OPTIMIZATION OF GROUNDSTORAGE HEAT PUMP SYSTEMS FOR SPACE CONDITIONING OF BUILDINGS

Per Fahlén

Chalmers University of Technology

PARTICIPANTS

A: **Akademiska Hus**
Tomas Hallén

B: **IVT AB**
Jim Fredin, Urban Kronström

C: **Nibe AB**
David Kroon, Holger Svensson

D: **Thermia Värme AB**
Patrik Albinsson

E: **York Refrigeration AB**
Jakob Granström

F: **Wilo AB**
Rolf Jonasson

G: **Grundfos AB**
Patrik Petersson

H: **Pipetech**
Anders Sirkiä

I: **NCC**
Magdalena Kvernes

J: **SWECO Theorells AB**
Lars Olof Matsson

K: **ÅF-Infrastruktur AB**
Jörgen Eriksson, Nils Dafgård

L: **Borrentreprenörerna → Geotec**
Jan Olof Arnbom

M: **Carrier AB**
Ib Hagsten

N: **ICA Fastigheter Sverige AB**
Per-Erik Jansson, Ulf Hägglund

O: **Fastighetsägarna Stockholm**
Per Forsling

P: **Huurre**
Anders Ek

Q: **TAC**
Per-Göran Persson

Chalmers: P Fahlén, Saqib Javed, J Claesson, T Lindholm
Lund University: Göran Hellström
Donghua University: Yasu Zhou

TARGETS

- **Targets for the research:**
  - A calculation tool for complete system optimization
  - Identification of key efficiency factors (for optimization)
  - Identification of energy efficient system designs for a few (to be specified) applications

- **Target levels for market penetration** (conditions to be decided)**:**
  - Space conditioning of office buildings with $< 20\ kWh_{el}/m^2/year$ and $< 5\ kWh_{heat}/m^2/year$
  - Space conditioning of apartment buildings with $< 40\ kWh_{el}/m^2/year$

WORK PLAN (1)

- **Previous work**
  - Data bases (Fridoc, compendex …), personal contacts (project group)
- **State-of-the-art review (analysis and synthesis)**
  - Practical experience, measured results, estimate of future potential
  - Modelling tools, identification of the need for development and measurements for validation; suitable ways to proceed
- **Overview and classification of current system designs**
  - Inventory of review, classification and selection of systems for further investigations (modelling and measurement)
- **Field tests**
  - Inventory of existing and need for new tests, planning and start of measuring program, analysis and synthesis

WORK PLAN (2)

- **Theoretical analysis**
  - Development of component models (e.g. collector, heat pump, heat exchangers, pumps, fans etc.)
  - Comparison of calculations and measurements
  - Simulation of selected system solutions with variation of design values (sensitivity analysis: how critical is the system design for the technical and economic result?)
  - Identification of strengths and weaknesses of different designs
- **Reporting, presentation and dissemination of results**
  - Intermediate work reports for each sub-task
  - International conferences: IEA, IIR, ASHRAE
  - National conferences: Effsys Annual Meeting, Energitinget
  - Scientific articles: Journal of the IIR, Energy and buildings, ASHRAE
  - Popular articles: ScanRef, Energi och Miljö, VVS-Forum
  - LICENTIATE THESIS

TIME PLAN

Period: YEAR	2007				2008				2009			
Activity / quarter	1	2	3	4	1	2	3	4	1	2	3	4
Project planning												
1 Literature survey												
2 State-of-the-art report												
3 Current systems: inventory												
4 Field tests												
5.1 Theory: Modelling												
5.2 Theory: Simulation												
5.3 Theory: Analysis and synthesis												
6 Presentation of results (lic., conferences, articles)												

RELATED PROJECTS (1)

