Refrigerant systems and their energy performance

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What is efficiency

- Efficiency is the relation between output and input
- In the refrigeration industry the output is the cooling capacity measured in [kW] and the input is the power also measured in [kW] which is need, to reach the desired cooling capacity
- In HVAC an refrigeration industry output power is always thermal
- Input power is either electrical or mechanical, except absorption and adsorption chiller which are not scope of this presentation
- In HVAC and refrigeration industry

Efficiency = cooling capacity [kW] / power input [kW]

Definition of efficiency COP

- In the HVAC and refrigeration industry existing different abbreviations terms of efficiency figures
- Most common and worldwide widely used is the COP
- **COP** is an abbreviation and stands for **C**oefficient **O**f **P**erformance
  COP = cooling capacity [kW] / power input [kW]
  and as valid for full load (100% cooling capacity) only
- In the USA COP is sometimes given as
  Efficiency = kW/ton = power input [kW] / cooling capacity [tons]
  used in content with big chillers and refrigeration system or even as used small systems (residential units)
  COP = cooling capacity [BTU/h] / (power input [kW] * 3413) or
  in content with heat pumps
  COP = condensing capacity / [BTU/h] / (power input [kW] * 3414)

Conversion factor US units

conversion factor for power units

- 10.000 BTUh = 2,9307107 kW
- 1 kW = 3412.142 BTUh
- 12000 BTUh = 1 ton = 3,513725 kW
- 1 kW = 0,284345 ton
  Sometimes BTUh is written as BTU/h

conversion factor for power units

- 10.000 BTU = 2,9307107 kWh
- 10.000 BTU = 2521,644 kcal
- 1 kWh = 3412.142 BTU
- 1 kcal = 3,96567 BTU

Definition of efficiency - EER

- In Europe the same performance figure is called EER
- **EER** is an abbreviation and stands for **E**nergy **E**fficient **R**atio
- EER = cooling capacity [kW] / power input [kW]
  and as valid for full load (100% cooling capacity) only
- The EER is in Europe always used for any kind of cooling application
  EER = cooling capacity [kW] / power input [kW]
- In Europe the COP is used to specify the performance of heat pumps
  COP = condensing capacity [kW] / power input [kW] this is equal to
  COP = (cooling capacity + power input [kW]) / power input [kW]

Measuring of efficiency - EER

- The EER was established by EUROVENT
- EUROVENT is an independent organization for testing various kind of equipment such like cooling towers, dry coolers, chillers, heat exchanger, fan coils and many other one
- EUROVENT provides the test results online
  link to the main page: www.eurovent-certification.com
- The test results for chillers are always given for leaving water temperature of 7[°C] with 12[°C] water return
- In case of air cooled chillers: ambient air intake is 35 [°C]
- In case of water cooled chillers: leaving condense water at 35 [°C] and entering condenser water at 30 [°C]
- EUROVENT provides an good opportunity to compare efficiency of chillers, but only at the given temperatures

Part Load Efficiency ESEER

- EER is only valid for part load
- Chillers usually operate at full load only during a limited period of time during a year working with EER is sometimes not useful to work with
- Therefore the part load performance is much closer to reality and EUROVENT decided to certify, together with full load efficiency, an average annual part load efficiency of chillers
- A study partly funded by the European Commission through SAVE Program was performed and an index called **ESEER** – **E**uropean **S**easonal **E**nergy **E**fficiency **R**atio- has been defined
- ESEER is similar to IPLV (Integrated Part Load Value) - used by ARI in USA, takes into account several parameters in order to establish an average use of chillers throughout Europe: weather data, building load characteristics, operational hours etc.

