Book of presentations of the International Workshop on High Temperature Heat Pumps

Elmegaard, Brian; Zühlsdorf, Benjamin; Reinholdt, Lars; Bantle, Michael

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International Workshop on High Temperature Heat Pumps

11. September 2017
Copenhagen, Denmark

\[(EIv'')'' = q - \rho A \ddot{v}\]

\[\sqrt{17} \int_{a}^{b} \Theta + \Omega \int_{\infty}^{\infty} \chi^2 \sum\]

11. September 2017
Copenhagen, Denmark

DTU Mechanical Engineering
Department of Mechanical Engineering
Introduction

Modern society moves towards an electrified energy system based on wind, solar and other renewable sources. Utilizing these sources efficiently by heat pumps is highly attractive and a significant potential for improving the energy system by extensive adaptation of heat pumping technology in all fields exists. However, challenges are present for heat pump technology. In particular for high temperature applications like industrial processes and to some extent district heating, heat pumps are not yet commercially available. In some countries the expansion already occurs, but other places the development is much more limited. Some obstacles relate to regulations and boundary conditions which may not be favorable for heat pumps and electrification. But, the level of the technology will probably also improve with regards to temperature limits, efficiency, capacity, and economy, and hence inherently become an attractive alternative to fossil fuels.

The focus on developments for the future is apparent in both industrial and scientific research and development activities at all levels. DTU Technical University of Denmark, Danish Technological Institute and Norwegian SINTEF are all involved in these activities in collaboration with national and international partners.

Based on these common interests and the many exciting activities we decided to invite for a workshop for a broad audience ranging from manufacturers, system suppliers, industrial users, consultants, research institutes, and academia. The meeting attracted more than 60 participants attending the 18 talks and a final panel discussion on the 11. September 2017 in Copenhagen.

The talks were divided in four sessions focusing on

- Market Potential - Developments – Challenges
- Research and Development Projects
- Heat pump developments - Market ready products
- Case studies including realized projects

Altogether the presentations showed significant activity in both the Nordic countries, in Europe, and worldwide. Heat pumps are installed and investigated in various branches and both the foreseen industrial progress and the longer term perspectives indicated by academic research target the challenges and will soon make high temperature heat pumping far more attractive.

The concluding panel discussion involved Andrew J. Marina – Researcher at ECN (Energy Research Centre of the Netherlands), Kim Andre Lovas – Consultant, TINE SA Oslo, Morten Deding – Heat Pump Product Director Johnson Controls, Palle Lemminger – Manager, Innoterm A/S, and Petter Nekså – Chief Scientist, SINTEF. The panelists presented their suggestions on measures that will enhance the utilization of high temperature heat pumps in industry.
The following common conclusions were drawn from the discussion:

- Heat pumps are required for combating climate change
- Avoid wasting excess energy from industry by use of heat recovery
- Technical innovations for achieving lower specific investment costs should be achieved
- Equalize boundary conditions for heat pumps and other technologies
- Broader collaboration and interaction between technology developers and end-users will be beneficial
- Calculation tools may be useful for communicating the potentials to potential users
- Demonstration projects involving all parties including end-users, consultants, manufacturers as well as R&D can constitute a good opportunity to realize the before-mentioned suggestions

As organizers we are grateful to all participants and in particular the speakers for interesting and well-prepared presentations. In the following we present the collection of slides presented at the meeting.

Brian Elmegaard, Technical University of Denmark
Benjamin Zühlsdorf, Technical University of Denmark
Lars Reinholdt, Danish Technological Institute
Michael Bantle, SINTEF
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1.1. IEA HPT TP Annex 48: Heat Pump Application in commercial and industrial processes, Dr.-Ing. Rainer Jakobs (Information Centre on Heat Pumps and Refrigeration)
The IEA Technology Collaboration Programme on Heat Pumping Technologies, HPT TCP, and the Heat Pump Centre, the central information activity of the programme. [http://heatpumpingtechnologies.org](http://heatpumpingtechnologies.org)

The goal is to accelerate the implementation of heat pumps and related heat pumping technologies. Including air conditioning and refrigeration.

HPT TCP is member of IEA International Energy Agency (IEA), the programme was founded in 1978. HPT TCP has been active since almost 40 years.

There are today 16 member countries: Austria, Belgium, Canada, Denmark, Finland, France, Italy, Germany, Japan, the Netherlands, Norway, South Korea, Sweden, Switzerland, United Kingdom and the United States.

Annexes = Projects
One of the main activities within the programme is to run collaborative research, development, demonstration and deployment projects. They are called Annexes and they are conducted on a combination of cost sharing and task-sharing basis by the participating countries.

One person/organization is appointed to manage the Annex, to be the Operating Agent of the Annex.

1.1. IEA HPT TP Annex 48: Heat Pump Application in commercial and industrial processes, Dr.-Ing. Rainer Jakobs (Information Centre on Heat Pumps and Refrigeration)

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**Workshop on High Temperature HPs**

**11.9.17 Kobenhavn K**

**Agenda**

- **IEA HPT TCP Annex 35 + 48**

  - Background
  - Market overview, barriers for applications
  - Technology
  - Case Studies
  - Summary and outlook


---

**Heat Source and Heat Sink in Industrial Heat Pumps**

- **Space Heating**
- **Drying Process**
- **Process Other Heat**

**Condenser**

**Evaporator**

**Compressor Work**

**Ground-Air-Water**

**Cooling Tower**

**Excess Waste Heat Exhaust**

**Others**
IEA HPP - IETS Annex 35/13: Application of Industrial Heat Pumps

- As a joint venture of the IEA Implementing Agreements Industrial Energy-related Technologies and Systems (IETS) and Heat Pump Programme (HPP)
- 9 IEA countries: A CDN D DK F JAP Korea NL S
- 15 participating organizations
- Operating agent: IZW e.V. Germany
- Start date: 01st May 2010  End date: 30th April 2014
- Report: 31st October 2014  689 pages
  - 39 R&D projects
  - 115 applications
  - 85 publications of the participants

IEA HPP Annex 48: Industrial Heat Pumps, Second Phase

- IEA countries: A CH DK F JAP UK
- Operating agent: IZW e.V. Germany
- Start date: 01st April 2016  End date: 31st March 2019

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Total pages: 689

Background
Task 1:
Heat Pump Energy situation, energy use, market overview, barriers for application
A, CDN, DK, F, D, Japan, Korea, NL, S

Final energy consumption (9,060 PJ) in Germany 2010 by sector /BMWI 2012

- Transport: 28.2%
- Industry: 28.1%
- Private households: 28.5%
- Trade and services: 15.2%
1.1. IEA HPT TP Annex 48: Heat Pump Application in commercial and industrial processes, Dr.-Ing. Rainer Jakobs (Information Centre on Heat Pumps and Refrigeration)
Barriers and Solutions

Challenging Heat & Electricity Prices

→ Focus on Countries with favorable Price Ratios:
  - Sweden
  - Finland
  - Bulgaria
  - Netherlands
  - France
  - etc.

→ Focus on Rural Areas without Gas Networks

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Market overview

Average electricity pricing (2010)

SELECTED WORLD RESIDENTIAL ELECTRICITY PRICES, 2010

~ 0.09 US$/kWh

Source: International Energy Agency

Market overview

Source: Natural Resources Canada
Heat Pump Energy situation, energy use, market overview, barriers for application

The country reports show that the industrial energy consumption in the participating countries varies between 17 to 58% with great differences of the manufacturing sectors.

The barriers can be solved, as shown in the results of the Annex:

- short payback periods are possible (less than 2 years),
- high reduction of CO₂-emissionen (up to more than 50%),
- temperatures higher than 100 °C are possible,
- supply temperatures lower than 100 °C are standard.

Task 3:

R & D Projects

A, CDN, DK, F, D, Japan, Korea, NL
High-temperature HPs of Austrian manufacturers: E.g.

Company Ochsner offers HPs with new refrigerant ("Öko 1"): non-flammable, not toxic for heat sink temperatures up to 95°C (temp. difference 5 to 10 K)

Two different types:
- IHWS for a temperature lift from 10 to 95°C
- IHWS for a temperature lift from 40 to 95°C

High-temperature heat pump (Ochsner, 2013)

Closed-cycle mechanical heat pump
- Transcritical CO₂ cycle
- Single-stage compression reverse Rankine cycle
- Two-stage compression reverse Rankine cycle
- Cascade reverse Rankine cycle

Open-cycle hybrid vapor recompression heat pumps
- Hybrid means “mechanical and thermal”
Cascade Reverse Rankine Cycle Heat Pump using R410A *

Specifications of the Heat Pump

- Rated Heating Power (kW): 14.0
- Rated COP*: 3.5
- Leaving Temperature Range (°C): 50 to 90
- Ambient air temperature range (°C): -15 to 43


Technology

Technology
EDF projects to reach temperatures > 100 °C

Alter ECO Project
Partnership: Rhodia, Arkema, Danfoss, CIAT, ...
VHT HP
140°C – 250 kW
Integrator: CLAUGER

Technical Partnership
EDF /Johnson Controls
HT/VHT HP
100°C/120°C – 700 kW

ANR PACO Project
Partnership: Johnson-Control, France Évaporation, CETHIL, AgroParistech, Matmeca ...
VHT HP with water
140°C – 700 kW
Manufacturer: JCI
Manufacturer JCI/F-Évaporation

Task 4: Case studies

A, CDN, DK, F, D, Japan, Korea, NL
### Case Studies

Source: NT Japan Annex 35

<table>
<thead>
<tr>
<th>Application, Industry</th>
<th>Member Country</th>
<th>Year</th>
<th>System</th>
<th>Refrigerant</th>
<th>Cooling</th>
<th>Heating</th>
<th>Drying</th>
<th>Waste heat</th>
<th>Heating Capacity</th>
<th>Supply temperature</th>
<th>Pay back period</th>
<th>Reduction CO₂</th>
<th>Reduction energy/cost</th>
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<td>A eld</td>
<td>2013</td>
<td>Mech Compr</td>
<td>R-134a</td>
<td>W</td>
<td>257 kW</td>
<td>55 °C</td>
<td>75%</td>
<td>420</td>
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<td>Ice rink</td>
<td>A</td>
<td>2013</td>
<td>Mech Compr</td>
<td>R-717</td>
<td>W</td>
<td>413 kW</td>
<td>60 °C</td>
<td>75%</td>
<td>422</td>
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<td>R-717</td>
<td>W</td>
<td>370 kW</td>
<td>63-77 °C</td>
<td>5.7 a</td>
<td>426</td>
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<td>109</td>
<td>10-12 °C</td>
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<td>5.6 kW</td>
<td>n. a.</td>
<td>21.5%</td>
<td>463</td>
<td></td>
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<tr>
<td>Wood drying high temp</td>
<td>CDN eld</td>
<td></td>
<td>Mech Compr</td>
<td>D</td>
<td></td>
<td>2 x 65 kW</td>
<td>n. a.</td>
<td>50%</td>
<td>471</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Washing metal items</td>
<td>DK 2011</td>
<td></td>
<td>Mech Compr</td>
<td>R-134a</td>
<td>H</td>
<td>25 kW</td>
<td>60 °C</td>
<td>2.5 a</td>
<td>493</td>
<td></td>
<td>50%</td>
<td></td>
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<tr>
<td>Food: Slaughter-house</td>
<td>D 2011</td>
<td></td>
<td>Mech Compr</td>
<td>R-744</td>
<td>C&amp;H</td>
<td>800 kW</td>
<td>90 °C</td>
<td>510 t/a</td>
<td>500</td>
<td></td>
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<tr>
<td>Food: Dairy</td>
<td>D 2011</td>
<td></td>
<td>Mech Compr</td>
<td>R-717</td>
<td>W</td>
<td>3.45 MW</td>
<td>58 °C</td>
<td>30-40%</td>
<td>506</td>
<td></td>
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<td></td>
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</tbody>
</table>

1.1. IEA HPT TP Annex 48: Heat Pump Application in commercial and industrial processes, Dr.-Ing. Rainer Jakobs (Information Centre on Heat Pumps and Refrigeration)
### Workshop on High Temperature HPs 11.9.17 Kobenhavn K

<table>
<thead>
<tr>
<th>Application, Industry</th>
<th>Member Country</th>
<th>Year</th>
<th>System</th>
<th>Refrigerant</th>
<th>Cooling</th>
<th>Heating</th>
<th>Drying</th>
<th>Waste heat</th>
<th>Heating Capacity</th>
<th>Supply temperature</th>
<th>Pay back period</th>
<th>Reduction CO₂</th>
<th>Reduction energy/cost</th>
<th>Report page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food: Dairy</td>
<td></td>
<td>2011</td>
<td>Mech Compr</td>
<td>R-717</td>
<td>W</td>
<td>3.45 MW</td>
<td>58°C</td>
<td>30-40%</td>
<td>5 a</td>
<td>506</td>
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<tr>
<td>Coating Powder</td>
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<td>2012</td>
<td>Mech Compr</td>
<td>D</td>
<td>240 kW</td>
<td>45°C</td>
<td>531</td>
<td></td>
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<tr>
<td>Food: Malt production</td>
<td></td>
<td>2010</td>
<td>Mech Compr</td>
<td>R-717</td>
<td>D</td>
<td>3,250 kW</td>
<td>35°C</td>
<td>546</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Food: Brewery</td>
<td></td>
<td>2012</td>
<td>Mech Compr</td>
<td>R-134a</td>
<td>H</td>
<td>77 kW</td>
<td>55°C</td>
<td>&lt; 6 a</td>
<td>547</td>
<td></td>
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<tr>
<td>Transformer casing (painting)</td>
<td>Jap</td>
<td>2009</td>
<td>Mech Compr</td>
<td>R-744</td>
<td>D</td>
<td>110 kW</td>
<td>80-120°C</td>
<td>13%</td>
<td>565</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Automotive (painting)</td>
<td>Jap</td>
<td>2009</td>
<td>Mech Compr</td>
<td>R-407E</td>
<td>D</td>
<td>566 kW</td>
<td>n. a.</td>
<td>47%</td>
<td>569</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Automotive – Washing process</td>
<td>Jap</td>
<td>2009</td>
<td>Mech Compr</td>
<td>R-134a</td>
<td>C &amp; H</td>
<td>8 x 45.3 kW</td>
<td>65°C</td>
<td>75%</td>
<td>575</td>
<td></td>
<td></td>
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<tr>
<td>Greenhouse</td>
<td></td>
<td>2010</td>
<td>Mech Compr</td>
<td>R-401A</td>
<td>6 x 18 kW</td>
<td>20°C</td>
<td>63%</td>
<td>580</td>
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<td></td>
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<tr>
<td>Food: Drying of french fries</td>
<td>NL</td>
<td>2012</td>
<td>Mech Compr</td>
<td>R-717</td>
<td>D</td>
<td>880 kW</td>
<td>70°C</td>
<td>70%</td>
<td>NL-06</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Greenhouse Tomatoes</td>
<td>NL</td>
<td>2003</td>
<td>Mech Compr</td>
<td>R-134a</td>
<td>C&amp;H</td>
<td>3 x 1.25 MW</td>
<td>42-50°C</td>
<td>29%</td>
<td>NL-27</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

#### Case studies

**Company:** MOHREN

**Compression heat pump in in a brewery:**

- **NH₃ Compression HP (COFELY)**
- **370 kW heating capacity**
- **Waste heat from:**
  - air compressor
  - chillers
- **Heat upgrade from ca. 40 to 77 °C**
- **Space and process water heating**
- **ROI: 5,7a**

Source: klima:aktiv

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**Source:** Rene Rieberer [TU Graz] HPP Annex 35 Workshop – May 12th, 2014, Montreal

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**Fish farm heat recovery**

Overall system COP: 7.9  
Payback period: 1.28 year

Source:

**Heat pump-assisted drying**

Industrial high-temperature HP for softwood drying (354 m³)

- 2 HPs – total 130 kW  
- HFC-236fa  
- Split HPs with remote condensers

- > 19 300 Liters of water removed/cycle  
- SMER: 1.46 to 2.52 kg Water/kWh (compressors + blowers)  
- Energy savings: 27 to 57 % vs. oil

Source:
Selected applications of industrial heat pumps in Germany - Size

Collection of 18 heat pump applications in the German industry:

- 13 use waste heat to provide space heating
- 5 use waste heat to provide process heat

![Bar graph showing the distribution of heat pump applications by size.](image)

Selected applications of industrial heat pumps in Germany - Temperatures

Collection of 18 heat pump applications in the German industry:

- 13 use waste heat to provide space heating
- 5 use waste heat to provide process heat

![Bar graph showing the temperature distribution for heat pump applications.](image)
1.1. IEA HPT TP Annex 48: Heat Pump Application in commercial and industrial processes, Dr. -Ing. Rainer Jakobs (Information Centre on Heat Pumps and Refrigeration)

### Temperature ranges and types of heat used in industries

<table>
<thead>
<tr>
<th>Type of industry</th>
<th>Process</th>
<th>Temp. used [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>General machinery and tools</td>
<td>Drying</td>
<td>40  60  80  100  120</td>
</tr>
<tr>
<td>Electronic components and devices</td>
<td>Drying</td>
<td>80  100  120</td>
</tr>
<tr>
<td>Electronic components and devices</td>
<td>Washing</td>
<td>40  60  80  100  120</td>
</tr>
<tr>
<td>Electronic components and devices</td>
<td>Degreasing</td>
<td>40  60  80  100  120</td>
</tr>
<tr>
<td>Transport machinery</td>
<td>Drying</td>
<td>40  60  80  100  120</td>
</tr>
<tr>
<td>Food</td>
<td>Sterilization</td>
<td>40  60  80  100  120</td>
</tr>
<tr>
<td>Food</td>
<td>Washing</td>
<td>40  60  80  100  120</td>
</tr>
<tr>
<td>Food</td>
<td>Sterilization</td>
<td>40  60  80  100  120</td>
</tr>
<tr>
<td>Beverage</td>
<td>Sterilization</td>
<td>40  60  80  100  120</td>
</tr>
<tr>
<td>Beverage</td>
<td>Washing</td>
<td>40  60  80  100  120</td>
</tr>
</tbody>
</table>

**The use rate classified by temperature of hot water in Japan**

If hot water can be produced up to 90°C by heat pump, about 80% of hot water demand can be covered.