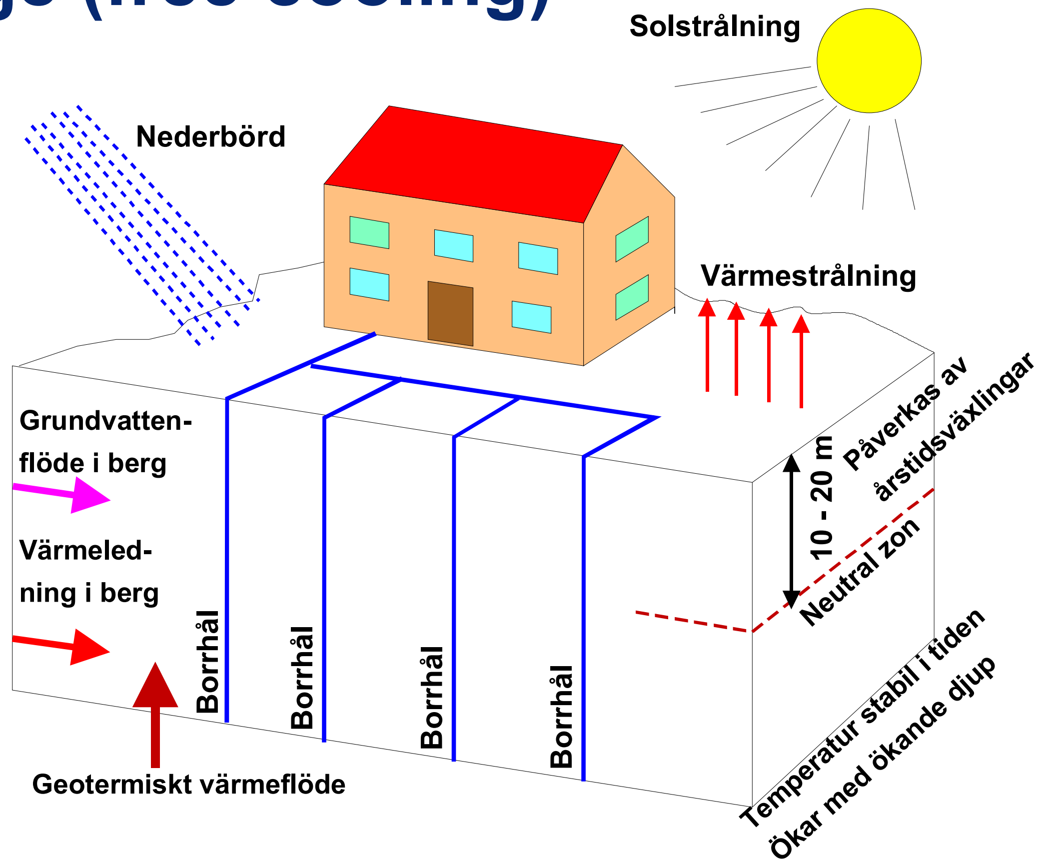
- **Optimized operation of heat pump systems (VSD)**
  - Fredrik Karlsson, SP/CTH Building Services Engineering
- **Efficiency of building related pump and fan operation (VSD)**
  - Caroline Markusson, CTH Building Services Engineering
  - Johan Åström, CTH Electric Power Engineering
- **Energy efficient cooling coils and brine systems (laminar flow)**
  - Caroline Haglund Stignor, SP/LTH/CTH Building Services Eng.
- **Control-on-demand ventilation – Intelligent supply-air devices (VAV)**
  - Mari-Liis Maripuu, CTH Building Services Engineering
- **Environmental assessment of air-conditioning systems**
  - Katarina Heikkilä, CTH Building Services Engineering
- **Free-cooling (general, air, sorptive, desiccant, cooling towers)**
  - Torbjörn Lindholm, CTH Building Services Engineering

RELATED PROJECTS (2)

- **Recharging of boreholes using ventilation air**
  - Per Fahlén, CTH Building Services Engineering
- **GSHP with integrated liquid-loop HRV**
  - Per Fahlén, CTH Building Services Engineering
- **Dynamic thermal networks**
  - Johan Claesson, CTH Building Physics
- **Control-on-demand heating, cooling and ventilation**
  - Per Fahlén, CTH Building Services Engineering
- **Energy efficient shopping centres**
  - Sofia Stensson, SP/CTH Building Services Engineering
- **Supermarkets**
  - Ulla Lindberg, SP/CTH Building Services Engineering
- **Integrated, intelligent control-on-demand**
  - Mohsen Soleimani Mohseni, CTH Building Services Engineering

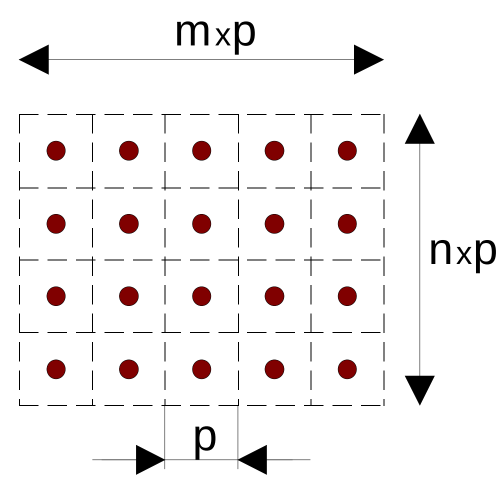
APPLICATION
Ground-source with heating cooling and storage (free cooling)

- Heat source
- Heat sink
- Heat storage



BOREHOLE SYSTEM – Important design factors

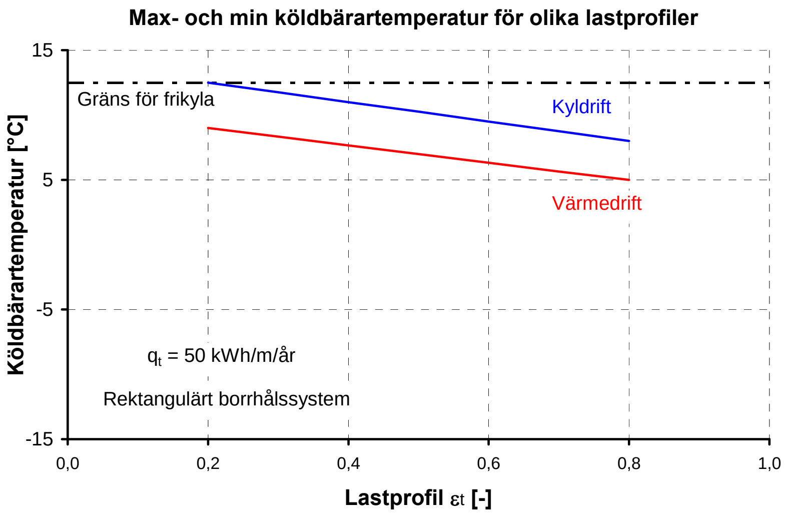
- **Building load profile**
  - Relation between heating and cooling
- **Borehole load**
  - Specific heat uptake in winter [kWh/m/year]
  - Specific heat input in summer [kWh/m/year]
- **Bore hole system geometry**
  - Number of holes and their depth
  - Borehole pitch
  - Ratio of length/width (rectangular or linear configuration)