Definition ESEER

Operative ESEER temperatures and coefficients for air cooled and water cooled chillers in Europe:

	ESEER parameters		
Part Load Ratio	**Air temperature (°C)**	**Water temperature (°C)**	**Weighting coefficients**
100	35	30	3 %
75	30	26	33 %
50	25	22	41 %
25	20	18	23 %

ESEER is calculated as follows:
ESEER = A.EER100% + B.EER75% + C.EER50% + D.EER25%
With the following weighting coefficients:
A = 0.03 ; B = 0.33 ; C = 0.41 ; D = 0.23

- ESEER is basically the summarizing of the EER at 3%, 33%, 41% and 23% - ESEER assumes that the load correlates with the temperature
- ESEER is an assumption for buildings but may not be correct for industrial application as load doesn't drop with ambient temperature, however it is a possibility to compare efficiency of chillers on their quality

Definition IPLV

- The **IPLV** stands for **I**ntegrated **P**art **L**oad **V**alue
- The idea is very similar to the ESEER but is used in the USA
- There are different standards for water or air cooled chillers
- The definitions were made by AHRI and are based temperatures measured in Fahrenheit and flow rate measured in gallons per minute per ton.
- Similar to the ESEER there are COP Figures for 25%, 50%, 75% and 100 % of load. They are called A, B, C, D
- The Formula for calculation is:
  IPLV (or NPLV) = 0.01A+0.42B+0.45C+0.12D
- If a chiller is designed to operate at different conditions as IPLV definition, the part load value is the called **NPLV**, which stands for: **N**on Standard Part Load Value

Simple Methods of Measuring COP

A simple method to measure efficiency by measuring the evaporation temperature and the condensing temperature provides this formula:

COP = (te [°C] + 273,15) / ((tc [°C]+273,15) - (te [°C])+273,15) * F

te …. evaporation temperature [°C]
tc …. condensation temperature [°C]
F…... compressor grading factor (=exegetic efficiency)

- F for high quality compressors 0,55
- F for medium quality compressors 0,50
- F for low quality compressors 0,45

This could be done following the next 4 steps.

Measuring Pressure on Low and High Side

- 1st step: measure evaporating and condensing pressure

Gaining the evaporating temperature

- 2rd step: from the refrigerant table taking the evaporating temperature

Refrigerant: R404A, R125/143a/134a (44/52/4), R404A								
Reference: DuPont SUVA HP62								
T	P	Vl	Vg	Hl	Hg	R	Sl	Sg
°C	Bar	dm^3/kg	m^3/kg	kJ/kg	kJ/kg	kJ/kg	kJ/(kgK)	kJ/(kgK)
-17	3,382	0,844	0,05876	176,05	358,36	182,32	0,9111	1,6228
-16	3,507	0,8467	0,05673	177,38	358,97	181,59	0,9162	1,6224
-15	3,635	0,8495				180,86	0,9214	1,622
-14	3,767	0,8523				180,13	0,9265	1,6215
-13	3,903	0,8551				179,38	0,9316	1,6211
-12	4,043					178,63	0,9367	1,6207
-11	4,186	0,861				177,84	0,942	1,6204
-10	4,333	0,864				177,08	0,947	1,62
-9	4,484	0,867				176,3	0,9522	1,6196
-8	4,639	0,8701	[illegible]	[illegible]	[illegible]	175,52	0,9573	1,6192
-7	4,798	0,8733	0,04177	189,6	364,32	174,72	0,9624	1,6189
-6	4,961	0,8765	0,04041	190,98	364,9	173,91	0,9676	1,6186
-5	5,128	0,8798	0,03911	192,37	365,47	173,1	0,9727	1,6182

read the relative pressure 3,043 bar from the manometer and add 1 bar for absolute pressure

Gaining the Condensing Temperature

- 3rd step: from the refrigerant table taking the condensing temperature

Refrigerant: R404A, R125/143a/134a (44/52/4), R404A

Reference: DuPont SUVA HP62

T	P	Vl	Vg	Hl	Hg	R	Sl	Sg
°C	Bar	dm^3/kg	m^3/kg	kJ/kg	kJ/kg	kJ/kg	kJ/(kgK)	kJ/(kgK)
32	14,9	1,0613	0,01269	249	382,87	133,88	1,1668	1,6055
33	15,281	1,0688	0,01233	250,72	383,19	132,47	1,1723	1,6049
34	15,669	1,0766	0,01197	252,46	383,49	131,03	1,1778	1,6044
35	16,065	1,0845	0,01162	254,21	383,78	129,57	1,1833	1,6038
36	16,468	1,0928	0,01128	255,97	384,06	128,08	1,1889	1,6032
37	16,879	1,1013	0,01096	257,75	384,32	126,56	1,1945	1,6026
38	17,297	1,11	0,01064	259,55	384,56	125,01	1,2001	1,6019
39	17,723	1,1191	0,01033	261,37	384,79	123,43	1,2058	1,6012
40	18,157	1,1284	0,01002	263,2	385,01	121,81	1,2115	1,6005
41	18,599	1,1381				120,16	1,2173	1,5997
42	19,049	1,1482				118,47	1,223	1,599
43	19,507	1,1586				116,74	1,2289	1,5981
44	19,974					114,97	1,2347	1,5972
45	20,449	1,1806				113,16	1,2406	1,5963
46	20,932	1,1922				111,31	1,2466	1,5953
47	21,424	1,2043				109,4	1,2526	1,5943

