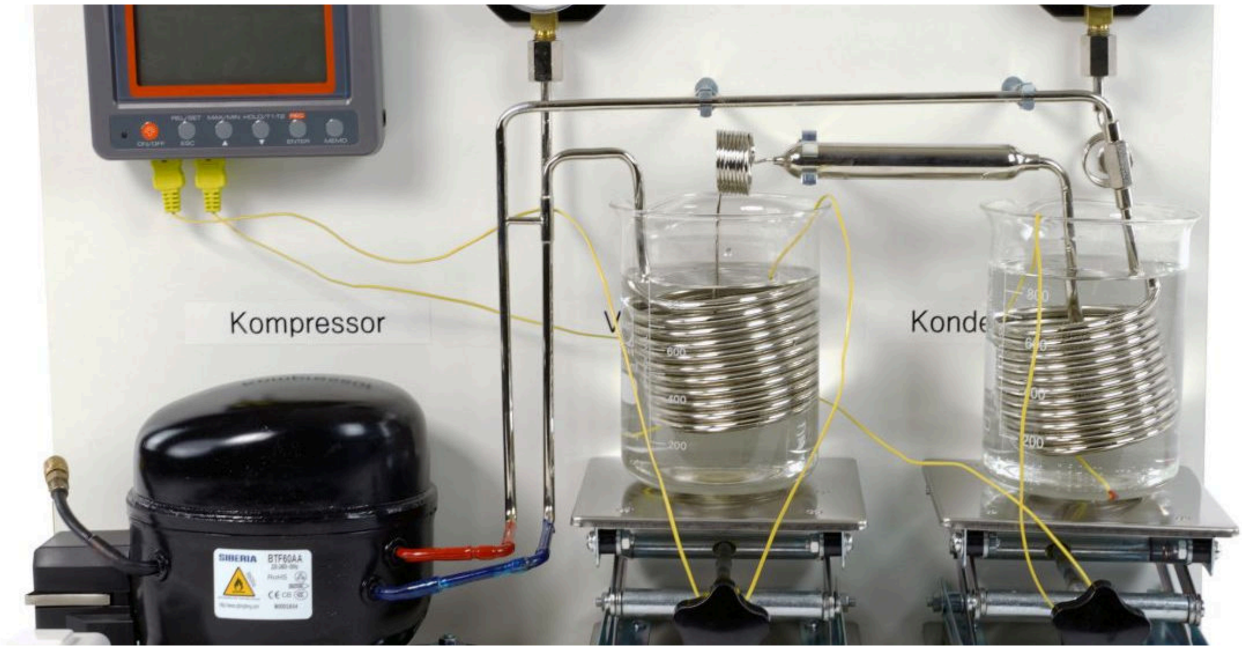
Electric compression heat pump

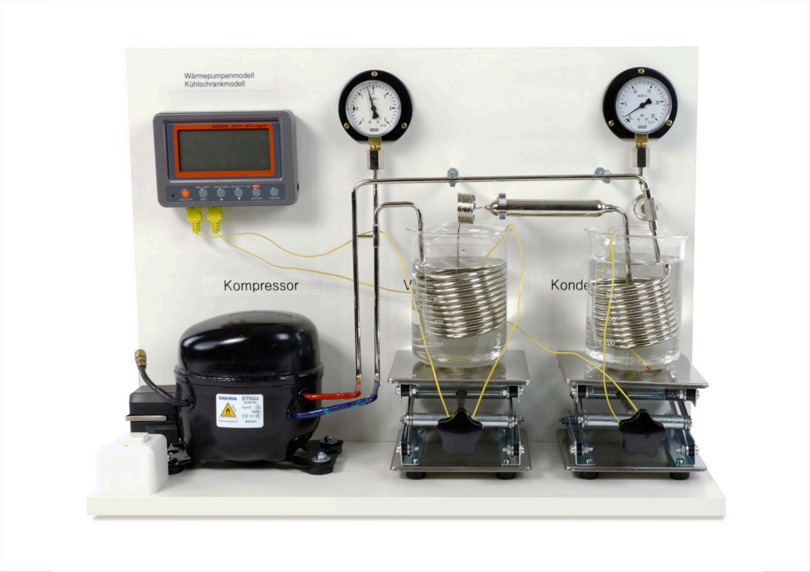


Physics > Thermodynamics > Heat transfer

Difficulty level	Group size	Preparation time	Execution time
hard	-	10 minutes	30 minutes

Teacher information

Application



The heat pump is a thermodynamic device that transfers heat from a colder location to a warmer location by consuming work. It is based on the principles of the Carnot cycle and utilizes of thermodynamics.