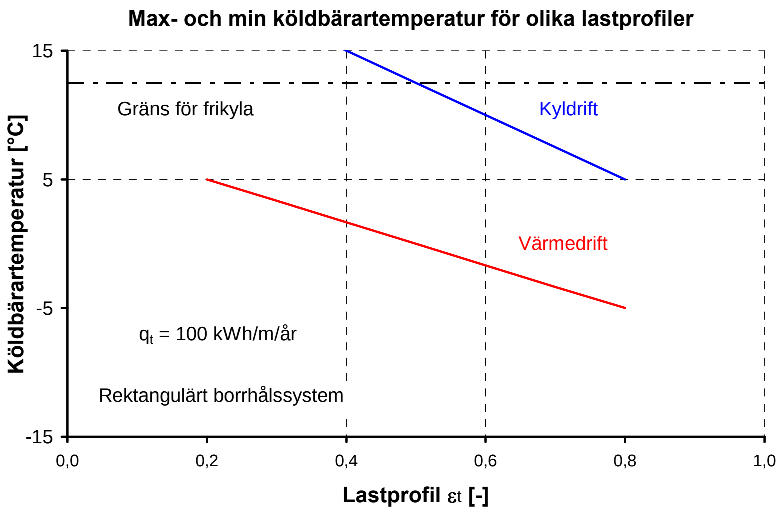
Antal hål N = mxn
Rektangulär geometri

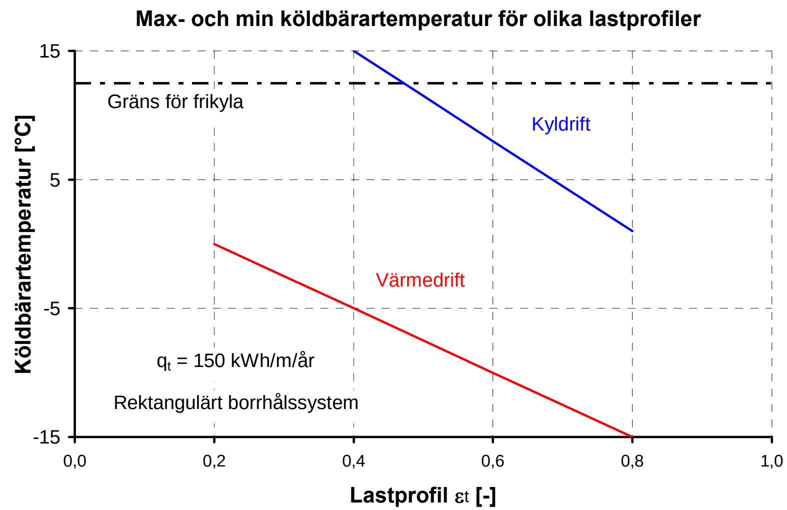
Linjär geometri, antal hål N = mxn

INFLUENCE OF LOAD PROFILE ON TEMPERATURE

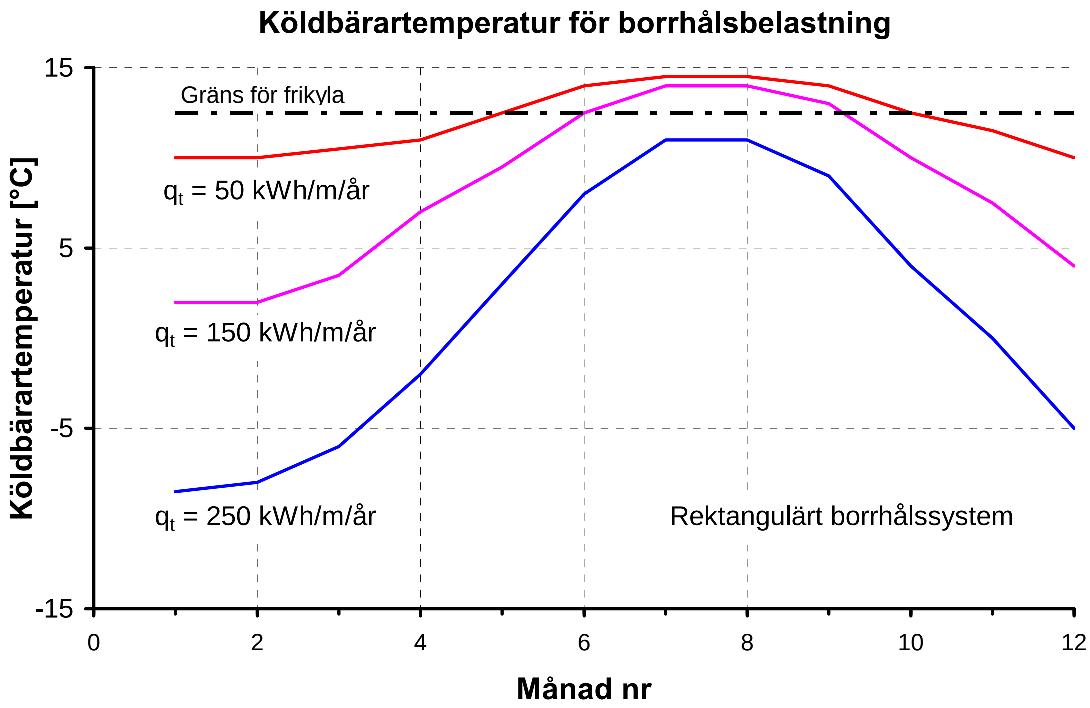


- **Rectangular systems with storage require more careful sizing than linear**





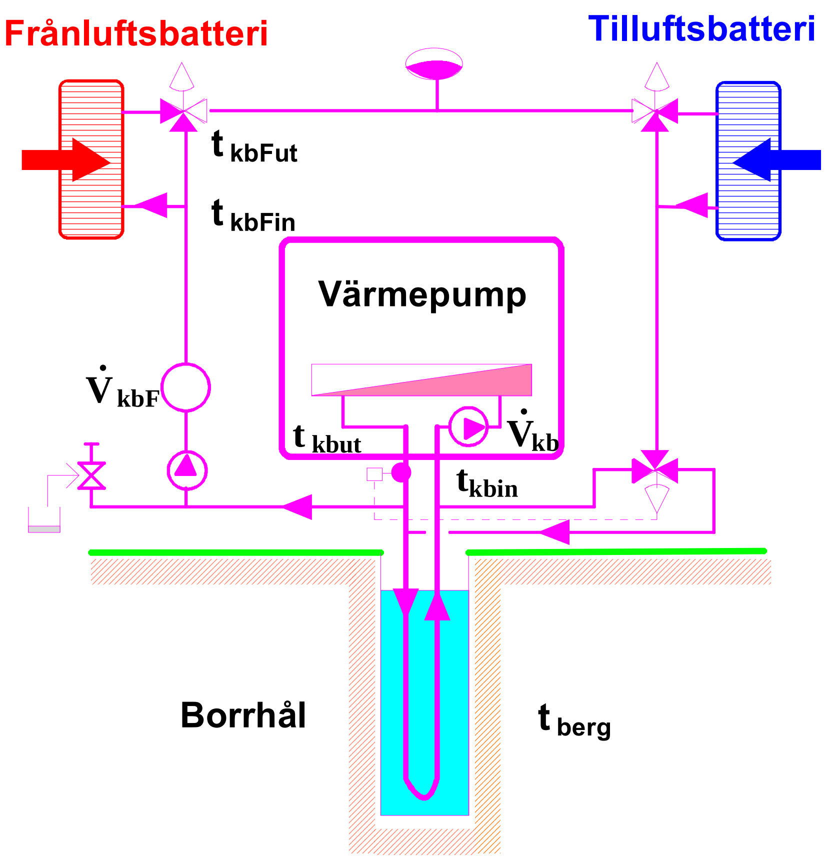
EXAMPLE OF TEMPERATURE VARIATION



Three different borehole loads with the same ratio between heat uptake and heat rejection in the borehole (rectangular geometry)

