating the substance, and its restoration during cooling, are observed in projection on the wall. As the system approaches the critical point, the substance scatters short-wave light particularly intensively; the entire contents of the pressure chamber appears red-brown. This critical opalescence is due to the variations in density, which increase significantly as the system approaches the critical point.

Note: The dissolution of the phase boundary during heating can be observed best when the pressure chamber is heated as slowly as possible using a circulation thermostat.

Cat. No.	Description	P 2.4.3.1(a)	P 2.4.3.1(b)	P 2.4.3.1(c)
371 401	Pressure chamber for demonstrating the critical temperature	1	1	1
450 60	Lamp housing	1	1	1
450 51	Lamp, 6 V/30 W	1	1	1
460 20	Aspherical condensor	1	1	1
460 03	Lens, f = + 100 mm	1	1	1
461 11	Right angled prism	1	1	1
521 210	Transformer, 6 V AC, 12 V AC/ 30 W	1	1	1
382 33	Thermometer, -10 to +150 °C	1		
666 193	Temperatur sensor, NiCr.Ni		1	
666 190	Digital thermometer with one input		1	
303 28	Steam generator, 550 W/230 V	1		
667 194	Silicone tubing. int. dia. 7 x 1.5 mm, 1 m	2	2	2
664 104	Beaker, 400 ml, ss, hard glass	1		
666 768	Circulation thermostat, + 30 - 100 °C		1	1
460 43	Small optical bench	1	1	1
300 01	Stand base, V-shape, 28 cm	1	1	1
301 01	Leybold multiclamp	4	4	4
524 009	Mobile-CASSY			1
524 0673	NiCr-Ni Adapter S			1
529 676	NiCr-Ni Temperature sensor 1.5 mm			1
666 7703	Pump set		1	1

Brownian motion of smoke particles (P 2.5.1.1)

P 2.5.1

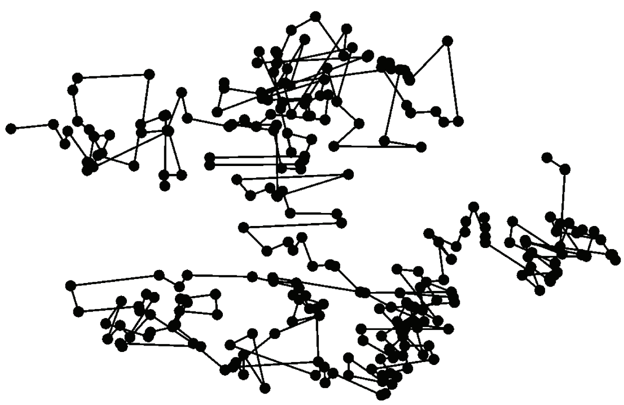
Brownian motion of molecules

P 2.5.1.1 Brownian motion of smoke particles

Cat. No.	Description	P 2.5.1.1
662 078	Microscope MIC 805	1
372 51	Smoke chamber	1
450 60	Lamp housing	1
450 51	Lamp, 6 V/30 W	1
460 20	Aspherical condensor	1
521 210	Transformer, 6 V AC, 12 V AC/ 30 W	1
300 02	Stand base, V-shape, 20 cm	1

A particle which is suspended in a gas constantly executes a motion which changes in its speed and in all directions. *J. Perrin* first explained this molecular motion, discovered by *R. Brown*, which is caused by bombardment of the particles with the gas molecules. The smaller the particle is, the more noticeably it moves. The motion consists of a translational component and a rotation, which also constantly changes.

In this experiment, the motion of smoke particles in the air is observed using a microscope.



Schematic diagram of Brownian motion of molecules

P 2.5.2

Laws of gases

P 2.5.2.1 Pressure-dependency of the volume of a gas at a constant temperature (Boyle-Mariotte's law)

P 2.5.2.2 Temperature-dependency of the volume of a gas at a constant pressure (Gay-Lussac's law)

P 2.5.2.3 Temperature-dependency of the pressure of a gas at a constant volume (Amontons' law)

Pressure-dependency of the volume of a gas at a constant temperature (Boyle-Mariotte's law) (P 2.5.2.1)

The gas thermometer consists of a glass tube closed at the bottom end, in which a mercury stopper seals the captured air at the top. The volume of the air column is determined from its height and the cross-section of the glass tube. When the pressure at the open end is altered using a hand pump, this changes the pressure on the sealed side correspondingly. The temperature of the entire gas thermometer can be varied using a water bath.