### Temperature Applied for IHP

<table>
<thead>
<tr>
<th>Industry</th>
<th>Industrial process</th>
<th>Temp. [°C]</th>
<th>Industry</th>
<th>Industrial process</th>
<th>Temp. [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food production</td>
<td>Freezing foods</td>
<td>-60 ~ -30</td>
<td>Food production</td>
<td>Lumber dehumidifier</td>
<td>40 ~ 60</td>
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<tr>
<td></td>
<td>Cooling of chicken</td>
<td>-20 ~ 5</td>
<td></td>
<td>Freezing exhibit case</td>
<td>-20 ~ -10</td>
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<tr>
<td></td>
<td>Cooling of noodle</td>
<td>1 ~ 3</td>
<td></td>
<td>Hot water supply for cooking room</td>
<td>60 ~ 80</td>
</tr>
<tr>
<td></td>
<td>Sterilization and cooling of milk</td>
<td>3 ~ 5, 70 ~ 75</td>
<td></td>
<td>Heating for indoor pool water</td>
<td>~ 35</td>
</tr>
<tr>
<td></td>
<td>Ham production</td>
<td>2 ~ 80</td>
<td></td>
<td>Heating for hot spring</td>
<td>~ 60</td>
</tr>
<tr>
<td></td>
<td>Retort pouch</td>
<td>3 ~ 5, 70 ~ 75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fermentation of Japanese sake</td>
<td>14 ~ 15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fermentation and temperature control of wine</td>
<td>16 ~ 20</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Seaweed drying</td>
<td>20 ~ 30</td>
<td></td>
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<td></td>
<td>Temperature control of yeasts and bread</td>
<td>22 ~ 30</td>
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<tr>
<td></td>
<td>Fermentation of miso and shoyu</td>
<td>27 ~ 28, 38 ~ 40</td>
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<td>Rice koji drying</td>
<td>35</td>
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<tr>
<td>Low temperature storage</td>
<td>Pre-cooling</td>
<td>1 ~ 6</td>
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<tr>
<td>agriculture</td>
<td>Cooling &amp; washing for milking process</td>
<td>0 ~ 4, 40 ~ 60</td>
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<tr>
<td></td>
<td>Mushroom cultivation</td>
<td>13 ~ 20</td>
<td></td>
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<td></td>
<td>Temperature control for slop culture</td>
<td>15 ~ 25</td>
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<tr>
<td></td>
<td>Greenhouse cultivation</td>
<td>18 ~ 32</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Dehumidifier cultivation</td>
<td>20 ~ 23</td>
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<tr>
<td></td>
<td>Heating for stock breeding</td>
<td>20 ~ 30</td>
<td></td>
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<tr>
<td></td>
<td>Egg incubation</td>
<td>36 ~ 38</td>
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</tr>
</tbody>
</table>


Source: NT Japan | Annex 48

International Workshop on High Temperature Heat Pumps 22 of 174
Problems of Practical Heat Usage in Factory

- **A large amount of low temperature heat is wasted.**

  Processes in a factory generate exhausted heat in different forms. All input energy in a factory is finally wasted as low level of heat.

- **Low effective use of steam boiler system**

  Practical steam supply system has nearly 50% of heat loss generated in processes of boiler, piping and drain.

- **Constant temperature of heat supply**

  Heat in a factory is used for heating, drying, washing, etc. at different heat levels. However, heat of constant temperature is supplied for those purposes.

- **Separate heat supply for heating and cooling**

  It is required for both heating and cooling in production processes. Different technologies are separately adopted for heating and cooling.
### Selection of Best Practices

<table>
<thead>
<tr>
<th>No</th>
<th>Industry</th>
<th>Process applied</th>
<th>Location</th>
<th>Year of installation</th>
<th>User (company)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Food</td>
<td>Heating/cooling</td>
<td>Hyogo</td>
<td>2010</td>
<td>Kosmos Food, co. Ltd</td>
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<tr>
<td>21</td>
<td>Machinery</td>
<td>Heating/cooling</td>
<td>Aichi</td>
<td>2010</td>
<td>Aishin A W, Ltd</td>
</tr>
<tr>
<td>43</td>
<td>Chemicals</td>
<td>Distillation/concentration</td>
<td>Hokkaido</td>
<td>–</td>
<td>Hokkaido Bioethno, Ltd</td>
</tr>
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<td>83</td>
<td>Food</td>
<td>Distillation/concentration</td>
<td>Kochi</td>
<td>2015</td>
<td>Muroto Deep Sea Water, Ltd</td>
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<tr>
<td>94</td>
<td>Machinery</td>
<td>Heating</td>
<td>Mie</td>
<td>2013</td>
<td>Fuji Electric co.Ltd</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>HP system</th>
<th>Refrigerant</th>
<th>Compressor type</th>
<th>Heating/cooling capacity (kW)</th>
<th>Supply temperature (°C)</th>
<th>Heat source/ heat sink</th>
<th>Savings energy (%)</th>
<th>Savings CO₂ emissions (%)</th>
<th>Savings energy cost (%)</th>
<th>Evaluation</th>
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<tbody>
<tr>
<td>Water-source hot water supply HP</td>
<td>CO₂</td>
<td>reciprocate</td>
<td>628</td>
<td>90</td>
<td>Simultaneous heating/cooling</td>
<td>–</td>
<td>84</td>
<td>87</td>
<td>80</td>
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<tr>
<td>Water-source HP chiller</td>
<td>R134a</td>
<td>screw</td>
<td>66</td>
<td>65</td>
<td>Simultaneous heating/cooling</td>
<td>40</td>
<td>80</td>
<td>80</td>
<td>79</td>
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<tr>
<td>Water-source steam supply HP</td>
<td>R245fa</td>
<td>roots</td>
<td>9,250</td>
<td>120</td>
<td>Exhausted heat of cooling tower</td>
<td>43</td>
<td>79</td>
<td>79</td>
<td>78</td>
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<tr>
<td>Mechanical vapor recompression</td>
<td>steam</td>
<td>reciprocate</td>
<td>–</td>
<td>70</td>
<td>Exhausted steam</td>
<td>46</td>
<td>40</td>
<td>46</td>
<td>78</td>
</tr>
<tr>
<td>Water-source steam supply HP</td>
<td>R245fa</td>
<td>reciprocate</td>
<td>30</td>
<td>120</td>
<td>Exhausted cooling water of cogeneration</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>55</td>
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</table>

### Case studies

**Source:** NT Japan  
Annex 48

### Best Practice 2 Outline

<table>
<thead>
<tr>
<th>ID</th>
<th>Annex</th>
<th>Installed Year</th>
<th>Industry</th>
<th>Processes</th>
<th>Application</th>
<th>Purposes</th>
<th>System</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>#21</td>
<td>35</td>
<td>2010</td>
<td>Machinery (Automobile Parts Production)</td>
<td>Cutting, Washing</td>
<td>Simultaneous Hot Water (65°C) and Cold Water (15°C) Supply</td>
<td>Reduction of Boiler Steam</td>
<td>Water-to-Water and Air-to-Water Heat Pumps (6+8=14 units)</td>
<td>CO₂ Reduction: 80%, Energy Cost Reduction: 79%</td>
</tr>
</tbody>
</table>
1.1. IEA HPT TP Annex 48: Heat Pump Application in commercial and industrial processes, Dr.-Ing. Rainer Jakobs (Information Centre on Heat Pumps and Refrigeration)

**Best Practice 2 System**

*Before*

- Cutting Process
- Washing Process
- Work
- Cutting Liquid 20°C
- Washing Liquid 60°C
- 30m Steam
- Chiller
- Boiler

*After*

- Cutting Process
- Washing Process
- Work
- Cutting Liquid 20°C
- Washing Liquid 60°C
- 15°C
- Boiler
- Steam
- Heat Pump

- Simultaneous heating & cooling heat pump was installed for heating of washing liquid and cooling of cutting liquid.
- Heating COP: 3, Cooling COP: 2, Total COP: 5
- Installing heat pump near process can reduce heat loss from piping.

---

**Best Practice 2 Operation**

*Simultaneous Heating & Cooling Operation Mode*

- 10°C
- 15°C
- 60°C
- 65°C
- Evaporator
- Compressor
- Condenser

*Cooling Operation Mode*

- 10°C
- 15°C
- 65°C
- Evaporator
- Compressor
- Condenser

*Heating Operation Mode*

- 50°C
- 65°C
- Evaporator
- Compressor
- Condenser

- Switching operation modes can cope with unbalance between heating and cooling demands.
1.1. IEA HPT TP Annex 48: Heat Pump Application in commercial and industrial processes, Dr.-Ing. Rainer Jakobs (Information Centre on Heat Pumps and Refrigeration)

Best Practice 2: Effects

- CO₂ Emission
  - 80% reduced
  - 1,094 tons/year reduced

- Primary Energy Consumption
  - 84% reduced
  - 437 kL/year reduction
    (Fuel oil equivalent)

- Energy Cost
  - 79% reduced
  - 26 million JPY/year

- Payback Period
  - 3.5 years

Best Practice 1: Outline

<table>
<thead>
<tr>
<th>ID</th>
<th>#2</th>
<th>Annex</th>
<th>35</th>
<th>Installed Year</th>
<th>2010</th>
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</thead>
<tbody>
<tr>
<td>Industry</td>
<td>Food (Freeze-Dried Foods Production)</td>
<td></td>
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</tr>
<tr>
<td>Processes</td>
<td>Food Processing, Sterilization, Washing, Building Air-Conditioning</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Application</td>
<td>Simultaneous Hot Water (90°C) and Cold Water (10°C) Supply</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purposes</td>
<td>Renewal of Facilities, Energy Saving, Energy Cost Reduction</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>System</td>
<td>Water-to-Water Heat Pumps (3 units)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refrigerant</td>
<td>CO₂ (Trans-critical Cycle), Heating Capacity: 80kW/unit</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Effects</td>
<td>CO₂ Reduction: 87%, Energy Cost Reduction: 80%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Payback Period: within 5 years (estimated)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Case studies*
Applying Heat Pump Technology to Agricultural Production *

Industry: Fruit Cultivation  
Process: Green House Air-conditioning  
Application: Space Heating in Winter and Space Cooling in Summer  
Purpose: Reduction of Fuel Heavy Oil in Winter and Air-conditioning in Summer  
System overview: Air-to-Air Inverter-controlled Greenhouse Heat Pumps using R410A (7 Units) with Heating Capacity 18 kW (20 °C) and Cooling Capacity 16 kW (27 °C) , Twin Type 6 Sets and Single Type 1 Set  
Effect: Primary energy consumption was reduced by 49%.

<table>
<thead>
<tr>
<th>Type</th>
<th>Twin</th>
<th>Single</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Indoor Units</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Cooling (Standard) COP</td>
<td>5.48</td>
<td>3.86</td>
</tr>
<tr>
<td>Heating (Standard) COP</td>
<td>5.50</td>
<td>4.90</td>
</tr>
<tr>
<td>Heating (Cold climate) COP</td>
<td>3.77</td>
<td>3.20</td>
</tr>
</tbody>
</table>

Cross sectional view of a greenhouse


Case studies Choyu WATANABE et al ; IEA HPP Workshop, HPC2014 in Montreal, Canada

CO₂ Heat Pump Air Heater for Drying Process *

Industry: Laminate Printing  
Process: Drying, Cooling  
Application: Hot Air Supply to Drying Zone and Cool Water Supply to Cooling Roller  
Purpose: Reduction of Steam (Fuel Gas)  
System Overview: Water-source Heat Pump Using CO₂ Refrigerant (1 Unit) for Hot Air Supply with Heating Capacity 110 kW, Operating Range of Hot Air Leaving Temperature 80 to 120 °C and That of Heat Source Water Entering Temperature 5 to 32 °C, COP

Total COP: 5.9

Reciprocating-type compressor

Heating air: from 20 to 100 °C  
Heating Capacity: 110 kW  
Heating COP: 3.4

Cooling water: from 30 to 25 °C  
Cooling Capacity: 81 kW,  
Cooling COP: 2.5

Total COP: 5.9


Case studies Choyu WATANABE et al ; IEA HPP Workshop, HPC2014 in Montreal, Canada
Summary

- Heat pumps can provide high temperatures up to 100 °C at large heating capacities (several MW).
- Industrial heat pump systems reach payback times between 2 and 7 years.
- Heat pumps become especially economical feasible, when both hot and cold side are used.
- Heat pumps are ready for the industry!

Barriers and threats:
- Insufficient knowledge about industrial processes among HVAC planners.
- Rising electricity prices (e.g. in Germany), while gas and oil prices remain stable or decrease.

Outlook

- Main Goal of the new HPT-Annex 48 is to overcome difficulties and barriers for the market introduction of industrial heat pumps.
- Collected cases studies of industrial branches with a large potential, should be analyzed.
- Development of a web based information platform for heat pumps in industrial and commercial application.
- Creating information material for IHP (training) courses.
- The IHP potential for more efficient use of energy and reduction of greenhouse gas emission should be prepared for policy makers.
Many thanks for your kind attention

Herzlichen Dank für Ihre freundliche Aufmerksamkeit

24 - 25 October 2017 // Nuremberg

https://www.hp-summit.de/
High Temperature Heat Pumps in Dutch Industry
Market Potential and Challenges in Implementation

Andrew Marina
International Workshop on High Temperature Heat Pumps - Copenhagen
11th September, 2017

Presentation Outline

- Industrial Energy use in the Netherlands
- Requirement for active heat recovery technologies (heat pumps) in industrial processes
- Results of industrial heat pump market study
- Challenges in implementing heat pumps in practice
• Requirement for a transition to a sustainable energy system
  – Move away from our reliance on fossil fuels
• Sustainable energy system can be achieved through a combined approach:
  – Transition to renewable energy sources - Wind, solar, etc.
  – Reductions in final energy consumption (FEC) through energy efficiency measures

Introduction

80% of the final industrial energy use is used for heating purposes

**Industrial Energy Usage & Case for Heat Pumps**

**Final Energy Consumption**

- Industry: 597 PJ (29%)
- Transport: 836 PJ (41%)
- Residential: 598 PJ (29%)
- Services: 598 PJ (29%)
- Agriculture: 598 PJ (29%)

**Industry**
- Metal
- Chemical
- Paper
- Food and Beverage

**Transport**
- Rail
- Cars
- Aviation
- Shipping

**Other Sectors**
- Residential
- Services
- Agriculture
Dutch Industry

- Final energy consumption
  - 597 PJ

- Energy use dominated by selected sectors
  - Chemical and petrochemical
  - Iron and steel
  - Food and beverage

- Refinery sector is the additional piece of the pie
  - Similar processes to the chemical sector

- Total combined energy consumption
  - 744 PJ

Transitioning to Sustainable Energy Sources

Current Industrial Energy Mix (Incl. Refinery)

- Share of renewables in electricity system growing at greater rate than heating system
- Increasing shares of renewable electricity enable alternate heating technologies
Utilising Waste Heat in Industry

- **Heat** is the primary driver for a number of industrial processes
  - Low temperature after use in the process → heat is discarded to ambient

- **Waste heat** is an untapped energy source
  - Recovery can lead to large reductions in primary energy consumption

- **Technologies for waste heat recovery** – Active or Passive:
  - **Passive**: Heat is reused directly in the process
  - **Active**: Heat is converted to a higher temperature or another form of energy (electricity, cold)

- **Limits to the amount of passive heat recovery**
  - Industrial processes designed for passive reuse of waste heat
  - Elaborate heat exchanger networks

- **Integration of active technologies is essential to fully exploit the potential for waste heat in industry**

Heat Pumps in Industrial Processes

- **Heat pump** is an active technology able to upgrade the temperature of a waste heat source with electrical energy input
  - Performance limited by thermodynamic laws:
    \[
    \text{COP}_{\text{THEORETICAL}} = \frac{T_{\text{Sink}}(K)}{T_{\text{Sink}}(K) - T_{\text{Source}}(K) - \frac{\dot{Q}_{\text{Sink}}}{W_{\text{IN}}}}
    \]

- **Growing drivers for the implementation for heat pumps**
  - Take advantage of renewable electricity and waste heat
  - Electrical input a factor of 2 – 5 lower than process heat output
  - Falling CAPEX
  - Increases in technology development
  - Ability to operate a high temperatures
  - Low payback times
Heat Pump in Industrial Process

- Assumptions → 8000 hr/y, PEF 2.5
  - Reduction in FEC – 122 TJ
  - Reduction in PEC – 68 TJ
- Further assumptions → Steam price 20 €/tonne, Elec. price 50 €/MWhr
  - Reduction in OPEX costs – 0.7 M€/y

Process Heat Demand
Dutch Industry

- Heat pumps well suited to deliver process heat temperature below 200°C
  - Paper and pulp industry (25 PJ)
  - Food and beverage industry (83 PJ)
  - Chemical industry (282 PJ)
  - Refinery industry (147 PJ)
- Focus on these sectors within market studies
  - 72% of the industrial energy usage
  - Heat <200°C accounts for approximately 194 PJ
  - 36% of energy consumption in these sectors, 26% of total industrial consumption
Determining the Heat Pump Market Methodology

