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In collaboration with Neal Elliott and Ed Rightor, ACEEE
Low Temperature Industrial Processes Workshop
February 3, 2021
Fundamentals of Heat Pumps

Heat Useful (Sink), $T_{\text{sink}}$

Heat Source, $T_{\text{source}}$

Energy In: Work or Heat

$Q_{\text{sink}}$

$Q_{\text{source}}$

Heat Pump Lift Temperature

$\text{COP}_{\text{heating}} = \frac{Q_{\text{sink}}}{\text{Energy In}}$

$\text{COP}_{\text{carnot, heating}} = \frac{T_{\text{sink}}}{(T_{\text{sink}} - T_{\text{source}})}$

$\text{COP}_{\text{heating}} = \text{Carnot Eff.} \times \text{COP}_{\text{carnot, heating}}$

Heat pump Carnot Eff. ranges from ~30 - 60%

Less lift temperature equals greater heat pump efficiency
Typical HTHP heat sources and sinks

- **Space Heating**: 30°C to 70°C
- **Drying Process**: 100°C to 250°C
- **Process Heat**: Steam 100°C to 220°C, Hot water 50°C to 120°C
- **Cooling Tower**
- **Process Waste Exhaust Heat**
- **Process vapor condensation**
- **Heat Pump**
- **Ground Air Water**
- Industrial Heat Pumps: Experiences, Potential and Global Environmental Benefits

- 8 countries collaborated
- 35 processes evaluated for IHP potential across all 8 countries
- Each country performed IHP market study (see right hand box for US IHP Study)

US IHP Market Study
- US study screened 42 processes; 26 found for economic IHP potential
- 8 processes accounted for most (68%) of IHP economic energy savings
  - Corn milling
  - TMP pulp
  - Unbleached kraft linerboard
  - Beet sugar refining
  - Bleached kraft pulp
  - Bleached kraft pulp and paper
  - High fructose corn syrup
  - Synthetic rubber

https://heatpumpingtechnologies.org/annex21/
US DOE 1995 Industrial Heat Pump Market Study found 2-5% net process heat savings; 170 - 350 TBtu/yr

Exhibit ES.3
Potential IHP Net Energy Savings (Projected 2010 Savings)

| Source | Hagler Bailly, August 1994 |
|        | Prepared for Annex 21 |

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas ($/MMBtu)</td>
<td>$6.56</td>
<td>$3.85</td>
</tr>
<tr>
<td>Electricity Price (cts/kW-hr)</td>
<td>4.28 cts</td>
<td>6.83 cts</td>
</tr>
<tr>
<td>Electricity Price ($/MMBtu)</td>
<td>$22.16</td>
<td>$20.00</td>
</tr>
<tr>
<td>Electricity/Gas Price Ratio</td>
<td>3.37</td>
<td>5.19</td>
</tr>
</tbody>
</table>

Study 1995 Energy Prices
Recent energy prices are lower than in 1995

### 4 High Temperature Heat Pump Types

<table>
<thead>
<tr>
<th>Cycle Type</th>
<th>High Temperature Heat Pump Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed Cycle</td>
<td>Mechanical vapor compression heat pump</td>
</tr>
<tr>
<td>Closed Cycle</td>
<td>Heat activated heat pump: absorption or heat transformer</td>
</tr>
<tr>
<td>Open Cycle</td>
<td>Mechanical vapor re-compression (MVR) heat pump</td>
</tr>
<tr>
<td>Open Cycle</td>
<td>Thermal vapor re-compression (TVR) or steam ejector heat pump</td>
</tr>
</tbody>
</table>

**Closed Cycle Mechanical Vapor Compression Heat Pump**

**Absorption heat pump**

**Mechanical vapor recompressor**

**Steam ejector**
Heat Integration and Proper Placement of HTHPs with PINCH technology

Example Composite curves of heating and cooling streams

Example Grand Composite Curve
Heat Integration and Proper Placement of HTHPs with PINCH technology

Example Composite curves of heating and cooling streams

Example Grand Composite Curve
Heat Pump should pump heat around pinch point

$Q + W$

W

Heat Pump

Q

Heat delivery

Heat extraction

$Q_H$

$Q_C$

Pinch Point
Key IHP barriers in the US

Low level of awareness of the technical possibilities and economic feasibility among end users, engineering firms, suppliers, etc.