HEATING – COOLING - VENTILATION

- **Recharging:**
  - exhaust-air coil ON
  - supply-air coil OFF
- **Cooling**
  - exhaust-air coil OFF
  - supply-air coil ON
- **Heat recovery**
  - exhaust-air coil ON
  - supply-air coil ON



DEMAND FOR HEATING AND COOLING

- **Building level**

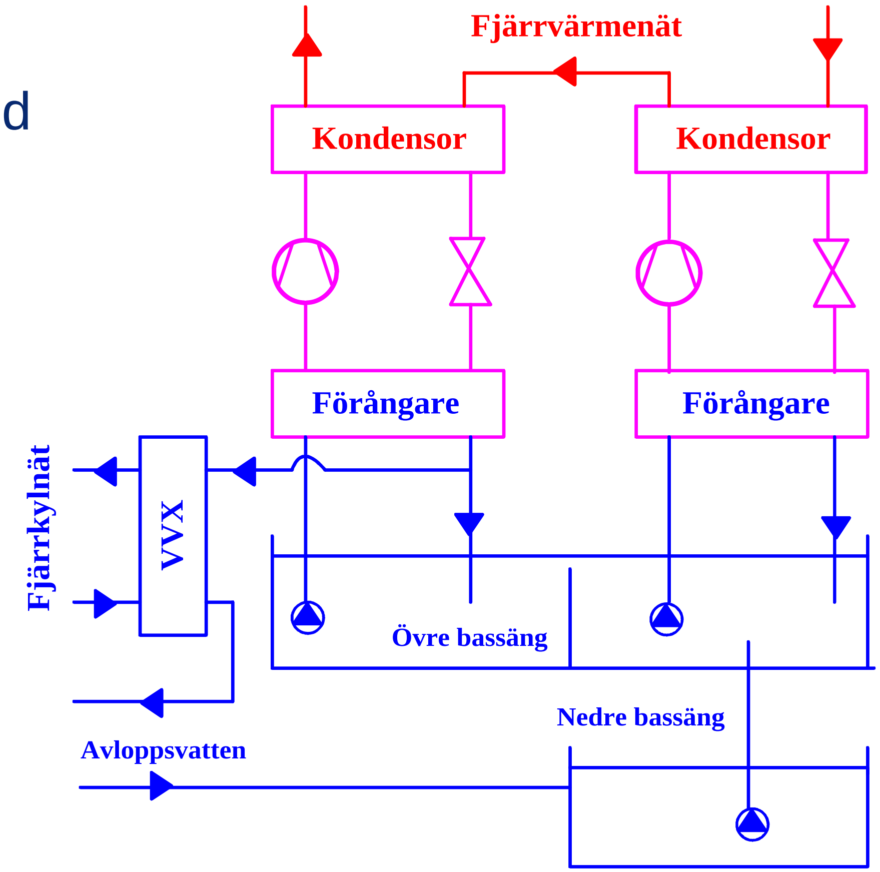
  Balance between surplus and deficit of heat within the building (own supply unit)

- **Block level**

  Balance between adjacent buildings (block centrals)