- Bottom up approach for determining the heat pump market
- Focus on sectors which have high heating requirements at $T < 200^\circ C$
- Collate generalized information from processes within these industries
  - Partial process heat and waste heat information
  - Temperature levels
  - Heat quantities
  - Media contained
  - Focus on heat streams suitable for heat pump utilization
  - Determine typical production rates and operating hours for processes
- Couple with production statistics from PRODCOM or industry bodies
- Verification utilizing top down approach
  - Energy usage statistics - EUROSTAT

Case Study – Heat Pump Assisted Distillation Column

- Production of Styrene through the dehydrogenation of ethylbenzene
  - Energy usage of approx. 11 PJ in NL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reboiler Temperature</td>
<td>102°C</td>
</tr>
<tr>
<td>Condenser Temperature</td>
<td>45°C</td>
</tr>
<tr>
<td>Pinch Temperature</td>
<td>90°C</td>
</tr>
<tr>
<td>Reboiler Duty</td>
<td>2.2 GJ/tonne</td>
</tr>
<tr>
<td>Condenser Duty</td>
<td>1.7 GJ/tonne</td>
</tr>
<tr>
<td>Typical Plant Capacity</td>
<td>200 kT/a</td>
</tr>
<tr>
<td>Columns in NL</td>
<td>5</td>
</tr>
</tbody>
</table>

- Calculation of the thermal performance through
  - Estimation based on Carnot limitations
  \[
  \text{COP}_{\text{THEORETICAL}} = 0.5 \frac{T_{\text{SINK}}(K)}{T_{\text{SINK}}(K) - T_{\text{SOURCE}}(K) - W_{\text{IN}}} \frac{Q_{\text{SINK}}}{W_{\text{IN}}}
  \]

<table>
<thead>
<tr>
<th>COP</th>
<th>Reduction in FEC (PJ)</th>
<th>Reduction in PEC (PJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3</td>
<td>1.62</td>
<td>0.56</td>
</tr>
</tbody>
</table>

- Total in database - 57 distillation columns in chemical industry covering manufacture of 19 chemical products
NL Heat Pump Market Overview

- Overview of the NL industrial heat pump market can be achieved through use waste heat and process heat signatures and quantities
- Key parameters:
  - HP evaporator (source) temperature
  - HP condenser (sink) temperature
  - HP thermal output power
- Key figures:
  - Total cumulative potential: 2.4 GW
  - Number of individual applications: 108
  - Total possible heat pump installations: 340
  - Average condenser power: 7.0 MW
  - Reduction in FEC/PEC: 45 PJ / 15 PJ

Challenges in Implementation

1.2. High temperature heat pumps in Dutch industry: Market potential and challenges in implementation, A. J. Marina (ECN)
Challenging Economics

- Low cost of energy as well as process utility equipment makes economics for heat pumps challenging
  - Cost target of <200 €/kWth for heat pumps to be competitive
- Previous example:
  - 5 MWth
  - Cost saving 0.7 M€/year
  - Payback time of 3 years → CAPEX = 210 €/kWth
- Differing temperature conditions and thermal powers lead to differing business cases
  - Average condenser power of 7 MW
  - Higher frequency of occurrences of lower power machines → More challenging economics
- What about integration costs?
  - Limited electrical infrastructure on-site
  - No standard method for integration

Other Challenges

- Perceived risks as emerging technology
- Coupling to existing heat integrated plants
- Conservative energy efficiency targets
  - Limited subsidies for energy efficiency compared to renewable energy
  - Focus on process equipment or process techniques
- Energy is not the core business
  - But... changing due to customer demands
- Competing technological options
  - Government intervention
Summary

- Large industrial sector in the Netherlands
  - Energy use dominated by chemical, iron and steel, food and beverage and refinery sectors

- Growing driver for heat pumps in industry
  - Take advantage of renewable electricity generation and waste heat from processes
  - Suitable for delivering process heat temperatures up to 200°C

- Utilized a bottom up approach to determine the industrial heat pump market in NL
  - Potential 2.4 GW installed capacity over 340 installations

- Industrial heat pumps face a number of challenges preventing implementation
  - High capital costs combined with low energy prices
  - Perceived technology risk and conservative energy efficiency targets

Contact

Andrew Marina
Thermal Systems Researcher
E: marina@ecn.nl
T: +31 88 515 4408

ECN
Westerduinweg 3, P.O. Box 1,
1755 LE, Petten, 1755 ZG, Petten,
The Netherlands The Netherlands

www.ecn.nl
1.3. Energy demand in the Norwegian industry and possibilities for high temperature heat pumps, Michael Bantle (SINTEF)
1. What is a high temperature for an industrial heat pump?

Non-representative questionnaires:

- Condensation at 80°C → TRL 8 – 9
- Condensation at 100°C → TRL 6 – 8
- Condensation at 120°C → TRL 6 – 7
- Condensation at 150°C → TRL 4 – 6

Conclusion (for today): heat sink temperature above 100°C can be considered as high temperature heat pumps (higher as industrial standard)

1. A HTHP also requires a relative high temperature heat source (< 100 °C) → valuable heat from downstream processes
2. A industrial HTHP is a system integration in one or more processes and creates dependencies
2. Energy Demand in Norway

**Overall energy use and cost for Norwegian industry**

- Industry locations well distributed all over Norway
- Industry often located in places without high external heat demand

*Location and name of the largest energy-intensive industries in Norway per 2012*

*Ref: Energiintensiv industri - En beskrivelse og økonomisk analyse av energiintensiv industri i Norge. NVE - Norges vassdrags- og energidirektorat; 2013*
1.3. Energy demand in the Norwegian industry and possibilities for high temperature heat pumps, Michael Bantle (SINTEF)

2. Energy Demand in Norway

Based on total energy use, not total heat demand
=> Slightly over-estimated

Percentage of energy demand

2. Energy Demand in Norway

The energy above 100°C is quite often supplied in the form of steam

Based on total energy use, not total heat demand
=> 10 000 GWh

2. Steam based energy demand in USA

<table>
<thead>
<tr>
<th>Sector</th>
<th>On-site steam generation (TWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic, glass and cement</td>
<td>50</td>
</tr>
<tr>
<td>Basic metals</td>
<td>100</td>
</tr>
<tr>
<td>Manufacture of textiles, fabricated metals, machinery and manufacturing n.e.c.</td>
<td>150</td>
</tr>
<tr>
<td>Food and beverage</td>
<td>200</td>
</tr>
<tr>
<td>Paper and wood products</td>
<td>300</td>
</tr>
<tr>
<td>Refined petro. and chemicals</td>
<td>400</td>
</tr>
</tbody>
</table>

Based on total energy use, not total heat demand
=> 10 000 GWh
### 3. Excess heat inventory in Norway

#### From reporting industries only

<table>
<thead>
<tr>
<th>Industry</th>
<th>Reported energy use (TWh/year)</th>
<th>Reported waste heat</th>
<th>Waste heat as steam (GWh/year)</th>
<th>Waste heat vs. energy use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacture of food products, beverages</td>
<td>0.5</td>
<td>14.4 %</td>
<td>18 %</td>
<td>13</td>
</tr>
<tr>
<td>Wood, wood products and paper products</td>
<td>11.2</td>
<td>44.2 %</td>
<td>4 %</td>
<td>198</td>
</tr>
<tr>
<td>Cement and building block processing</td>
<td>1.9</td>
<td>45.4 %</td>
<td>0 %</td>
<td>0</td>
</tr>
<tr>
<td>Chemistry</td>
<td>2.0</td>
<td>158.1 %</td>
<td>6 %</td>
<td>190</td>
</tr>
<tr>
<td>Aluminium</td>
<td>18.5</td>
<td>12.0 %</td>
<td>0 %</td>
<td>0</td>
</tr>
<tr>
<td>Basic metals</td>
<td>8.3</td>
<td>57.8 %</td>
<td>3 %</td>
<td>144</td>
</tr>
</tbody>
</table>

Based on an average steam price of 0.29 NOK/kWh (SSB, 2008) and the total reported waste heat as steam (545 GWh in 2008)

- Reported waste heat as steam represents a loss of about 158 MNOK for the 72 participating Norwegian industries.
- 158 MNOK is about 10% of the district heating sales incomes in Norway in 2008

Generally underestimated:
- Not all Norwegian Industry
- Steam waste heat may be condensed and not reported

Ref: ENOVA / Norsk Energi / NEPAS, Utnyttelse av spillvarme fra norsk industry. 2009

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**International Workshop on High Temperature Heat Pumps**

44 of 174
4. Process most suited for HTHP
(Heat sink and source in the same process)

Chemical industry
- Distillation
- Compression
- Thickening

Food and Beverages
- Evaporation
- Cooking
- Pasteurisation
- Sterilisation
- Drying

Paper and Paper Products
- Bleaching
- Cooking
- Drying

Iron, Steel, Non-Ferrous / Fabricated metal
- Drying

4. Processes suited for HTHP

Assumptions
- Excess steam: 100°C and 1 bar
- Isentropic efficiency: 0.7
- Pressure ratio limitation: 2.5

Condensing temperature vs. Pressure ratio

COP vs. Condensing temperature

1 step - 2 steps - 3 steps
5. Return of Investment

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>Norway</td>
<td>Germany</td>
<td>Norway</td>
</tr>
<tr>
<td>Heat Sink °C</td>
<td>150</td>
<td>150</td>
<td>180</td>
</tr>
<tr>
<td>Heat Source °C</td>
<td>110</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>Pressure Outlet BarA</td>
<td>5.0</td>
<td>5.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Steam Flow Rate (kg/h)</td>
<td>2,000</td>
<td>2,000</td>
<td>2,000</td>
</tr>
<tr>
<td>Electrical Power (kW)</td>
<td>304</td>
<td>304</td>
<td>461</td>
</tr>
<tr>
<td>Heat Recovered (kWh)</td>
<td>1,430</td>
<td>1,430</td>
<td>1,552</td>
</tr>
<tr>
<td>COP (W/W)</td>
<td>4.70</td>
<td>4.70</td>
<td>3.36</td>
</tr>
<tr>
<td>ROI</td>
<td>+</td>
<td>++</td>
<td>-</td>
</tr>
</tbody>
</table>

Based on:
- electricity 0.15€/kWh Germany, 0.07€/kWh Norway;
- gas 0.04€/kWh Germany, 0.06€/kWh Norway.
Conclusion

1. High temperature heat pumps start at heat sink temperature of 100°C
   a. Technical limitations above 200°C
2. Food, Paper, Chemical and Metal industry have energy demands within this temperature limits
   a. Potential for Norway: estimated 10 TWh could be supplied by HTHP
   b. Reasonable to assume that 20% of this potential is feasible
3. Currently this energy is primarily supplied by steam (produced by fossil fuel)
   a. HTHP are benchmarked against fossil fuel prices
4. HTHP should supply heat sink in the form of steam
   a. Interesting technology for several industries which are using steam as energy carrier
5. Available excess heat is not completely monitored and “missing”
6. Identified some “ideal” processes for HTHP where heat sink and heat source are from one process
7. CAPEX and Return of investment give requirements for COP and costs:
   a. COP > 4 (→ challenging in many ways, depending on energy prices)
   b. Investment < 100-200 €/kWinstalled (at least have the potential at TRL 8-9)

Thank you for your attention
1.3. Energy demand in the Norwegian industry and possibilities for high temperature heat pumps, Michael Bantle (SINTEF)
1.4. Energy demand and excess heat of industrial processes in Denmark, Fabian Bühler (DTU)

**Industrial energy demand and excess heat in Denmark**

Fabian Bühler, Benjamin Zühlsdorf and Brian Elmegaard

International Workshop on High Temperature Heat Pumps
September 2017 in Copenhagen, Denmark

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**Introduction**

**Motivation**

Process heat requirements in the industry and availability of excess heat for the internal and external recovery (using heat pumps).

**Approach**

- Energy use in Denmark
- Energy saving obligations in Denmark
- Process heat demand in the manufacturing industry
- Profile and availability of industrial excess heat
- Some conclusions for (high temperature) heat pumps
1.4. Energy demand and excess heat of industrial processes in Denmark, Fabian Bühler (DTU)

Energy use in the Denmark

- Share of industry in total energy use [%]
- Energy use in industry [PJ]

Utility services 30.30%
Agriculture, forestry and fishing 1.61%
Construction 1.28%
Mining and quarrying 1.51%

Energy Savings in Denmark

Since 2006: Network and distribution companies have obligation to realize energy saving projects at end users

Last agreement: 10.1 PJ/year in the period 2016-2020

Since 2017: Heat pumps for district heating included

In 2015: 43 % of the savings obtained in manufacturing industry

J.nr.2017-3329.
Energy and exergy analysis

Exergy flows [TJ] for thermal process heating in the Danish industry

Heating demand in Denmark

- Total energy use 108.7 PJ/year
- District Heating Demand of 96 PJ/year
  - 2.6 PJ covered by excess heat
  - > 4.9 PJ coverable by industrial excess heat
Industrial excess heat in Denmark

- Total of 212 PJ of excess heat per year
- 23% of excess heat from industry and 28% from utility
- Total excess heat in manufacturing industry 22.6 PJ/year

- Drying, Evaporation and refrigeration main excess heat sources
- Highest temperatures from furnaces, boilers and melting operation

Evaluation of utilization pathways

<table>
<thead>
<tr>
<th>Industry</th>
<th>External Utilisation</th>
<th>ORC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utility</td>
<td></td>
<td>Electricity</td>
</tr>
<tr>
<td>Buildings</td>
<td></td>
<td>Heat Pump</td>
</tr>
<tr>
<td>Construction</td>
<td></td>
<td>DH or Process</td>
</tr>
<tr>
<td>Off-Shore (Oil and Gas)</td>
<td></td>
<td>Direct</td>
</tr>
<tr>
<td>Transport (Road and Shipping)</td>
<td></td>
<td>LTDH</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Internal Utilisation</th>
<th>Abs. Cooler</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cooling</td>
</tr>
<tr>
<td></td>
<td>ORC</td>
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<tr>
<td></td>
<td>Electricity</td>
</tr>
<tr>
<td></td>
<td>Heat Pump</td>
</tr>
<tr>
<td></td>
<td>Process Heat</td>
</tr>
<tr>
<td></td>
<td>Direct</td>
</tr>
<tr>
<td></td>
<td>Room Heat</td>
</tr>
</tbody>
</table>
1.4. Energy demand and excess heat of industrial processes in Denmark, Fabian Bühler (DTU)
1.4. Energy demand and excess heat of industrial processes in Denmark, Fabian Bühler (DTU)

**Spatial-analysis of excess heat**

- Spatial and temporal analysis of the 22 largest manufacturing industries with 2584 production units.

**Identifying heating symbiosis**

- Excess heat potential from
  - Industry (2500)
  - Power plants (1200)
  - Waste water treatment (100)
- Heating demand in District heating areas (222) and industry
High Temperature Heat Pumps

Internal vs. external utilization
- Potential to use excess heat in district heating
- Internal recovery potential in industries requires more detailed site-specific process knowledge

Demand and Excess heat mapping
- Potential for heat pumps in district heating
- Temperature profiles of heating demand and excess heat indicate potential for HTHP
- Excess heat size on site level suggests large potential in HP 10-50 kW

More research on potentials required
- Which part of heating demand is covered by steam/water/direct heat?
- Recovery potential in the different processes itself?

Thank you for your attention!

