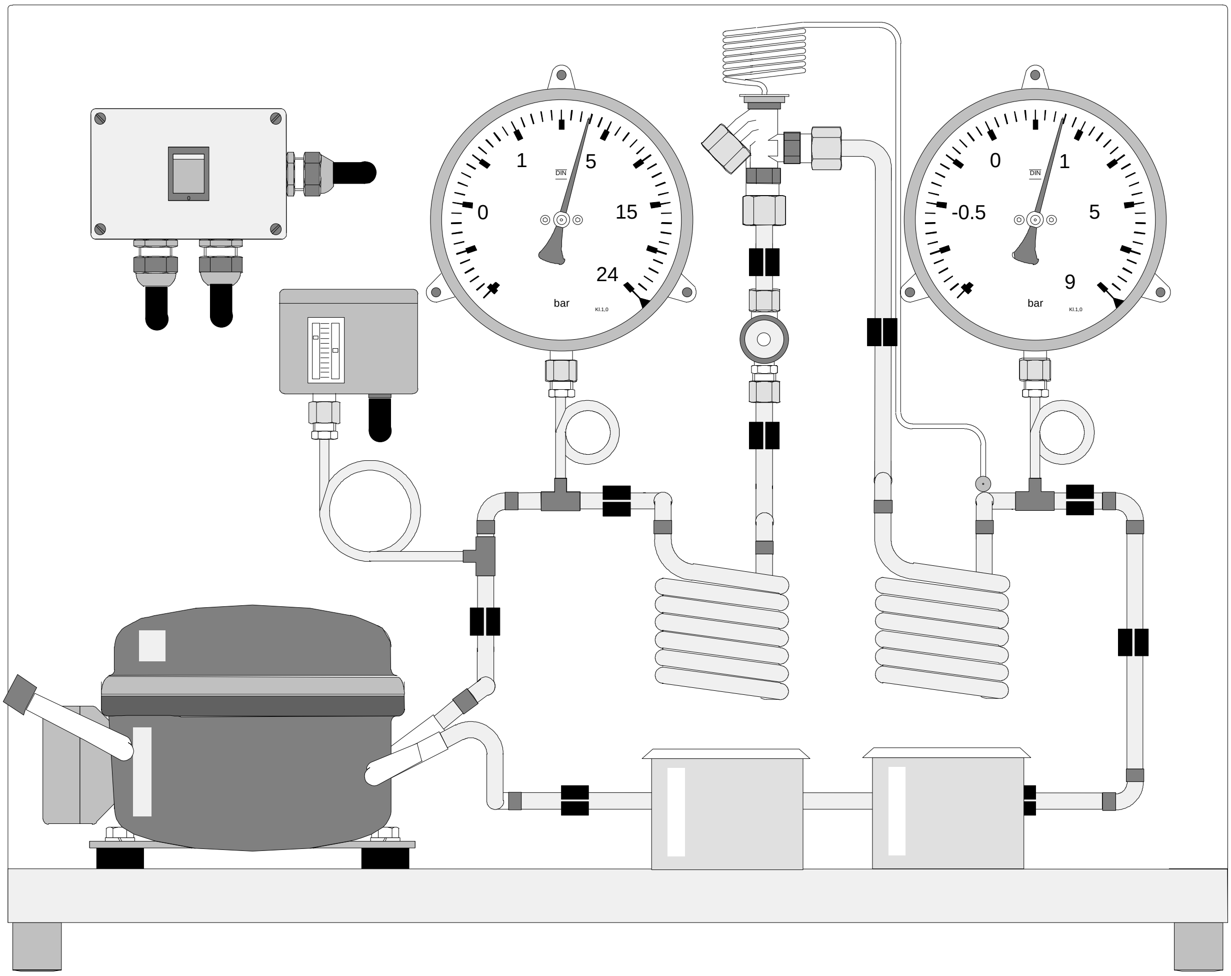
Experiment Instructions

ET101 Basic Heat Pump Demonstrator

ET 101 Basic Heat Pump Demonstrator



Experiment Instructions

Publication no.: 916.000 00B 101 12 10/2009

Table of Contents

1 Introduction

The **ET 101 heat pump demonstrator** represents a fully functional model of an water/water heat pump.

The bench-top unit covers the following areas of tuition in the field of heating and refrigeration engineering:

- Familiarisation with the basic construction of heat pumps
- Components of thermal engines, heat pumps and refrigeration systems
- Familiarisation with cyclic processes
- Working with p-h diagrams
- Basics of refrigeration engineering

The bench-top unit exclusively contains components which are also used in industrial heat pumps and refrigeration systems.

