THERMODYNAMIC CYCLE

The operating principle of a heat pump is based on the physical property that "the boiling point of a fluid increases with pressure". By lowering pressure, a medium can be evaporated while an increase of pressure will lead to condensation.

For large scale industrial applications, Ammonia is the most suitable refrigerant. It is mostly used in a pump system.

Log P-h diagram

To understand the principle of operation of an mechanical heat pump, a log P-h dagram can be used. A log P-h diagram shows all state variables of the refrigerant. On the horizontal axis enthalpy (h) is shown. The vertical axis has a logaritmic scale and shows pressure. The other lines show:

Red: Temperature [°C]

Blue: Entropy [kJ/kg]

Green: Specific volume [m3/kg]

The black line divides the graph according to the different states of Ammonia (NH3). On the left its fluid phase is shown. On the right side Ammonia is in its gaseous state. Below the black curve a combination of both gaseous and liquid Ammonia can be found. The area above the highest point is called the transkritical area.

The thermodynamic cycle

The log p-h diagram shows a cycle for a mechanical heat pump. The points represent the different components of the he
condensation temperature of 80 °C and an evaporation temperature of 40 °C is taken as an example.

1-2 The compressor: With a compressor the pressure of the gaseous refrigerant is increased from 15 to 40 bar. Ideally the er
reality the entropy will increase somewhat, because the electric energy needed to power the compressor is partly absorbed by
NH3 gas will rise to 120 °C.

2-3 The condensor: The condensor delivers useful energy. In the condenser the superheated gas is cooled from 120 °C to 80
temperature of 80 °C, until all vapour has become liquid. The liquid flows to the expansion device.

3-4 Expansion device: Inside the expansion device the pressure is reduced from 40 to 15 bar. Due to the expansion a mixt
This mixture flows to the liquid separator.

4-5/1 Liquid seperator: Inside the liquid seperator both fluid (5) and gaseous (1) Ammonia can be found. Its most importan
The vapour flows to the compressor; the liquid is pumped over the evaporators.

5-6 Evaporator: The liquis ammonia at the bottom of the seperator is pumped over the evaporator(s). Inside the evapora
constant temperature of 40 °C. The energy needed for evaporation is delivered by a source of waste heat. The mixture of
seperator (6) and is separated again in liquid and vapour.

Coefficient of Performance

The efficiency of refrigeration systems and heat pumps is denoted by its Coefficient Of Performance (COP). The COP is determined by the ratio between energy usage of the compressor and the amount of useful cooling at the evaporator (for a refrigeration instalation) or useful heat extracted from the condensor (for a heat pump). A high COP value represents a high efficiency.

Most of the electric energy needed to drive the compressor is released to the refrigerant as heat. Therefore more heat is available at the condensor than is extracted at the evaporator of the heat pump.

For a heat pump a COP value of 4 means that the addition of 1 kW of electric energy is needed to have a release of 4 kW of heat at the condensor. At the evaporator side 3,0-3,5 kW of heat is extracted. The additional heat is generated by the compressor. On the other hand: For a refrigeration system a COP of 4 indicates that 1 kW of electricity is needed for a evaporator to extract 4 kW of heat. Due to this important difference in COP definition, for a heat pump one often speaks of COPh. In this abbreviation 'h' means heating.

The efficiency of a heat pump, COPh, depends on several factors. Especially the temperature difference between waste h factor. The temperature difference between condensation and evaporation temperature mainly determines the efficiency: th The figure on the left shows the influence of this temperature difference on the COPh value. These values are based on figu refrigerant Ammonia. The figure shows an increase in COPh with an increasing evaporation temperature. Futhermore it condensation temperature. In general the COPh decreases with an increase in temperature difference between condensatio indication of the dependence of the COPh of an Ammonia heat pump as a function of this temperature difference.

Another important factor that influences efficiency is the applied refrigerant. Ammonia, for example, is a very efficient r temperature of 30 °C and condensation temperature of 70 °C. These same conditions only give a COPh of 4,5 for refrige efficiency of a heat pump are system controls, efficiency of pheripheral equipement like fans, pumps, etc.