The performance of a heat pump is described by the coefficient of performance (COP), which represents the ratio of the heat output to the work input.

Other teacher information (1/2)

PHYWE excellence in science

Prior knowledge

The students have to be familiar with units like pressure, temperature, mass, volume and can perform calculations with them. In addition, they have to be familiar with general good laboratory practice and general laboratory safety regulations.

Scientific principle

The operation of a heap pump can be modeled using the ideal gas law. The state variables such as pressure, temperature, and volume of the working fluid in the heat pump are take into account to describe the heat transfer process.

Other teacher information (2/2)

PHYWE excellence in science

Learning objective

In this experiment, the students are getting familiar with different behaviours of gases and deep their knowledge in physical equations. By going through the different parts with the same volume of air in the experiment while changing the external influences, they get to know the correlation of pressure, temperatur and volume. It is a simple introduction in thermodynamics.

Tasks

The ideal gas law can be emplyed in this context to model the cahnges in the state of the working fluid in the heat pump, allowing for the anylysis and optimization of the system´s performance and efficiency. It provides a quantitative description of the thermodynamic procces occurring in the heat pump and supports the development and improvement of this technology.

Theory (1/3)

Fig. 1: compression heat pump principle using the example of hot water supply for domestic installations

The theory of heat pumps is based on the principles of thermodynamics and heat transfer. A heat pump is a device that moves thermal energy from a colder region to a hotter region, requiring the input of mechanical work or energy. It operates on the principle that heat flows naturally from a higher temperature to a lower temperature region.

The primary components of a heat pump include a compressor, an evaporator, a condenser, and an expansion valve. The working fluid, often a refrigerant, circulates through these components to facilitate the heat transfer process.

Theory (2/3)

Fig. 2: principle of the heat pump using the example of the refrigerator

The basic operation of a heat pump involves the following steps:

1. Evaporation: The working fluid evaporates in the evaporator coil, absorbing heat from the cold source (e.g., outdoor air or ground). This causes the refrigerant to change from a liquid to a gas, known as vaporization.
2. Compression: The compressor then increases the pressure and temperature of the gaseous refrigerant, thereby increasing its energy. This process requires the input of mechanical work.

Theory (3/3)

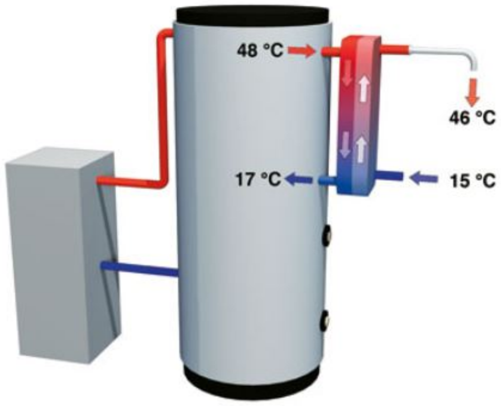


Fig. 3: hot water heating with heat pump

3. Condensation: The high-pressure, high-temperature refrigerant flows to the condenser coil, where it releases heat to the hot side (e.g., indoor air or water). The refrigerant condenses back into a liquid state.

4. Expansion: The expansion valve reduces the pressure of the liquid refrigerant, causing it to expand and evaporate once again in the evaporator coil

By continuously cycling through these steps, a heat pump can transfer heat from a colder region to a hotter region, effectively providing heating or cooling to a desired space or medium.

Safety instructions

- When handling chemicals, you should wear suitable protective gloves, safety goggles, and suitable clothing.
- For this experiment the general instructions for safe experimentation in science lessons apply.
- For H- and P-phrases please consult the safety data sheet of the respective chemical.