In the first experiment, the air column is maintained at a constant room temperature T. At an external pressure p_0, it has a volume of V_0 bounded by the mercury stopper. The pressure p in the air column is reduced by evacuating air at the open end, and the increased volume V of the air column is determined for different pressure values p. The evaluation confirms the relationship

$$p \cdot V = p_0 \cdot V_0 \text{ for } T = \text{const. (Boyle-Mariotte's law)}$$

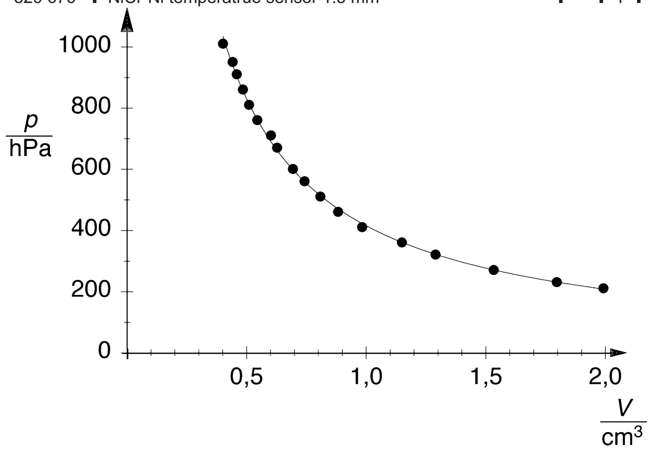
In the second experiment, the gas thermometer is placed in a water bath of a specific temperature which is allowed to gradually cool. The open end is subject to the ambient air pressure, so that the pressure in the air column is constant. This experiment measures the volume V of the air column as a function of the temperature T of the water bath. The evaluation confirms the relationship

$$V \propto T \text{ for } p = \text{const. (Gay-Lussac's law)}$$

In the final experiment, the pressure p in the air column is constantly reduced by evacuating the air at the open end so that the volume V of the air column also remains constant as the temperature drops. This experiment measures the pressure p of the air column as a function of the temperature T of the water bath. The evaluation confirms the relationship

$$p \propto T \text{ for } V = \text{const. (Amontons' law)}$$

Cat. No.	Description	P 2.5.2.1	P 2.5.2.2 (a)	P 2.5.2.2 (b)	P 2.5.2.3 (a)	P 2.5.2.3 (b)
382 00	Gas thermometer	1	1	1	1	1
666 190	Digital thermometer with one input		1		1	
666 193	Temperatur sensor, NiCr.Ni		1		1	
300 02	Stand base, V-shape, 20 cm	1	1	1	1	1
300 42	Stand rod, 47 cm	1	1	1	1	1
301 11	Clamp with jaw clamp	2	2	2	2	2
375 58	Hand vacuum and pressure pump	1			1	1
666 767	Hot plate, 150 mm dia., 1500 W		1	1	1	1
664 103	Beaker, 400 ml, ss, hard glass		1	1	1	1
524 009	Mobile-CASSY			1		1
524 0673	NiCr-Ni Adapter S			1		1
529 676	NiCr-Ni temperatrue sensor 1.5 mm			1		1



Pressure-dependency of the volume at a constant temperature (P 2.5.2.1)

Determining the adiabatic exponent C_p/C_V of air after Rüchard (P 2.5.3.1)

Determining the adiabatic exponent C_p/C_V of various gases using the gas elastic resonance apparatus (P 2.5.3.2)

P 2.5.3

Spezific heat of gases

P 2.5.3.1 Determining the adiabatic exponent C_p/C_V of air after Rüchard

P 2.5.3.2 Determining the adiabatic exponent C_p/C_V of various gases using the gas elastic resonance apparatus

Cat. No.	Description	P 2.5.3.1	P 2.5.3.2
371 04	Marriot's flask, 10 l	1	
371 05	Oscillation tube, apparatus for determination of cp/cV	1	
313 07	Stopclock I, 30s/15min	1	
317 19	Aneroid barometer, 980 – 1045 mbar	1	
590 06	Plastic beaker, 1000 ml	1	
675 3100	Vaseline, 50 g	1	
371 07	Gas elastic resonance apparatus		1
665 914	Gas syringe with 3-way stopcock, 100 ml:1		1
665 918	Holder for gas syringe, 100 ml, plastic		1
522 621	Function generator S 12, 0.1 Hz to 20 kHz		1
575 471	Counter S		1
531 120	Ammeter, AC, $I = 1$ A, e.g. Multimeter LD analog 20		1
300 02	Stand base, V-shape, 20 cm		1
660 980	Fine regulating valve for Minican gas cans		1
660 985	Minican gas can, neon		1
660 999	Minican gas can, carbon dioxide		1
667 194	Silikone tubing, i. d. 7 x 1.5 mm, 1 m		1
604 481	Rubber tubing 4 mm Ø		1
604 510	Connector straight, PP, Ø 4 … 15 mm		1
500 422	Connecting lead, blue, 50 cm		1
501 45	Pair of cables, 50 cm, red and blue		1
501 46	Pair of cables, 100 cm, red and blue		1