Fabian Bühler
PhD Student
DTU Mechanical Engineering
Email fabuhl@mek.dtu.dk
Phone +45 22471020
2 Research and Development Projects

2.1 Review on high temperature heat pumps – Market overview and research status, Cordin Arpagas (NTB Buch)

2.2 High temperature heat pump development at AIT, Michael Lauermann (AIT)

2.3 Generic fist assessment tool and high temperature heat pump development at DTI, Lars Reinholdt (DTI)

2.4 Development of a Propane-Butane cascade high temperature heat pump, Opeyemi Bamigbetan (NTNU)

2.5 Working fluids for high temperature heat pumps, Benjamin Zühlsdorf (DTU)
2.1. Review on high temperature heat pumps – Market overview and research status, Cordin Arpagaus (NTB Buch)

Outline

1. Market overview of commercially available industrial HTHP systems
   • Cycles, refrigerants, application limits, efficiencies

2. Research status
   • Screening of research activity
   • Experimental and theoretical studies, cycles, refrigerants, supply temperatures, operating ranges

3. Refrigerants
   • Selection criteria, properties, GWP, price, efficiency, safety

4. Conclusions
2.1. Review on high temperature heat pumps – Market overview and research status, Cordin Arpagaus (NTB Buch)

Classification of heat pumps (focus on compression heat pumps)

Development of temperature levels

adapted from Nellissen and Wolf (2015)

Potential for high temperature heat pumps – Process heat in industry

Theoretical potential for HTHPs in Switzerland

Technical potential of process heat in Europe accessible with industrial heat pumps

Overview of processes in different industrial sectors
Temperature levels and technology readiness level

<table>
<thead>
<tr>
<th>Sector</th>
<th>Process</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>Drying</td>
<td>100 - 250</td>
</tr>
<tr>
<td></td>
<td>Bleaching</td>
<td>150 - 200</td>
</tr>
<tr>
<td></td>
<td>De-inking</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulp &amp;</td>
<td>Drying</td>
<td>40 - 250</td>
</tr>
<tr>
<td></td>
<td>Blending</td>
<td>40 - 100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical</td>
<td>Compression</td>
<td>110 - 110</td>
</tr>
<tr>
<td></td>
<td>Distillation</td>
<td>130 - 140</td>
</tr>
<tr>
<td></td>
<td>Concentration</td>
<td>130 - 140</td>
</tr>
<tr>
<td></td>
<td>Boiling</td>
<td>80 - 110</td>
</tr>
<tr>
<td></td>
<td>Evaporation</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sector</th>
<th>Process</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food</td>
<td>Drying</td>
<td>40 - 250</td>
</tr>
<tr>
<td></td>
<td>Blending</td>
<td>40 - 100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood</td>
<td>Drying</td>
<td>40 - 100</td>
</tr>
<tr>
<td></td>
<td>Blending</td>
<td>40 - 100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Technology Readiness Level (TRL): 1 = Laboratory research, 6 = commercial available, HP 70 – 100°C, key technology prototype status, technology development, HTMP 90°C, 140°C commercial available

Data sources:

Selection of industrial HTHPs with supply temperatures > 90°C

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Product</th>
<th>Refrigerant</th>
<th>Max. supply capacity [kW]</th>
<th>Heating capacity [kW]</th>
<th>Compressor type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kobelco (Steam Grow Heat Pump)</td>
<td>SGH 185, SGH 120, HEM HR00, HEM 90A</td>
<td>R134a/5R2254a/5R245fa</td>
<td>120°C 190°C</td>
<td>70 – 600 kW, 70 – 370 kW</td>
<td>Double screw</td>
</tr>
<tr>
<td>Vicking Heating Engines AS</td>
<td>HeatMaster</td>
<td>R134a/R245fa, R134a/R245fa</td>
<td>150°C</td>
<td>28 – 188 kW</td>
<td>Piston</td>
</tr>
<tr>
<td>Ochsner</td>
<td>IWDS</td>
<td>R134a/OkK10/30 (R245fa)</td>
<td>130°C 95°C</td>
<td>170 – 750 kW, 100 – 320 kW</td>
<td>Screw</td>
</tr>
<tr>
<td>Hybrid Energy</td>
<td>Hybrid Heat Pump</td>
<td>R717 (NH3)</td>
<td>120°C</td>
<td>0.5 – 25 MW</td>
<td>Piston</td>
</tr>
<tr>
<td>Mayekawa</td>
<td>Eco Solano, Eco Cube Uno</td>
<td>R744 (C02), R744 (C02)</td>
<td>120°C 90°C</td>
<td>65 – 90 kW, 45 – 110 kW</td>
<td>Screw</td>
</tr>
<tr>
<td>Dürr Thermae</td>
<td>Therma2</td>
<td>R744 (C02)</td>
<td>110°C</td>
<td>45 – 2200 kW</td>
<td>Piston</td>
</tr>
<tr>
<td>Combitherm</td>
<td>Sonderanfertigung</td>
<td>R245fa</td>
<td>100°C</td>
<td>20 – 300 kW</td>
<td>Piston</td>
</tr>
<tr>
<td>Fritscher</td>
<td>Unitop 55, Unitop 60</td>
<td>R134a, R134a</td>
<td>50°C 90°C</td>
<td>5 – 20 MW</td>
<td>Turbo (2-stage)</td>
</tr>
<tr>
<td>Star Refrigeration</td>
<td>Neopump</td>
<td>R717 (NH3)</td>
<td>90°C</td>
<td>0.35 – 15 MW</td>
<td>Screw</td>
</tr>
<tr>
<td>GEA Refrigeration</td>
<td>GEA Grasso FX P 63</td>
<td>R717 (NH3)</td>
<td>90°C</td>
<td>2 – 4.5 MW</td>
<td>Double screw</td>
</tr>
<tr>
<td>Johnson Controls</td>
<td>HeatPAC HPX, HeatPAC Screw</td>
<td>R717 (NH3), R717 (NH3)</td>
<td>90°C 90°C</td>
<td>326 – 1324 kW, 230 – 1315 kW</td>
<td>Piston, Screw</td>
</tr>
<tr>
<td>Mitsubishi</td>
<td>ETW-L</td>
<td>R134a</td>
<td>90°C 90°C</td>
<td>340 – 600 kW</td>
<td>Turbo (2-stage)</td>
</tr>
<tr>
<td>Viessmann</td>
<td>Vitocal 350-HT Pro</td>
<td>R134a</td>
<td>90°C</td>
<td>148 – 223 kW</td>
<td>Piston (2-stage)</td>
</tr>
</tbody>
</table>
2.1. Review on high temperature heat pumps – Market overview and research status, Cordin Arpagaus (NTB Buch)

Industrial HTHPs – Heating capacities vs. achievable supply temperatures

<table>
<thead>
<tr>
<th>Max supply temperature [°C]</th>
<th>Heating capacity [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>165°C</td>
<td>100,000</td>
</tr>
<tr>
<td>150°C</td>
<td>10,000</td>
</tr>
<tr>
<td>130°C</td>
<td>1,000</td>
</tr>
<tr>
<td>120°C</td>
<td>100</td>
</tr>
<tr>
<td>110°C</td>
<td>10</td>
</tr>
<tr>
<td>100°C</td>
<td>1</td>
</tr>
<tr>
<td>95°C</td>
<td>0.1</td>
</tr>
<tr>
<td>90°C</td>
<td>0.01</td>
</tr>
</tbody>
</table>

- **Kobelco SGH 165**
- **Vicking Heat Booster**
- **Ochsenner IWWDS**
- **Hybrid Energy AS**
- **Kobelco SGH 120**
- **Mayekawa Eco Sirocco**
- **Our Thermea thermeco2**
- **Ochsenner IWWDS 330 ER3**
- **Combitherm**
- **Trioterm Unitorp 22**
- **Ochsenner IWHS ER3**
- **Flioterm Unitorp 50**
- **Johnson Controls Titan OM**
- **GEA Grasso FXP 63 bar**
- **Mitsubishi ETW-L**
- **Johnson Controls HPX**
- **Johnson Controls Screw**
- **Viessmann Vitoval 350-HT Pro**
- **Kobelco HEM-HR90, HEM-90A**
- **Mayekawa Eco Cute Unimo**

Commercial HTHPs – cycles, COPs and pictures

- **Kobelco SGH 120 / 165**
  - (IEA, 2014a; Kaida et al., 2015; Kuronoki, 2012; Watanabe, 2013)
  - $T_r/T_m (\alpha(T_m))$ COP 3.2

- **Mayekawa transcritical CO₂ heat pump Eco Sirocco**
  - (IEA, 2014a; Mayekawa, 2010; Watanabe, 2013)
  - $T_r/T_m (\alpha(T_m))$ COP 2.9

- **Ochsenner IWHS 460 ER3 screw compressor, 380 kW**
  - (Ochsenner, 2015)
  - $T_r/T_m (\alpha(T_m))$ COP 4.6

- **Ochsenner IWWDS 330 ER3 screw compressor, 312 kW**
  - (Ochsenner, 2015)
  - $T_r/T_m (\alpha(T_m))$ COP 2.65

- **Hybrid Heat Pump**
  - (Jensen et al., 2015a, 2015b)
  - $T_r/T_m (\alpha(T_m))$ COP 2.8

- **Thermea HHR1000 with 6 piston compressors, up to 1100 kW**
  - (Osthermea GmbH, 2016; IEA, 2014a; Thermea, 2012)
  - $T_r/T_m (\alpha(T_m))$ COP 3.5
2.1. Review on high temperature heat pumps – Market overview and research status, Cordin Arpagaus (NTB Buch)

Commercial HTHPs – cycles, COPs and pictures

Research status on HTHPs – Publications, projects, cycles, operating ranges

Cycles

COP vs. supply temperature

Average values:
COP = 3.9 ± 0.8
ΔTLift = 57 ± 15 K
2.1. Review on high temperature heat pumps – Market overview and research status, Cordin Arpagaus (NTB Buch)
2.1. Review on high temperature heat pumps – Market overview and research status, Cordin Arpagaus (NTB Buch)
Achieved COPs of experimental research projects vs. supply temperature at constant temperature lifts ($\Delta T_{\text{lift}}$)

Refrigerants for HTHPs

Selection criteria

Which refrigerants are suitable for HTHPs?

Refrigerant properties

Critical temperature vs. GWP

Safety

Efficiency
Refrigerants – selection criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Required properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal suitability</td>
<td>High critical temperature, low critical pressure</td>
</tr>
<tr>
<td>Environmental</td>
<td>ODP = 0, low GWP, short atmospheric life</td>
</tr>
<tr>
<td>Safety</td>
<td>Non-toxic, non-combustible (safety group A1)</td>
</tr>
<tr>
<td>Efficiency</td>
<td>High COP, low pressure ratio, minimal overheat to prevent fluid compression, high volumetric capacity</td>
</tr>
<tr>
<td>Availability</td>
<td>Available on the market, low price</td>
</tr>
<tr>
<td>Other factors</td>
<td>Good solubility in oil, thermal stability of the refrigerant-oil mixture, lubricating properties at high temperatures, material compatibility with steel and copper</td>
</tr>
</tbody>
</table>

Critical temperature vs. GWP

GWP <50  50 < GWP <1'000  GWP >1'000
### Refrigerants – properties

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>Description</th>
<th>Chemical formula</th>
<th>$T_c$ ($^\circ$C)</th>
<th>$P_c$ (bar)</th>
<th>ODP</th>
<th>GWP</th>
<th>SG</th>
<th>$M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-113</td>
<td>1,2,3,2-Trimethyl-1,2,2-trifluoromethane</td>
<td>CCl$_3$CF$_3$</td>
<td>314.0</td>
<td>33.9</td>
<td>0</td>
<td>1.0</td>
<td>A1</td>
<td>47.0</td>
</tr>
<tr>
<td>R-114</td>
<td>1,2,3,2-Tetrafluoro-1,2,2-trifluoromethane</td>
<td>OFCl$_2$OFCl</td>
<td>314.0</td>
<td>33.9</td>
<td>0</td>
<td>1.0</td>
<td>A1</td>
<td>47.0</td>
</tr>
<tr>
<td>R-134a</td>
<td>1,1,1,2-Tetrafluoroethane</td>
<td>CH$_2$FCF$_3$</td>
<td>301.3</td>
<td>45.6</td>
<td>0</td>
<td>0.0</td>
<td>B1</td>
<td>26.1</td>
</tr>
<tr>
<td>R-134b</td>
<td>1,1,1,2-Tetrafluoroethane</td>
<td>CH$_2$FCF$_3$</td>
<td>301.3</td>
<td>45.6</td>
<td>0</td>
<td>0.0</td>
<td>B1</td>
<td>26.1</td>
</tr>
<tr>
<td>R-124a</td>
<td>1,1,1,2-Tetrafluoroethane</td>
<td>CH$_2$FCF$_3$</td>
<td>301.3</td>
<td>45.6</td>
<td>0</td>
<td>0.0</td>
<td>B1</td>
<td>26.1</td>
</tr>
<tr>
<td>R-124b</td>
<td>1,1,1,2-Tetrafluoroethane</td>
<td>CH$_2$FCF$_3$</td>
<td>301.3</td>
<td>45.6</td>
<td>0</td>
<td>0.0</td>
<td>B1</td>
<td>26.1</td>
</tr>
<tr>
<td>R-125a</td>
<td>1,1,1,2-Tetrafluoroethane</td>
<td>CH$_2$FCF$_3$</td>
<td>301.3</td>
<td>45.6</td>
<td>0</td>
<td>0.0</td>
<td>B1</td>
<td>26.1</td>
</tr>
<tr>
<td>R-125b</td>
<td>1,1,1,2-Tetrafluoroethane</td>
<td>CH$_2$FCF$_3$</td>
<td>301.3</td>
<td>45.6</td>
<td>0</td>
<td>0.0</td>
<td>B1</td>
<td>26.1</td>
</tr>
<tr>
<td>R-224a</td>
<td>1,1,1,2-Tetrafluoroethane</td>
<td>CH$_2$FCF$_3$</td>
<td>301.3</td>
<td>45.6</td>
<td>0</td>
<td>0.0</td>
<td>B1</td>
<td>26.1</td>
</tr>
<tr>
<td>R-224b</td>
<td>1,1,1,2-Tetrafluoroethane</td>
<td>CH$_2$FCF$_3$</td>
<td>301.3</td>
<td>45.6</td>
<td>0</td>
<td>0.0</td>
<td>B1</td>
<td>26.1</td>
</tr>
</tbody>
</table>

**Notes:**
- **$T_c$** = critical temperature
- **$P_c$** = critical pressure
- **ODP** = Ozone Depletion Potential (R11=1.0)
- **GWP** = Global Warming Potential (CO$_2$=1.0, 100 years EU F-Gas regulation 517/2014)
- **SG** = Safety group (DIN EN 378-1, 2008, ASHRAE 34)
- **$M$** = Molecular weight

---

**2.1. Review on high temperature heat pumps – Market overview and research status, Cordin Arpagaus (NTB Buch)**
Theoretical studies – Efficiency range for 1-stage cycles with different refrigerants

\[ \Delta T_{\text{lift}}: \text{temperature lift} \]
\[ \Delta T_{\text{sh}}: \text{superheating} \]
\[ \Delta T_{\text{sc}}: \text{subcooling} \]
\[ \eta_{\text{comp}}: \text{isentropic compressor efficiency} \]

<table>
<thead>
<tr>
<th>Reference</th>
<th>( \Delta T_{\text{lift}} )</th>
<th>( \Delta T_{\text{sh}} )</th>
<th>( \Delta T_{\text{sc}} )</th>
<th>COP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fukuda et al. (2014)</td>
<td>5</td>
<td>20</td>
<td>10</td>
<td>3.5</td>
</tr>
<tr>
<td>Kortmann (2014)</td>
<td>5</td>
<td>5</td>
<td>0.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Brümmer (2015)</td>
<td>11</td>
<td>5</td>
<td>0.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Brümmer et al. (2016)</td>
<td>10</td>
<td>5</td>
<td>0.75</td>
<td>4.5</td>
</tr>
<tr>
<td>Pöllinger (2015)</td>
<td>5</td>
<td>5</td>
<td>0.5</td>
<td>5.0</td>
</tr>
<tr>
<td>Pöllinger et al. (2015)</td>
<td>5</td>
<td>5</td>
<td>0.5</td>
<td>5.0</td>
</tr>
<tr>
<td>Pöllinger et al. (2016)</td>
<td>20</td>
<td>5</td>
<td>0.8</td>
<td>7.0</td>
</tr>
<tr>
<td>Kortmann and Keyuma (2018)</td>
<td>5</td>
<td>60</td>
<td>1</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Possible concept for a HTHP laboratory prototype

**HFO refrigerants**

- **R1336mzz(Z)**: 171.3°C, 29.0 bar
- **R1233zd(E)**: 165.5°C, 36.2 bar
- **R1234ze(Z)**: 150.1°C, 35.3 bar
- **R1234yf**: 109.4°C, 36.4 bar, 94.7°C, 33.8 bar

**Decision criteria:**

1. Thermodynamic suitability \((T_{\text{crit}} > 150°C, \text{allows subcritical, good efficiency at high temperatures})\)
2. Environmental compatibility \((\text{GWP} < 10, \text{ODP} = 0, \text{future-proof according to F-Gas regulation})\)
3. Safety \((\text{no or only low flammability})\)
4. Natural refrigerants R600 and R600a excluded due to flammability \((A3)\), other refrigerants due to lack of information and availability
2.1. Review on high temperature heat pumps – Market overview and research status, Cordin Arpagaus (NTB Buch)

Conclusions – Market overview

- **More than 20 HTHP models** identified with supply temperatures > 90°C from 13 manufacturers (e.g. Vicking HeatBooster with 150°C, Ochsner IWWDS with 130°C, Kobelco SGH120, Mayekawa Eco Sirocco, and Hybrid Energy Heat Pump with 120°C)
- **Heat source**: water, brine, waste heat (17 to 65°C)
- **COP**: 2.4 to 5.8 at a temperature lift of 40 to 95 K
- **Heating capacity**: from about 20 kW to 20 MW
- **Refrigerants**: R245fa, R717 (NH3), R744 (CO2), R134a, R1234ze(E)
- **Compressors**: 1- and 2-shaft screws, 2-stage turbo, pistons (parallel)
- **Cycles**: usually 1-stage, optimization by IHX, parallel compressors, economizer, intermediate injection, 2-stage cascade (R134a/R245fa) or with a flash economizer

Conclusions – Research status

- **Highest supply temperature of 160°C** at AIT (Vienna), 1-stage cycle with IHX and R1336mzz(Z)
- **At least 10 research projects** reached > 100°C
- **Heating capacity**: lab scale 12 kW, larger prototypes >100 kW
- **COPs** (at 120°C supply temperature): 5.7 to 6.5 (30 K temperature lift), 2.2 to 2.8 (70 K)
- **Cycles all 1-stage**: partly with IHX and/or economizer with intermediate injection
- **Refrigerants**: R1336mzz(Z), R718 (H2O), R245fa, R1234ze (Z), R601, LG6 (Siemens), ÖKO1 (contains R245fa, Ochsner), ECO3 (R245fa, Alter ECO), HT125 (ILK, Dresden)
- **Compressors**: piston in lab systems
- **HFO refrigerants**: thermodynamic suitable, good efficiency, GWP <10, ODP = 0, safe, future-proof according to F-Gas regulation
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2.1. Review on high temperature heat pumps – Market overview and research status, Cordin Arpagaus (NTB Buch)

Barriers to the wider spread of industrial HTHPs

- **Low level of awareness** about the technical possibilities and application potentials among main actors
- **Lack of knowledge** about the integration into processes
- **Requirements of low payback times** (< 3 years)
- **Competing technologies** generating high temperatures using fossil fuels at low energy prices
- **Lack of available refrigerants** in the high temperature range with low GWP
- **Lack of pilot and demonstration systems**

*According to Fleckl et al. (2015), Hartl et al. (2016), IEA (2014), Jakobs et al. (2010), Noack (2016), Rieberer et al. (2014)*
2.2. High temperature heat pump development at AIT, Michael Lauermann (AIT)

