Heat

Thermodynamic cycle
Heat pump

LD
Physics
Leaflets

P2.6.3.3

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

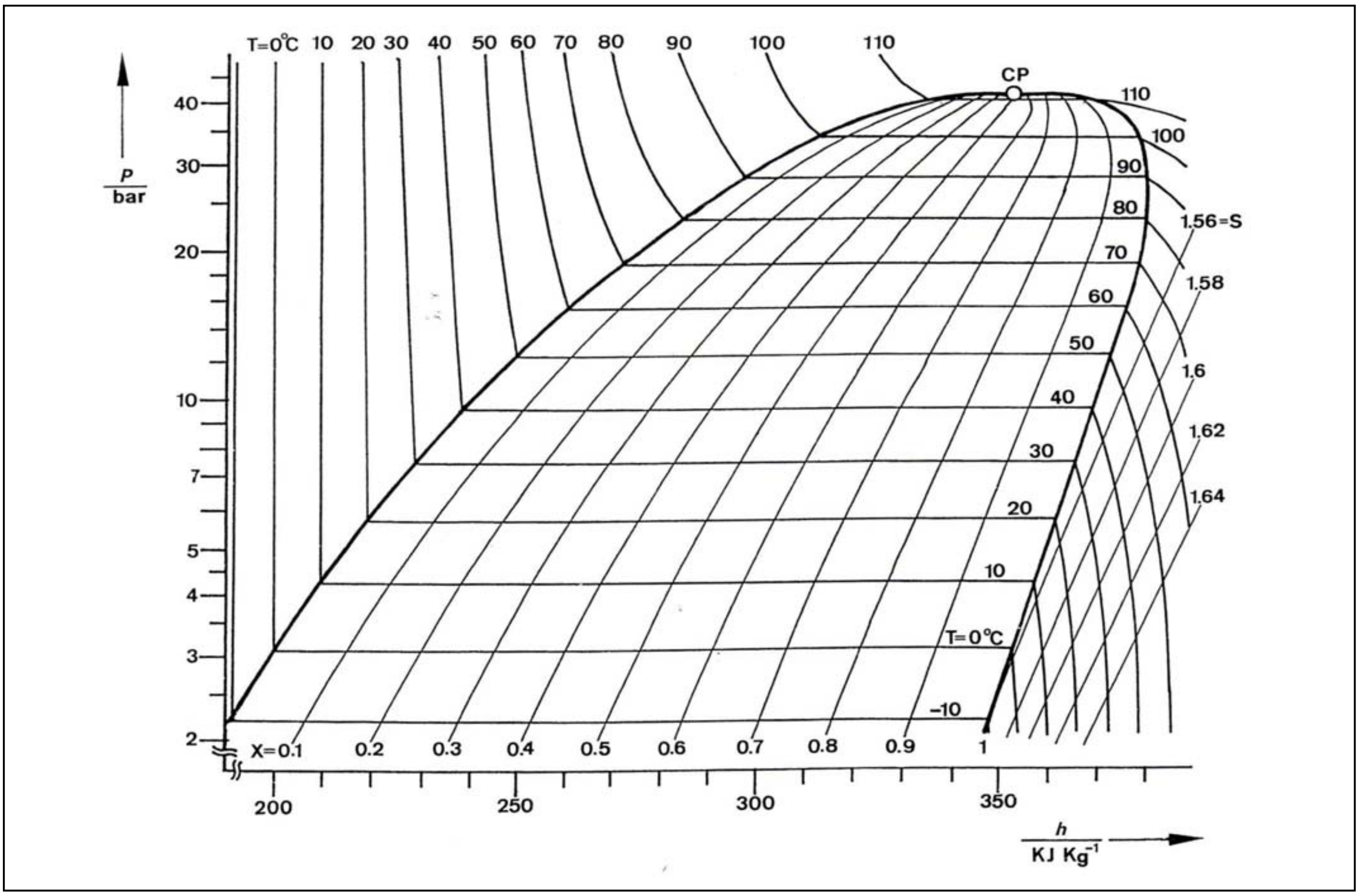
Objects of the experiment

- To know the basic structure and the application of a Mollier diagram.
- To be able to represent the thermo-dynamic cycle of the heat pump in a Mollier diagram using the measured data.
- To use the Mollier diagram for determining the mass flow of the coolant.