read the relative pressure 18,974 bar from the manometer and add 1 bar for absolute pressure

Calculation of COP

- 4th step: calculation of COP
  - te: take -12 [°C] from the second last slide
  - te: take 44 [°C] from the last slide before

Enter in this formula assuming medium range compressor F=0,5:
F represents the exergetic efficiency of the compressor.

COP = (te [°C] + 273,15) / ((tc [°C]+273,15) - (te [°C])+273,15) * F

COP = (-12 + 273,15) / ((44 + 273,15) - ((-12 + 273,15)) * 0,5 = 2,3

Measuring and monitoring entire systems

- On complex systems it make sense to measure devices continuously
- For example a chiller plant with three chiller and three cooling towers
- The overall energy consumption comes from:
  1. the chiller (three piece)
  2. the cooling tower fans (three piece)
  3. the condenser pumps (three piece)
  4. the evaporator pumps (three piece)
- To know how the energy flows it is necessary to install measurement instruments
- All the measurement instruments are linked together in a network
- In most cases they are communicating using a bus system
- Very common is the M-Bus

Monitoring Devices

- Usually most of the devices are electricity meters, measuring the actual power [kW] and consumption (energy) [kWh]
- For a chiller plant even heat meter are necessary
- For the example on the last page we would need
  - the chiller (2 heat meter, and optional one electricity meter)
  - the cooling tower fans (3 electricity meter)
  - the condenser pumps (3 electricity meter)
  - the evaporator pumps (3 electricity meter)
- All this meters are continuously measuring, counting (storing) the actual power [kW], transferring the information to central base unit (e.g. a server system). A software provides different tools to analyze the energy consumption and efficiency of the plant

International Systematical Energy Management Standard

- ISO 50001 is the international standard how the setup a monitoring and management system
- It is based on the individual energy flow (gas, electricity, hot water, steam) of a plant, considering efficiency
- ISO50001 covers beneath measurement, optimization of production and process, machines in plant, management and organization
- even the purchasing department – it should not only look for the cheapest solution but should consider the entire cost of a new system, considering, cost of installation, energy consumption, service & maintenance cost, disassembly and disposal at life cycle end

What influences the efficiency of refrigeration systems

- Evaporating temperature
- Condensing temperature
- Pressure drop due to:
  - pipework including valves
  - heat exchanger
- Variable flow of:
  - fluids (water, water/glycol, others)
  - vapor and gases (air, refrigerant)
- Control system (quality of control design)
- Service and maintenance

What influence has the evaporator

- Reducing the evaporating temperature by 1 [°C] causes a worse COP
- Depending on the refrigerant and system COP drops between 1,5 % and 3 %
- Example refrigeration:
  - Rising the evaporating temperature from -35 [°C] to -30 [°C] provides a better COP between 10% and 15%
- Example chiller:
  - Rising the evaporating temperature from 2 [°C] to 5 [°C] provides a better COP of app. 10%
- A good overall design is considering this effect
- The system temperature should be close as possible to the evaporating temperature –> the approach temperature should be as small as possible

What influence has the condenser

- Reducing the condensing temperature by 1 [°C] offers a better COP
- Depending on the refrigerant COP rises between 2 % and 3 %
- Example Refrigeration:
  - Lowering the condensing temperature from 50 [°C] to 45 [°C] provides a better COP between 12% and 15%
- Example chiller:
  - Lowering the evaporating temperature from 40 [°C] to 35 [°C] provides a better COP of app. 15%
- A good overall design is considering this effect
- The media outlet temperature of the condenser should be close as possible to the coolant media temperature (air, water, water/glycol –> the approach temperature should be as small as possible