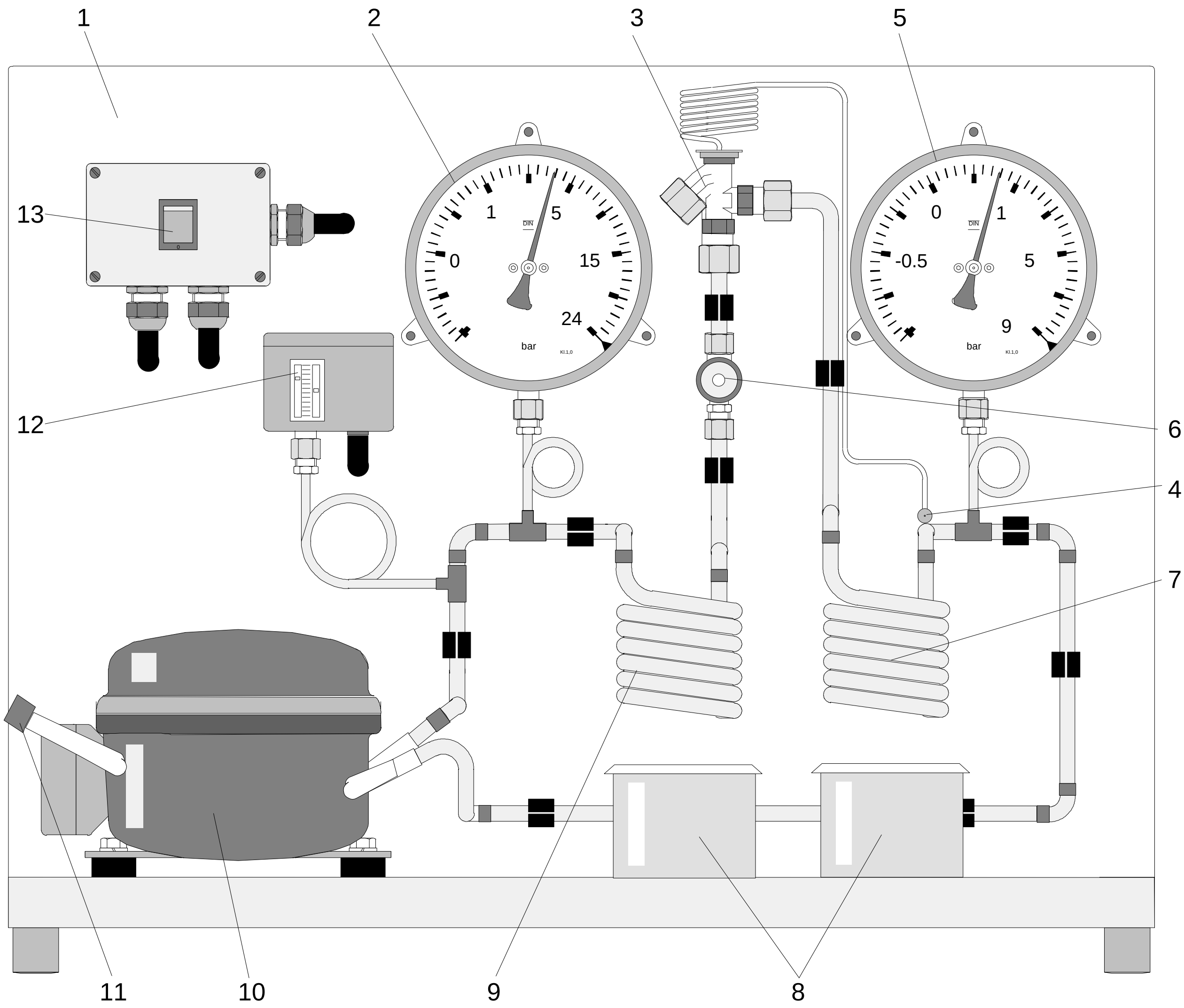
The unit is primarily intended for producing qualitative assessments. Quantitative measurements can, however, also be carried out.

Always follow the safety regulations (Chapter 3) when using the unit!

The ET 101 heat pump demonstrator unit is intended for **use in education and training.** Its use in industrial environments in particular is forbidden.

2 Unit description

2.1 Unit construction



1. Frame
2. Manometer for high-pressure side (HP)
3. Expansion valve with
4. Temperature sensor
5. Manometer for low-pressure side (LP)
6. Sight glass (refrigerant)
7. Evaporator
8. Water tank
9. Condenser
10. Compressor
11. Filler valve
12. Pressostat
13. Main switch

2.2 Unit function

The **ET 101 heat pump demonstrator** includes a complete heat pump with original refrigeration engineering components. The temperature sink is a water tank, from which heat energy is drawn. This heat is fed back in a second water tank. The system is characterized by the following features:

- The entire system is laid out clearly on a wall chart.
- Original refrigeration engineering components mean the setup is practice-oriented.
- An environmentally friendly refrigerant (R134a, CFC-free) is used.
- The robust construction of the unit means it is ideally suitable for use in erveryday tuition.

The expansion valve fitted in the system is a thermostatic expansion valve with an evaporator temperature sensor, and is set to a minimum evaporator outlet temperature of T_V= -2°C.

The delivery side of the compressor is protected against overload by a Pressostat.

A sight glass in front of the expansion valve allows the flowing refrigerant to be observed.

2.3 Operation

The unit is switched on by throwing the main switch. **No other settings need to be made!**

The compressor has an overload protection device provided by a thermostatic switch. If the switch is tripped, switch off the main switch, allow the system to cool, and then switch it back on again.