Principles

The *Mollier* diagram allows to visualize the energy and the phase transitions of the coolant in compressor-operated heat pumps quantitatively. The coordinates of the *Mollier* diagram (Fig. 1) are the specific enthalpy h (horizontal axis) and the pressure p (vertical axis) of the coolant. The unit of specific enthalpy h (representing the „content of heat“) is kJ/kg, the unit of the pressure p is bar. For clarity reasons the pressure axis is represented in logarithmic scale.

Fig. 1: Simplified lg(p)-h diagram according to Mollier



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The coolant is generally present as a mixture of gas and liquid. Its enthalpy h depends on the amount x of gas ($0 \le x \le 1$ – related to the total volume), and on the pressure p. Generally the following tendency is observed: the higher the amount of gas the larger is the heat energy content, and the energy content is generally increasing with rising pressure.

For the case of *completely condensed* coolant (x = 0) the relation between pressure p and enthalpy h in the Mollier diagram is represented by the so called ”boiling line“.

For the opposite case of *completely evaporated* coolant (x = 1) the p-h relation is represented by the so called „dew line“ (Fig. 1). Left of the ”boiling line“ the coolant is represented as a liquid only, right of the “dew line“ as a (superheated) gas. Both of these boundary lines meet each other in the “critical point“ CP.

The lg(p)-h diagram according to *Mollier* consists of the following lines:

- Isothermic lines T = const. (lines of constant temperature),
- Isentropic lines S = const. (lines of constant entropy),
- lines with x = const. (lines of constant phase ratio) in the “condensation region“ between “boiling line“ and “dew line“.

Hence the *Mollier* diagram contains the complete information about the thermo-dynamic behavior of the used coolant. Therefore it allows by means of a few temperature and pressure measurements a deep insight into the thermodynamic cycle of the heat pump.

Apparatus

1 Heat pump	389 521
1 Joule and Watt Meter	531 831
1 Digital Thermometer	666 209
3 Temperature Sensor, NiCr-Ni	666 193
1 Digital stopwatch	313 12

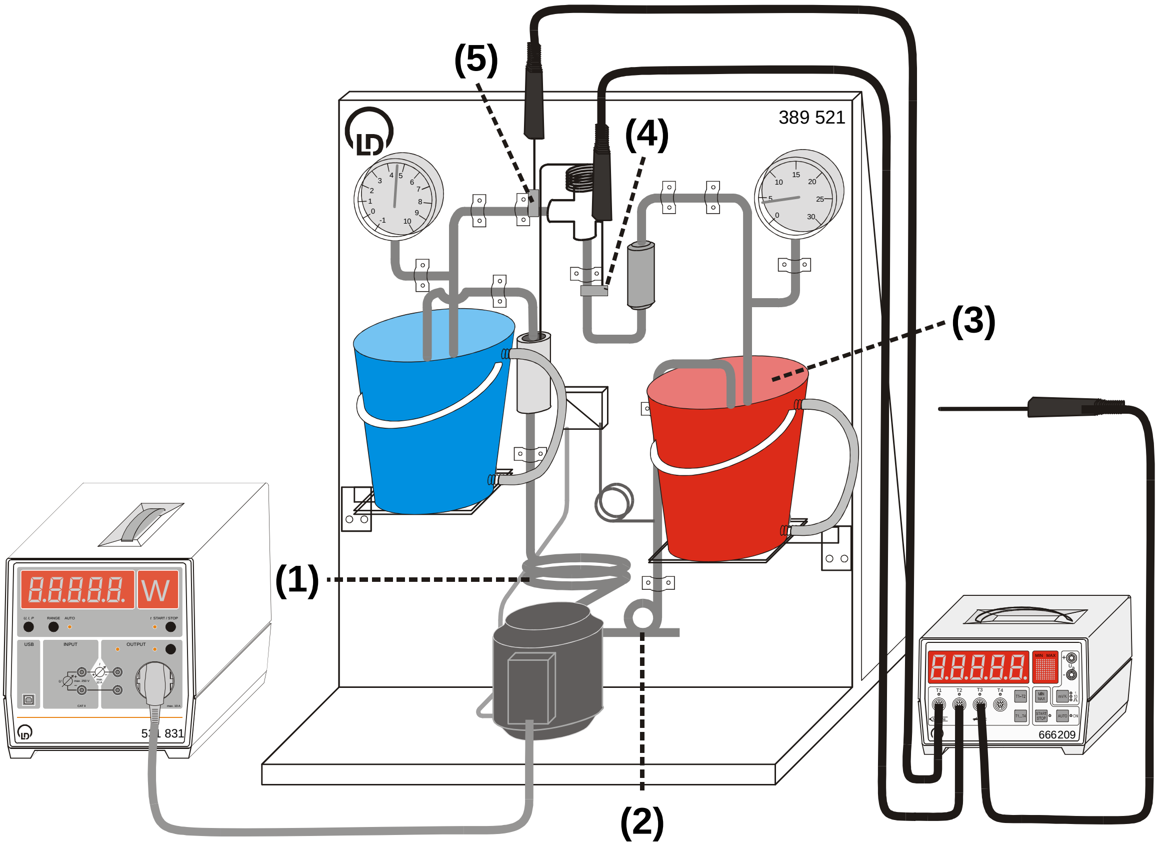
Additionally recommended:

RS 232 cable, 9-pole	729 769

additionally required:

1 PC with Windows 98 or higher

Fig. 2: Experimental setup with temperature measuring points schematically.



In this experiment the temperature and pressure are measured as well on the evaporator side and on the liquefier side. From these data the mass flow of the coolant is calculated on the base of the lg(p)-h diagram. Instead of the temperatures of the coolant temperatures of the copper tubes are used. They are directly accessible by external measurement. However, the corresponding measuring values are naturally shifted slightly towards temperature of the surrounding (room temperature). The pressure values indicated on the manometers represent relative pressure. They have to be transformed to absolute pressure values by adding the atmospheric pressure of 1 bar.

Setup

Safety notes

Mind the safety notes of the instruction sheet 389 521 for the heat pump.

- The coolant circuit is pressureized. Do not attempt to open this circuit under any circumstances.
- Do not thermally insulate the compressor; this can cause the device overheat.

- Fix the copper holders contained in the accessories of the heat pump at the temperature measuring points marked with (4) and (5) in Fig. 2.
- Bring a drop of oil or heat-conducting paste (available in electronics shops) in each borehole and insert temperature sensors.
- Also prepare the temperature measuring points (1) and (2) each with a drop of oil or heat-conducting paste.
- Fill the red and blue vessels up to the 4 l mark with tap water and bring them in experimental position around the copper tube windings by their supports.
- Connect Joule and Watt Meter between mains socket and heat pump.
- After switching on the Joule and Watt Meter wait until the unit display (on the right side) has become stable and shows “µV“.
  Set the unit of the display by pressing 2 times the button quantity (“U, I, P“) to “µW“. Set the range of the display by pressing 9 times the range button (“RANGE“) to “0.0 W“.

  The button (“t START/STOP“) is not be used here. Do not press the black button in the output panel („OUTPUT“) after switching on the Joule and Watt Meter.

Carrying out the experiment

- Switch on the heat pump by pressing the black button in the output panel of the Joule and Watt Meter.
- Stir the water in the cold and warm vessel during a preliminary run of 10 to 15 min.
- During the following measurement the water in both in the warm and cold vessel have to be stirred slowly but permanently.
- After the preliminary run the third temperature sensor is used to measure T_1, T_2, T_3 and T_6 within a short time. Further the values of T_4 and T_5 have to be read off quickly as well as the pressures p_1 and p_2.
- After 2 min the values of T_3 and T_6 are read off again.
- Read off the electrical power consumption P of the compressor on the Joule and Watt Meter.