HIGH TEMPERATURE HEAT PUMP DEVELOPMENT
at Austrian Institute of Technology GmbH

MICHAEL LAUERMANN
Research Engineer
Energy Department
Sustainable Thermal Energy Systems
Giefinggasse 2 | 1210 Vienna | Austria
T +43 50550-6414 | M +43 664 88390714 | F +43 50550-6679
michael.lauermann@ait.ac.at | http://www.ait.ac.at

AIT RESEARCH AREAS

Energy
- Sustainable Thermal Energy Systems
- Electric Energy Systems
- Sustainable Buildings and Glass
- Photovoltaic Systems
- Environmental Resources & Technologies

Health & Bioreources
- Bioreources
- Molecular Diagnostics
- Biomedical Systems
- Digital Health Information Systems

Digital Safety & Security
- Security & Communication Technologies
- Visual Surveillance and Insight
- Smart Sensor Solutions
- Dependable Systems Engineering
- Information Management

Vision, Automation & Control
- High-Performance Image Processing
- Autonomous Systems
- Complex Dynamical Systems

Mobility Systems
- Transportation Infrastructure Technologies
- Dynamic Transportation Systems

Low-Emission Transport
- Electric Drive Technologies
- Light Metals Technologies Ramshofen

Technology Experience
- Capturing / Measuring Experience
- Future Interface Paradigms
- Experience Oriented Thinking

Innovation Systems & Policy
- Digital Innovation
- Foresight & Institutional Change
- Policies for Change
MARKET TRENDS AND DEVELOPMENT NEEDS

- General Framework
  - Energy efficiency directive
  - Load flexibilisation
  - Reduction of energy requirements and CO₂ emissions
  - F-Gas regulation

- Industrial heat pump as market chance for Europe
  - 45% of industrial heat demand lower than 150°C
  - Relevant sectors: Food, Chemical, Pulp&Paper, Non metal mineral, Metals
  - Relevant processes: Pre-heating, Drying, Distillation, Evaporation, Cooking, Sterilisation, etc.
2.2 High temperature heat pump development at AIT, Michael Lauermann (AIT)

MOST USEFUL APPLICATIONS

Simultaneous Heating and Cooling

Industrial Drying

11.09.2017
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MOST USEFUL APPLICATIONS

Waste Heat Recovery

STATE OF THE ART & ONGOING RESEARCH - USEFUL TEMPERATURE ABOVE 80°C
THEMATIC DEVELOPMENT:
HIGH TEMPERATURE HEAT PUMP

2.2 High temperature heat pump development at AIT, Michael Lauermann (AIT)
HIGHBUTANE
Concept of a new butane high temperature heat pump

Motivation
- Industrial heating processes account for 25% of Austria’s final energy demand. An industrial heat pump lifting waste heat beyond 100 °C is needed to realize more efficient processes, thus reduce energy demand and CO2 emissions.

Aim
- Butane shall be used in a single-stage heat pump process to lift industrial waste heat from 60 °C to 130 °C. Heat exchangers will be evaluated with respect to the charge and system configurations of use cases will be developed and experimentally validated.

Highlights
- Identifying suitable processes
- Validated Dymola model
- Ejector utilisation
- CFD-heat & mass transfer
- Experimental

Results
- Performance increase with Ejector
- CFD model is being validated
- Potential cost saving of 300,000 EUR per year

HIGHBUTANE
Concept of a new butane high temperature heat pump

Results
- Pressure ratio: 1.3
- Entrainment ratio: 0.3
Motivation

- Industrial heating consumes a significant fraction of the energy consumed globally. Heating at temperatures higher than about 100 °C is predominantly provided through combustion of fossil fuels with uncertain prices and well recognized environmental impacts. A significant fraction of industrial input energy is lost as low temperature waste heat that could be lifted by high temperature heat pumps to process relevant temperatures.

Aim

- Validation of a novel high temperature refrigerant (DR-2) in process heat pumps with condensation temperatures up to 160 °C.

Highlights

- Novel high temperature refrigerant (DR-2)
- Lab scale heat pump
- Experimental analysis with condensation temperatures up to 155 °C
- Energetic and economic evaluation

Results

- Short term operation of a lab scale machine with a heating capacity of around 12kW.
- Experimental investigation of the coefficient of performance (COP) at different temperature levels.
- Economic evaluation including the CO2 savings potential for selected industrial applications.

Basic cycle

- Suction gas HX (IHX)

- COP vs. cooling temperature

- Basic cycle configuration

- Cycle with internal suction gas heat exchanger

- COP improvement with suction gas superheating
DRYPUMP
Efficient drying with heat pumps

Aim
- To solve substantial industrial research issues in the context of using compression heat pumps for industrial drying
- To achieve energy savings up to 80%, CO₂ emission savings up to 68% and primary energy savings up to 65% in the medium term

Highlights
- Large industrial applications
- Useful temperature up to 170 °C
- Heating capacity up to 350 kW
- Energy savings up to 80%

Results
- Development of technical viable concepts
- Experimental proof of concept of three heat pump installations
- Optimized discontinuous drying process

---

2.2. High temperature heat pump development at AIT, Michael Lauermann (AIT)
**2.2. High temperature heat pump development at AIT, Michael Lauermann (AIT)**

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**DRYFICIENCY**

**Efficient drying with heat pumps on industrial scale**

- Overall objective: to lead energy-intensive sectors of the European manufacturing industry to high energy efficiency and a reduction of fossil carbon emissions by means of waste heat recovery.
- Aim: consortium will elaborate technically and economically viable heat pump solutions for upgrading idle waste heat streams to process heat streams at higher temperature levels up to 180 °C and will demonstrate them in three industrial drying processes (brick, pet care/feed and food industry).
- Consortium:
  - RTOs: AIT (Michael Hartl): Lead, SINTEF
  - Technology providers and integrators: Rotrex, Bitzer Kühlmaschinenbau, Chemours Fluorchemicals, Fuchs Europe Schmierstoffe, EPCON
  - Demonstration partners: Wienerberger, Agrana, Mars Petcare
  - Dissemination exploitation partners: RTDS, EHPA
- Project volume: € 6,5 Mio. (EC Funding: € 5 Mio.)

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**SUMMARY**

- Heat Pumps are a mature technology. Carefully integrated, they are highly reliable and lifetime up to 40 years is proven.
- Heat Pumps for Industrial applications are still widely unknown.
- AIT works together with technology providers to bring high temperature heat pumps to the industry.
- DRYficiency will demonstrate high temperature heat pump solutions for drying processes.
2.2. High temperature heat pump development at AIT, Michael Lauermann (AIT)
Generic first assessment tool

Motivation

Postulate: Heat pumps are just “nice to have”

- The only purpose is heat supply in a more appropriate way (like cost (incl. taxes), CO₂ footprint, CSR, ...)
- They do not solve technical problems
  It is “all” about COP...
  (....and first cost, maintenance...)

- Many heat pump solutions exists
- A way to first assessment is needed...???
Heat pump COP and system design calculations

Theoretical limit: Carnot cycle

\[ \text{COP}_{\text{HP,Car}} = \frac{\theta}{\theta - \theta_L} \quad (\text{T in K}) \]

Constant temperature source and sink: 15/90°C > COP_C = 4.84

Higher COP by splitting up

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Higher COP by splitting up

<table>
<thead>
<tr>
<th>Process</th>
<th>$T_L$ [°C]</th>
<th>$T_H$ [°C]</th>
<th>COP$_{HP,stu}$ [-]</th>
<th>$Q_H$ [kW]</th>
<th>$P$ [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-a</td>
<td>35</td>
<td>90</td>
<td>6,60</td>
<td>1</td>
<td>0,1515</td>
</tr>
<tr>
<td>B-b</td>
<td>30</td>
<td>84</td>
<td>6,61</td>
<td>1</td>
<td>0,1513</td>
</tr>
<tr>
<td>C-c</td>
<td>25</td>
<td>78</td>
<td>6,62</td>
<td>1</td>
<td>0,1510</td>
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<tr>
<td>D-d</td>
<td>20</td>
<td>72</td>
<td>6,63</td>
<td>1</td>
<td>0,1507</td>
</tr>
<tr>
<td>E-e</td>
<td>15</td>
<td>66</td>
<td>6,65</td>
<td>1</td>
<td>0,1504</td>
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<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>0,7549</td>
</tr>
</tbody>
</table>

COP = 6,62 (+37%)

Lorenz COP

$COP_{HP,lor} = \frac{T_{lim,H}}{T_{lim,H} - T_{lim,L}}$

(+ 51%)

<table>
<thead>
<tr>
<th>No.</th>
<th>Heat source (°C)</th>
<th>Heat sink (°C)</th>
<th>COP$_C$</th>
<th>COP$_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ex.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>8 &gt; 4</td>
<td>85 &gt; 95</td>
<td>4,84</td>
<td>7,33</td>
</tr>
<tr>
<td>B</td>
<td>40 &gt; 15</td>
<td>60 &gt; 90</td>
<td>4,8</td>
<td>7,3</td>
</tr>
<tr>
<td>C</td>
<td>25 &gt; 20</td>
<td>70 &gt; 110</td>
<td>4,3</td>
<td>5,4</td>
</tr>
<tr>
<td>D</td>
<td>80 &gt; 20</td>
<td>85 &gt; 90</td>
<td>5,2</td>
<td>9,4</td>
</tr>
</tbody>
</table>

Theoretical maximum COP

![Graph showing the relationship between source outlet temperature and COP]
(First) system design calculation

Theoretical COP can be used for first assessment analysis of system design without knowing the heat pump technology.

Carnot and Lorenz efficiency:
- How good a real heat pump system is compared to theoretical maximum

\[ \eta_{Car} = \frac{COP_{HP}}{COP_{HP,Car}} \quad \eta_{Lor} = \frac{COP_{HP}}{COP_{HP,Lor}} \]

(First) system design calculation

- In the best industrial refrigeration systems 60\% of COP$_C$ have been realized, so high COP can also be expected by heat pumps...

\[ COP_{HP} = COP_{HP,Lor} \eta_{Lor} \quad > \quad COP_{HP,Lor} = \frac{COP_{HP}}{\eta_{Lor}} \]

Example:
- System requirement to the heat supply: 150°C
- Based on the precalculations (energy cost etc.) COP = 3.0 is needed.
- Using \( \eta_{Lor} = 60\% > \) \( COP_{HP,Lor} = \frac{3.0}{0.6} = 5 \)
Fundamental process analysis

Case:
- Sink: Heating from 35 to 80°C
- Source: Cooling from 25 to 15°C
- COP_C = 5.4, COP_L = 8.9

Pinch temperature 1K
- COP_C = 5.3 > -2.7%
- COP_L = 8.5 > -4.8%
2.3. Generic fist assessment tool and high temperature heat pump development at DTI, Lars Reinholdt (DTI)

Industrial heat pump development at DTI

- Flexible Energy Optimized Split Condenser Ammonia Heat Pump - Foscap
- Mixed Refrigerant Heat Pump - MiReHP
- Ultra-high temperature hybrid heat pump for process application - HighHeat
- Development of Rotrex turbocompressor for steam compression
- Experimental Development of Electric Heat Pumps in Greater Copenhagen District Heating System – SVAF 2
- Direct contact heat exchangers (water vapor, heat uptake at freezing)
- Projects on COP optimization of heat pump cycles
- Heat pumps and storage (hot and/or cold)

Development of ultra-high temperature hybrid heat pump for process application - HighHeat

Objective

- to increase the operating limits of the hybrid process by using the new standard components for higher pressures.
- demonstrate that it is possible to develop an efficient and reliable heat pump process for high temperatures up to 180-250°C.
- Investigation of possible implementation into the processes at the end users in the consortium and the conduction of a general market survey.
- Demonstration at an end user in the consortium.

Funded by the Danish EUDP program no. 64011-0351. Ends Dec 2018.
2.3. Generic fist assessment tool and high temperature heat pump development at DTI, Lars Reinholdt (DTI)

Absorption compression heat pump process

Absorption compression heat pump process
2.3. Generic fist assessment tool and high temperature heat pump development at DTI, Lars Reinholdt (DTI)

Absorption compression heat pump process

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2.3. Generic fist assessment tool and high temperature heat pump development at DTI, Lars Reinholdt (DTI)

800kW three-stage system in sewage treatment plant

\[ T_{L,i} = 22.5^\circ C, \ T_{L,o} = 19.4^\circ C, \ T_{H,i} = 79.1^\circ C, \ T_{H,o} = 108.4^\circ C, \]
\[ Q_H = 540 \text{ kW}, \ P_{tot} = 198 \text{ kW}. \]
\[ \text{COP}_{HP} = 2.72, \ \eta_{Car} = 63\%, \ \eta_{Lor} = 54\% \]

Summing up

- It is suggested to use COP_{Lor} for comparing actual heat pump performance (\eta_{Lor})
- It is suggested to use COP_{Lor} and \eta_{Lor} as base for system analysis including ecomonics

Question:
- Is (first assessment) tools needed?
2.3. Generic fist assessment tool and high temperature heat pump development at DTI, Lars Reinholdt (DTI)

Thank you

Lars Reinholdt
Danish Technological Institute
lre@teknologisk.dk
Phone: +45 7220 1270
Development of Propane-Butane cascade high temperature heat pump
Early test rig results

Research motivation

- Industrial processes with heat demand between 110 – 150 °C
  - Process water, Pasteurization, Sterilization, Cleaning, Drying, Distillation

- Industrial processes with excess heat between 30 – 100 °C
  - E.g. Heat at condensers of ammonia refrigeration unit
Research motivation, current solution

- Industrial processes with heat demand between 100 – 150°C
  - Process water, Pasteurization, Sterilization, Cleaning, Drying, Distillation

- Industrial processes with excess heat between 30 – 100°C
  - E.g. Heat from condensers of ammonia refrigeration unit

• Boilers

• Cooling towers, Dry coolers

Research motivation, HTHP

- Industrial processes with heat demand between 100 – 150°C
  - Process water, Pasteurization, Sterilization, Cleaning, Drying, Distillation

- Industrial processes with excess heat between 30 – 100°C
  - E.g. Heat from condensers of ammonia refrigeration unit
2.4. Development of a Propane-Butane cascade high temperature heat pump, Opeyemi Bamigbetan (NTNU)
2.4. Development of a Propane-Butane cascade high temperature heat pump, Opeyemi Bamigbetan (NTNU)

HTHP Design, Water cycle

- Requires modification

HTHP Design, Instrumentation

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Number of units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>16</td>
</tr>
<tr>
<td>Pressure</td>
<td>10</td>
</tr>
<tr>
<td>Flowmeters</td>
<td>4</td>
</tr>
<tr>
<td>Electricity (Compressors)</td>
<td>2</td>
</tr>
<tr>
<td>Speed (Compressors)</td>
<td>2</td>
</tr>
</tbody>
</table>
2.4. Development of a Propane-Butane cascade high temperature heat pump, Opeyemi Bamigbetan (NTNU)
Parameters and performance results

Summary

- Operating conditions are still random, unable to accurately and independently adjust inlet temperatures
- Simple modification required
- Results are not sufficient for proper evaluation
- High temperature heat delivery up to 115 °C from a heat source at 30 °C
- High temperature difference at heat sink from 35 °C to 115 °C
- Stable operation of prototype compressor with an average total compressor efficiency of 70%
Working fluids for high temperature heat pumps

International Workshop on High Temperature Heat Pumps
11.09.2017 - Copenhagen

Benjamin Zühlsdorf, Brian Elmegaard

Section of Thermal Energy
Email: bezuhls@mek.dtu.dk
Tlf.: +45 452 54103

Agenda
• Motivation
• Screening Method
• Case I: Heat recovery at spray dryer (Arla)
• Case II: Excess heat to DH
• Conclusions
Motivation

Heat Pump:
Heat Source: \(100 \, ^\circ\text{C} \rightarrow 70 \, ^\circ\text{C}\)
Heat Sink: \(100 \, ^\circ\text{C} \rightarrow 130 \, ^\circ\text{C}\)

Butane
COP = 4.12, \(p_{\text{evap}} = 7.2 \, \text{bar}, \ p_{\text{cond}} = 27.7 \, \text{bar}\)

Exergetic Efficiency = 62 %

Exergy Product 62%
Exergy Destruction 38%

Compressor 12%
TV 9%
Condenser 7%
Evaporator 10%

Exergy Destruction
38%
Exergetic Efficiency = 62 %
### Motivation

**Heat Pump:**

Heat Source: 100 °C → 70 °C  
Heat Sink: 100 °C → 130 °C

- **Butane**
  - COP = 4.12, $p_{evap} = 7.2$ bar, $p_{cond} = 27.7$ bar

- **50 % DME / 50 % Pentane**
  - COP = 5.56, $p_{evap} = 9.36$ bar, $p_{cond} = 25$ bar

### Working Fluid Screening:  
Thermodynamic Model

$\dot{Q}_{Sink}$ → Simulation of all possible binary mixtures, considering 14 HCs + 4 HFOs.
2.5. Working fluids for high temperature heat pumps, Benjamin Zühlsdorf (DTU)
Case I:
Heat recovery at spray dryer (Arla)

<table>
<thead>
<tr>
<th>Component</th>
<th>Temperature [°C]</th>
<th>Mass Flow Rate [kg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drying Air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>15</td>
<td>43.7</td>
</tr>
<tr>
<td>2</td>
<td>70</td>
<td>43.7</td>
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<tr>
<td>3</td>
<td>70</td>
<td>61.5</td>
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<tr>
<td>4</td>
<td>210</td>
<td>43.7</td>
</tr>
<tr>
<td>Excess Air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>70</td>
<td>61.5</td>
</tr>
<tr>
<td>Source</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>≈45</td>
<td>61.5</td>
</tr>
<tr>
<td>Sink</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>65</td>
<td>14.8</td>
</tr>
<tr>
<td>8</td>
<td>≈40</td>
<td>14.8</td>
</tr>
<tr>
<td>9</td>
<td>75</td>
<td>10.6</td>
</tr>
<tr>
<td>10</td>
<td>130</td>
<td>10.6</td>
</tr>
</tbody>
</table>
2.5. Working fluids for high temperature heat pumps, Benjamin Zühlsdorf (DTU)