2.4 Commissioning

Prior to commissioning the system into operation, the two plugs on the tops of the manometers must be cut off to render the manometers functional.

Also, wait a few minutes for the refrigerant to settle before starting up.

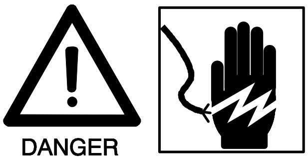
The system is started up by connecting the compressor to the mains power. The compressor is then activated by throwing the main switch.

2.5 Care and maintenance

The unit is maintenance-free. The system should be **protected against frost**.

Please do not make any alterations to the compressor, the expansion valve or the Pressostat. They are factory-set to enable the unit to function properly.

3 Safety



Important! Electrical voltage.

You should therefore observe the following safety instructions:

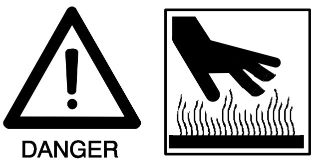
- Before opening the main switch cabinet and working on the electrics, disconnect the mains plug!
- Protect the main switch cabinet against water incursion!
- **In case of danger switch off the main switch and disconnect power to the system by unplugging the mains plug!**

- Never manipulate the service product circuit (by opening up screw fittings or the like)! The system is under pressure!

The service product (refrigerant R134a) is environmentally hazardous and may escape, so

- **Suction off the refrigerant properly** before carrying out repairs!
- Do not adjust the Pressostat. It is factory-set!
- Do not adjust the expansion valve!

- If the compressor’s thermostatic switch is tripped, allow the system to cool off. Check the operating pressures after restarting!



- **Danger of burns!** The pipework from the compressor to the condenser becomes very hot. Do not touch it during operation!

4 Theory

4.1 Cyclic process

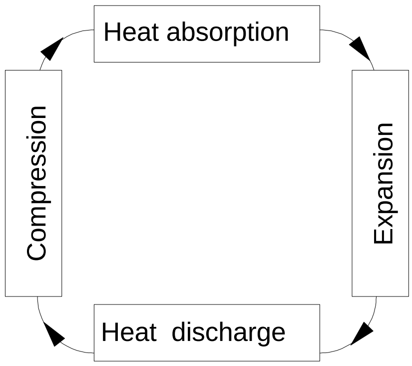


Fig.: 1

The basis for the functioning of a heat pump is a thermodynamic cyclic process.

In a thermodynamic cyclic process a service medium (e.g. R134a) passes through various changes of state in a pre-set sequence. The changes of state are repeated cyclically, so the service medium repeatedly returns to its initial state. That is why the process is termed a cyclic process.

Change of state refers to compression, expansion, heating or cooling:

- Compression means absorption of mechanical energy
- Expansion means discharge of mechanical energy
- Heating means absorption of thermal energy (heat)
- Cooling means discharge of thermal energy

In a change of state the state variables such as pressure, specific volume or temperature of the service product, change. Gas or easily evaporated liquids may be used as the service product. Pure liquids are unsuitable, because they are incompressible.

Skilful sequencing of various changes of state can cause thermal and mechanical energies to be exchanged by way of the service product; that is, the service product acts as an energy transfer medium.

The changes of state do not need to occur at clearly separated intervals. Often heat is discharged during compression, for example. The variations involved in changes of state is interlinked. Compression, for example, generally leads to

- an increase in temperature *T*
- an increase in pressure *p*
- a reduction in volume *V*

For gases, this interlinking of state variables can be described with the so-called thermal state equation for ideal gases:

$$p \cdot v = R \cdot T \qquad (4.1)$$

In this, *p* is the absolute pressure, *v* the specific volume (volume referred to mass), *R* the specific gas constant and *T* the absolute temperature (in Kelvins).

In observing the change of state of a gas, a distinction must be made between two states:

- 1 - State of the gas before the change of state
- 2 - State of the gas after the change of state

The cases in which one of the state variables remains unchanged (=constant) during the change of state are of special significance, and so have their own designations:

Special cases of the state equation			
Designation:	Isobaric		
Change of state	Isochoric		
Change of state	isothermic		
Change of state			
Condition:	*p = constant*	*v = constant*	*T = constant*
State equation:	$\frac{v_1}{v_2} = \frac{T_1}{T_2}$	$\frac{p_1}{p_2} = \frac{T_1}{T_2}$	$\frac{p_1}{p_2} = \frac{v_2}{v_1}$
	Gay-Lussac's law		Boyle-Mariotte's law

A change of state without heat discharge is termed an **isentropic change of state** (the specific entropy, see Chapter4.5, remains constant), a change of state without exchange of heat is termed an **adiabatic change of state.**

In pure compression or expansion without heat discharge or absorption (isentropic or adiabatic respectively), the necessary mechanical energy $W_{1,2}$ for the change of state from state 1 to state 2 is calculated as

$$W_{1,2} = m \frac{R}{\kappa - 1}(T_1 - T_2) \qquad (4.2)$$

or

$$W_{1,2} = m \frac{R}{\kappa - 1}(p_1 v_1 - p_2 v_2) \quad . \qquad (4.3)$$

κ is the isentropic exponent,

m is the mass of the gas.