Lack of knowledge on how to integrate heat pumps into existing industrial processes

Lack of best practice examples to create trust in new type of process heating solution

Most times one-off, tailor-made design and many times need to be integrated to process

Long payback on investment due to low natural gas price and/or high electric to natural gas price ratio

Competing process heating energy efficiency options

Heat storage could be required

Existing technology limited by heat pump output temperature (~160 deg. C, 320 deg. F)

Limited domestic equipment suppliers – EU, Japan
Mechanical Vapor Compression Heat Pump Payback
versus Heat Pump Lift Temperature

**Assumptions**
- Waste steam heat = 100 deg C
- Heat pump size = 1 MW
- Heat pump cost = $200,000
- Hours of operation = 8,500 hrs/yr
- Heat exchanger delta T = 10 deg C
- Carnot efficiency = 45%
- Maintenance cost = 3% of capital cost
- Electricity price = 6.83 cts per kW-hr
- Natural gas price = $3.85 per MMBtu

Heat pump working fluid limit, 160 deg C
What are major technology opportunities that are NOT currently being researched?

Advanced High Temperature Heat-Activated Heat Pumps – Type 1 and 2

Absorption Heat Pump

- Type 1
  - COP ~ 1.6

- Type 2
  - COP ~ 0.5

Temperature nodes:
- $T_{\text{hot}}$
- $T_{\text{useful}}$
- $T_{\text{source}}$
- $T_{\text{ambient}}$
Example Economics for 1 MW Heat Transformer

Q sink = 1 MW @ T sink = 150 deg. C (steam)
Q source = 2 MW @ T source 100 deg. C (steam)
Q cold = 1 MW @ T cold = 30 deg. C
Heat Transformer Cost = $1.5 Mil ($1,500 per kW, pilot unit)
Annual maintenance cost = 2% of 1.5 Mil = $30,000 per year
Electricity requirements = 40 kW
Electricity price = 6.83 cts per kW-hr
Operating hours = 8,760 hrs per year
Annual electricity cost = $24,000 per year
Total operating cost = $54,000
Natural gas cost = $3.85 per MMBtu (avg. US industrial price, 2019)
Steam cost = $5.90 per 1000 lb steam
Steam cost savings¹ = $194,000 per year

Payback = $1,500,000 / ($194,000 - $54,000) = 10.7 yrs

Note 1 – assume 1MW Heat Transformer produces 3750 lbs steam per hr @ 150C and avoids boiler steam and cooling tower costs @ $5.90 per 1000 lbs steam. Boiler steam costs account for energy cost (natural gas cost and boiler combustion efficiency) and chemical cost needed to treat boiler water.
Private communication Riyaz Papar, January, 2021
Heat Transformer Payback versus Natural Gas Price

Assumptions:
- Waste steam heat = 100 deg C
- Heat pump size = 1 MW
- Heat pump delivery temp. = 150 deg C
- Heat pump lift temp. = 60 deg C
- Hours of operation = 8,760 hrs/yr
- Maintenance cost = 2% of capital cost
- Electricity consumption = 4% of heat delivery
- Electricity price = 6.83 cts per kW-hr

Heat transformer specific capital cost:
- $1,500 / kW
- $1,200 / kW
- $900 / kW

Avg. US industrial price (2019): $4.67 per MMBtu
Emerging heat-activated heat pump technology

QPinch

Heat-activated heat pump by reversible chemical reaction

phosphoric acid to diphosphoric and water

$$\text{H}_4\text{P}_2\text{O}_7 + \text{H}_2\text{O} \rightleftharpoons 2\text{H}_3\text{PO}_4$$

$$T_{\text{sink}}$$ up to 220 deg. C

Minimal electricity requirements; waste heat-driven

Lift temperature = 40 - 100 deg. C

Multi megawatt demos planned; independent validation needed for:
- Cost and performance
- Reliability and material durability
- Impact on process control
What are the most critical research priorities in HTHPs?

• **Heat-activated heat pumps R&D should focus on:**

  - Developing various Type 1 and 2 cycles and configurations to demonstrate performance and cost
  - Demonstrate heat pump material durability in actual industrial settings and conditions.
  - Demonstrate heat pump operability and reliability in varied industrial processes to prove out economics
  - Prove heat pump working fluids are safe and environmentally benign

• **Technology development R&D targets**

  - Specific capital cost (total installation) < $1,000 per kW
  - Heat delivery > 200 deg. C and ideally > 250 deg. C
  - Lift temperature up to 100 deg. C
Conclusions

There’s reason to be optimistic about High Temperature Heat Pumps

1. **New perspective by industry:** Companies that are serious about decarbonizing their energy footprints will consider HTHPs if they yield significant (>5 – 10%) energy savings and decarbonization at a reasonable payback, e.g., less than 5 years.