In the case of adiabatic changes in state, the pressure p and the volume V of a gas demonstrate the relationship

$$p \cdot V^{\kappa} = \text{const.}$$

whereby the adiabatic exponent is defined as

$$\kappa = \frac{C_p}{C_V}$$

i.e. the ratio of the specific heat capacities C_p and C_V of the respective gas.

The first experiment determines the adiabatic exponent of air from the oscillation period of a ball which caps and seals a gas volume in a glass tube, whereby the oscillation of the ball around the equilibrium position causes adiabatic changes in the state of the gas. In the equilibrium position, the force of gravity and the opposing force resulting from the pressure of the enclosed gas are equal. A deflection from the equilibrium position by Δx causes the pressure to change by

$$\Delta p = -\kappa \cdot p \cdot \frac{A \cdot \Delta x}{V},$$

A: cross-section of riser tube

which returns the ball to the equilibrium position. The ball thus oscillates with the frequency

$$f_0 = \frac{1}{2\pi} \cdot \sqrt{\frac{\kappa \cdot p \cdot A^2}{m \cdot V}},$$

around its equilibrium position.

In the second experiment, the adiabatic exponent is determined using the gas elastic resonance apparatus. Here, the air column is sealed by a magnetic piston which is excited to forced oscillations by means of an alternating electromagnetic field. The aim of the experiment is to find the characteristic frequency f_0 of the system, i.e. the frequency at which the piston oscillates with maximum amplitude. Other gases, such as carbon dioxide and nitrogen, can alternatively be used in this experiment.

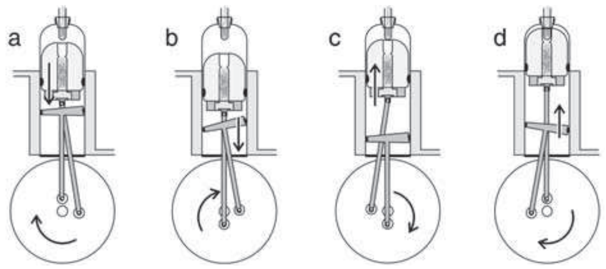
P 2.6.1

Hot-air engine: qualitative experiments

P 2.6.1.1 Operating a hot-air engine as a thermal engine

Operating a hot-air engine as a thermal engine (P 2.6.1.1)

The hot-air engine (invented by *R. Stirling*, 1816) is the oldest thermal engine, along with the steam engine. In greatly simplified terms, its thermodynamic cycle consists of an isothermic compression at low temperature, an isochoric application of heat, an isothermic expansion at high temperature and an isochoric emission of heat. The displacement piston and the working piston are connected to a crankshaft via tie rods, whereby the displacement piston leads the working piston by 90°. When the working piston is at top dead center (a), the displacement piston is moving downwards, displacing the air into the electrically heated zone of the cylinder. Here, the air is heated, expands and forces the working piston downward (b). The mechanical work is transferred to the flywheel. When the working piston is at bottom dead center (c), the displacement piston is moving upwards, displacing the air into the water-cooled zone of the cylinder. The air cools and is compressed by the working cylinder (d). The flywheel delivers the mechanical work required to execute this process.



The experiment qualitatively investigates the operation of the hot-air engine as a thermal engine. Mechanical power is derived from the engine by braking at the brake hub. The voltage of the heating filament is varied in order to demonstrate the relationship between the thermal power supplied and the mechanical power removed from the system. The no-load speed of the motor for each case is used as a measure of the mechanical power produced in the system.