- **Community level**

  Balance between groups of buildings (district heating, district cooling)



SUMMARY

- Non-residential buildings with large heat surplus ⇨ demand for cooling
- Heat pumps can handle heating and cooling simultaneously (natural relation approx. 3:2)
- Borehole system provides stable temperature and possibility of storage (free cooling)
- GSHP systems may achieve very high efficiency but require careful analysis of real heating and cooling demand
- Design and sizing of heat pump, heating and cooling system (temperature!) and borehole system important for efficiency and economy

KEY FACTORS FOR EFFICIENCY

- **Temperature level** (*COP* changes by 2-3 % per °C!)
- **Heat exchangers** (temperature difference, pressure drop, material, pressure level)
- **Compressor** (type, sizing, capacity control)
- **Pumps and fans**

  (efficiency,

  operating time, capacity control)

$$COP_{vpa,medel} = \frac{\bar{\dot{Q}}_{vpa} + \frac{R_{p1}}{R_{vpa}} \cdot \dot{W}_{e,p1}}{\dot{W}_{e,m} + \frac{R_{p1}}{R_{vpa}} \cdot \dot{W}_{e,p1} + \frac{R_{p2}}{R_{vpa}} \cdot \dot{W}_{e,p2}}$$

- **Refrigerant** (efficiency,

  long-term acceptability, cost, safety)
- **Brine** (efficiency, corrosivity, stability, cost, safety, environment)

TEMPERATURE LEVEL AND PARASITIC POWERS

- **Influence on *COP***
  - Drive units and temperature levels:

$$\frac{\Delta COP_1}{COP_1} = -\frac{\Delta \dot{W}_{e,vp}}{\dot{W}_{e,vp}} = \left[\frac{\Delta T_{kb}}{T_1 - T_2} - \frac{T_2}{T_1} \cdot \frac{\Delta T_{vb}}{T_1 - T_2} - \frac{\dot{W}_{e,p}}{\dot{W}_{e,vp}} \right]$$

- **Example with recharging**
  - ΔT_{kb} = +4 K should give $\Delta COP/COP \approx$ +10 %
  - But ΔT_{vb} >+4 K, $\Delta w_{e,p}/w_{e,vp}$ = -9-10-24 ≈ -43 %
  - Total reduction by 40 - 60 %!

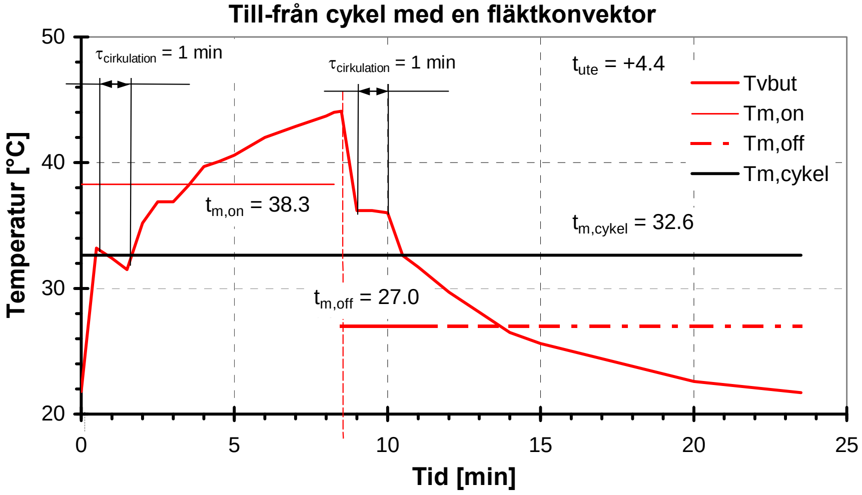
EXAMPLE: FAN COIL

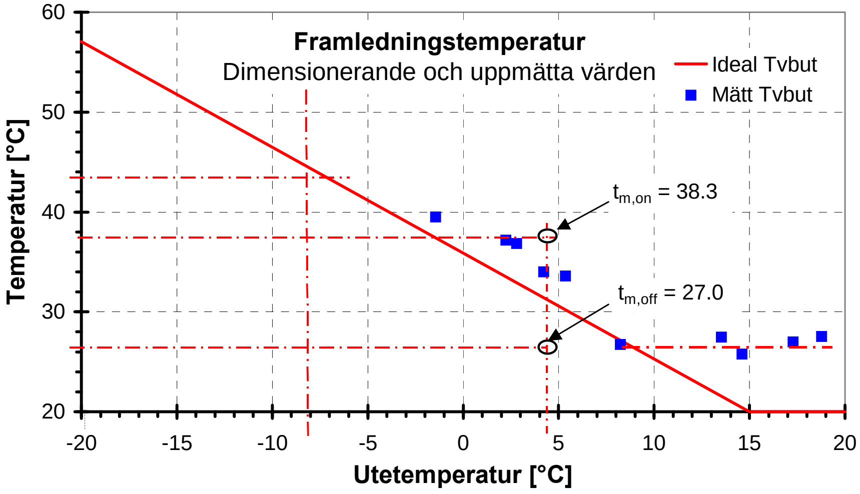
- **Control**
- Coil fan on
- Heat pump on-off