2. **R&D justified to build domestic High Temperature Heat Pump industry:** Advanced heat-activated heat pumps could be a game-changer to greatly expand the number of economic opportunities in the US process industries even with only modest increases in natural gas prices. Cost-shared R&D in the US should help build the domestic supplier base for high temperature heat pumps.

3. **Technology development is not enough:** Further technology development is needed and justified but needs to be coupled with effective energy policy and/or incentives to motivate all participants in HTHP market – end users, vendors, engineering firms and energy efficiency program administrators/utilities.
Background Slides
### Mechanical vapor compression heat pumps; reference Cordin Arpagaus, 2020

#### Supplier update – market overview

**Selection of industrial heat pumps with heat supply temperature $\geq 90^\circ\text{C}$**

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Country</th>
<th>Product</th>
<th>Refrigerant</th>
<th>Max. $T_{\text{Supply}}$</th>
<th>Heating capacity</th>
<th>Compressor type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kobe Steel</td>
<td>Japan</td>
<td>SGH 165</td>
<td>R134a/R245fa</td>
<td>165 $^\circ\text{C}$</td>
<td>70 – 660 kW</td>
<td>Double screw</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SGH 120</td>
<td>R245fa</td>
<td>120 $^\circ\text{C}$</td>
<td>70 – 370 kW</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>HEM-HP10,-90A</td>
<td>R134a/R245fa</td>
<td>90 $^\circ\text{C}$</td>
<td>70 – 230 kW</td>
<td></td>
</tr>
<tr>
<td>Viking Heating Engines AS</td>
<td>Norway</td>
<td>HeatBooster</td>
<td>R1336mzz(Z)</td>
<td>160 $^\circ\text{C}$</td>
<td>28 – 188 kW</td>
<td>Piston</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HeatBooster S4</td>
<td>R245fa</td>
<td>130 $^\circ\text{C}$</td>
<td>92 – 172 kW</td>
<td>(4 parallel)</td>
</tr>
<tr>
<td>Ochsner</td>
<td>Germany</td>
<td>IWWDS S2R3b</td>
<td>R134a/ÖKO1</td>
<td>130 $^\circ\text{C}$</td>
<td>170 – 750 kW</td>
<td>Screw (TWIN unit upto 1.5 MW)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IWWDS ER3b</td>
<td>ÖKO1 (R245fa)</td>
<td>130 $^\circ\text{C}$</td>
<td>120 – 400 kW</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>IWWHS ER3b</td>
<td>ÖKO1 (R245fa or R1233zd)</td>
<td>95$^\circ\text{C}$</td>
<td>60 – 840 kW</td>
<td></td>
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<tr>
<td>Frigopol (&amp; AIT)</td>
<td>Norway</td>
<td>HighButane 2.0</td>
<td>R600</td>
<td>130 $^\circ\text{C}$</td>
<td>50 kW</td>
<td>Piston</td>
</tr>
<tr>
<td>Hybrid Energy</td>
<td>Norway</td>
<td>Hybrid Heat Pump</td>
<td>R717 (NH$_3$)</td>
<td>120 $^\circ\text{C}$</td>
<td>0.25 – 2.5 MW</td>
<td>Piston</td>
</tr>
<tr>
<td>Mayekawa</td>
<td>Norway</td>
<td>Eco Sirocco</td>
<td>R744 (CO$_2$)</td>
<td>120 $^\circ\text{C}$</td>
<td>65 – 90 kW</td>
<td>Screw</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eco Cute Unimo</td>
<td>R744 (CO$_2$)</td>
<td>90 $^\circ\text{C}$</td>
<td>45 – 110 kW</td>
<td></td>
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<tr>
<td>Combitherm</td>
<td>Germany</td>
<td>HWW 245fa</td>
<td>R245fa</td>
<td>120 $^\circ\text{C}$</td>
<td>62 – 252 kW</td>
<td>Piston</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HWW R1234ze</td>
<td>R1234ze(E)</td>
<td>95 $^\circ\text{C}$</td>
<td>85 – 1301 kW</td>
<td></td>
</tr>
<tr>
<td>ENGIE (ex-Dürr thermo)</td>
<td>Germany</td>
<td>Thermocool, HHR</td>
<td>R744 (CO$_2$)</td>
<td>110 $^\circ\text{C}$</td>
<td>45 – 1200 kW</td>
<td>Piston (up to 6 parallel)</td>
</tr>
<tr>
<td>Oilon</td>
<td>Norway</td>
<td>ChillHeat</td>
<td>R134a</td>
<td>100 $^\circ\text{C}$</td>
<td>30 – 1000 kW</td>
<td>Piston (up to 6 parallel)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>P60 bis P450</td>
<td>R1234ze(E)</td>
<td>95 $^\circ\text{C}$</td>
<td>0.6 – 3.6 MW</td>
<td>Turbo (two-stage)</td>
</tr>
<tr>
<td>Friotherm</td>
<td>Switzerland</td>
<td>Uniflow 22</td>
<td>R1234ze(E)</td>
<td>90 $^\circ\text{C}$</td>
<td>9 – 20 MW</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Uniflow 50</td>
<td>R134a</td>
<td>90 $^\circ\text{C}$</td>
<td>9 – 20 MW</td>
<td></td>
</tr>
<tr>
<td>Star Refrigeration</td>
<td>UK</td>
<td>Neatpump</td>
<td>R717 (NH$_3$)</td>
<td>90 $^\circ\text{C}$</td>
<td>0.35 – 15 MW</td>
<td>Screw (Vilter VSHY 76 bar)</td>
</tr>
<tr>
<td>GEA Refrigeration</td>
<td>UK</td>
<td>GEA Grasso</td>
<td>R717 (NH$_3$)</td>
<td>90 $^\circ\text{C}$</td>
<td>2 – 4.5 MW</td>
<td>Double screw (63 bar)</td>
</tr>
<tr>
<td>Johnson Controls</td>
<td>Norway</td>
<td>HeatPAC HPX</td>
<td>R717 (NH$_3$)</td>
<td>90 $^\circ\text{C}$</td>
<td>326 – 1324 kW</td>
<td>Piston (60 bar)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HeatPAC Screw</td>
<td>R717 (NH$_3$)</td>
<td>90 $^\circ\text{C}$</td>
<td>230 – 1315 kW</td>
<td>Screw</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Titan OM</td>
<td>R134a</td>
<td>90 $^\circ\text{C}$</td>
<td>5 – 20 MW</td>
<td>Turbo</td>
</tr>
<tr>
<td>Mitsubishi</td>
<td>Japan</td>
<td>ETW-L</td>
<td>R134a</td>
<td>90 $^\circ\text{C}$</td>
<td>340 – 600 kW</td>
<td>Turbo (two-stage)</td>
</tr>
<tr>
<td>Viessmann</td>
<td>Germany</td>
<td>VitoCal 350-HT Pro</td>
<td>R1234ze(E)</td>
<td>90 $^\circ\text{C}$</td>
<td>148 – 390 kW</td>
<td>Piston (2 to 3 in parallel)</td>
</tr>
</tbody>
</table>

