Exergy analysis of cooling systems and strategies

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Relevance

- The demand for ventilation and cooling of buildings is an increasing share of Europe's total energy use in buildings
- The performance of HVAC systems is usually evaluated based on the first law of thermodynamics. Exergy-optimized systems make use of low temperature differences, which makes it possible to put to use renewable sources.
- Aim of this paper is to show the potential for optimization of three hybrid cooling systems
- This potential is addressed performing an exergy analysis of the cooling demand of a generic office building and of three supply systems, which use chillers in conjunction with evaporative cooling

Building model

Office building

Floor area : 1200 m² Walls area: 500 m², U-value of 0.15 W/(m² K) Windows area : 250 m², U-value 1 W/(m² K) Internal loads: 10 W/m² External loads: 15 W/m² Set-point temperature, indoor environment : 26 °C Outdoor temperature: 30°C

Reference conditions

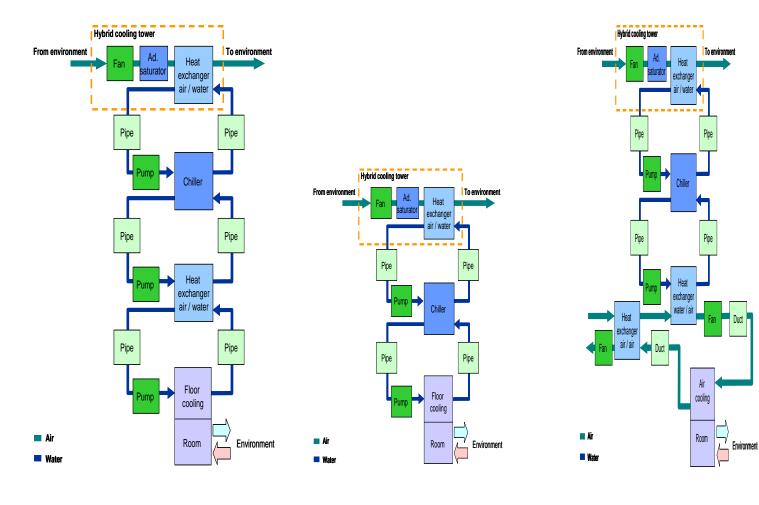
Environment temperature: 30 °C Environment pressure : 110 kPa. Humidity ratio: 0.01 kg_w/kg_a, RH= 40%.

Calculation of the cooling load, steady-state

 $Q_{cooling} = U_{windows} A_{windows} (T_{in} - T_{out}) + U_{walls} A_{walls} (T_{in} - T_{out}) + Q_{int} + Q_{ext}$

The obtained cooling load has been in all the three cases 31,500 W, delivered cooling power : 26 W/m²

Cooling systems description



System 1

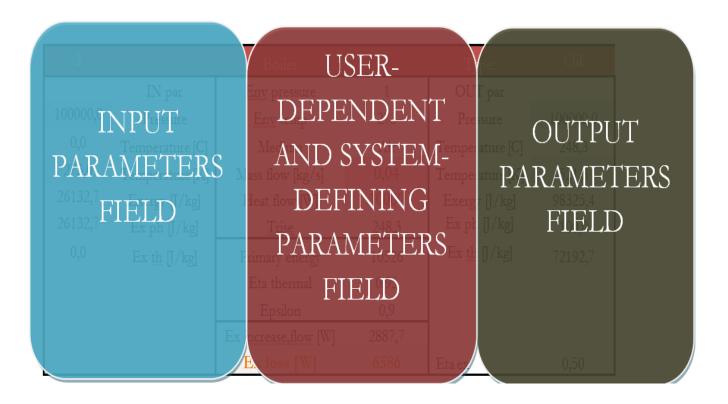
System 2

System 3

Software tool: SEPE

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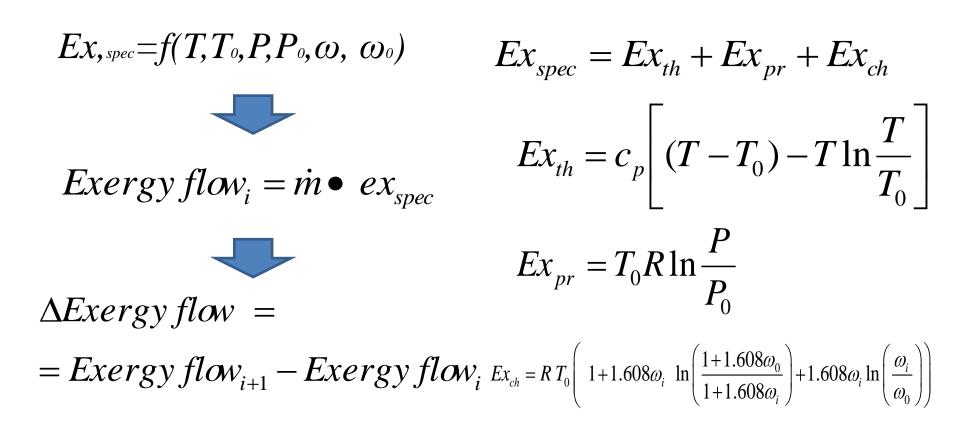
Components