- **Temperature**
- On-temperature > mean temperature
- Example: t_{out} = 4,4 °C

$$\bar{t}_{w1,on} - \bar{t}_{w1,cycle} = 5{,}7\,°C$$

$$\Rightarrow \Delta COP \approx -10\,till - 15\,\%$$

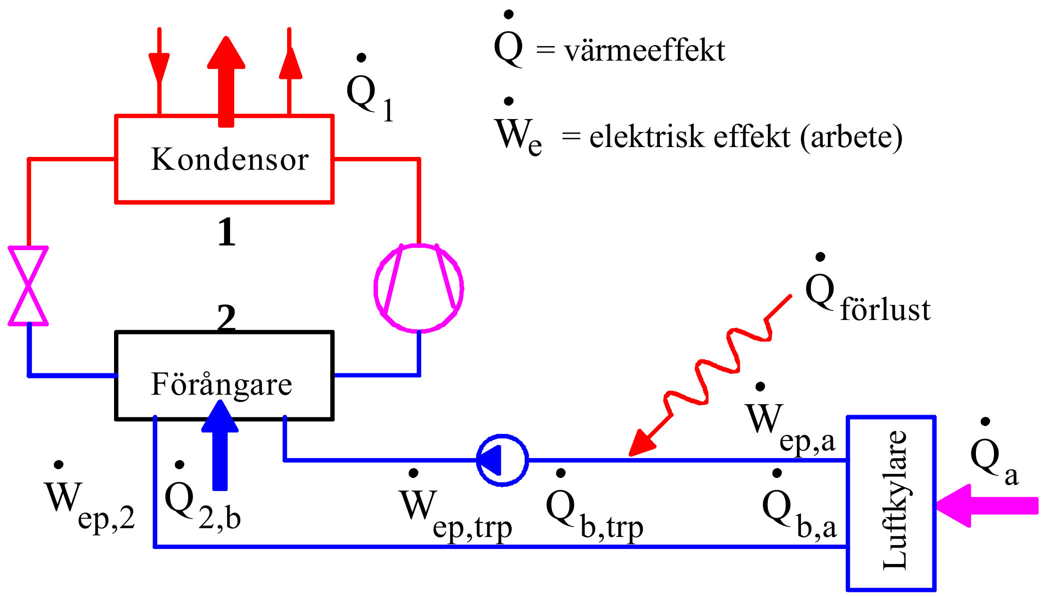




PARASITIC POWERS

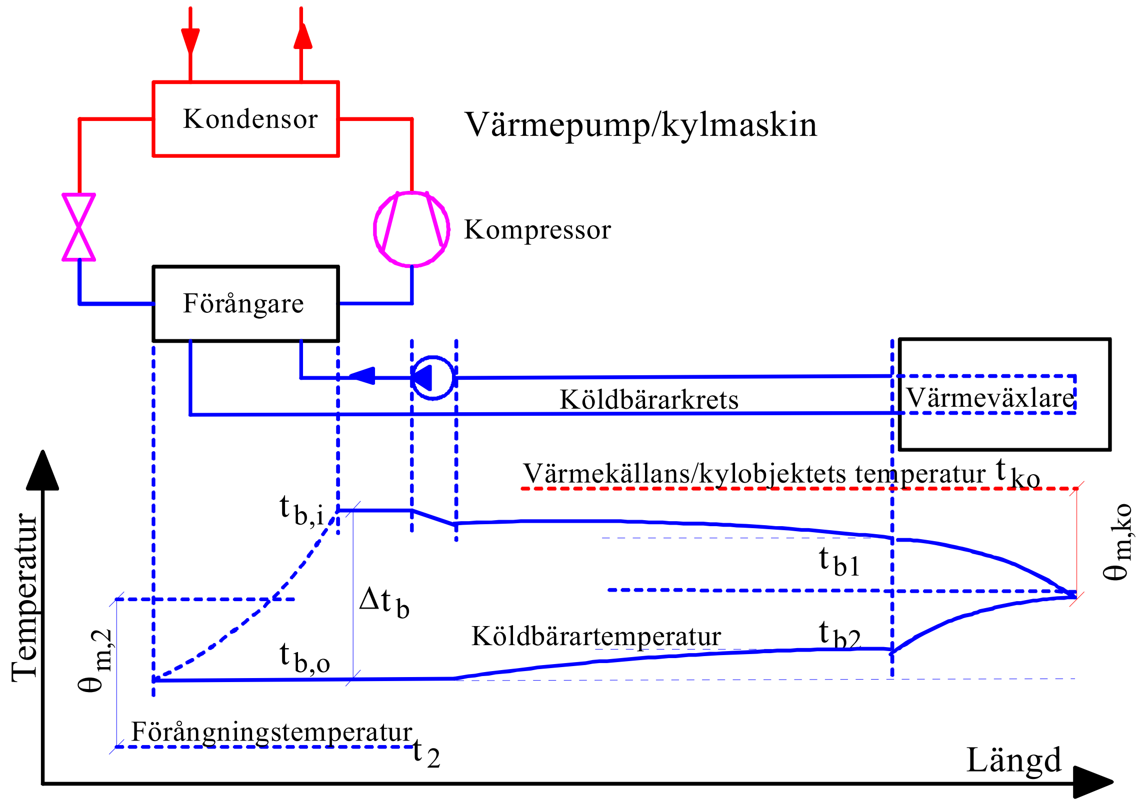
- Heat gain (”cooling loss”)
- Heat transfer resistance
- Heat transfer pressure drop
- Heat transport pressure drop