For isochoric heating or cooling (i.e. same volume, but increasing or decreasing temperature) the following applies for input or output heat quantity Q1,2

$$Q_{1,2} = m \cdot c_v \, (T_2 - T_1) \qquad (4.4)$$

C_V is the specific heat capacity of the gas under observation at constant volume. A distinction must be made between two kinds of specific heat capacity:

- Heating from T_1 to T_2 causes a pressure increase, the volume remains constant: c_V
- The heating brings about an increase in volume, the pressure remains constant: c_p

From the specific heat capacity the isentropic exponent κ is produced as:

$$\kappa = \frac{c_p}{c_v} \tag{4.5}$$

In reality, ideal gases are practically never encountered. The observation of changes of state with liquids or vapours as with common service products for heat pumps is much more complicated, and uses other state variables such as entropy or enthalpy, with the aid of caloric state equations.

4.2 Example: Steam plant

Steam plant circulation process

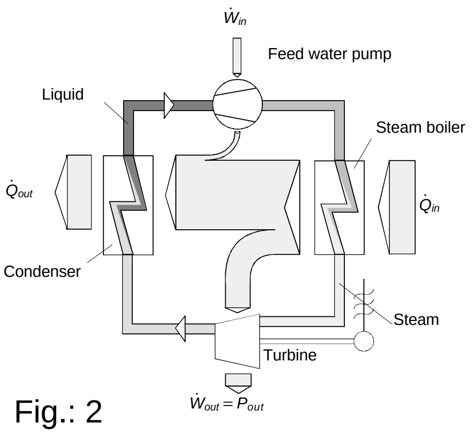


Fig.: 2

Steam plant (steam turbines, steam locomotives) is the oldest application of a cyclic process. As will be shown, a steam plant is, so to speak, the reverse of a heat pump.

The steam plant uses water as its service product. The cyclic process can be divided into four consecutive changes of state:

- First the water is compressed by a low pressure by means of the feed water pump in the highly pressurised steam boiler. The mechanical energy W_{in} is used up in the process.
- In the steam boiler the water is evaporated by addition of heat energy $\dot{Q}_{in}$. The temperature rises, the pressure remains constant.
- The hot, high-pressure steam flows into the turbine. There the steam gives off its internal energy in the form of mechanical energy W_{out} to the turbine blades. The pressure and temperature fall again.
- Finally the steam condenses in the condenser, with further heat being discharged $\dot{Q}_{out}$.

The condensate is routed back to the boiler feed water pump and the cycle begins again. The service product, water, thus circulates in the cyclic process. That is why the process is termed a closed cyclic process.

Cyclic processes in which the service product continually has to be replaced, and is not recycled, are termed open cyclic processes. These also include the spark-ignition and diesel processes with which modern car engines operate.

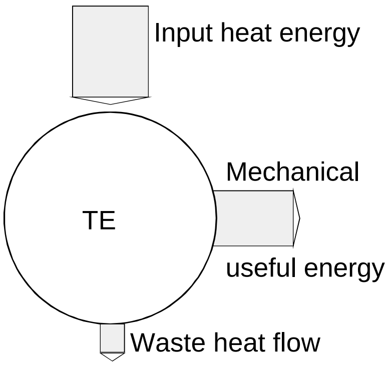


Fig.: 3

In the steam plant shown, therefore, heat energy can be converted into mechanical energy (with a specific waste heat flow). Machines in which processes of this kind occur are termed thermal engines (TE). These also include cyclic processes with purely gaseous service products, as in gas turbine plants or hot-air engines (Sterling engine).

4.3 Example: Heat pump

Whereas the steam plant process concentrates on the conversion of thermal energy into mechanical energy, the heat pump utilises the effect of heat transport. The term "heat pump" can be explained by the following illustration: heat is pumped from a low temperature level to a high temperature level, using up mechanical energy. The mechanical energy is not lost, but is also discharged at the higher temperature level, in the form of thermal energy.

In a heat pump the cyclic process of the steam plant is run through in reverse order. Consequently, the direction of the heat flow is also reversed:

- A **compressor** compresses the vaporous service product, whereby mechanical energy W_{in} is absorbed.

Heat pump circulation process

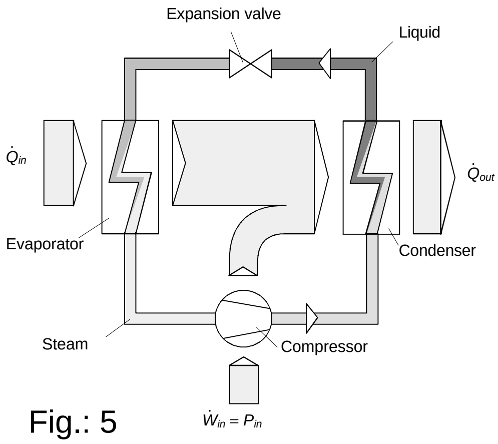


Fig.: 5

- In the **condenser** the heat $\dot{Q}_{out}$ is drawn off of the service product (at the same temperature) and the medium is liquefied.
- In an **expansion valve** pressure is relieved from the liquid service product, thereby cooling it down.
- An **evaporator** evaporates the service product, with heat absorption $\dot{Q}_{in}$.