What influence has pressure drop

- Each pipe, valve, heat exchanger have pressure drop
- Pressure drop is a loss, which has to be compensated
- Machines such like compressors, pumps and fans have to do this compensation, and needing more energy (power) to do so
- There is a physical law, saying, that pressure drop is a square function on volume flow. And the hydraulic power is pressure drop * flow
- Therefore pressure drop has a great impact on the energy consumption of pumps, fans and even compressors
- As a refrigeration system is build of many components such like pipes, valves or even pumps and fans, pressure drop has to be carefully considered during the first design phase
- Too small diameter of pipes or to high pressor drops of heat exchanger will immediately lead to inefficient systems

What influence has variable flow

- Auxiliary devices such like pumps or fans are often on / off controlled
- Today are electronic controllers available providing variable speed
- Examples are frequency converters (FC) or phase cutting controllers
- Using variable speed on pumps and fans, variable flow is possible almost anywhere
- One exception is the chilled water pump (needs always constant flow)
- There is a physical law, saying, that energy consumption drops in a cube function on any flow machine (examples are fans, pumps, centrifugal compressors) when flow will be reduced
- Example: Cooling Tower has 2 fans with 10 [kW] each at 100% load
- At part load 50% with on / off control 1 fan with 10 [kW] is active
- At part load 50% with FC control 2 fans are active $10*(1/2)^3 = 1,25$ [kW]