Case I:
Heat recovery at spray dryer (Arla)

Heat Pump:
Heat Source: 65 °C → 40 °C, excess heat
Heat Sink: 75 °C → 130 °C, air preheating, \( \hat{Q}_{\text{sink}} = 2.25 \text{ MW} \)

- **Ammonia**
  - COP = 2.99, \( V_{\text{flow,Comp,in}} = 713.4 \text{ m}^3/\text{h} \)
  - \( p_{\text{evap}} = 11.7 \text{ bar}, p_{\text{cond}} = 86.2 \text{ bar} \)

- **Butane**
  - COP = 2.86, \( V_{\text{flow,Comp,in}} = 3415 \text{ m}^3/\text{h} \)
  - \( p_{\text{evap}} = 2.83 \text{ bar}, p_{\text{cond}} = 29.5 \text{ bar} \)

- **60% DME / 40% Pentane**
  - COP = 3.28, \( V_{\text{flow,Comp,in}} = 2135 \text{ m}^3/\text{h} \)
  - \( p_{\text{evap}} = 4.57 \text{ bar}, p_{\text{cond}} = 31.7 \text{ bar} \)

Case II:
Excess heat to DH

Heat Pump:
Heat Source: 40 °C → 25 °C, e.g. excess heat from air liquefaction process
Heat Sink: 50 °C → 85 °C, e.g. district heating (DH), \( \hat{Q}_{\text{sink}} = 1 \text{ MW} \)

- **Ammonia**
  - COP = 4.07, \( V_{\text{flow,Comp,in}} = 410.6 \text{ m}^3/\text{h} \)
  - \( p_{\text{evap}} = 8.57 \text{ bar}, p_{\text{cond}} = 42.6 \text{ bar} \)

- **60% DME / 40% Isopentane**
  - COP = 4.72, \( V_{\text{flow,Comp,in}} = 1136 \text{ m}^3/\text{h} \)
  - \( p_{\text{evap}} = 3.59 \text{ bar}, p_{\text{cond}} = 14.6 \text{ bar} \)
Conclusions

- Utilization of mixtures:
  - Enhances range of applications for limited set of fluids
  - Possibility of matching temperature glides
  - Glide matching in evaporator has dominating influence
  - Reduction of superheating improves the glide match
  - Significant performance increase possible by use of mixtures
    - Case in introduction: COP = 4.12 → 5.49 (+33 %)
    - Case I (Spray Dryer): COP = 2.86/2.99 → 3.28 (+10/15 %)
    - Case II (DH): COP = 4.07 → 4.72 (+16 %)

- Future work:
  - Experimental validation at DTI: ThermCyc/MIREHP
3 Heat pump developments – Market ready products

3.1 Industrial heat pumps: Present and in the future, Morten Deding (John-son Controls)

3.2 Temperature limitations for large ammonia heat pumps in district heating, Kenneth Hoffmann (GEA)

3.3 16 years with high temperature hybrid heat pumps, Bjarne Horntvedt (Hybrid Energy)

3.4 Steam compression and the development of a cost effective turbo compres-sor, Lars Reinholdt (DTI) & Michael Bantle (SINTEF)

3.5 Development and testing of HeatBooster, Mattias Nilsson (Viking Heat Engines)
3.1. Industrial heat pumps: Present and in the future, Morten Deding (Johnson Controls)
Present products trends
Split in technology towards segment

• Traditional refrigeration segments
  • Single stage products on reciprocating compressors
  • Capacity <2MW and temperature 55-75-90°C
  • ROI/CAPEX is often the barrier
  • Heat pumps is not primary heat supply

• District heating segment
  • Large capacity above 10MW screws or centrifugal
  • Small capacity below 10MW two-stage reciprocating
  • 3-5 years project cycle from feasibility study to order
  • Temperature 72-85°C
  • Multiple running conditions
  • FAT +SAT test
  • Strict terms and conditions
3.1. Industrial heat pumps: Present and in the future, Morten Deding (Johnson Controls)

Kalundborg fjernvarme

Production of heating from cold sewage water:
6 pcs Dual PAC SMC108/HPX716 two-stage heat pumps

Design specifications
Cold side = +13°C / +3°C
Hot side = +52°C / +82°C
Cooling capacity = 7,380 kW
Heating capacity = 10,000 kW
Power consumption = 2622 kW
COP heat = 3.24

– ENERTHERM Heat Pump Case
District heating / cooling application in Paris La Defense

OM TURBO MASTER – Heat Pump
Industrial HP (combined chilling and heating)

Heating capacity 11.3 MW 800 m³/h from 77.5°C to 90°C
Cooling capacity  7.3 MW 780 m³/h from 12°C to 4°C
Absorbed Power  4.2 MW
COP: 4.4  (11.3 + 7.3) / 4.2

• York Multi stage compressor : M 438 (4 stages compression )
• Motor : 4.5 MW - 6KV - 1450 rpm – Soft starter
• Gear Box: 1 450 to 5 400 rpm
• 3 Interstages cooling for thermodynamic cycle efficiency
• Integrated sub cooler
• Shell & Tube condenser (CS plain tubes)
• Shell & Tubes evaporator (enhanced copper tubes)
• Weight : Empty 90 T Operating 113 T
• MWP water side 23 barg Refrigerant side 41.3 barg
3.1. Industrial heat pumps: Present and in the future, Morten Deding (Johnson Controls)

**ENERTHERM Heat Pump Case**
District heating / cooling application in Paris La Defense

**Vestmanner Iceland**

*Production of heating from cold seawater:*

4 stk. Twin Heat PAC 193S single-stage heat pumps Sabroe
Single stage cycle with economizer

Design specifications
- Cold side: $+6^{\circ}/+2^{\circ}$ C
- Hot side: $+38^{\circ}/+77^{\circ}$ C
- Cooling capacity: 7,370 kW
- Heating capacity: 10,370 kW
- Power consumption: 3,190 kW
- COP$_{heat}$: 3,24
Future products trends

- **Traditional refrigeration segments**
  - Bring down running cost and improve service life
  - Lot of heating demands at 100-150 °C
  - Steam re-compression
  - Reduce charge

- **District heating segment**
  - Waste heat from industry
  - Low GWP and Natural refrigerants preferable
  - Low charge
  - High temperatures for transmission circuits >85 °C
3.1. Industrial heat pumps: Present and in the future, Morten Deding (Johnson Controls)

**Refrigerants for all temperature levels**

- Evaporation up to 110°C
- Condensation up to 125°C
- Capacity: 800kW to 10MW
- R245fa
- Technology based on YMC²

**« Valenthin » project**

- Evaporation up to 110°C
- Condensation up to 125°C
- Capacity: 800kW to 10MW
- R245fa
- Technology based on YMC²
3.1. Industrial heat pumps: Present and in the future, Morten Deding (Johnson Controls)

PACO2 project
Steam re-compression

- Evaporation 90 - 110°C
- Condensation up to ~150°C
- 25K per stage
- Capacity: 1000kW to 3MW

... Technology based on YK R718

Screw compressors next generation
HPSH 2709+2712

Business Opportunity
- Heat pumps for Europe – ammonia refrigerant
- Fuel gas booster compressor feeding natural gas to power generation turbines
- Process gas compression for higher pressures
- District heating Europe or Asia

Product Description
- High pressure screw compressor with 273 mm rotor diameter
- Max water temp ~ 195 °F / (95 °C)
- Targeting 1300 psi (90bar) discharge / 1000 psi (69bar) suction
3.1. Industrial heat pumps: Present and in the future, Morten Deding (Johnson Controls)

Screw compressors
HPSH 2709+2712

On-site performance
3.1. Industrial heat pumps: Present and in the future, Morten Deding (Johnson Controls)

Heat pump Losses and Tolerances

COP_{Heat} = \frac{P_{heat}}{P_{line}}

P_{heat} = f \left( \text{Fouling}_{hot}; \text{Fouling}_{cold}; \text{Pressure loss}_{suction}; \text{Pressure loss}_{discharge}; P_{RM}; \text{Pressure loss}_{Eco}; P_{cooling} \pm 5\% \right)

P_{line} = f \left( \text{Eta}_{motor}; P_{motor} \pm 0.5\%; P_{RC}; P_{shaft} \pm 5\% \right)

Heat pump Losses and Tolerances

Capacity and Performance

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3.2 Temperature limitations for large ammonia heat pumps in district heating, Kenneth Hoffmann (GEA)

**Temperature limitations for large ammonia heat pumps in district heating**

KENNETH HOFFMANN, SEPTEMBER, 2017

**Why do we need heat pumps in district heating**

- Why burn gas at 600°C to create 21°C in your home – Waste of exergy
- Decarbonisation of electricity grid makes heat pumps a zero carbon heat source
- Heat pumps is the most efficient use on natural energy source.
- Sustainable biomass only harness 1% of the solar energy
- Using seawater, sewage water, waste water, ground source water, cooling tower water etc, gives high efficient heating all year, independent on ambient temperature.
- Proven technology, competitive investment
- District heating / District cooling is key to improved energy optimisation for carbon neutral EU by 2050
- District heating converting from steam to water based system across Europe
- Temperatures of network at getting reduced each year.
3.2 Temperature limitations for large ammonia heat pumps in district heating, Kenneth Hoffmann (GEA)
Old PED limitations when using ammonia screw compressors

- For 52 bar ammonia heat pump PED describes that a 10% margin is required

52 bar - 10% = 46.8 bar (86.7°C) – set point for safety valve
45.8 bar (85.7°C) Internal safety valve
45.3 bar (85.2°C) alarm
44.3 bar (84.1°C) compressor limiting

= Maximum design point: 83°C condensing pressure
= 80 - 82°C hot water from heat pump

New PED limitations when using ammonia screw compressors

- For 52 bar ammonia heat pump PED describes that a less than 10% margin is required by applying good safety device

52 bar -10% = 50.5 bar (90.3°C) – set point for safety valve
49.0 bar (88.8°C) Internal safety valve
48.5 bar (88.4°C) alarm
48.0 bar (87.9°C) compressor limiting

= Maximum design point: 87°C condensing pressure
= 85°C hot water from heat pump

Commercial range of ammonia heat pumps have now increased to supply temperature of 85°C
Small district heating schemes

**GEA M-screw compressor**

- Greatly improved efficiency in part load and full load
- New valves with lower pressure drop
- Wider speed range enables 1000 - 4500 rpm screw packages
- Larger Vi range enables higher efficiency
- 5 – 7% efficiency improvement

*Now in 52 bar design*
### Standard M-screw compressor based heat pumps

**GEA RedASTRUM Concept**

<table>
<thead>
<tr>
<th>Type</th>
<th>Compressor Model</th>
<th>Cooling capacity [kW] at +40/+35°C</th>
<th>Heating capacity [kW]</th>
<th>Heating water temperature [°C]</th>
<th>Shaft power [kW] at 3600rpm</th>
<th>COP&lt;sub&gt;He&lt;/sub&gt; at compressor shaft</th>
<th>COP&lt;sub&gt;He&lt;/sub&gt; at 3600rpm</th>
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</thead>
<tbody>
<tr>
<td>1000</td>
<td>HR-G21T-S2</td>
<td>1045</td>
<td>1255</td>
<td>+50/+70</td>
<td>215</td>
<td>5.84</td>
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<tr>
<td></td>
<td>HR-G21T-S2</td>
<td>960</td>
<td>1170</td>
<td>+60/+70</td>
<td>215</td>
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</tr>
<tr>
<td></td>
<td>HR-G28T-S2</td>
<td>955</td>
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<td>+80/+80</td>
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<tr>
<td></td>
<td>HR-G28T-S2</td>
<td>870</td>
<td>1155</td>
<td>+70/+80</td>
<td>285</td>
<td>4.05</td>
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<tr>
<td>1300</td>
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<tr>
<td></td>
<td>HR-G21T-S2</td>
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<td>1465</td>
<td>+60/+70</td>
<td>265</td>
<td>5.53</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HR-G28T-S2</td>
<td>1185</td>
<td>1540</td>
<td>+60/+80</td>
<td>360</td>
<td>4.28</td>
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<tr>
<td></td>
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<td>1075</td>
<td>1430</td>
<td>+70/+80</td>
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<tr>
<td>1500</td>
<td>MR-H17T-S2</td>
<td>1710</td>
<td>2060</td>
<td>+50/+70</td>
<td>355</td>
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<tr>
<td></td>
<td>MR-H17T-S2</td>
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<td>+60/+70</td>
<td>355</td>
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<tr>
<td></td>
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<td>2010</td>
<td>+60/+70</td>
<td>465</td>
<td>4.32</td>
<td></td>
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<tr>
<td></td>
<td>MR-H24T-S2</td>
<td>1410</td>
<td>1875</td>
<td>+70/+80</td>
<td>465</td>
<td>4.03</td>
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<tr>
<td>2000</td>
<td>MR-L20T-S2</td>
<td>1970</td>
<td>2360</td>
<td>+50/+70</td>
<td>390</td>
<td>6.05</td>
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<tr>
<td></td>
<td>MR-L20T-S2</td>
<td>1815</td>
<td>2200</td>
<td>+60/+70</td>
<td>390</td>
<td>5.65</td>
<td></td>
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<tr>
<td></td>
<td>MR-L27T-S2</td>
<td>1795</td>
<td>2310</td>
<td>+60/+80</td>
<td>520 R²</td>
<td>4.44</td>
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<tr>
<td></td>
<td>MR-L27T-S2</td>
<td>1635</td>
<td>2155</td>
<td>+70/+80</td>
<td>520 R²</td>
<td>4.14</td>
<td></td>
</tr>
</tbody>
</table>

**Coolant:** +40°C/+35°C

**Heating duty:** 900kW – 2200 kW

**Hotwater supply:** Upto 85°C

**Low ammonia charge**

**Water/water or Cascade**

Larget district heating schemes

---

*3.2. Temperature limitations for large ammonia heat pumps in district heating, Kenneth Hoffmann (GEA)*
3.2 Temperature limitations for large ammonia heat pumps in district heating, Kenneth Hoffmann (GEA)

### Screw compressors used for ammonia heat pumps

![Screw compressors](image)

#### GEA Grasso SH
- 4 models

#### GEA Grasso M
- 4 models

#### GEA Grasso LT
- 16 models

<table>
<thead>
<tr>
<th>Models</th>
<th>Swept volume in m³/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>231</td>
</tr>
<tr>
<td>D</td>
<td>326</td>
</tr>
<tr>
<td>E</td>
<td>321</td>
</tr>
<tr>
<td>G</td>
<td>372</td>
</tr>
<tr>
<td>H</td>
<td>471</td>
</tr>
<tr>
<td>L</td>
<td>326</td>
</tr>
<tr>
<td>M</td>
<td>544</td>
</tr>
<tr>
<td>N</td>
<td>708</td>
</tr>
<tr>
<td>P</td>
<td>805</td>
</tr>
<tr>
<td>R</td>
<td>1,040</td>
</tr>
<tr>
<td>S</td>
<td>1,290</td>
</tr>
<tr>
<td>T</td>
<td>1,460</td>
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<tr>
<td>V</td>
<td>1,860</td>
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<td>W</td>
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<tr>
<td>Y</td>
<td>2,740</td>
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<tr>
<td>Z</td>
<td>3,250</td>
</tr>
<tr>
<td>XA</td>
<td>4,900</td>
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<tr>
<td>XB</td>
<td>5,800</td>
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<td>XC</td>
<td>6,800</td>
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<tr>
<td>XD</td>
<td>7,170</td>
</tr>
<tr>
<td>XF</td>
<td>8,560</td>
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<tr>
<td>XG</td>
<td>9,807</td>
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</table>