Measuring example

The measured values are summarized in the following table:

Table 1: Measuring results for:

power consumption of the compressor: P = 112 W

Mass of the warm water reservoir: m_{water} = 4 kg

Measuring point (Fig. 2)	pressure	Initial temperature	Temperature after 2 min
(1)	p_1 = 2.6 bar	T_1 = 10.0 °C	
(2)	p_2 = 9.0 bar	T_2 = 55.5 °C	
(3)		T_3 = 30.1 °C	T'_3 = 31.5 °C
(4)		T_4 = 20.1 °C	
(5)		T_5 = 0.6 °C	
(6)		T_6 = 2.6 °C	T'_6 = 1.5 °C

Evaluation and results

The characteristic line of the circular process is drawn in the lg(p)-h diagram according to the measuring values (Fig. 3). The initial values of p_1 and T_1 determine point (1). From the lg(p)-h diagram is visible that the coolant is gaseous in this state and from the horizontal axis follows the enthalpy h_1 = 360 kJ/kg.

Now the compressor is condensing the gas to the pressure value p_2. The compression is carried out so fast that there will occur nearly no heat exchange between gas and cylinder (i.e. also no exchange of entropy). The Point (2) is placed therefore on the isentropic line (S = const.) which is going through point (1). The temperature T_2 of the gas in state (2) is indicated in the diagram to be 60 °C (5 °C higher than the measured temperature T_2 at the compressor output).

In the liquefier (3) the gas is cooled down to 38 °C (reaching of the “dew line“ in the diagram). Afterwards liquefaction starts which is completed in the lower part of the liquefier (“boiling line“). Before leaving the liquefier the liquid is cooled down to T_3 = 30.1 °C by the surrounding water bath.