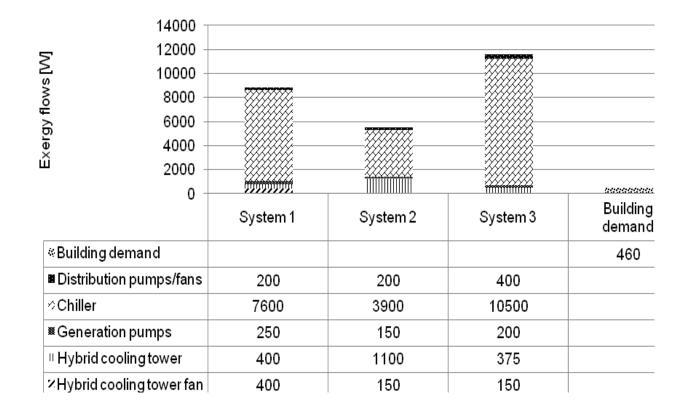
Nodes description

| | Nee | Chiller Env pressure [Pa] | 110000 | OUT and | | | | | | | |
|---------|-------------------------|------------------------------|---------|--------------------------|--------------------|------------------|-------------------|--------------------|--------|-------------------|---------|
| 99500.0 | IN par Pressure [Pa] | Env temp [K] | 303 | OUT par Pressure [Pa] | 99500.0 | | | | | | |
| 38.1 | | Medium | Water | | 41,5 | | | | | | |
| 311.1 | Temperature [C] | Mass flow [kg/s] | 2,5 | emperature [C | 314.5 | | | | | | |
| 0.0 | Temperature [K] | Heat descharged [W] | 35186 | emperature [K | 0,0 | | | | | | |
| | Ex ch,s [J/kg] | | | Ex ch,s [J/kg] | , | | | | | | |
| -10,5 | Ex ph,s [J/kg] | Delta exergy [W] | 1105 | Ex ph,s [J/kg] | -10,5 | | | | | | |
| 449,2 | Ex th,s [J/kg] | dp | 4000,00 | Ex th,s [J/kg] | 891,1 | | | | | | |
| 438,7 | Ex total,s [J/kg] | | | Ex total,s [J/kg | 880,6 | | | | | | |
| 0 | RH [%] | | | RH [%] | 0 | | | | | | |
| 0,007 | x [kgw/kga] | | | x [kgw/kga] | 0,007 | | | | | | |
| 1096,7 | Exergy total [W] | Cp [J/kgK] | 4180 | xergy total [W | 2201,4 | | | | | | |
| | | COP th | 16,04 | Delta exergy | 1023,7 | | | | | | |
| | | COP act | 8,02 | | | | | | | | |
| | | Eta irr | 0,5 | | | | | | | | |
| | | Electric power [W] | 3900 | Exergy loss [| 2876,3 | | | Pipe | | | |
| | IN par | Env pressure [Pa] | 110000 | OUT par | | | IN par | Env pressure [Pa] | 110000 | OUT par | |
| 00000,0 | Pressure [Pa] | Env temp [K] | 303 | Pressure [Pa] | 06000,0 | ▶ 96000,0 | Pressure [Pa] | Env temp [K] | 303 | Pressure [Pa] | 94500,0 |
| 22,1 | Temperature [C] | Medium | Water | emperature [C | 18,5 | 18,5 | Temperature [C] | Medium | Water | Temperature [C] | 18,5 |
| 295,1 | Temperature [K] | Mass flow [kg/s] | 2,1 | emperature [k | • 291,5 | • 291,5 | Temperature [K] | Mass flow [kg/s] | 2,1 | Temperature [K] | 291,5 |
| 0,0 | Ex ch,s [J/kg] | Heat subtracted [W] | 31286 | Ex ch,s [J/kg] | 0,0 | 0,0 | Ex ch,s [J/kg] | Pressure loss [Pa] | 1500 | Ex ch,s [J/kg] | 0,0 |
| -10,0 | Ex ph,s [J/kg] | Delta exergy [W] | 1024 | Ex ph,s [J/kg] | -14,0 | -14,0 | Ex ph,s [J/kg] | Q loss [W] | 0 | Ex ph,s [J/kg] | -15,5 |
| 437,1 | Ex th,s [J/kg] | dp | 4000 | Ex th,s [J/kg] | 928,6 | 928,6 | Ex th,s [J/kg] | T drop [K] | 0,0 | Ex th,s [J/kg] | 928,6 |
| 427,1 | Ex total,s [J/kg] | | | Ex total,s [J/kg | 914,6 | 914,6 | Ex total,s [J/kg] | | | Ex total,s [J/kg] | 913,1 |
| 0 | RH [%] | | | RH [%] | 0 | 0 | RH [%] | | | RH [%] | 0 |
| 0,007 | x [kgw/kga] | | | x [kgw/kga] | 0,007 | 0,007 | x [kgw/kga] | | | x [kgw/kga] | 0,007 |
| | Exergy total [W] | Cp [J/kgK] | 4180 | xergy total [W | 1920,6 | 1920,6 | Exergy total [W] | Exergy loss [W] | 3 | Exergy total [W] | 1917,4 |
| 896,9 | | | | | | | | | | | |