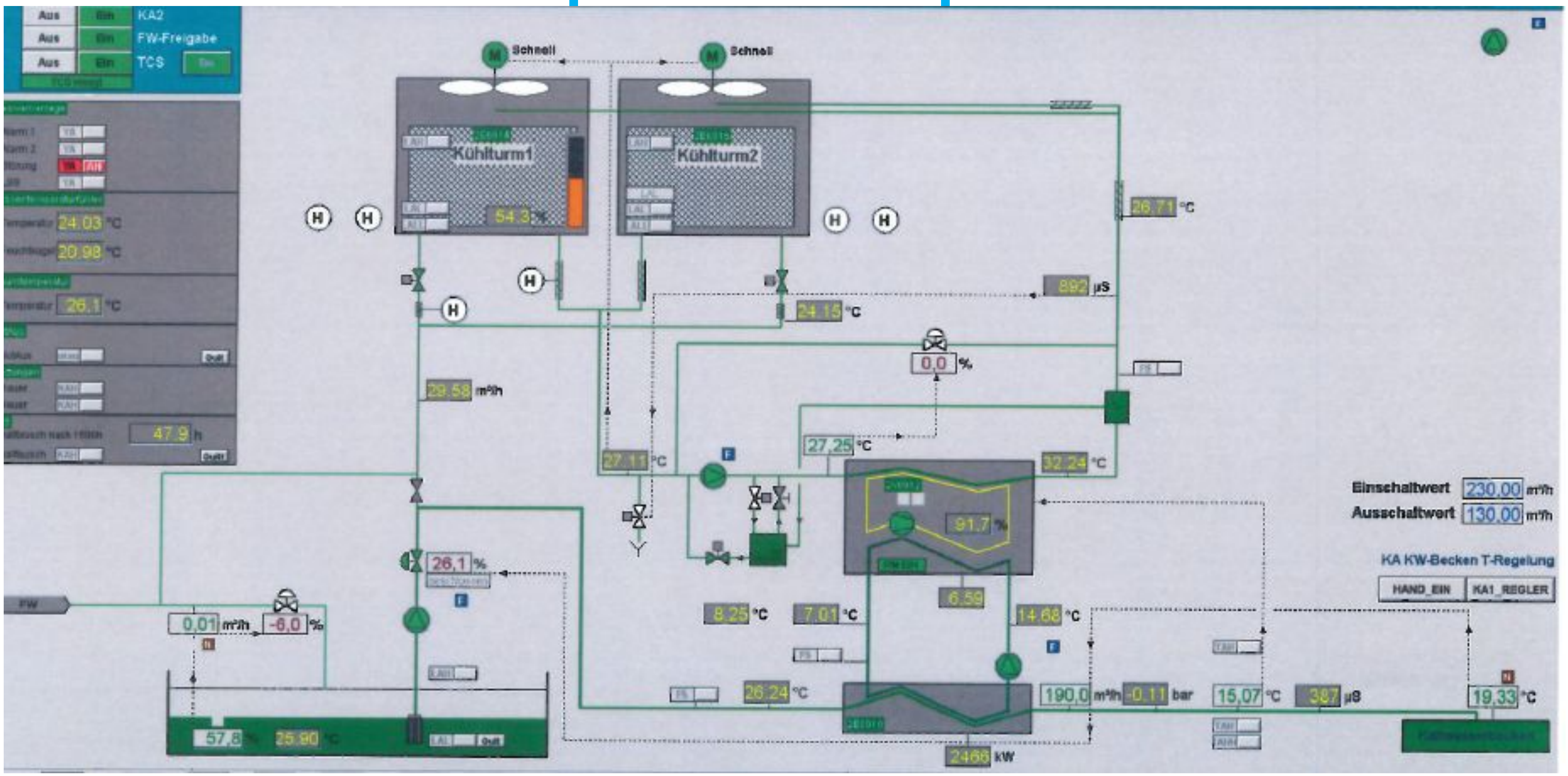
What influence has maintenance

- And even service and maintenance has a huge influence of the energy consumption of refrigeration systems, here are some examples:
- Dirty heat exchanger will dramatically lower the COP, a dirty condenser will lower the COP between 5% and 15%
- The same is true for dirty or frozen evaporator
- Clogged filter will increase the pressure drop of the system an will lead to much higher consumption
- And even the compressor needs service to make it smooth running with a minimum of friction loss
- Or belt driven devices, e.g. on cooling tower fans. If the belt is not stretched enough, the requires air flow is not given any more. As a result the condensing temperature is rising, and this leads to a worse COP