Carnot efficiency

The theoretical maximum efficiency of a heat pump is described by the Carnot-efficiency:

The equation shows that the Carnot-efficiency depends on the condensation and evaporation temperature. With an ideal co achieve the Carnot efficiency. However, in practice there are a lot of parameters that have a negative influence on the effici product of the Carnot efficiency and the system efficiency:

The system efficiency is usually 50% to 70%.

Lorentz efficiency

With a transcritical heat pump the Carnot-efficiency can not be used, because there is no condensation temperature, but a ten maximum efficiency of a transcritical heat pump is described by the Lorentz efficiency.

Tm is the mean temperature in the gas cooler. This temperature is calculated from the temperature at the inlet and the outlet c

Similar to Carnot, the Lorentz efficiency will not be reached in practice due to all kind of losses. To determine the real account:

Refrigerants

A variety of refrigerants are available for usage in mechanical heat pumps. With each of them having their own advantages and disadvantages the choice of refrigerant depends on several criteria.

Selection criteria

In general the following criteria must be taken into account:

Pressure: At a given temperature the condensation pressure is different for different refrigerants. For certain refrigerants at high temperatures, pressure will become too high and normal heat pump components can no longer be applied. Low pressure is another risk: for low pressures the volume that needs to be swept increases. This requires larger components and thus an increase in investments. The figure below shows the temperature of evaporation as a function of pressure for several commonly used refrigerants.

At the download-page fysical properties of several commonly used refrigerants can be downloaded.

Critical temperature: Above a certain temperature a refrigerant reaches its supercritical area. Within the supercritical range the fluid and gaseous phase of the refrigerant can no longer be distinquished.

Energy efficiency: The efficiency of a heat pump depends on the choice of refrigerant.

Natural versus synthetic refrigerants: Most synthetic refrigerants (HFC's) contribute strongly to the greenhouse effect in case of leakage. This impact can be 3000 times higher as compared to CO_2.

Besides the criteria mentioned above, several other factors are also involved in decision making. Investment costs, required size of the installation and safety and permits have to be taken into account when deciding what refrigerant to use.

Refrigerant tags

All refrigerants are denoted by a code. The code is started by a letter 'R' (Refrigerant) and followed by a number. From
deduced:

R000-R399: Chemical refrigerants of which the composition is determined by their code number. General code: Rxyz= R(
(number of F atoms). R134, for example, consists of two C atoms, 4 H atoms and 4 F atoms: $C_2H_2F_4$.

R400-series: Zeotrope mixtures of refrigerants that do not have a evaporation point but rather a evaporation range. Evapora
during the increase of temperature with a few degrees.

R500-series: Azeotrope mixtures with a fixed evaporation point.

R600-series: Other organic refrigerants.

R700-series: Inorganic refrigerants.

Refrigerants for heat pumps

Below, several frequently used refrigerants in heat pumps are described.

R134a is used as a refrigerant for medium sized or large heat pump systems. As compared to refrigerants R407c and R41
compared to refrigerant NH_3 its efficiency is lower. The pressure in R134 is fairly low. Due to this the volume that needs to
therefore higher investments are needed for installation.

R407c and R410a are frequently used in small to medium sized heat pump sytems. These refrigerants are regularly used in i
air conditioning and heating. R410a is supercritical above a temperature of 71 °C. Above this temperature a difference betwe
made. R410a can be applied in low temperature heat pump systems. As compared to R134a the volume that can be swept
investement costs. On the other hand: its efficiency as compared to R134a is lower as well.

R600 (butane) and R600a (isobutane) are used for refrigeration installations. These refrigerants are also suitable for use
higher than 80 °C. Many refrigerants give high pressures at these temperature levels. For R600 and R600a the increase
Because of a fire and explosion hazard, installations with R600 and R600a should meet safety requirements of NPR-7600.

R717 (Ammonia) is the most suitable refrigerant for usage in a heat pump in industrial environments. Ammonia has a hig
temperatures of 80 °C. Expectations are that this range will soon be widened up to temperatures of 90 °C. Furhtermore, Ar
contribute to the greenhouse effect. Ammonia has been frequently used as a refrigerant in refrigeration systems. The experie
to this, can be used when installing heat pumps with Ammonia as a refrigerant. It is inflammable and toxic but due to its s
Ammonia installation should meet the requierements of PGS-13.