The service product is now fed back to the compressor and the cyclic process begins again.

4.4 Comparison: Heat pump/Refrigerator

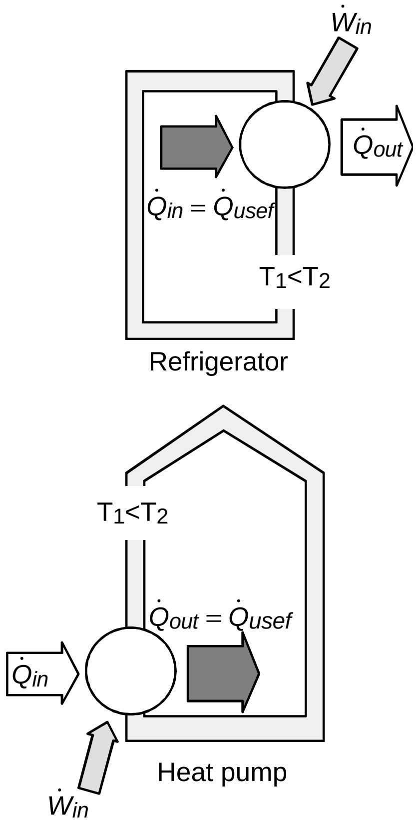


Abb.: 4

In terms of function, the heat pump is identical to the refrigerator. There, too, heat is pumped from a low energy level 1 (from the refrigerator) to a higher energy level 2 (in the environment). Whereas in the case of the heat pump the output heat $\dot{Q}_{ab}$ is used, the benefit for the refrigerator comes from the input heat $\dot{Q}_{zu}$.

The consumption should be equivalent to the required mechanical energy W_{in}.

The advantage of processes with vaporous/ liquid service product lies in the high energy transfer density. During evaporation the service medium absorbs the evaporation heat with low temperature differences. In condensation it discharges it again. The evaporation heat in the service products used is very much greater than the quantity of heat to be transferred via the specific heat capacity of the steam.

Example: Water

The quantity of heat required to evaporate 1 kg of water is 2256 kJ, whereas a temperature increase of that steam from 100°C to 200°C only requires 199 kJ of heat (at 1 bar in each case).

A high energy density saves a lot of money: compact high-performance systems can be constructed.

The heat pump process can also be easily carried out with a purely gaseous service product. Systems based on the Sterling principle are constructed, but are highly complex and expensive.

4.5 Heat pump process in the p-h diagram

The changes of state in a cyclic process can be advantageously plotted in a p-h diagram.

In the p-h diagram the pressure p is plotted over the specific enthalpy h.

Enthalpy H is designated as the total energy content of a gas or vapour. It is composed of the internal energy U, a measure for the thermal energy content of a substance, and the displacement work $p \cdot V$.

$$H = U + p \cdot V \qquad (4.6)$$

Referred to the mass, here too specific variables are obtained:

$$h = u + p \cdot v \qquad (4.7)$$

with the specific internal energy $u = u_0 + c_V(T - T_0)$

Because basically only differences are being observed, u_0 and T_0 are in principle freely selectable reference points.

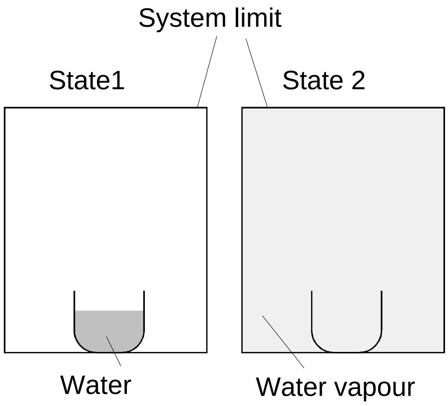


Fig.: 6

At this point it is beneficial to define another key state variable, the entropy *S*. The entropy can be illustrated based on a bucket placed in an enclosed room and filled with water:

In state 1 the water in the bucket has the temperature *T*; the air temperature is the same, so heat exchange is not possible.

If the bucket is left standing for a few days, the water evaporates (state 2) and turns to water vapour within the room (provided the air is able to absorb the water). The temperatures are still equal, and no energy could reach the outside beyond the system limit. The enthalpy of the water has therefore remained the same, but the entropy has increased! Why is that?

The water molecules are now evenly distributed around the room, and are in the natural steady state. This is the state with the lowest degree of "order", that is, with the maximum "disorder". To get the water vapour back into the bucket, that is, to increase the degree of order, work would need to be expended.

The entropy is a measure for the order of substances. It assumes the highest value in the state of maximum disorder. All substances naturally strive to achieve the state of maximum entropy!

The unit of entropy *S* is J/K, the unit of the specific entropy *s* (referred to the mass) is J/kgK.