Setup and Procedure

Tasks

Pressures and temperatures in the circulation of the electrical compression heat pump are measured as a function of time when it is operated as a water-water heat pump. The energy taken up and released is calculated from the heating and cooling of the two water baths. When it is operated as an air-water heat pump, the coefficient of performance at different vaporiser temperatures is determined.

Equipment

Position	Material	Item No.	Quantity
1	Heat pump, compressor principle	04373-93	1
2	Temperature meter digital, 4-2	13618-00	1
3	Temperature sensor: Universal -50 ... +300 °C Type-K	EAK-TF-55	2
4	Heat conductive paste, 60 g	03747-00	1
5	Digital stopwatch, 24 h, 1/100 s and 1 s	24025-00	1
6	Beaker, Borosilicate, low form, 1000 ml	46057-00	2
7	Glass rod,boro 3.3,l=300mm, d=7mm	40485-05	2
8	Power meter digital	07049-01	1
9	Lab jack, 150 x 150 mm	02074-02	2

Additional equipment

Position	Material	Quantity
1	PC with Windows XP® or higher	1

Setup (1/3)

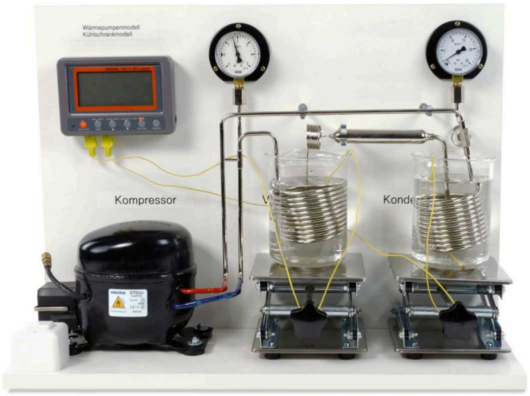


Fig. 4: Assembled experiment

1. Water-water heat pump:
Pour a measured quantity of water into both water reservoirs so that the heat exchanger is completely immersed. Care is to be taken to ensure that the water on the condenser side is not colder than that on the vaporiser side.
Measure all pressures and temperatures before switching on the heat pump:

Condenser side:

p_1 = Pressure

Θ_1 = Water temperature

Θ_{Co} = Temperature at the condenser outlet

Setup (2/3)

Vaporiser side:

p_2 = Pressure

Θ_{Ci} = Water temperature

Θ_{Vo} = Temperature at the condenser outlet

Switch on heat pump and stop-clock and measure pressure and temperatures on condenser and vaporiser side alternately (e.g. every minute). Cease measurements after approx. 30 min.

Setup (3/3)

- 2. Air-water heat pump:
  Remove water reservoir on the vaporiser side, carefully dry heat exchanger coils. Make three series of measurements with air-water heat pump. At the start of each series of measurements the water temperature is approx. 20°C, the volume of water is measured out (mark water level, drain off warm water and refill with cold water up to the mark).
  Set up a hot air blower approx. 30 cm away from the vaporiser coil and blow a stream of cold air on to the vaporiser. Switch on the heat pump and measure the temperature at the outlet of the vaporiser Θ_{Vo} and the water temperature Θ_1 as a function of time.
  Duration of a series of measurements approx. 20 min, until Θ_1 > 30°C and $\Theta_{Vo} \approx$ const.
  Repeat series of measurements with stream of hot air and then without stream of air.

Theory (1/3)

The Mollier (h, log p) diagram, in which p is the pressure and h the specific enthalpy of the working substance, is used to describe the cyclic process in heat technology. Fig. 5 shows an idealised representation of the heat pump circuit

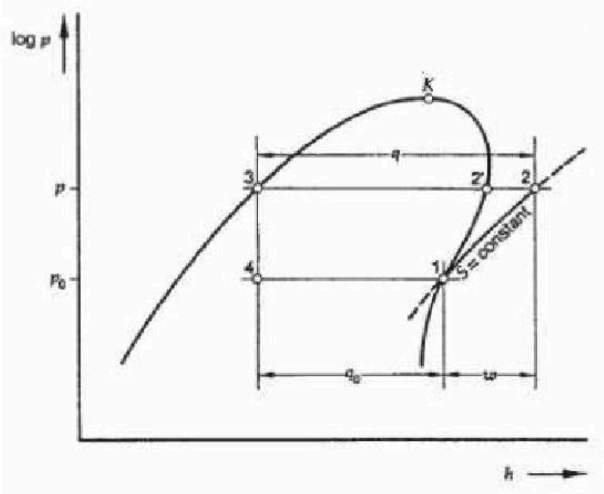


Fig. 5: h, log p diagram of a heat pump, ideal curve.