### Large Heat pump references

<table>
<thead>
<tr>
<th>Project</th>
<th>Date</th>
<th>Country</th>
<th>Temperature (Chilled water flow / hot water flow)</th>
<th>Heating capacity</th>
<th>COPₜ</th>
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<tbody>
<tr>
<td>Fynsværket</td>
<td>2008-06</td>
<td>DK</td>
<td>+30°C / +55°C</td>
<td>2,815 kW</td>
<td>7.20</td>
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<tr>
<td>Copenhagen Towers</td>
<td>2008-10</td>
<td>DK</td>
<td>+10°C / +60°C</td>
<td>2,955 kW</td>
<td>4.51</td>
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<tr>
<td>Tetra Pak 2</td>
<td>2009-12</td>
<td>SWE</td>
<td>+25°C / +70°C</td>
<td>1,380 kW</td>
<td>5.47</td>
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<tr>
<td>Sarsborg</td>
<td>2010-01</td>
<td>NO</td>
<td>+27°C / +80°C</td>
<td>2,000 kW</td>
<td>3.81</td>
</tr>
<tr>
<td>Nestlé Biessenhofen 2</td>
<td>2010-01</td>
<td>NO</td>
<td>+30°C / +70°C</td>
<td>1,170 kW</td>
<td>4.88</td>
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<tr>
<td>Valldal Fjernvarme</td>
<td>2011-01</td>
<td>NO</td>
<td>+1°C / +70°C</td>
<td>1,285 kW</td>
<td>2.60</td>
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<tr>
<td>Skagerak Energi</td>
<td>2011-09</td>
<td>NO</td>
<td>-2°C / +70°C</td>
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<td>3.02</td>
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<tr>
<td>Bio Energi</td>
<td>2011-12</td>
<td>CZ</td>
<td>+28°C / +80°C</td>
<td>4,090 kW</td>
<td>4.93</td>
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<tr>
<td>Unilever</td>
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<td>NL</td>
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<td>1,416 kW</td>
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<tr>
<td>Sognad 1</td>
<td>2012-06</td>
<td>NO</td>
<td>-2°C / +68°C</td>
<td>2,450 kW</td>
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<tr>
<td>Brista</td>
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<td>7,250 kW</td>
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<tr>
<td>Sarsborg II</td>
<td>2012-07</td>
<td>NO</td>
<td>+20°C / +80°C</td>
<td>3,080 kW</td>
<td>3.05</td>
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<tr>
<td>Kalnes Energisentral</td>
<td>2012-12</td>
<td>NO</td>
<td>+10°C / +56°C</td>
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<tr>
<td>NTNU</td>
<td>2013-07</td>
<td>NO</td>
<td>+4°C / +81°C</td>
<td>1,315 kW</td>
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<td>Holmen</td>
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<td>NO</td>
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<td>2,450 kW</td>
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<tr>
<td>HP Oatly</td>
<td>2014-07</td>
<td>SWE</td>
<td>+7°C / +78°C</td>
<td>560 kW</td>
<td>3.11</td>
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<tr>
<td>Kroogy</td>
<td>2015-01</td>
<td>GER</td>
<td>+30°C / +83°C</td>
<td>4,500 kW</td>
<td>4.70</td>
</tr>
<tr>
<td>Vietnam</td>
<td>2016-06</td>
<td>VTN</td>
<td>+6°C / +60°C</td>
<td>12,000 kW</td>
<td>4.62</td>
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<tr>
<td>Copenhagen Markets</td>
<td>2016-06</td>
<td>DK</td>
<td>+6°C / +75°C</td>
<td>3,200 kW</td>
<td>3.05</td>
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<tr>
<td>EON Malmoe</td>
<td>2017-10</td>
<td>SWE</td>
<td>+8°C / +66°C</td>
<td>40,000 kW</td>
<td>3.50</td>
</tr>
</tbody>
</table>
3.2 Temperature limitations for large ammonia heat pumps in district heating, Kenneth Hoffmann (GEA)

**Ground source heat pump for a hotel (Denmark)**

Copenhagen Towers

- Cooling: 10-18°C
- Heating: 30-60°C

- Heat pump and heat exchangers
- Boiler
- Control-system
- Well

Peak chilling duty is 4.1 MW
Peak heating duty is 2.9 MW
Chilled water system is designed for 10°C/18°C
Heating water system is designed for 60°C/30°C
Heating COP 3.9, Cooling COP 40

**40 MW Ammonia Heat Pump (Sweden)**

- 4 off XD compressors
- Heat sink: district heating water 57°C to 66°C
- Heating COP >3.50
- Shell and tube evaporator
- Plate and shell condenser
- Heat source: Sewage water 14°C to 8°C
Geothermal (Romania)

DH Supply 80 - 120°C

DH Return 40 - 60°C

140°C

15°C

Well

HX

65-85°C

Flue gas condensation (Sweden)

APPLICATION:

Any heat driven combined heat and power plant

Process heating or district heating

Flue gas 150°C

Water 30°C

Heating Water 55°C

Heating Water 65°C

Water 60°C

Turbine/Boiler

Heating Water 90°C
Conclusion

1. Heat pumps only need a little **electrical energy** to raise the temperature of the waste heat to useful level.
2. By using heat pumps the decarbonisation of the electricity grid will ensure **future reduction in CO₂ emissions**.
3. Using water based heating system instead of steam makes implementation of **heat pumps cheaper and improve efficiency**.
4. It is now possible to achieve **85°C water with a 52bar design heat pump**
5. Large heat pumps in the building services sector can help communities **reach their zero emission targets**

GEA Heat pumps 2017
Our Challenge at the start

Selling expensive, unfamiliar technology, replacing an existing energy solution in a field of business often characterized by optimistic, half-baked technologies.
The Company: History

• Founded in 2004
• Institute for Energy Technology (IFE) in Norway
• Commissioned plants in dairies, slaughter houses, fish feed producers, bio gas production plants, district heating and process industries
• More than 400,000 hours economic running in industry – equal to 46 years continues running

The Technology: What is a Hybrid Heat Pump?

• Natural working medium (50/50 water and ammonia)
• Uses Standard refrigeration equipment for ammonia
• Can deliver 120 °C at low pressure (25 bar)
• Offers unique flexibility after commissioning (by changing mixing ratio and circulation number)
• Yields exceptional COP’s, especially with large glides (Δt’s) on hot and cold side
3.3. 16 years with high temperature hybrid heat pumps, Bjarne Horntvedt (Hybrid Energy)

The Technology: COP – Carnot vs. Lorenz

<table>
<thead>
<tr>
<th>No.</th>
<th>Heat Source</th>
<th>Heat Sink</th>
<th>COP\textsubscript{Carnot}</th>
<th>COP\textsubscript{Lorenz}</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8 &gt; 4</td>
<td>85 &gt; 95</td>
<td>4.0</td>
<td>4.3</td>
</tr>
<tr>
<td>B</td>
<td>40 &gt; 15</td>
<td>60 &gt; 90</td>
<td>4.8</td>
<td>7.3</td>
</tr>
<tr>
<td>C</td>
<td>25 &gt; 20</td>
<td>70 &gt; 110</td>
<td>4.3</td>
<td>5.4</td>
</tr>
<tr>
<td>D</td>
<td>80 &gt; 20</td>
<td>85 &gt; 90</td>
<td>5.2</td>
<td>9.4</td>
</tr>
<tr>
<td>E</td>
<td>55 &gt; 20</td>
<td>50 &gt; 90</td>
<td>5.2</td>
<td>10.5</td>
</tr>
</tbody>
</table>

- COP\textsubscript{Lorenz}: Heat source and sink glide
- COP\textsubscript{Carnot}: Heat source and sink glide

Experiences: Commercial Challenges

- Significant CAPEX
- Elaborate and complex procurement and decision making processes
- Technological skepticism
- Small company
Experiences: Solutions

• Holistic approach to the total energy system
• Tailor made solutions
• Project ownership & user commitment
• High commercial focus, strong sales organization
• Bold and competent partners

16 years, where are we?

• Hybrid Energy have most experience by tailor fitting high temperature heat pumps into industrial processes.
• Generation 3 hybrid heatpump with water/ammonia optimizes COP at different running conditions.
• Just delivered largest ever hybrid heat pump unit commissioned in Norway in 2017 at Borregaard (2 MW).
• First installation in the French dairy market will be commissioned this fall (2017) in cooperation with our strategic partner Engie Axima in France.
• Green shift offers new possibilities
• Increased environmental commitments in blue-chip companies
• Increased awareness among consultants about existing well proven and market ready solutions for high temperature heat pumps.
Steam compression and the development of a cost effective turbo compressor
PSO project “Water vapor compressor based on Rotrex gear”
Lars Reinholdt

Water as working fluid

- As ‘green’ as it gets
- As safe as it gets
- No global warming effect
- Cheap and easily available
- Non toxic
- Non flammable
- No break-down product
- Relative low pressure
Water as working fluid

Physical properties
- Low working pressure
  - 60°C: 0.2 bar a
  - 85°C: 0.6 bar a
  - 100°C: 1 bar a
  - 120°C: 2 bar a
  - 180°C: 10 bar a
- High heat of evaporation
  - ~2200 kJ/kg @ 100°C

Water Vapor Compressor
- Two types of prototype turbocompressors developed
  Axial (chiller)  Centrifugal (HP)
3.4. Steam compression and the development of a cost effective turbo compressor, Lars Reinholdt (DTI) & Michael Bantle (SINTEF)

**Turbo compressor: Design base**

![Graph showing different optimal design for different application](image)

**Cost effective radial air compressor**

**Rotrex planetary gear**

How it works:

Programme:

- **C8**: 240,000 rpm - 5 kW input power
- **C15**: 200,000 rpm - 15 kW input power
- **C30**: 120,000 rpm - 30 kW input power
- **C38**: 90,000 rpm - 50 kW input power
Compressor design

PSO project no. 344-009 “Water vapor compressor based on Rotrex gear”
- DTI, Rotrex, Weel & Sandvig, Spirax Sarco, Xvaporator, Union Engineering, Johnson Controls Denmark

Specifications by the project group:

<table>
<thead>
<tr>
<th>Type of user</th>
<th>Inlet conditions</th>
<th>Capacity</th>
<th>Temperature difference</th>
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</thead>
<tbody>
<tr>
<td>Heat pump Unit supplier</td>
<td>65 – 85 C</td>
<td>100 – 1000 kW</td>
<td>20 – 30</td>
</tr>
<tr>
<td>Steam system supplier</td>
<td>65 – 144 C</td>
<td>500 – 1000 kg/h</td>
<td>15 – 20</td>
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<tr>
<td>Process Industry</td>
<td>90 – 110</td>
<td>100 – 1200 kW</td>
<td>15 – 35</td>
</tr>
<tr>
<td>Waste recovery, concentration</td>
<td>85 - 110</td>
<td>500 – 1000 kg/h</td>
<td>15 – 20</td>
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<tr>
<td>Process Consultants</td>
<td>65 - 150</td>
<td>0,4 – 3 MW</td>
<td>15 – 30</td>
</tr>
<tr>
<td>Drying consultants</td>
<td>30 - 130</td>
<td>200 – 2500 kg/h</td>
<td>5 – 30</td>
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</tbody>
</table>

Compressor design

Specifications is a trade between
- Efficiency
- Pressure ration (temperature lift)
- Capacity (maximum load on gear and material)
- Lifetime
- Specification:
  - Speed 90,000 RPM
  - PRts 2.6
  - ΔT 25°C
  - Efficiency $h_{ts}$ 75%
  - Volume flow 0,45 m³/s
  - Capacity (at 90°C inlet) 360 kW
3.4. Steam compression and the development of a cost effective turbo compressor, Lars Reinholdt (DTI) & Michael Bantle (SINTEF)

Compressor design
- Design specification based on high end design tool

Final compressor and testrig
3.4. Steam compression and the development of a cost effective turbo compressor, Lars Reinholdt (DTI) & Michael Bantle (SINTEF)

Compressor design

- Test results

- Efficiency documented
- Gear oil temperature little higher than expected > lower max. RPM

Application examples

Steam generation… concentration… recompression… Drying…

Vessel / process
Heat exchanger / evaporator
compressor
Steam at 110 °C
Liquid at 100 °C
Liquid at 60 °C
3.4. Steam compression and the development of a cost effective turbo compressor, Lars Reinholdt (DTI) & Michael Bantle (SINTEF)

Thank you

Lars Reinholdt
Danish Technological Institute
lre@teknologisk.dk
Phone: +45 7220 1270
3.4. Steam compression and the development of a cost effective turbo compressor, Lars Reinholdt (DTI) & Michael Bantle (SINTEF)

11. September 2017
Workshop: High Temperature Heat Pump
Copenhagen, Denmark

Steam compression and the development of a
cost effective turbo compressor

Key Goals
• Reduction of specific energy consumption by
  60-80 % for drying/dehydration/evaporation processes, by recovering of waste heat
• Phase-in of renewable energy sources into thermal processes ideally resulting in CO2-free production
• Development of cost-efficient high temperature industrial heat pumps for industrial thermal processes with minimum global warming potential (GWP) & minimum negative environmental impact
• Increasing competitiveness of the European industry
• Become the leading pioneers by being the first to deliver to market
Boundary conditions for steam dryer (full scale)

<table>
<thead>
<tr>
<th>Product</th>
<th>Mass flow in: $\dot{m}_i$</th>
<th>Moisture content in: $MC_i$</th>
<th>Mass flow out: $\dot{m}_o$</th>
<th>Moisture content out: $MC_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow in: $\dot{m}_i$</td>
<td>10000 kg/h</td>
<td>25%</td>
<td>7895 kg/h</td>
<td>5%</td>
</tr>
<tr>
<td>Drying agent (process steam)</td>
<td>Mass flow in: $\dot{m}_{DA}$</td>
<td>Temperature in: $T_{DA}$</td>
<td>Mass flow out: $\dot{m}_{DA}$</td>
<td>Temperature out: $T_{DA}$</td>
</tr>
<tr>
<td>Mass flow in: $\dot{m}_{DA}$</td>
<td>65684 kg/h</td>
<td>155±5°C</td>
<td>67789 kg/h</td>
<td>110°C</td>
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<tr>
<td>Mechanical vapor recompression (MVR)</td>
<td>Mass flow: $\dot{m}_{MVR}$</td>
<td>Temperature in: $T_{MVR}$</td>
<td>Pressure in: $P_{MVR}$</td>
<td></td>
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<tr>
<td>Mass flow: $\dot{m}_{MVR}$</td>
<td>2105 kg/h</td>
<td>110°C</td>
<td>1 bar</td>
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<tr>
<td>Water out</td>
<td>Mass flow: $\dot{m}_{water}$</td>
<td>Temperature: $T_{water}$</td>
<td>Pressure: $P_{water}$</td>
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<tr>
<td>Mass flow: $\dot{m}_{water}$</td>
<td>2105 kg/h</td>
<td>&lt;100°C</td>
<td>1 bar</td>
<td></td>
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<tr>
<td>Drying process (MC 25% → 5% at 155±5°C)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SEC</td>
<td>0.78 kWh/kg</td>
<td></td>
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<td></td>
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</tbody>
</table>
3.4. Steam compression and the development of a cost effective turbo compressor, Lars Reinholdt (DTI) & Michael Bantle (SINTEF)
3.4. Steam compression and the development of a cost effective turbo compressor, Lars Reinholdt (DTI) & Michael Bantle (SINTEF)
3.4. Steam compression and the development of a cost effective turbo compressor, Lars Reinholdt (DTI) & Michael Bantle (SINTEF)
2 stage setup

Outlet of stage 2:
- Super heated water vapor
- 250 °C
- 6.5 bar (abs)
- Mass flow 800 kg/hr (0.222 kg/s)

Inlet of stage 2:
- Super heated water vapor
- 145 °C
- 3.2 bar (abs)
- Mass flow 800 kg/hr (0.222 kg/s)

Water spray cooling:
- 120 °C
- Flow: 0.026 kg/s

Inlet of stage 1:
- Water vapor
- 110 °C
- Atmospheric pressure
- Flow: 0.196 kg/s

* Water spray cooling system not included in deliverables

WP2: Deliverables

3.4. Steam compression and the development of a cost effective turbo compressor, Lars Reinholdt (DTI) & Michael Bantle (SINTEF)
De-Supeheating

- Requires a certain pipe-length (residue time for the water to evaporate)
- Pipe diameter is smaller than we would like to have it
  - Increase pressure loss for our compressors
    - Loss if efficiency
    - Start-up procedure?
- Evaluated as necessary
  - between stage 1 and stage 2
  - after stage 2 and before MVR-condenser

Heat Pump Demonstration Unit
Conclusions and Discussion Open Loop

- Overall: good progress on the development
- Currently building together the prototype unit
- Until end of October testing in single stage
- From November 2017 testing in multistage (target 2000 hours)

Questions ? Comments ?
3.5. Development and testing of HeatBooster, Mattias Nilsson (Viking Heat Engines)
3.5. Development and testing of HeatBooster, Mattias Nilsson (Viking Heat Engines)

### The Product Plan

- **1st Generation:**
  - CraftEngine™ Demo
  - 10 kW_{el}, 10 – 40 kW_{th}

- **2nd Generation:**
  - CraftEngine™ 10 & 40
  - 200 kW_{th}

- **HEATBOOSTER S4**
  - CraftEngine™ Large-series
  - HEATBOOSTER X-series
  - 200 kW_{th}, 10 – 40 kW_{el}, 10 kW_{el}

- **Future...**

### How It Works

The HeatBooster is a high-temperature heat pump, which uses electricity to raise the temperature of a heat source in an efficient way.

- **Input temperature range:** 30 – 120 °C
- **Output temperature range:** 80 – 160 °C
- **COP* = 2 to 7**

*COE (Coefficient of Performance) indicates the ratio of output heat divided by electrical input added to the reciprocating compressor. The ratio depends strongly on the temperature lift.

Q_{in} 150 kW_{th}, Process or waste heat

Q_{out} 200 kW_{th}, Useful heat at a higher temperature level
In this case, the HeatBooster consumes one (1) part of electricity to lift five (5) parts of heat to a 30°C higher temperature.

Performance examples of different working fluids:

Example, see above (blue mark): A 90°C heat source and 120°C heat sink result in a COP of 5
Possible Applications

The industry needs large amounts of process heat
- Coal, oil, gas or electric heaters are usually used for this purpose
- These kinds of heaters can be replaced by the HeatBooster

Industrial heat pumps increase energy efficiency
- Costs and emissions can be reduced
- Payback periods of 1 to 3 years are possible

HeatBooster reaches the highest temperatures (> 150 °C)
- Commercial HTHPs generally reach < 90 °C
- HeatBooster uses gas compression
- Flexible integration with regards to temperature change in water loops and possibilities for steam production

Installation Example

48 kWel
152 kWth
200 kWth
90°C
80°C
110°C
120°C
17 t/h

The HeatBooster S4 constitutes a complete heat pump system with compressors, process components, electronics, software and so on.

COP = 4.1
### Installation Example - Multistage

**HeatBooster**

- **Q\textsubscript{in}**: 150 kW\textsubscript{th}
- **Q\textsubscript{out}**: 200 kW\textsubscript{th}
- **37.5 kW\textsubscript{el}**
- **COP = 4**

\[ \text{COP}_{\text{combined}} = \frac{200}{37.5 + 50} = 2.29 \]

The given values are example values.