R744 (CO_2) is another natural rerfigerant. It is used in refrigeration installations, often in combination with Ammonia co
Ammonia in the system. For low temperature freezer applications a system can be built up of CO_2 compressors combi
temperature is 31 °C. Above this temperature condensation does not take place at a constant temperature, instead it occurs
Therefore the heat pump can only be applied in situations where a potential user allows for heating at non-constant temperatu
do function above the supercritical temperature: CO_2supercritical heat pumps.

R718 (Water) can also be used as a refrigerant. Water has the advantages that it is easily obtained and does no damage to t

temperatures (> 100 °C). At these temperatures pressures in other refrigerants can become too high. A disadvantage of the
state. A relatively high compressor capacity is nescessary because to this.

Mechanical heat pump

The mechanical heat pump is the most prevailing heat pump to be applied commercially. Its principle of operation: Inside a mechanical heat pump the pressure of a refrigerant is increased with the use of a compressor. Due to this increase in pressure, the condensation temperature rises. Most installations have an electric motor to drive the compressor. Two types of mechanical heat pumps are available: a system that with direct expansion of the refrigerant at the inlet of the evaporator (dx system) and a so called 'pump system' heat pump where liquid refrigerant is pumped to the evaporators. Both types are described in more detail below.

DX-system

The figure on the right shows a system with direct expansion. Direct expansion implies that the entire refrigerant volume at
evaporator. Due to the expansion, a large part of the fluid refrigerant evaporates, denoted as flash gas. The refrigerant, l
evaporator. Only the liquid part of the refrigerant has the ability to evaporate in the evaporator. When the refrigerant is to
refrigerant flows to the compressor. The superheating is necessary to prevent the compressor from damage due to liquid slu
the expansion device, is controlled by the degree of superheating measured at the outlet of the evaporator. The compress
temperature at the compressor outlet.

Pump

The other type of the mechanical heat pump is the pump system heat pump. The figure on the left shows its principle of o
vessel. From this vessel, fluid refrigerant is pumped to the evaporator(s). Inside the evaporator the refrigerant is partly
refrigerant flows back to the seperator vessel. This vessel separates the refrigerant in liquid and vapour. The liquid is pumpe
the compressor. An advantage of this system is that smaller evaporators can be used as compared to dx systems with t
refrigerant solely. On the other hand, an additional refrigerant pump and seperation vessel are needed. Pump system heat pur
industrial applications. The majority of heat pumps with Ammonia are built as a pump system type. Ammonia dx systems a
expansion device. Besides, overheating of the refrigerant in dx systems causes high discharge temp

Absorption heat pump

Where a mechanical heat pump is driven by electric energy, an absorption heat pump is driven by thermal energy. This thermal heat is delivered by steam or by combustion of natural gas. Absorption heat pumps are very useful in situations where both heating and cooling is required.

The principle of operation of an absorption heat pump is based on absorption and evaporation of a refrigerant. An absorption medium as wel as a refrigerant have to be chosen. Well known pairs are:

1. Litium-bromide (LiBr) and water, in this case water is the refrigerant and LiBr the absorption medium.
2. Ammonia and water, with Ammonia as the refrigerant and water as absorption medium.

Principle of operation

The figure on the right shows the principle of operation of an absorption heat pump. It is based on a heat pump that uses
absorption heat pump consists of two loops. The loop on the right represents the absorption medium and the circulation loop

Cycle of the absorpt

At the intersection of P_1/T_2, thermal energy is added to the generator of the heat pump. As a result the refrigerant is eva pressure. The absorption medium is lowered in pressure with the use of an expansion device and flows towards the abs absorbed (intersection P_0/T_1). Due to the absorption proces, useful heat is released at an intermediate temperature. The pr pump and flows back to the generator. To increase efficiency, an internal heat exchanger is used to preheat the cold mixture

Refrigeration

At the intersection of P_1/T_2, thermal energy is added to the generator of the heat pump. As a result the refrigerant is eva pressure. The gas flows towards the condensor. Inside the condensor the NH_3 releases heat to its environmentis and will co in pressure inside an expansion device and flows towards the evaporator. At low temperature (at intersection point P_0/T_0) he will evoporate. Waste heat can be used as heat source, but it is also possible to use the evaporator for cooling purposes. The where it is absorbed in water. Due to the absorption useful heat is released.