Theory (2/3)

The curve running through the critical point K delineates the wet vapour zone in which the liquid phase and gas phase coexist. In
this zone the isotherms run parallel to the h axis.

Starting from point 1, the compressor compresses the working substance up to point 2;

in the ideal case this action proceeds without an exchange of heat with the environment, i.e. isentropically (S = const.).

On the way from point 2 to 3 useful heat is released and the working substance condenses.

Then the working substance flows through the restrictor valve and reaches point 4.

Theory (3/3)

The specific amounts of energy q_0 and q taken up and released per kg and the specific compressor work w required can be read off directly as line segments on the graph.

$q_0 = h_1 - h_3$

$q = h_2 - h_3$

$w = h_2 - h_1$

For evaluation purposes the data for the working substance R134a in the wet vapour zone are set out in Table 1.

Evaluation (1/12)

1. Water-water heat pump

Fig. 6 shows the curve of the temperatures against time in the case of operation as a water-water heat pump. The temperature of the working substance does not change during vaporisation or during condensation. Superheating of the vapour occurs before the condenser (see Fig. 5; point 2 lies outside the wet vapour area).

On the vaporiser side the restrictor valve thermostat ensures that the vapour is superheated so that liquid working substance does not enter the compressor. Point 1 (Fig. 5) therefore also lies outside the wet vapour zone in the actual heat pumping process.

Evaluation (2/12)

In the diagram can be seen, the Temperatures at the inlet and outlet of the vaporiser until $\Theta_V i$, until $\Theta_V o$ and condenser until $\Theta_C o$ (o) as a function of the operating time; continuous curves: temperature in water reservoirs.

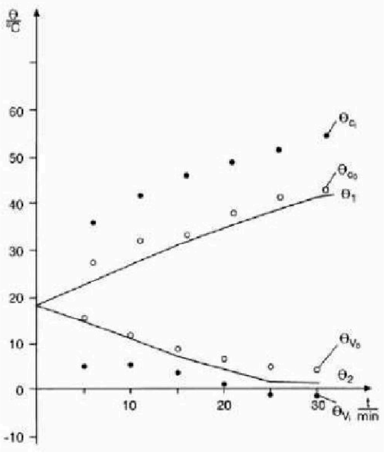


Fig. 6: Temperatures at the inlet and outlet of the vaporiser

Evaluation (3/12)

In Fig. 7 some of the measured pairs of pressure and temperature values are plotted and compared with the values from Table 1.
It is to be borne in mind here that the pressure gauges in the circuit indicate pressure in excess of atmospheric pressure.

It can be seen from the graph that supercooling of the liquid working substance also occurs in the actual heat pumping process,
i. e. point 3 (Fig. 5) also lies outside the wet vapour zone

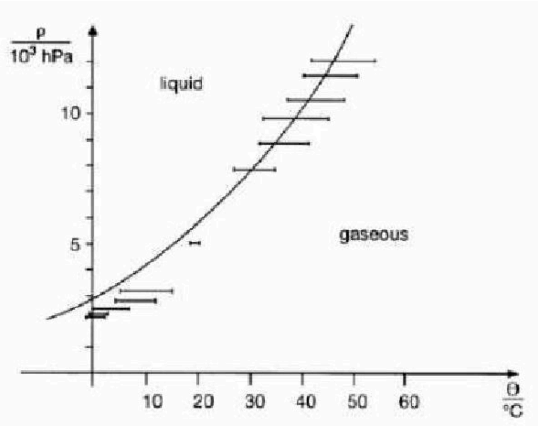


Fig. 7: Interdependence of (absolute) pressure and boiling temperature of the working substance (test value interval for vaporiser and condenser) when the heat pump is operating; continuous curve: in accordance with eqn. 1.