4.5.1 Construction of a p-h diagram

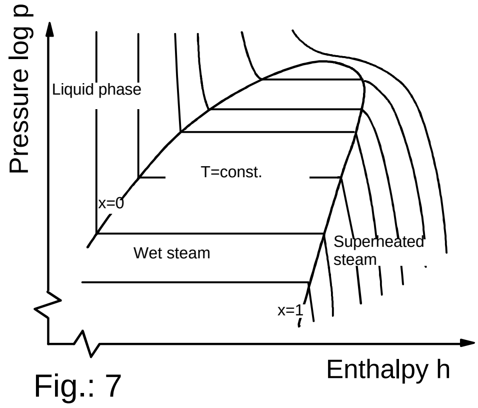


Fig.: 7

Each of the various service products has its own p-h diagram, in which the liquid-phase, wet-steam and hot-steam zones are plotted. Wet steam means that the service product is a mixture of liquid and steam. The temperature in the wet steam zone precisely corresponds to the boiling point. In the hot steam zone the service product is pure steam (superheated steam); the temperature is always above boiling point.

Curves for constant temperatures T (isotherms), constant steam content x and constant entropy s (isentropes) can also be plotted.

The curve x=1 (steam content 100%) always delimits the wet steam zone from the hot steam zone; the curve x=0 (liquid content 100%, steam content 0%) is the borderline between the liquid phase and the wet steam zone.

In the wet steam zone the isotherms always run horizontally!

4.5.2 Ideal cyclic process

The changes of state resulting in the heat pump cyclic process are now transferred into the p-h diagram:

1-2 : Isentropic compression until final compression temperature with superheating of the service medium, no heat discharge

2-2' : Isobaric cooling until condensation temperature, discharge of the superheating enthalpy $h_{2,2'}$

2'-3 : Isobaric condensation, discharge of the condensation enthalpy $h_{2',3}$

3-4 : Relaxation in the wet steam zone, no enthalpy discharge, cooling and partial evaporation

4-1 : Isobaric evaporation, absorption of the evaporation enthalpy $h_{4,1}$

Heat pump cyclic process

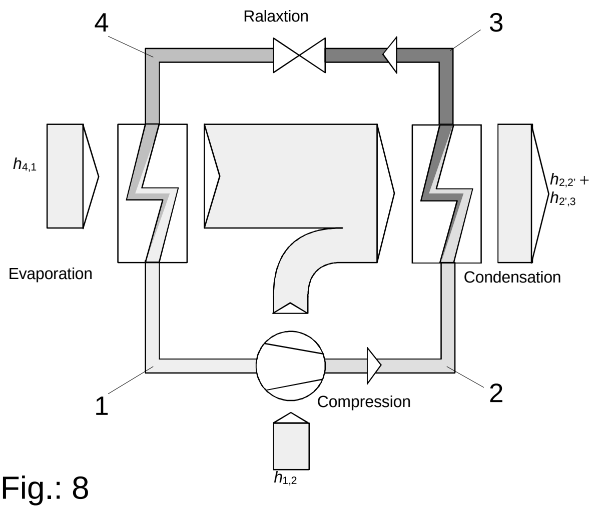


Fig.: 8

p-h-Diagram of a heat pump

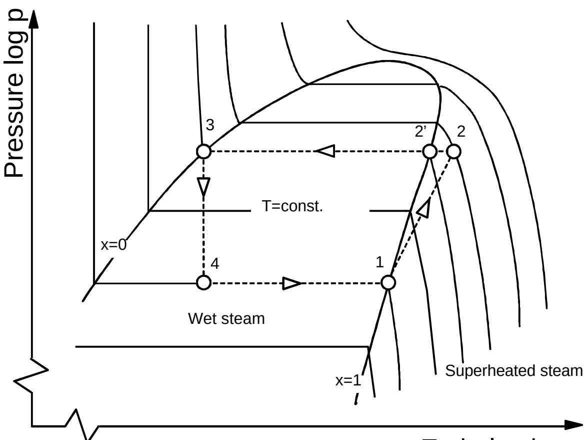


Fig.: 9

4.5.3 Actual cyclic process

Actual p-h-diagram of a heat pump

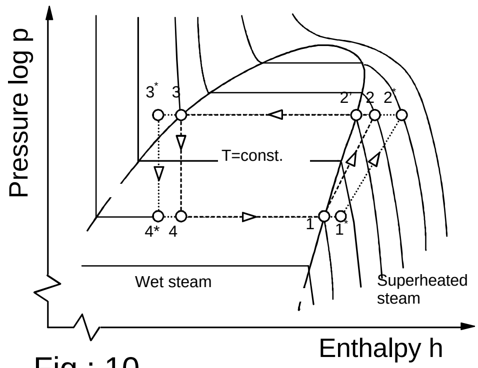


Fig.: 10

The main difference between the actual and the ideal cyclic process is that the compression is not isentropic (i.e without discharge of heat), but runs along the line 1*-2* due to internal friction in the service product steam and heat losses in the compressor. Thus, more work must be expended on the compressor to achieve the same final pressure.