A2EP Briefing: Advances in industrial heat pumps – 3 September 2020

[16]
Figure 11. Ratio of industrial electricity to gas price by state. Calculation based on average annual electricity prices and Henry Hub natural gas prices within states. Sources: EIA 2020b, 2020e.
Market challenges

Electricity to gas price ratio

For small scale industrial end-users with
2 GWh/a to 20 GWh/a electricity
3 GWh/a to 28 GWh/a gas
# IHP types: Pros and Cons

What are the pros and cons of various HTHP types?

<table>
<thead>
<tr>
<th>Type</th>
<th>Prime Mover</th>
<th>Pros</th>
<th>Cons</th>
<th>Typical COP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed cycle compression</td>
<td>Electricity (Motor) or Fuel (Heat Engine)</td>
<td>- Good COP for moderate lift temperature</td>
<td>- Requires low electric-fuel price ratio</td>
<td>3 to 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Multiple vendors</td>
<td>- Limited supply temperature to ~320F supply</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Electricity only on site</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat-activated (Type 1)</td>
<td>Fuel (Process Heat or Steam)</td>
<td>- Uses lower cost fuel as driver</td>
<td>- High CapEx</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Minimal moving parts</td>
<td>- Limited vendors</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Higher supply temperature ~400F</td>
<td>- Emerging technology</td>
<td></td>
</tr>
<tr>
<td>Heat-activated (Type 2)</td>
<td>Waste heat</td>
<td>- Uses free waste heat as driver</td>
<td>- High CapEx</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Minimal moving parts</td>
<td>- Limited vendors</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Higher supply temperature ~400F</td>
<td>- Emerging technology</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>- Requires cold sink</td>
<td></td>
</tr>
<tr>
<td>MVR</td>
<td>Electricity (Motor) or Fuel (Heat Engine)</td>
<td>- Good COP for moderate lift temperature</td>
<td>- Requires low electric-fuel price ratio</td>
<td>3 to 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Electricity only on site</td>
<td>- High speed compressor</td>
<td></td>
</tr>
<tr>
<td>TVR</td>
<td>Steam</td>
<td>- Low CapEx</td>
<td>- Low energy efficiency</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Simple and low maintenance</td>
<td></td>
<td></td>
</tr>
</tbody>
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