Evaluation (4/12)

The vaporisation and condensation of the working substance may be observed through the sight glasses of the heat pump. As the restrictor valve controlled by a thermostat lets through varying quantities of working substance, the scene is not always uniform. The energy flow on the condenser and vaporiser side is calculated from the heating and cooling of the water bath.

$$\dot{Q} = c \cdot m_W \frac{\Delta\Theta}{\Delta t} \quad (1)$$

$c =$ Specific heat capacity of water

$m_W =$ Mass of the water

$\frac{\Delta\Theta}{\Delta t} =$ Temperature change per unit time

Evaluation (5/12)

The energy flows are not constant but, apart from the operating condition of the heat pump (charge in the circuit, setting of the restrictor valve, instantaneous compressor power) are, above all, dependent upon the temperature difference between vaporiser and condenser.

The measured values from Figs. 5 and 6 are evaluated at the moment t = 10 min.
Mass of water in each water reservoir $m_W = 4.8 \text{ kg}$

Condenser heat flow

$$\dot{Q} = 269 \text{ W}$$

Vaporiser heat flow

$$Q_0 = 235 \text{ W}$$

Evaluation (6/12)

The compressor power fluctuates with time. On average it is P = 120 W.
The resulting performance figure is therefore

$$\varepsilon = \frac{\dot{Q}}{P} = 2.2.$$

The ratio of the actual stroke volume V to the geometrical stroke volume V_g of the compressor is called the volumetric efficiency λ the compressor:

$$\lambda = \frac{V}{V_g}$$

Assuming an ideal heat pumping process, the actual volume flow $\dot{V}$ of the working substance in the circuit and the volumetric
efficiency λ of the compressor can be calculated from the vaporiser heat flow with the aid of eqn. 1.

Evaluation (7/12)

$$V = \frac{v \cdot \dot{Q}_0}{h_1 - h_3}$$

(v = specific volume of the vapour)

Pressure on the vaporiser side at

$$t = 10 \text{ min}$$

$$p_0 = 3.1 \cdot 10^3 \text{ hPa}$$

Pressure on the condenser side at

$$p_0 = 3.1 \cdot 10^3 \text{ hPa}$$

from table 1

Evaluation (8/12)

$$h_1 \ = \ 399.84 \cdot \mathrm{kJ/kg}$$

$$h_3 \ = \ 247.47 \cdot \mathrm{kJ/kg}$$

$$v = 0.0647 \cdot \mathrm{m^3/kg} \ = \ 64.7 \ \mathrm{l/kg}$$

Hence

$$\dot{V} \ = \ 100 \ \mathrm{cm^3/s}$$

and the frequency of rotation of the piston

$$f \ = \ 1450 \ \mathrm{min}^{-1}$$

Evaluation (9/12)

We obtain a geometrical volume flow of

$$\dot{V}_g \ = \ V_g \cdot f \ = \ 123 \ \mathrm{cm^3/s}$$

and therefore a volumetric efficiency of the compressor

$$f \ = \ 1450 \ \mathrm{min}^{-1}$$

Evaluation (10/12)

The condenser heat flow of the heat pump is dependent upon the vaporiser temperature. When operating as an air-water heat pump, the vaporiser temperature remains approximately constant after approx. 10 min since, because of the blower, a virtually infinite reservoir of air is available.

Without the blower the vaporiser ices up, as the result of which its temperature likewise remains almost constant.

to compare the different modes of operation, the condenser heat flow $\dot{Q}$ is calculated using equation (1) at a water temperature of Θ_1 = 30°C.

The average vaporiser temperature Θ_{Vo}, the condenser heat flow $\dot{Q}$ and the performance figure ϵ (compressor power P = 120 W) for the different modes of operation are shown in the following table.

Evaluation (11/12)

Blower	θ_{Vo} **[°C]**	$\dot{Q}$ **[W]**	ϵ
hot	**12**	**276**	**2.1**
cold	**8**	**193**	**1.5**
without	**-10**	**117**	**0.9**

A blower is therefore necessary for operation of an economically working air-water heat pump.

Evaluation (12/12)

Θ	temperature
p	Pressure (absolute)
v	Specific colume of the vapour
h´	Specific enhalpy of the lquid (h_1)
h´´	Specific enthalpy of the vapour (h_3)