### Installation Example – Cascade

- **90°C**
- **70°C**

The cascade connection allows for a temperature lift of 45°C. Comparatively, you'd get a temperature lift of 60°C with one large system, which results in a lower COP.

The given values are example values.
Our Key Partners

AVL
- Collaborated since 2011
- World's largest independent engine design company
- > 8,000 employees and revenue of € 1.3 Billion (2015)
- AVL has invested in Viking Heat Engines

The Chemours Company
- Collaborated since 2015
- Large chemical company developing and producing environmentally friendly working fluids / refrigerants and more

GWK
- Supplier of high-quality cooling and heating technology products
- Current manufacturer of CraftEngine/HeatBooster process modules

Unique High-Temp. Heat Pump Technology

The future is electric
- The HeatBooster can reduce electricity consumption from 50 to 85 %
- The COP of the HeatBooster is typically around 50 % of the Carnot limit
- The HeatBooster can power a process without any CO₂ emissions

A potent, durable and highly flexible piston engine technology
- Used as a reciprocating piston expander in the CraftEngine™ and compressor in the HeatBooster
- Runs at 20-100 % load without significant efficiency penalty
- Durability of 80,000 hours
- Low maintenance requirements
- Can reach 160°C with current working fluids
- Suitable with environmentally friendly working fluids and thus part of a new technology generation

About Viking Heat Engines
- Over 40 employees in three locations around the world
- Highly qualified and experienced sales and development team
- € 50 Million Technology (research, development, testing, commercialization, etc.)
3.5. Development and testing of HeatBooster, Mattias Nilsson (Viking Heat Engines)
4 Case studies – Realized and not realized projects – Experiences – Economics

4.1 5 years of strategic sale of large heat pumps to the industry, Palle Lemminger (Innoterm)

4.2 TINE’s road to get the (high temperature) heat pump, Kim Andre Lovas (TINE)

4.3 Integration of high temperature heat pumps in industry, Fridolin Müller Holm (Viegand Maagoe) & Søren Gram (Svedan Industri Køleanlæg)

4.4 Steam Generation from district heating, Stefano Vittor (Olvondo Technology)
4.1. 5 years of strategic sale of large heat pumps to the industry, Palle Lemminger (Innoterm)

"5 years of strategic sale of large heat pumps to the industry"

Palle Lemminger – Innoterm A/S
Owner & CEO

In 2010-2012 consulting engineers concluded:
250-300 industrial high temperature heat pumps needed and wanted in Denmark.

Technically: Innoterm moves the sensor from the cold to the warm side.
Same materials and personnel for the heat pumps.
4.1. 5 years of strategic sale of large heat pumps to the industry, Palle Lemminger (Innoterm)

High temperature heat pump references:
- Arla Arinco, milk powder production in Videbæk
- Danish Crown, slaughterhouse in Holsted
- Tican, slaughterhouse in Thisted
- TDC, heat recovery from datacenter in Slet
- Løgumkloster district heating
- Dronninglund district heating
- Ringkøbing district heating
- Tønder district heating

Reference plant: 1200 kW heat pump, Arla Arinco, Videbæk, 2012

Two-step hybrid heat pump:
- Cooling capacity: 950 kW
- Heating capacity: 1200 kW
- Source temp.: 45 °C / 22 °C
- Outlet temp.: 55 °C / 85 °C
- COP(heat): 4.5

Equipped with:
- 1 Sabroe SMC 116L piston compressor
- 1 Sabroe SMC 108L piston compressor
- Refrigerant: R717 / R718

On the 1st of September 2017, the heat pump has been running for 33,500 hours, and delivered 35,400 MWh heat with an average COP of 4.57

This project is supported by EUDP
4.1. 5 years of strategic sale of large heat pumps to the industry, Palle Lemminger (Innoterm)

Reference plant: 988 kW heat pump, Danish Crown, Holsted, 2013

Supercharge heat pump:
- Heating capacity: 988 kW
- Evaporator temp.: 28 °C
- Condensing temp.: 61 °C
- COP(heat): 8

Equipped with:
- 2 Grasso 65HP piston compressors
- Refrigerant: R717

The heat pump is integrated in a 4.5 MW ammonia refrigeration plant built by Innoterm. The plant refrigerates the 120 cattle being slaughtered at the slaughterhouse every hour.

Reference plant: 1350 kW heat pump, TDC district heating, Slet, 2015

Two-step heat pump:
- Heating capacity: 1350 kW
- Source temp.: 16/9 °C
- Outlet temp.: 45/78 °C
- COP(heat): 4.0

Equipped with:
- 3 GEA piston compressors
- Refrigerant: R717

The heat pump is projected and built on-site in Slet, by Innoterm. The heat from rooms and server cooling is raised in temperature and used for heating and/or sale for the district heating. The heat pump supplements and replaces existing district heating as well as the existing cooling plant.
4.1. 5 years of strategic sale of large heat pumps to the industry, Palle Lemminger (Innoterm)

<table>
<thead>
<tr>
<th>Reference plant: 1100 kW heat pump, Løgumkloster district heating, 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Two-step hybrid heat pump:</strong></td>
</tr>
<tr>
<td>– Cooling capacity: 844-1005 kW</td>
</tr>
<tr>
<td>– Heating capacity: 1089 - 1207 kW</td>
</tr>
<tr>
<td>– Source temp.: 23 °C/17 °C</td>
</tr>
<tr>
<td>– Outlet temp.: 35 °C/60-85 °C</td>
</tr>
<tr>
<td>– COP(heat): 4.0 - 5.3</td>
</tr>
<tr>
<td>Equipped with:</td>
</tr>
<tr>
<td>– 1 Sabroe SMC 116L piston compressor</td>
</tr>
<tr>
<td>– 1 Sabroe SMC 112S piston compressor</td>
</tr>
<tr>
<td>– Refrigerant: R717 / R718</td>
</tr>
</tbody>
</table>

This heat pump is used for either direct heating the district or to move energy around in the plant between storage, sunpanels or return water.

This project is supported by EUDP.

<table>
<thead>
<tr>
<th>Reference plant: 4.5 mW air to water heat pump, Ringkøbing district heating and Tønder district heating</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Two-step heat pumps:</strong></td>
</tr>
<tr>
<td>– Heating capacity: 3,360/4500 kW</td>
</tr>
<tr>
<td>– Source temp.: Varying outdoor air</td>
</tr>
<tr>
<td>– Outlet temp.: 35/70 °C</td>
</tr>
<tr>
<td>– COP(heat): 4.5</td>
</tr>
<tr>
<td>Equipped with:</td>
</tr>
<tr>
<td>– 4 Sabroe piston compressors in 2 parallel two-step plants</td>
</tr>
<tr>
<td>– The compressors can be driven by gasmotors or electrical motors</td>
</tr>
<tr>
<td>– Kølemiddel: R717</td>
</tr>
</tbody>
</table>

Air is cooled in air cooler area, and the district heating is heated by both condensation- and motor heat.

The heat pump supplements the existing district heating.
Overview: wants and reality

- 5 different ministers since 2010
- Several different studies (Universities, consulting engineers, technical institutes), EUDP, VE, Rejseholderet, etc.
- Funding added / funding removed
- A lot of ‘talk’ on re-using the energy for district heating and electricity from windmills for HTHP
- Reality is different with taxes and fees, removing focus from the visions
- Today: most of the HTHP supported by EUDP or other funding
- If Denmark needs to be fossil free in 2050, we need to motivate the industry and district heating plants to invest in HTHP!

Questions?
TINE’s road to get the (high temperature) heat pump
Kim Andre Lovas
TINE SA

The TINE Group 2015

- Liquid products
- Solid products
- Special products
- Central warehouses/terminals

Good profit performance in 2015
- Revenues of NOK 22.2 billion
- Operating income NOK 1678 million
- Profit before tax NOK 1579 million

Industry
- 31 dairies
- 2 central warehouses
- 2 terminals
- Wholly and partly owned subsidiaries

Employees
- 5362

Owners
- 12,092 farmers (cows and goats)

Raw materials delivered (cows’ and goats’ milk)
- 1474 million litres
TINE’s climate objectives: Reduce greenhouse gas emissions by 30 per cent by 2020 (compared with the 2007 level)
• Conversion to bioenergy and district heating
• Energy efficiency
• Transport
• Food waste

Greenhouse Gases TINE

Overview of Greenhouse Gases 2015

- Production 31 %
- Transport 63 %
- Other 6 %
Our **success** depends on efficient transport, logistics and distribution

- Extreme requirements for quick processing, quality and hygiene when the raw material is fresh milk
- Collection of milk from 220,000 cows and 30,000 goats from about 10,000 locations, followed by delivery to 24,000 stores and delivery sites within a geographical area corresponding to Oslo–Rome
- Secure the consumers' requirements and expectations of Norwegian dairy products

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**On the road to Climate Neutral transport by 2020**
4.2. TINE’s road to get the (high temperature) heat pump, Kim Andre Lovas (TINE)

The environment

TINE 2014

- Total: 503 GWh
  - Heat: 305 GWh

- District heating: 95 GWh
- Electricity: 199 GWh
- Electricity heat: 114 GWh
- Oil: 17 GWh
- Gas: 116 GWh

- District heating sold: -37 GWh

Large demand for heat in the temperature range 90°C to 180°C

Large amounts of surplus heat available in the temperature range 30°C to 45°C

Total: 503 GWh

New Dairy Bergen

- 18,000 m²
- Capacity: 300,000 liter milk/daily
- Will be completed in 2019

Shall be the most efficient, future-oriented and profitable plant in the Nordic region
Challenges

- Relative small Dairy
- Operational stability
- Innovation/Technology readiness level

Utilities in the New Dairy

- **Boiler**
  - 105 °C
  - Hot water distribution

- **CIP**
  - 30-50 °C

- **Compressed air distribution**
  - 30-50 °C

- **Cooling plant**
  - 40 °C
  - Ice water to process

- **Room heating**
  - 67 °C

- **Waste heat**
  - 40 °C
  - (hot) Ice water back from process

*CIP=Clean in place*
4.2 TINE's road to get the (high temperature) heat pump, Kim Andre Lovas (TINE)

**Energy balance in the New Dairy**

- **Cooling plant**
- **Heat Pump**
- **Compressed air distribution**
- **CIP**
- **Other**
- **Hot water distribution**
- **Ice water**
- **to process**
- **(hot) Ice water pack from process**
- **Room heating**
- **6000m²**
- **≈130 Electric cars**
- **≈150 Electric cars**

**Goals**

- First Dairy in Norway completely supplied by heat pumps
- Specific energy from 0.24 kWh/liter to 0.15 kWh/liter product
- 30% reduction in energy use compared to existing Dairy in Bergen

**4.2. TINE's road to get the (high temperature) heat pump, Kim Andre Lovas (TINE)**
4.2 TINE’s road to get the (high temperature) heat pump, Kim Andre Lovas (TINE)

- Research projects like HighEff/HeatUp
- State Aid ENOVA
- Research partners like SINTEF
- Good Supplyers
AGENDA

1. Background
2. Project Development
3. Integration of disciplines
4. Heat pump design
4.3. Integration of high temperature heat pumps in industry, Fridolin Müller Holm (Viegand Maagøe) & Søren Gram (Svedan Industri Køleanlæg)
4.3. Integration of high temperature heat pumps in industry, Fridolin Müller Holm (Viegand Maagoe) & Søren Gram (Svedan Industri Køleanlæg)

INTEGRATION OF DISCIPLINES

Authorities
- Municipality
- Project proposal
- Application for dispensation
- Application for construction
- Binding answer from the tax authorities
- Danish Working Environment Authority

Client
- In house engineering
- Maintenance
- Production
- Procurement
- Management
- EHS

Suppliers
- Mechanical
- Electrical
- Building
- Civil
- HEAT PUMP

District heat
- Management
- In house engineering
- Subcontractors

PROJECT DEVELOPMENT

<table>
<thead>
<tr>
<th>Power</th>
<th>Energy</th>
<th>System COP</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-7 MJ/s</td>
<td>140 TJ/year</td>
<td>18.5</td>
</tr>
<tr>
<td>(38,700 MWh/year)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
HEAT PUMP DESIGN

High process water temperatures

- High process water temperatures: 75 / 60°C
- Small lift with hot water temperatures: 72 / 85°C
- Variable water flow both sides: 100 – 50%
- Small or no sub cooling and super heating
- Two units for flexibility and optimum efficiency
- Need for suction pressure protection
- Need for closing off to compressor during stand still

HEAT PUMP PERFORMANCE DATA

<table>
<thead>
<tr>
<th>UNIT No. 1 MAYEKAWA N4HS</th>
<th>Capacity [kW]</th>
<th>100%</th>
<th>75%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSORBED POWER [kW]</td>
<td>1.816</td>
<td>1.362</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>SPEED [min⁻¹]</td>
<td>1.170</td>
<td>0.877</td>
<td>0.775</td>
<td></td>
</tr>
<tr>
<td>LOAD [%]</td>
<td>100</td>
<td>100</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>PROCESS WATER TEMP. IN/OUT [°C]</td>
<td>75/67.5</td>
<td>75/67.5</td>
<td>75/67.5</td>
<td></td>
</tr>
<tr>
<td>DISTRICT HEATING WATER TEMP. IN/OUT [°C]</td>
<td>78.5/85</td>
<td>78.5/85</td>
<td>78.5/85</td>
<td></td>
</tr>
<tr>
<td>HEATING CAPACITY [kW]</td>
<td>1.676</td>
<td>1.241</td>
<td>0.830</td>
<td></td>
</tr>
<tr>
<td>COPh electricity [-]</td>
<td>9.0</td>
<td>9.2</td>
<td>8.6</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>UNIT No. 2 MAYEKAWA N4HS</th>
<th>Capacity [kW]</th>
<th>1.504</th>
<th>1.125</th>
<th>0.752</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSORBED POWER [kW]</td>
<td>1.186</td>
<td>0.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPEED [min⁻¹]</td>
<td>1.235</td>
<td>0.920</td>
<td>0.820</td>
<td></td>
</tr>
<tr>
<td>LOAD [%]</td>
<td>100</td>
<td>100</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>PROCESS WATER TEMP. IN/OUT [°C]</td>
<td>67.5/60</td>
<td>67.5/60</td>
<td>67.5/60</td>
<td></td>
</tr>
<tr>
<td>DISTRICT HEATING WATER TEMP. IN/OUT [°C]</td>
<td>72/78.5</td>
<td>72/78.5</td>
<td>72/78.5</td>
<td></td>
</tr>
<tr>
<td>HEATING CAPACITY [kW]</td>
<td>1.676</td>
<td>1.241</td>
<td>0.830</td>
<td></td>
</tr>
<tr>
<td>COPh electricity [-]</td>
<td>9.6</td>
<td>9.9</td>
<td>9.0</td>
<td></td>
</tr>
</tbody>
</table>

TOTAL HEAT [kW] 3.334 2.484 1.668
COPh electricity [-] 9.8 10.3 9.6

International Workshop on High Temperature Heat Pumps
Steam Production from District Heating

The issue

- District heating operators are looking for new revenue streams within their footprint
- Industrial customers offer an attractive demand for energy, but often at temperatures above district heating grid level
- Commercial available high temperature heatpumps can be used to meet industrial customers demand for temperatures up to 200°C enabling district heating operators to tap into new revenue streams
Steam Production from District Heating – Case study

City of Ålesund - Northwest cost of Norway

Tafjord Kraftvarme – District heating operator

Tine Meierier - Diary

District heat
Electricity
Steam

Business model

• Tafjord Kraftvarme supplies district heating to Olvondo technology

• Olvondo Technology uses district heating as source for steam production, lifting the temperature from 85°C to 184°C using its own SPP HighLift Heatpump technology

• Tine Meierier purchases the steam produced by the Olvondo Technology heatpumps

• Long term fixed energy supply contract
  - 10y duration
  - Fixed energy prices
  - Remote operated steam production
Facts & Figures:
- 12 GWh/y steam consumption (natural gas)
- Steam temperature 184 °C (10 bar)
- Constant consumption 51 weeks per year
- Heat pump energy supply up to 9.6 GWh/y
- Energy sourced from District Heating up to 5.2 GWh/y
- District heating temperature 85°C
- 3x SPP High Lift 104-6 Heatpumps

Basic system principle

District Heating → Electric Power → Steam

SPP High Lift heatpumps installed at AstaZeneca in Mölndal, Sweden
### Deliverables

- Increased energy consumption in the district heating grid of Tafjord Kraftvarme
- Reduced energy cost for steam production at Tine Meierier
- Significantly reduced carbon emissions from the diary by 1.800 t/y less CO₂, counting for 60% of total CO₂ emissions from the diary

### Assumptions:

- Energy consumption residential subscriber of 20.000 kWh per year
- Rough estimate of monthly distribution
**SPP HighLift Heatpump**

- Stirling principle
- Helium (R704) refrigerant
- Temperature lift > 100°C
- Source temperatures in the range 0 - 100°C
- Sink temperatures up to 200°C
- 500 kW heat + 250 kW cooling in the same process
5 Plenary Discussion: "What measures will enhance the utilization of (high temperature) heat pumps in industry?"

4.1 What measures will enhance the utilisation of HTHPs in industry, Petter Nekså (SINTEF)
5.1. What measures will enhance the utilisation of HTHPs in industry, Petter Nekså (SINTEF)
5.1. What measures will enhance the utilisation of HTHPs in industry, Petter Nekså (SINTEF)

Measures to enhance utilisation of HTHPs

- Select good cases for industrial demonstration
  - Reliable technology concepts
  - Utilise desire to reduce emissions of GHGs (incl HFCs)
  - Acceptable temperature lift (COP/ROI)
  - Utilise long term acceptable refrigerants (natural refr)
- Consider industrial clusters/thermal storage and networks