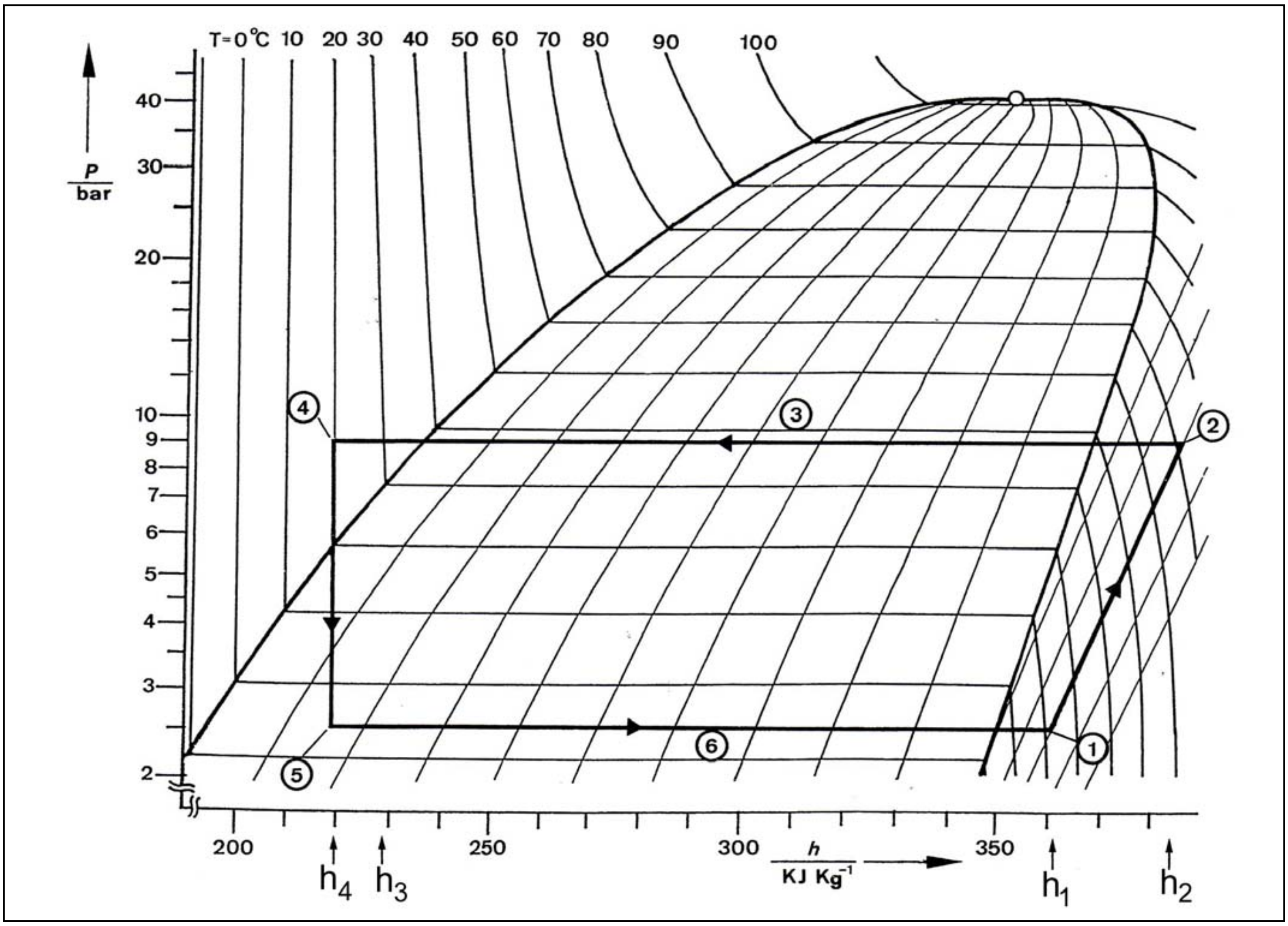


Fig. 3: Mollier diagram with measuring points of the thermodynamic cycle

On the way to the expansion valve the liquid is cooled down furthermore to T_4 = 20.1 °C indicated in the diagram by point (4). The enthalpy of the coolant is not changing during the following expansion. Immediately after the expansion (5) the amount of gas is $x_5 = 0.15$ (according to diagram). During the evaporation (6) the amount of gas increases further until the evaporation is completed (i.e. at reaching „dew line“).

Before leaving the evaporator the gas warms up to T_6 = 2.6 °C by the surrounding water bath. On the way to the compressor the gas is warming up further to approx. 10 °C, indicated by initial point (1).

The *Mollier* diagram gives now specific enthalpy values of the used coolant for each important point of the circular process (Fig. 3 and Table 2):

h_1 =	360 kJ/kg	(before compression)
h_2 =	384 kJ/kg	(after compression)
h_3 =	228 kJ/kg	(at leaving the liquefier)
h_4 =	220 kJ/kg	(immediately after expansion)

Determination of the mass flow of the coolant:

For the transfer of the heat energy Q_2 to the warm water reservoir an amount m of the coolant is necessary, which results from the relation:

$$Q_2 = m \cdot (h_2 - h_3)$$

Hence the mass flow of the coolant can be determined according to:

$$\frac{dm}{dt} = \frac{\Delta m}{\Delta t} = \frac{\Delta Q_2}{\Delta t \cdot (h_4 - h_2)} = -\frac{Q_2}{h_4 - h_2}$$

Q_2 can be measured by the temperature increase of the warm water reservoir:

$$Q_2 = m_{\mathbf{water}} \cdot c_{\mathbf{water}} \cdot (T'_3 - T_3)$$

Table 2: Circulation of the Coolant in the Heat Pump (Thermodynamic Cycle)

measuring point	State or Change of state	Phase (x =…)	Pressure	Temperature	Enthalpy
(1)	only gas	1,00	p_1 = 2,6 bar	T_1 = 10,0 °C	h_1 = 360 kJ/kg
	compression in the compressor	↓	↓	↓	↓
(2)	only gas	1,00	p_2 = 9,0 bar	T_2 = 55,5 °C	h_2 = 384 kJ/kg
(3)	cooling in the warm-water bath	↓	↓	↓	↓
	only gas	1,00	9,0 bar	38,0 °C	↓
(3)	liquefaction in the warm-water bath	↓	↓	↓	↓
	only liquid	0,00	9,0 bar	38,0 °C	↓
(3)	cooling in the warm-water bath	↓	↓	↓	↓
	only liquid	0,00	9,0 bar	T_3 = 30,1 °C	h_3 = 228 kJ/kg
(3)	cooling on the way to the expansion valve	↓	↓	↓	↓
(4)	only liquid	0,00	9,0 bar	T_4 = 20,1 °C	h_4 = 220 kJ/kg
	expansion in the expansion valve	↓	↓	↓	↓
(5)	mixture	0,15	2,6 bar	T_5 = 0,6 °C	↓
(6)	evaporation in the cold-water bath	↓	↓	↓	↓
	only gas	1,00	2,6 bar	0,6 °C	↓
(6)	heating-up in the cold-water bath	↓	↓	↓	↓
	only gas	1,00	2,6 bar	T_6 = 2,6 °C	↓
(6)	heating-up on the way to the compressor	↓	↓	↓	↓
(1)	only gas	1,00	p_1 = 2,6 bar	T_1 = 10,0 °C	h_1 = 360 kJ/kg