Cat. No.	Description	P 2.6.1.1
388 182	Hot-air engine	1
562 11	U-core with yoke	1
562 12	Clamping device	1
562 21	Mains coil with 500 turns for 230 V	1
562 18	Extra-low-voltage coil, 50 turns	1
501 33	Connecting lead, Ø 2.5 mm², 100 cm, black	2
388 181	Submersible pump, 12 V	1*
521 230	Low-voltage power supply	1*
667 194	Silicone tubing, int. dia. 7 x 1.5 mm, 1 m	2*
604 307	Can, 10 l	1*

* additionally recommended

Operating the hot-air engine as a heat pump and a refrigerating machine (P 2.6.1.3)

P 2.6.1

Hot-air engine: qualitative experiments

P 2.6.1.3 Operating the hot-air engine as a heat pump and a refrigerating machine

Cat. No.	Description	P 2.6.1.3
388 182	Hot-air engine	1
388 19	Thermometer	1
347 35	Experiment motor	1
347 36	Control unit for experiment motor	1
388 181	Immersion pump 12 V	1*
521 230	Low-voltage power supply	1*
667 194	Silicone tubing, int. dia. 7 x 1.5 mm, 1 m	2*
604 307	Can, 10 l	1*

* additionally recommended

Depending on the direction of rotation of the crankshaft, the hot-air engine operates as either a heat pump or a refrigerating machine when its flywheel is externally driven. When the displacement piston is moving upwards while the working piston is at bottom dead center, it displaces the air in the top part of the cylinder. The air is then compressed by the working piston and transfers its heat to the cylinder head, i.e. the hot-air motor operates as a heat pump. When run in the opposite direction, the working piston causes the air to expand when it is in the top part of the cylinder, so that the air draws heat from the cylinder head; in this case the hot-air engine operates as a refrigerating machine.

The experiment qualitatively investigates the operation of the hot-air engine as a heat pump and a refrigerating machine. In order to demonstrate the relationship between the externally supplied mechanical power and the heating or refrigerating power, respectively, the speed of the electric motor is varied and the change in temperature observed.

P 2.6.2

Hot-air engine: quantitative experiments

P 2.6.2.1 Frictional losses in the hot-air engine (calorific determination)

P 2.6.2.2 Determining the efficiency of the hot-air engine as a heat engine

P 2.6.2.3 Determining the efficiency of the hot-air engine as a refrigerating machine

Frictional losses in the hot-air engine (calorific determination) (P 2.6.2.1)

When the hot-air engine is operated as a heat engine, each engine cycle withdraws the amount of heat Q_1 from reservoir 1, generates the mechanical work W and transfers the difference $Q_2 = Q_1 - W$ to reservoir 2. The hot-air engine can also be made to function as a refrigerating machine while operated in the same rotational direction by externally applying the mechanical work W. In both cases, the work W_F converted into heat in each cycle through the friction of the piston in the cylinder must be taken into consideration.

In order to determine the work of friction W_F in the first experiment, the temperature increase ΔT_F in the cooling water is measured while the hot-air engine is driven using an electric motor and the cylinder head is open.

The second experiment determines the efficiency

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

of the hot-air engine as a heat engine. The mechanical work W exerted on the axle in each cycle can be calculated using the external torque N of a dynamometrical brake which brakes the hot-air engine to a speed f. The amount of heat Q_2 given off corresponds to a temperature increase ΔT in the cooling water.