Example best practice

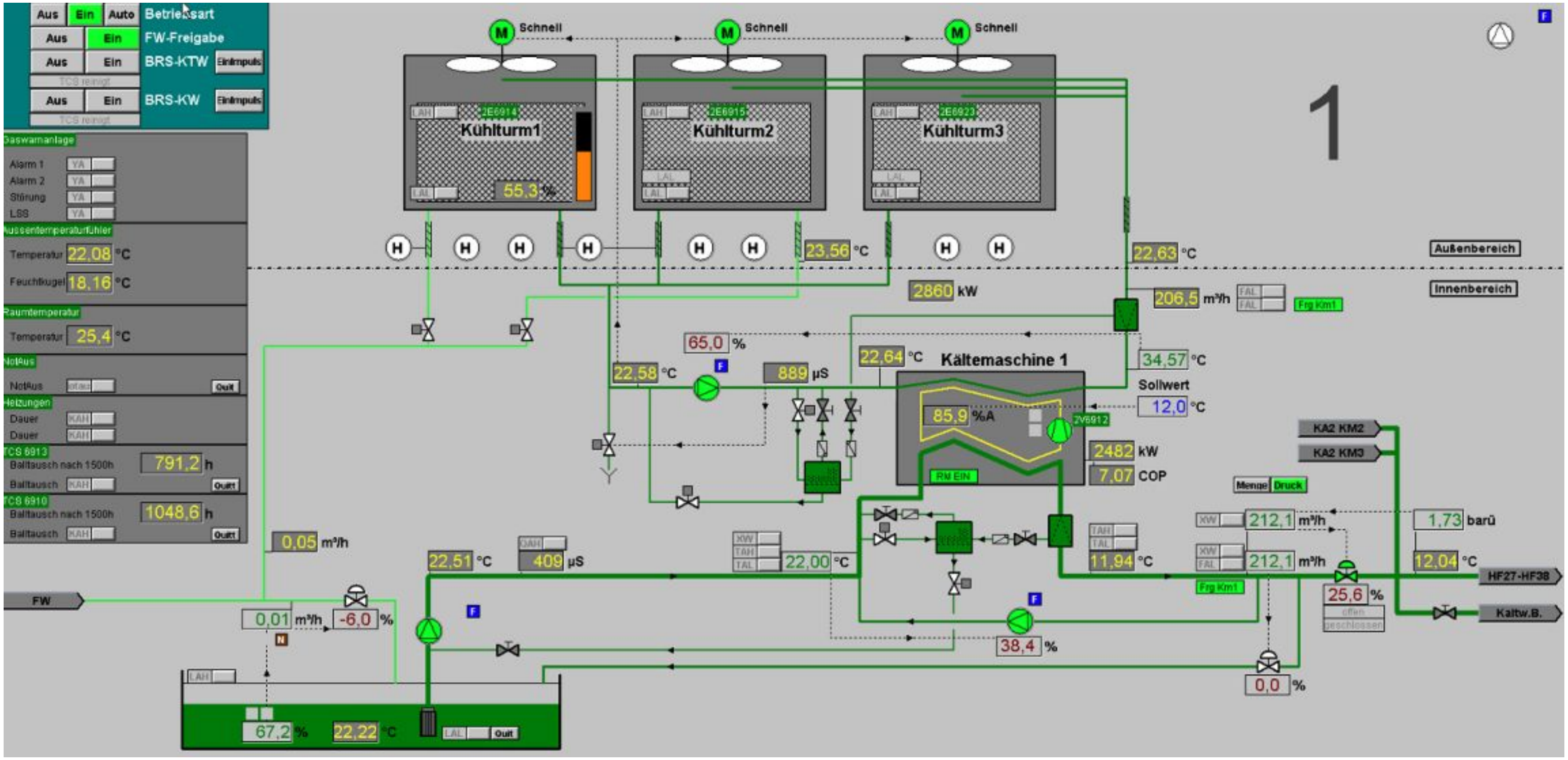
- An industrial plant has a 3 year old centrifugal chiller installed
- The capacity of this chiller was prior modification 2500 [kW]
- Chilled leaving water temperature was 7 [°C]
- Condenser leaving water temperature was 32 [°C]
- The COP was around 5,8
- The customer suffered during hot summer temperature because the desired capacity could not achieved
- Together with the customer we did a redesign of the hydraulic system
- It turns out that it is possible to run the system with far higher temperatures du to design change – chilled water leaving is now 12[°C]
- An additional cooling tower with special control was added as well

Example best practice



- before design change COP was 6, tower fans needed 65 kW

Example best practice



- After design change COP is 7, after further improving of control setup COP rises to 8, consumption of cooling tower dropped by 40%

Example best practice

- After modification of:
  - hydraulic design
  - modification of the control
  - installing of frequency converter
  - placing an additional cooling tower
  - and fine tuning of the control setup
  - average COP over the year is better than 8
  - kWh consumption of cooling tower dropped by 40%
  - and even water consumption dropped
  - instead of 2400 kW the chiller makes now 3000 kW
  - and even during this extreme summer with 40°C - no problem at all

Some benchmark of good COP

- The COP relates very much on the ambient temperature
- High temperature causes high condensing temperature
- As a result the power input and energy consumption is high
- Also important is to do the measurement at full load
- In addition the load (system) has to be stable
- Another influence is the evaporation temperature – of course this varies with the application
- In addition COP comparison between water and air cooled chillers is not correct, as for air cooled chillers the fan power is included, but on water cooled chillers it is not
- To check the entire system best way is to build the quotient of

  η = cooling capacity [kW] / (Pi chiller + Pi fans + Pi pumps) [kW]

Some benchmark of good COPs

Here are some benchmarks, COP varies due to different influences

- Water cooled chiller with cooling tower: COP: 5,7 up to 9
  example: centrifugal chiller or big screw chillers
- Water cooled chiller with dry cooler: COP 3,5 up to 4,5
- Air cooled chiller: COP 3,2 up to 4
- Cold room with evaporating condenser: COP 2,5 up to 3,3
- Cold room with dry condenser: COP 1,9 up to 2,6
- Deep temperature cold room with evaporating condenser:
  COP = 2,0 to 2,8
- Deep temperature cold room with dry condenser:
  COP = 1,2 to 2,0
- Remember: COP are valid on 100% of load

Thank you for your attention

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