$$\dot{W}_{ep} = \frac{\dot{V} \cdot \Delta p}{\eta_p}$$



TEMPERATURE DISTRIBUTION

- Two transfer differences
- One transport difference



CONTROL OF AIR FLOW

- **Thermal comfort: E.g. t_{room}**

$$t_{room} = t_{sa} + \frac{\dot{Q}_{\text{int}}}{K_{tot}}$$

$$K_t = -\frac{\dot{Q}_{\text{int}}}{C_a \cdot (U \cdot A / C_a + \dot{V}_{nom})^2}$$

$$\Delta t_{room} = \Delta t_{sa} + K_t \cdot \Delta \dot{V}_{vent}$$

- **Air Quality: E.g. CO_2**

$$c_{room} = c_{sa} + \frac{\dot{V}_{CO2}}{\dot{V}_{vent}}$$

$$K_{CO2} = -\frac{\dot{V}_{CO2}}{\dot{V}_{nom}{}^2}$$

$$\Delta c_{room} = \Delta c_{sa} + K_{CO2} \cdot \Delta \dot{V}_{vent}$$

SUPPLY AIR COOLING CAPACITY

- **Depends directly on**
  - **air flow rate**
  - **supply-air temperature**
  - **room temperature**

$$\dot{Q}_{sa} = K_{sa} \cdot (t_{sa} - t_{room})$$

$$\frac{\Delta \dot{Q}_{sa}}{\dot{Q}_{sa}} = \frac{\Delta \dot{V}_{sa}}{\dot{V}_{sa}} + \frac{\Delta t_{sa}}{(t_{sa} - t_{room})} - \frac{\Delta t_{room}}{(t_{sa} - t_{room})}$$

LOWER TEMPERATURE OR MORE FLOW?

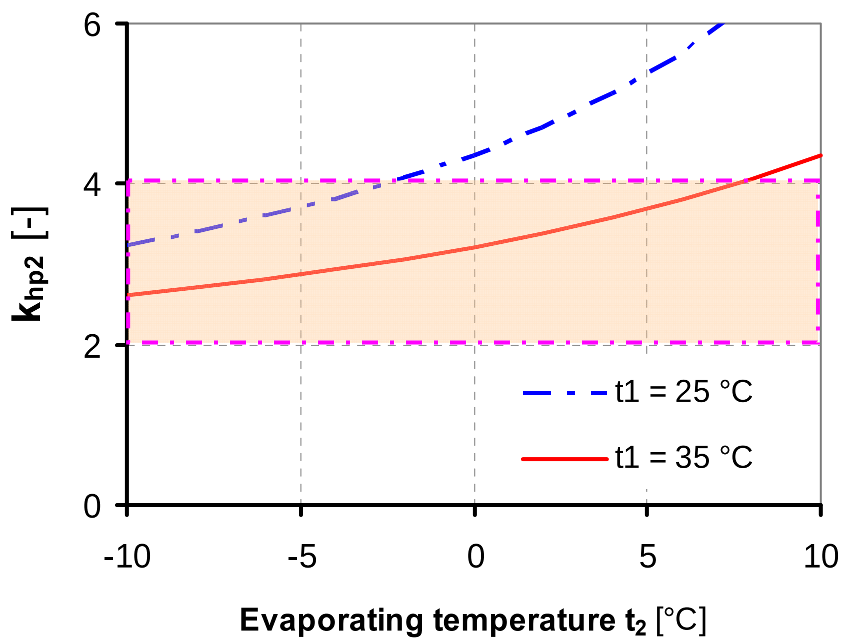
- **Lower temperature → higher compressor drive power**
- **Higher flow rate → higher fan power**

$$\Delta \dot{W}_e = \Delta \dot{W}_{hp} + \Delta \dot{W}_{e,f} =$$

$$= (k_{hp} \cdot \dot{W}_{hp} + k_f \cdot \dot{W}_{e,f}) \cdot \Delta t_{sa}$$

$$\frac{\Delta \dot{W}_e}{\Delta t_{sa}} = k_{hp} \cdot \dot{W}_{hp} \cdot (1 + \frac{k_f}{k_{hp}} \cdot \frac{\dot{W}_{e,f}}{\cdot \dot{W}_{hp}})$$

$$\frac{\Delta \dot{W}_e}{\Delta t_{sa}} = 0.03 \cdot \dot{W}_{hp} \cdot (1 - 25 \cdot \frac{\dot{W}_{e,f}}{\dot{W}_{hp}})$$



EXTERNAL OR INTERNAL ROOM COOLING

- **Requirement on SFP to make TC-controlled air flow more electricity efficient than a chiller** (n = 1,5 to 2):

$$SFP_{nom} < \left(\frac{\dot{q}_V}{COP_c}\right) \cdot \left(\frac{\dot{Q}_{sa}}{\dot{Q}_{nom}} - 1\right) \cdot \left(\left(\frac{\dot{Q}_{sa}}{\dot{Q}_{nom}}\right)^{n+1} - 1\right)^{-1}$$