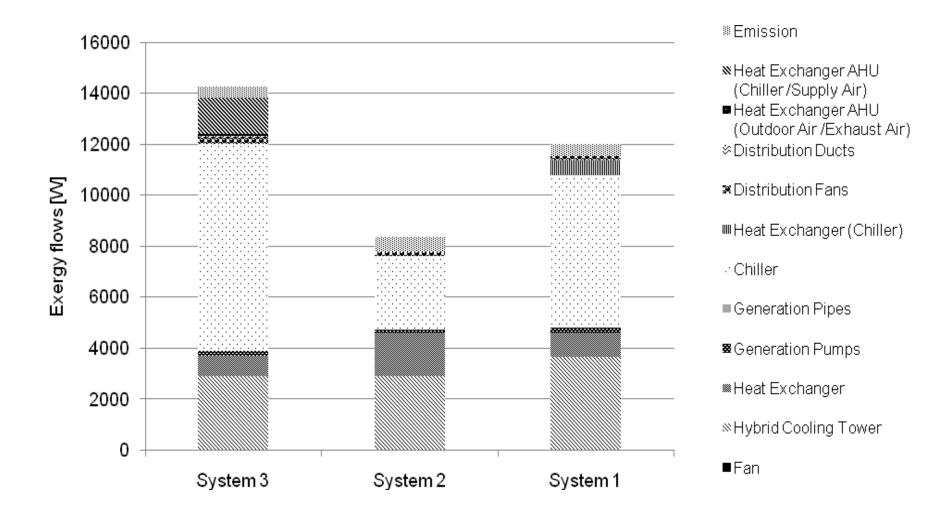
Exergy calculations



Exergy supply and demand of the analyzed systems



Exergy losses in the cooling systems



Conclusions

- All three systems have a low exergy efficiency. The exergy demand for the building is low.
- The main losses occur in the generation systems, chillers and hybrid cooling tower, and in the heat exchangers.
- The system with the highest exergy efficiency in the analysis is the System 2.
 - Water: lower temperature difference
 - No heat exchanger
- Direct distribution of the chiller output to the emission system doubles the exergy efficiency in comparison with a system where an intermediate heat exchanger is necessary.
- Exergy potential in the outdoor air at mid European humidity conditions: for System 2, the exergy gained from the outdoor air is in the level of the losses from the chiller.

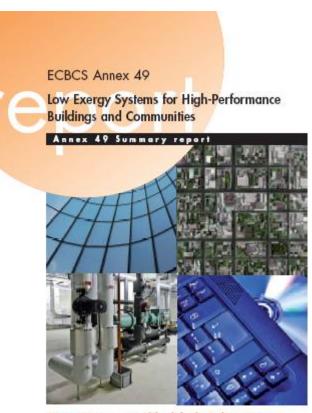
References

- Karlström, Petra, and Gudni Jóhannesson. "A general procedure to model the exergy performance of hybrid HVAC systems in buildings." *Bausim 2006.*
- Molinari, Marco. "SEPE: an excel calculation tool for exergy-based optimizations." *ECBCS Annex 49 Newsletter 6*, 2009.
- Molinari, M. 2009. A pressure and thermal exergy analysis of a waterborne and an airborne system, Proceedings of the 15th "Building Services, Mechanical and Building Industry Days" International Conference, Debrecen.

Aknowledgements

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http://www.annex49.com/background.html



"Exergy Assessment Guidebook for the Built Environment" Edited by Herena Toris and Dietrich Schwidt



FRAUNHOFER VERLAG

Thank you for your attention!