The final experiment determines the efficiency

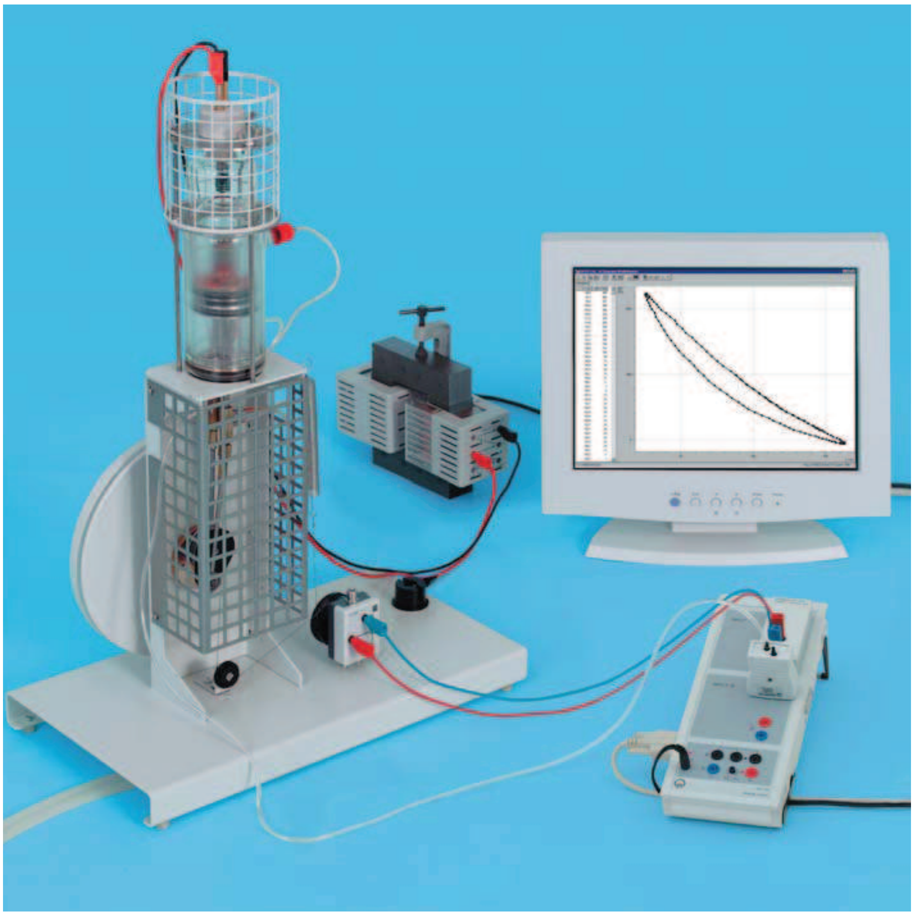
$$\eta = \frac{Q_1}{Q_1 - Q_2}$$

of the hot-air engine as a refrigerating machine. Here, the hot-air engine with closed cylinder head is driven using an electric motor and Q_1 is determined as the electrical heating energy required to maintain the cylinder head at the ambient temperature.

388 181	Immersion pump 12 V	1*	1*	1*
521 230	Low voltage power supply	1*	1*	1*
667 194	Silicone tubing, int. dia. 7 x 1.5 mm, 1 m	2*	2*	2*
604 307	Can, 10 l	1*	1*	1*

* additionally recommended

Cat. No.	Description	P 2.6.2.1	P 2.6.2.2	P 2.6.2.3
388 182	Hot-air engine	1	1	1
388 221	Accessories for hot-air engine	1	1	1
347 35	Experiment motor	1		1
347 36	Control unit for experiment motor	1		1
562 11	U-core with yoke		1	
562 12	Clamping device		1	
562 21	Mains coil with 500 turns for 230 V		1	
562 18	Extra-low voltage coil, 50 turns		1	
521 35	Variable extra-low voltage transformer S			1
575 471	Counter S	1	1	1
337 46	Forked light barrier, infra-red	1	1	1
501 16	Multicore connecting cable, 6pole, 1.5 m	1	1	1
531 120	Multimeter LD analog 20		1	1
531 130	Multimeter LD analog 30		1	1
313 17	Stopclock II, 60 s/30 min	1	1	1
314 141	Precision dynamometer, 1.0 N		1	
382 36	Thermometer, -10° to + 40 °C	1	1	1
300 02	Stand base, V-shape, 20 cm	1	2	1
300 41	Stand rod, 25 cm	1	1	1
300 42	Stand rod, 47 cm		1	
300 51	Stand rod, right-angled		1	
301 01	Leybold multiclamp		2	
590 06	Plastic beaker, 1000 ml	1	1	1
342 61	Set of 12 weights, 50 g each		1	
501 33	Connecting lead, Ø 2.5 mm^2, 100 cm, black		3	3
501 45	Pair of cables, 50 cm, red and blue		1	1



Hot-air engine as a heat engine: recording and evaluating the *pV* diagram with CASSY (P 2.6.2.4)

P 2.6.2

Hot-air engine: quantitative experiments

P 2.6.2.4 CASSY-S Hot-air engine as a heat engine: recording and evaluating the *pV* diagram with CASSY

Cat. No.	Description	P 2.6.2.4
388 182	Hot-air engine	1
562 11	U-core with yoke	1
562 12	Clamping device	1
562 21	Mains coil with 500 turns for 230 V	1
562 18	Extra-low voltage coil, 50 turns	1
529 031	Displacement transducer	1
524 031	Current supply box	1
524 064	Pressure sensor S ± 2000 hPa	1
524 010USB	Sensor CASSY	1
524 200	CASSY Lab	1
309 48	Cord, 10 m	1
352 08	Helical spring, 5 N; 0.25 N/cm	1
501 46	Pair of cables, 100 cm, red and blue	1
501 33	Connecting lead, Ø 2.5 mm^2, 100 cm, black	2
388 181	Immersion pump 12 V	1*
521 230	Low-voltage power supply	1*
667 194	Silicone tubing, int. dia. 7 x 1.5 mm, 1 m	2*
604 307	Can, 10 l	1*
	additionally required: PC with Windows 95/98/NT or higher	1

* additionally recommended

Thermodynamic cycles are often described as a closed curve in a *pV* diagram (*p*: pressure, *V*: volume). The work added to or withdrawn from the system (depending on the direction of rotation) corresponds to the area enclosed by the curve.