Volumetric fan power:

$$SFP = \frac{\dot{W}_{e,f}}{\dot{V}_a} \ [\mathrm{kW/m^3/s}]$$

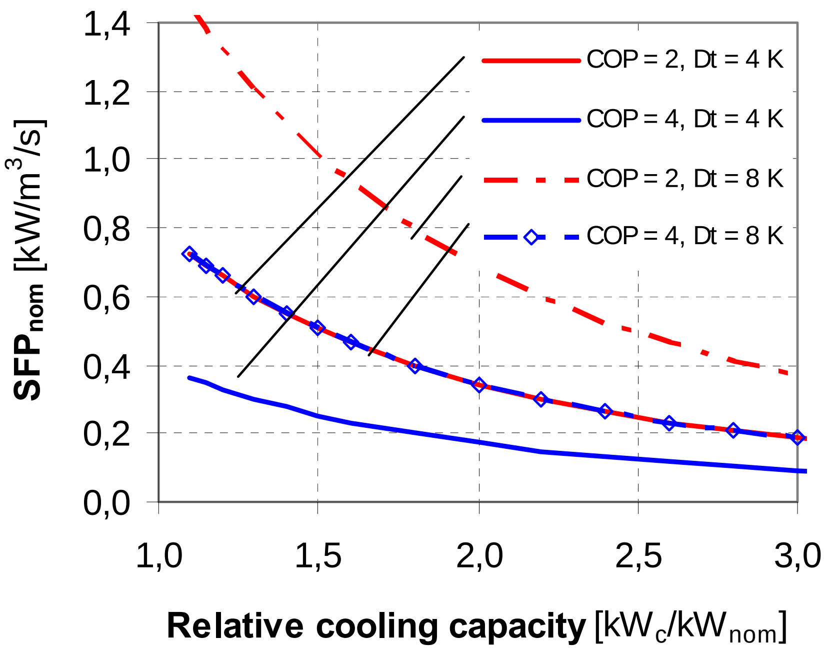
Volumetric cooling capacity:

$$\dot{q}_V = \frac{\dot{Q}_{sa,nom}}{\dot{V}_{sa,nom}} \ [\mathrm{kW/m^3/s}]$$

$$(\dot{q}_V \approx 1.2 \cdot (t_{sa} - t_{room}))$$

Relative cooling capacity:

$$\frac{\dot{Q}_c}{\dot{Q}_{nom}} \ [\mathrm{kW/kW}]$$



FAN POWER

- **Reduce SFP**
  - Raise fan efficiency
  - Reduce distribution pressure drop
  - Reduce AHU pressure drop (FI, HR, AH, AC)

$$SFP = \frac{\dot{W}_{e,f}}{\dot{V}_a} = \frac{\Delta p \cdot 10^{-3}}{\eta_f}$$

$$SFP = SFP_{nom} \cdot \left(\frac{\dot{V}_a}{\dot{V}_{a,nom}} \right)^n$$

Typical pressure drop Pa]

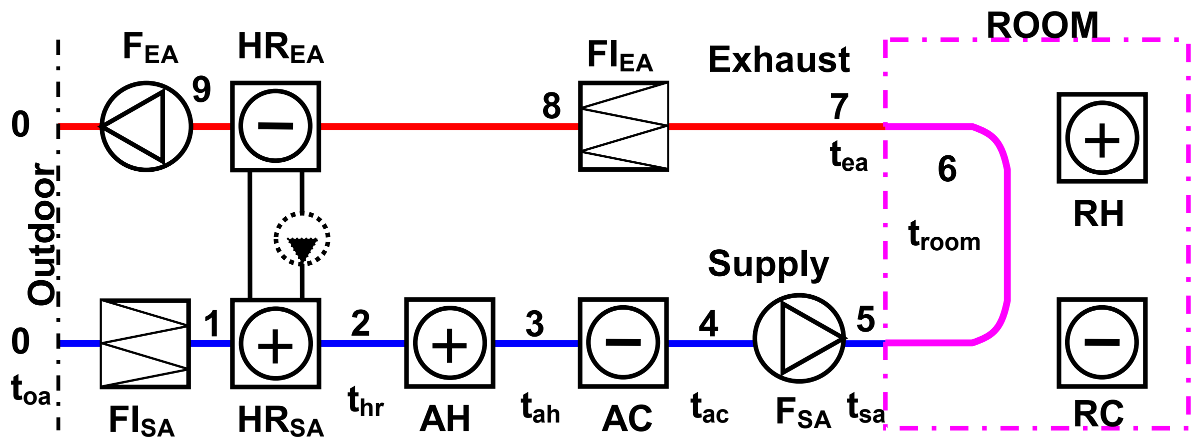
$\Delta p_{01} = -150$ $\Delta p_{78} = -150$

$\Delta p_{12} = -100$ $\Delta p_{89} = -100$

$\Delta p_{23} = -30$ $\Delta p_{90} = 500$

$\Delta p_{34} = -50$ plus ducts, dampers, terminals units

$\Delta p_{45} = 600$



CONTROL OF AIR CONDITIONING

- **Air flow based on AQ-requirement** (e.g. c_{CO2}<1000 ppm)
- **Room temperature based on TC-requirement** (e.g. 21 °C)
- **Keep t_{room} at the comfort minimum** (e.g. 21 °C)
- **Reduce heat recovery until $t_S = t_{S,min}$** (e.g. 17 °C)
- **Use deadband; $t_{room,min} < t_{room} < t_{room,max}$** (e.g. 21-25 °C)
- **Raise air flow based on max. of AQ- or TC-demand**
- **Use night cooling but watch the fan energy**
- **Start chiller when the marginal increase of fan power is larger than the chiller drive power**

OFFICE ECONOMY?

- Staff cost: 100 000 SEK/m^2/year
- Rent: 2 000 SEK/m^2/year
- Capital cost of HVAC: 200 - 1 000 SEK/m^2/year
- Energy cost: 100 - 500 SEK/m^2/year

GROUND STORAGE – PHASE II

- **Connecting the developed models**
- **Optimized design and size**
- **Optimized control**
  - Short-term: Feedback feed-forward
  - Medium-term: Predictive (day-night cooling-heating)
  - Long-term: Predictive (summer-winter balancing)
- **Case-studies**