With

m_{water} = 4 kg,

$c_{\mathrm{water}} = 4.2\ \frac{\mathrm{kJ}}{\mathrm{kgK}}$ and

Δt = 120 s

follows:

$$\frac{dQ_2}{dt} = \frac{m_{\mathrm{water}} \cdot c_{\mathrm{water}}\ (T_3' - T_3)}{\Delta t} = 0.196\ \frac{\mathrm{kJ}}{\mathrm{s}}$$

From this follows for the mass flow:

$$\frac{dm}{dt} = 1.26\ \frac{\mathrm{g}}{\mathrm{s}}$$

Determination of the effective compressor power:

During the compression the enthalpy of the coolant increases from 360 kJ/kg to 384 kJ/kg. This corresponds to the heat power of the compressor:

$$\frac{dQ_K}{dt} = (h_4 - h_1) \cdot \frac{dm}{dt} = 0.0302\ \frac{\mathrm{kJ}}{\mathrm{s}} = 30.2\ \mathrm{W}$$

The dQ_K/dt is the power which is necessary for compression in the ideal case, i.e. if the compressor would be operated without any power losses. In reality the electrical power consumption is measured as P = 112 W which means that only 27% are used properly for the compression.

The efficiency of the heat pump could be increased theoretically by a better heat insulation of the compressor. However, one have to ensure at the same time that the heat of the compressor is removed in a controlled way. As the compressor of the heat pump does not have any oil cooling the heat insulation of the compressor is not allowed in this experiment.

If dQ_2 / dt is the heating power at the warm water reservoir and dQ_1 / dt is the cooling power at the cold water reservoir, the power balance of the heat pump is given by (ideal case):

$$\frac{dQ_2}{dt} = \frac{dQ_1}{dt} + \frac{dQ_k}{dt}$$

From the measured values can be derived:

$$Q_1 = \frac{m_{water} \cdot c_{water}}{dt} \cdot (T_6 - T_6') = 0.154\ \frac{kJ}{s}$$

With this result follows:

$$\frac{dQ_k}{dt} = \frac{dQ_2}{dt} - \frac{dQ_1}{dt} = 0.195\ \text{kW} - 0.154\ \text{kW} = 42\ \text{W}$$

which approximately agrees with the above result of 30.2 W. The considerable deviation originates from the small temperature difference used in this derivation.

Efficiency number and temperature differential

From the lg(p)-h diagram can also be seen why efficiency of the heat pump ε (or performance number) is decreasing with increasing temperature differential ΔT between warm water and cold water reservoir:

$$\varepsilon = \frac{\Delta Q_2}{\Delta t \cdot P} = \text{const} \cdot \frac{\Delta Q_k}{\Delta t \cdot \frac{dQ_k}{dt}}$$

The minimum compressor power dQ_K / dt, which is necessary theoretically, is increasing approximately proportional with the temperature difference $\Delta T = T_2 - T_1$. On the other hand the difference of enthalpy $Q_2 = m \cdot (h_2 - h_3)$, representing the heat transport from the cold to the warm water reservoir increases only by a small amount with ΔT.

Supplementary information

R. Mollier (1863 until 1935) was an engineer and professor of thermodynamics at the technical university in Dresden, Germany. He developed enthalpy diagrams, to simplify the technical calculations for steam engines and refrigerating engines.

Literature: E. Ossner, MNU 35, p. 345 (1982)