Moreover, superheating 1-1* of the service product steam prior to compression is necessary, to reliably exclude the possibility of drops of liquid entering the compressor. The compressor would otherwise be damaged by liquid impacts.

Liquid subcooling 3-3* is used to reduce the portion of steam at the inlet into the evaporator. As a result, more evaporation heat 4*-1 can be absorbed.

4.6 Output coefficient

To be able to assess the efficiency of a heat pump, an output coefficient is introduced. It corresponds to the efficiency of thermal engines, and is determined from the ratio between work and benefit. The benefit is the output heat flow $\dot{Q}_{out}$, the work is the input power P_{in} or the input mechanical energy $\dot{W}_{in}$

$$\varepsilon = \frac{\dot{Q}_{out}}{\dot{W}_{in}} = \frac{\dot{Q}_{usef}}{P_{in}} \quad . \tag{4.8}$$

In contrast to the efficiency, which is always less than 1, the output coefficient is generally greater than 1. The output coefficient must therefore not be designated as the efficiency.

The output coefficient becomes greater than 1, due to the fact that the input heat $\dot{Q}_{in}$ is delivered "free" from the environment, and so is ignored as work.

4.6.1 Determining the output coefficient from the p-h diagram

Output coefficient from p-h-Diagram

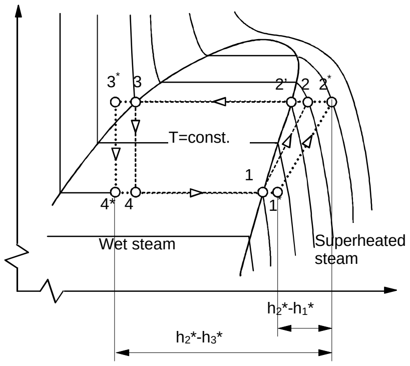


Fig.: 11

The amounts of energy converted in the cyclic process can be taken directly as enthalpy differences from the p-h diagram. Thus, the output coefficient can be determined for the ideal process in a simple manner:

$$\varepsilon = \frac{Q_{out}}{W_{in}} = \frac{h_2 - h_3}{h_2 - h_1} \qquad (4.9)$$

For the real process with induction gas superheating and liquid subcooling:

$$\varepsilon = \frac{h_2^* - h_3^*}{h_2^* - h_1^*} \, . \qquad (4.10)$$

In general, the output coefficient increases as the temperature difference between the absorption and discharge sides decreases. Also, a higher temperature level resulting from the service product used brings about a higher output coefficient.

5 Operation of the heat pump

The unit is not designed for quantitative measurements or experiments; the measurements and evaluations described therefore serve only as an aid to general understanding of heat pumps and to qualitative verification of the conditions described.

5.1 Experimental determination of the useful heat flow

5.1.1 Performing the measurement

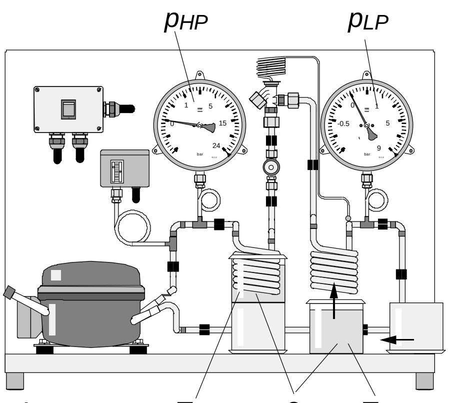


Fig.: 12

- Fill two vessels with cold water of approximately 25°C
- Position the vessels (8) as shown underneath the condenser and the evaporator. The bottom, upside-down, vessel, supports the top one.
- Measure the water temperatures in the two vessels with two laboratory thermometers)
- Switch on the compressor by throwing the main switch (13)
- Record and plot the measured values on the worksheet in the Appendix

5.1.2 Evaluation

Defined and measured variables:

t -	Time in sec.
m -	Water quantity per water vessel
p_{HP} -	Pressure upstream of the condenser
p_{LP} -	Pressure at the inlet into the compressor
T_{HP} -	Temperature of water being heated
T_{LP} -	Temperature of water delivering heat

The resulting heat delivered to the water being heated between states 1 (at the beginning) and 2 (at the point of measurement) is

$$Q_{out} = m \cdot c_p \cdot (T_{HP2} - T_{HP1}) \tag{5.1}$$

with $c_p = 4{,}19^{kJ}/_{(kg \cdot K)}$ - specific heat capacity of water.