Efficiency

Absorption heat pumps with natural gas as a heat source are commercially available. For the production of useful heat at a the condensor with water or air, the efficiency is approximately 150%. In other words: the addition of 1 kWh of natural gas r

Adsorption heat pump

The principle of operation of adsorption heat pumps is equal to that of the absorption heat pump. The only difference is that an adsorption heat pump uses solid-sorption instead of the liquid-sorption that is used in absorption systems. The material pairs stated below are regularly applied in adsorption heat pump systems.

Silica gel – H_2O

Zeolite – H_2O

Active carbon – MeOH

Active carbon/salt - NH_3

The adsorption principle is more and more used in small heat pump systems (70-500 kW), that are mainly used for cooling.

Transcritical CO2 heat pump

Above 31 °C, CO_2 is transcritical. For transcritical CO_2, heat intake at the evaporator takes place below the critical pressure of 71 bar. The release of heat within the gas cooler takes place above the critical pressure of 71 bar. Due to this, heat is released over a temperature range. This is in contrast with conventional compressor systems where heat release takes place at a fixed temperature. Therefore we talk about a gas cooler instead of a condenser; the refrigerant will not condensate, it is only cooled. The figure below shows the T-s diagram of a transcritical heat pump cycle with the refrigerant CO_2. A waste water flow (orange) is cooled in the evaporator from 28 °C to 23 °C and process water (pink) is heated in the gas cooler from 20 °C to 70 °C. The red lines are lines of constant pressure.

The blue line represents the transcritical heat pump cycle. The steps in the cycle are:

1 - 2 Compression to transcritical pressure
2 - 3 Gas cooling in transcritical area, to heat process water
3 - 4 Expansion to low pressure
4 - 5 Evaporation by cooling down the waste water flow
5 - 1 Superheating in evaporator

The efficiency of a transcritical

The efficiency of a heat pump is given by a COP. The COP of a heat pump is usually calculated using the evaporation t However, a transcritical heat pump has no condensation temperature, but a temperature range in the gas cooler. To c temperature (Tm) in this temperature range. This mean temperature is calculated using the temperature at the inlet of the g outlet of the gas cooler (point 3). Read more about this.

Advantages CO_2 transcritical heat pump:

For a high temperature lift at the side of the gascooler (at least 30-40 °C) and a low temperature of the water that ne CO_2 transcritical heat pump can be higher than conventional heat pumps.

Disadvantages CO_2 transcritical heat pump:

The temperature of the water that needs to be heated has to be low enough to make an efficient heat pump. When th water flowing in, the process will not be efficient. In this situation an Ammonia heat pump is a better solution.

The system works with high refrigerant pressures of more than 100 bar.

Hybrid heat pump

Hybrid heat pumps, or compression resorption heat pumps, combine technologies of an absorption and compression heat pump. Hybrid heat pumps use a mixture of media, for example, NH_3 and water. Due to changes in composition of the mixture caused by absorption and desorption, heat is extracted and emitted at a non-constant temperature. This temperature glide may lead to an increase in efficiency.

A hybrid heat pump consists of the following main components:

1. Desorber: in here waste heat is extracted by the mixture from the environment.
2. Separator: the seperator separates water and Ammonia.
3. Pump: the pump increases the water pressure.
4. Compressor: Ammonia is compressed to a high pressure inside the compressor.
5. Absorber: in here useful heat is released towards the environment.
6. Expansion element: in here the pressure of the mixture is lowered.

A large temperature glide for absorption and desorption is favourable to decrease the ratio of compression inside a heat pump. As compared to the conventional mechanical heat pump ,an equal lift in temperature can be realised with a lower compression ratio when using a hybrid heat pump. As a result a higher COP can be reached. To increase the range of the temperature glide, the sizes of absorber and desorber should be increased as well (making them more expensive). Proper adjustment of the temperature glides and temperature ranges of the heat pump, is therefore essential to maximize efficiency. The use of media that can condensate or evaporate will lower the COP dramatically.

Advantages of hybrid heat pumps:

The condensation temperature is higher as compared to conventional compression machines. This is due to the satur mixture than for a pure gaseous refrigerant flow.

In connection to what is mentioned above a large temperature lift is possible with a high COP.

Disadvantages of hybrid heat pumps:

Its technical complexity causes the hybrid heat pump to be expensive to install.

There is a limited number of manufacturers offering hybrid heat pumps.