In this experiment, the *pV* diagram of the hot air engine as a heat engine is recorded using the computer-assisted measured value recording system CASSY. The pressure sensor measures the pressure *p* in the cylinder and a displacement sensor measures the position *s*, from which the volume is calculated, as a function of the time *t*. The measured values are displayed on the screen directly in a *pV* diagram. In the further evaluation, the mechanical work performed as piston friction per cycle

$$W = -\int p \cdot dV$$

and from this the mechanical power

$$P = W \cdot f$$

f: no-load speed

are calculated and plotted in a graph as a function of the no-load speed.

P 2.6.3

Heat pump

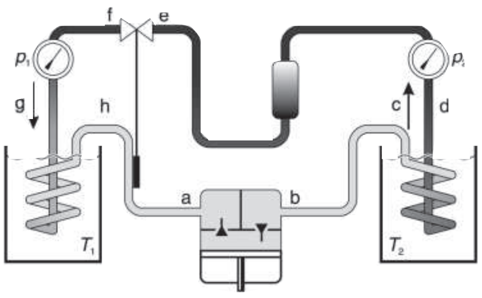
P 2.6.3.1 Determining the efficiency of the heat pump as a function of the temperature differential

P 2.6.3.2 Investigating the function of the expansion valve of the heat pump

P 2.6.3.3 Analyzing the thermodynamic cycle of the heat pump using the Mollier diagram

Determining the efficiency of the heat pump as a function of the temperature differential (P 2.6.3.1)

The heat pump extracts heat from a reservoir with the temperature T_1 through vaporization of a coolant and transfers heat to a reservoir with the temperature T_2 through condensation of the coolant. In the process, compression in the compressor (a-b) greatly heats the gaseous coolant. It condenses in the liquefier (c-d) and gives up the released condensation heat ΔQ_2 to the reservoir T_2. The liquefied coolant is filtered and fed to the expansion valve (e-f) free of bubbles. This regulates the supply of coolant to the vaporizer (g-h). In the vaporizer, the coolant once again becomes a gas, withdrawing the necessary evaporation heat ΔQ_1 from the reservoir T_1.



The aim of the first experiment is to determine the efficiency

$$\varepsilon = \frac{\Delta Q_2}{\Delta W}$$

of the heat pump as a function of the temperature differential $\Delta T = T_2 - T_1$. The heat quantity ΔQ_2 released is determined from the heating of water reservoir T_2, while the applied electrical energy ΔW is measured using the joule and wattmeter.

Cat. No.	Description	P 2.6.3.1	P 2.6.3.2	P 2.6.3.3
389 521	Heat pump pT	1	1	1
531 831	Joule and wattmeter	1		1
666 209	Digital thermometer with four inputs	1	1	1
666 193	Temperature sensor NiCr-Ni	2	2	3
313 12	Digital stopwatch	1	1	1
729 759	V24 Connection Cable, 9-pole	1*	1*	1*
	additionally required:			
	PC with Windows 98 or higher, 1 USB and 1 serial port	1*	1*	1*

* additionally recommended

In the second experiment, the temperatures T_f and T_h are recorded at the outputs of the expansion valve and the vaporizer. If the difference between these two temperatures falls below a specific limit value, the expansion valve chokes off the supply of coolant to the vaporizer. This ensures that the coolant in the vaporizer is always vaporized completely.

In the final experiment, a Mollier diagram, in which the pressure *p* is graphed as a function of the specific enthalpy *h* of the coolant, is used to trace the energy transformations of the heat pump. The pressures p_1 and p_2 in the vaporizer and liquefier, as well as the temperatures T_a, T_b, T_e and T_f of the coolant are used to determine the corresponding enthalpy values h_a, h_b, h_e and h_f. This experiment also measures the heat quantities ΔQ_2 and ΔQ_1 released and absorbed per unit of time. This in turn is used to determine the amount of coolant Δm circulated per unit of time.