The output heat power (useful heat flow) is thus

$$\dot{Q}_{out} = \frac{Q_{out}}{t} \tag{5.2}$$

The input power is composed of the input mechanical power P_{in} (compressor) and the heat power drawn from the second water vessel $\dot{Q}_{zu}$ (in the case of a refrigerator the cold output):

$$\dot{Q}_{in} = \frac{m \cdot c_p \cdot (T_{LP1} - T_{LP2})}{t} \tag{5.3}$$

In determining the output coefficient ε this drawn-off heat flow is not taken into account:

$$\varepsilon = \frac{\dot{Q}_{out}}{P_{in}} \tag{5.4}$$

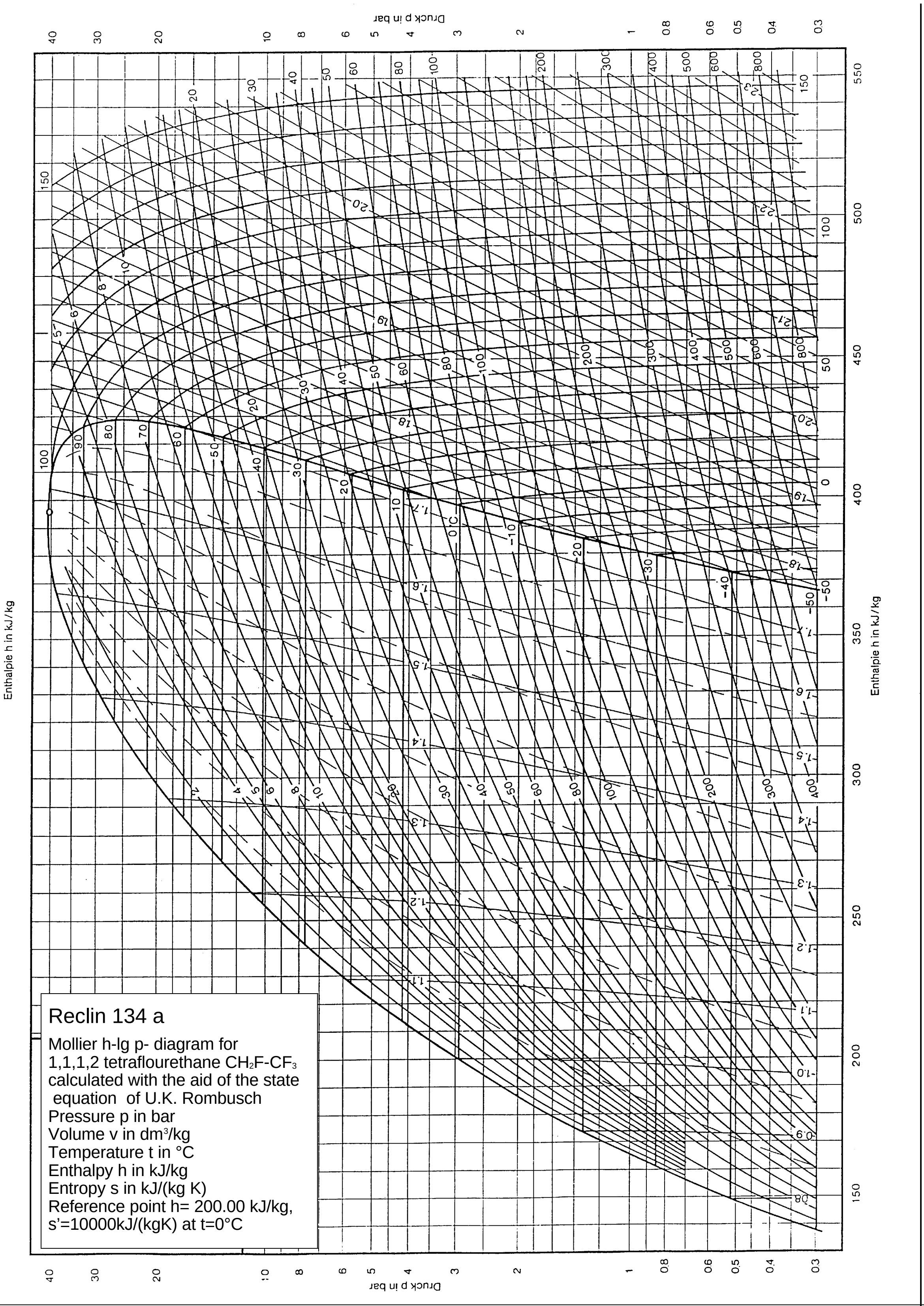
6 Appendix

6.1 Worksheet: Measured value recording

Water vessel content:__________________ ml

Time t [sec]	p_{HP} [bar]	p_{LP} [bar]	T_{HP} [°C]	T_{LP} [°C]

6.2 lg p - h diagram of refrigerant R 134 a



6.3 Technical data

Compressor:		
Type: Piston compressor		
Power consumption: at 5 / 40 °C	104	W
Cold output: at 5 / 40 °C	278	W
Manometer with temperature scale for R134a:		
Measuring ranges:	-1... 9	bar
	-1... 24	bar
Diameter:	160	mm
Expansion valve:		
Temperature sensor set to	T_V=-2	°C
Pressostat for pressure monitoring:		
Switch off compressor at	17	bar
Switch on compressor at	13	bar
Refrigerant:	Reclin R134a	
4 Water vessels, plastic		
Capacity: each	1.7	l
Power supply	230 V / 50 Hz, 6A	
Alternatives optional, see type plate		
Dimensions:		
WxHxD	750x600x350	mm^3
Weight:	25	kg

6.4 Index

S

T

U

W