2016 Purdue Conferences
Multi-Temperature Heat Pumps –
A Literature Review

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\textbf{SCCER}
EFFICIENCY OF INDUSTRIAL PROCESSES

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Outline

1. Motivation
2. Objectives
3. Heat pump cycles for multi-temperature applications
4. Advantages and challenges
5. Simulation study (COP, 2\textsuperscript{nd} Law efficiency) – comparison of cycles
6. Conclusions
Motivation

- Requirements of **heating & cooling at different temperature levels** at the same time
- **Upgrading low quality heat**
- **Research question:** Which multi-temperature heat pump cycles are reported in the literature?

![Diagram of potential heat sources and heat sinks](image)

- **Heat Sources**:
  - Ground Air Water
  - Cooling Tower
  - Waste Exhaust Heat Excess
  - Vapor Condensation

- **Heat Sinks**:
  - Space Heating
  - Drying Process
  - Process Heat

- **Temperature Ranges**:
  - > 35°C
  - > 70°C
  - 120 – 150°C
  - > 15°C
  - > 30°C
  - 50 – 100°C
  - -10 – 25°C

- **Single-stage heat pump cycle**

- **More advanced cycles are needed**

adapted from IEA (2014)
International Energy Agency
Objectives

1. **Screening of research activity** based on publications with focus on cycles with heating/cooling at **two temperature levels**
2. **Identification of design strategies** to reach multi-temperature levels
3. **Classification** of identified cycles
4. **Identification of trends** and research areas
5. **Comparison of cycles**
   1. COP (1st Law) and exergetic efficiency (2nd Law efficiency)
   2. Thermodynamic simulation based on EES software (Klein, 2015)

**Extended version of this study:**
Cordin Arpagaus, Frédéric Bless, Jürg Schiffmann, Stefan S. Bertsch,
SUPERMARKET REFRIGERATION

Multi-stage compressors
Cascades
(Multi)-ejectors

ambient air
+25°C

fresh food
+2°C

frozen food
-23°C
SUPERMARKET REFRIGERATION

Multi-stage compressors

Transcritical CO₂ booster system

HT: 21 to 32°C
MT: -10 to -5°C
LT: -35 to -30°C

(Advansor, 2015; Bitzer, 2014; Sharma et al., 2014)
SUPERMARKET REFRIGERATION

Cascades

Cascade cycle with secondary loop

HT: ambient air
MT: -7°C
LT: -29°C

(Bitzer, 2014; Hill Phoenix, 2011; Sharma et al., 2014)
**SUPERMARKET REFRIGERATION**

**(Multi)-Ejectors**

Multiple ejector cycle with CO₂

(Hafner et al., 2014; Schönenberger, 2014, 2013)
HOUSEHOLD REFRIGERATION

Expansion valves

Ejector

ambient air
+25°C

fresh food
+5°C

frozen food
-18°C
HOUSEHOLD REFRIGERATION

Expansion valves

Parallel expansion valve cycle with two evaporators

(Visek et al., 2014; Yoon et al., 2011, 2010)
HOUSEHOLD REFRIGERATION

Ejector

Subcritical ejector cycle

HT: 28 to 44°C
MT: -5 to 10°C
LT: -40 to -20°C

(Elakhdar et al., 2007)
AUTOMOTIVE AIR CONDITIONING

Expansion valve cycles

Ejector cycles

cooler
+40°C

cool air
+5°C

battery cooling
+20°C

HOUSEHOLD WATER HEATING

Multi-stage compressors
Cascades
Separated Gas Coolers

ground source +5°C

tsolar +40°C

hot water +60°C

Image Source: www.yorkshireenergysolutions.co.uk
HOUSEHOLD WATER HEATING

Separated Gas Cooler

Separated gas cooler and desuperheater for combined space and hot water heating

(Blanco et al. 2012, 2013a, 2013b)

HT: 65°C
MT: 30 to 45°C
LT: -5 to 5°C

R410A

Enthalpy

Pressure
INDUSTRIAL
WASTE HEAT RECOVERY

process heat +120°C

Multi-stage compressors

Cascades

drying process +70°C

waste heat +40°C

Image Source: https://commons.wikimedia.org/w/index.php?curid=7500704
<table>
<thead>
<tr>
<th>Application</th>
<th>Reference, Year</th>
<th>Multi-stage compressor</th>
<th>Multiple ejector</th>
<th>Expansion valve</th>
<th>Cascade</th>
<th>Secondary loop</th>
<th>Supported gas cooler</th>
<th>Refrigerant</th>
<th>Technology Readiness Level</th>
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Design strategies – classification of cycles

Cycles for multi-temperature heat pumps

Multi-stage cycles
- Multi-stage compressor
  - Industry: supermarket, heating, domestic hot water
  - Challenge: oil migration
  - TRL: key technology in supermarkets
- Expansion valve
  - Industry: household refrigeration
  - Challenge: energy efficiency
  - TRL: established in industry
- Ejector
  - Industry: supermarket
  - Challenge: capacity control
  - TRL: prototype in industry, publications
- Multi-ejector
  - Industry: supermarket
  - Challenge: capacity control
  - TRL: prototype status in industry

Cascade cycles
- Cascade
  - Industry: supermarket, high temperature heat pumps
  - Challenge: temperature gap
  - TRL: established in industry

Secondary loop
- Secondary loop
  - Industry: supermarket
  - Challenge: temperature gap and pumping losses
  - TRL: established in industry

Separated gas cooler
- Separated gas cooler
  - Industry: water heating in residential buildings
  - Challenge: energy efficiency
  - TRL: under development, publications

TRL: Technology Readiness Level (status 2016)
Comparison of cycles – efficiency analysis

Ref
Reference cycle with two parallel heat pumps

MC 1
Multi-stage compressor cycle with subcooler
(Stoecker, 1998)

MC 2
with open economizer
(Granwehr and Bertsch, 2012; Uhlmann et al., 2014)

MC 3
with closed economizer
(Granwehr and Bertsch, 2012)

MC 4
with booster system
(Advansor, 2015; Bitzer, 2014; Sharma et al., 2014)

CAS
Cascade
(Dincer & Kanoğlu, 2010; Kanoğlu, 2002)

EXV
Expansion valve
(Visek et al., 2014; Yoon et al., 2010, 2011)

EJ
Ejector
(Elakhdar et al., 2007)
Thermodynamic models - Assumptions

1. no pressure drops, no heat losses
2. no superheating, no subcooling
3. ideal heat exchangers and separators
4. cascade heat exchanger ($\Delta T_{CAS} = 5^\circ C$)
5. isenthalpic expansion
6. isentropic compressor efficiency ($\eta_c = 0.7$)
7. ejector model approach according to Kornhauser (1990)
   • 80% efficiencies for motive nozzle, suction nozzle and diffuser

Example: Ejector (EJ) cycle
### Operating conditions for the simulation

#### Heating Application

<table>
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<th>Examples</th>
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<td>• industrial heat pump</td>
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<td>• household heating</td>
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<td>• solar applications</td>
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<td>• water heating</td>
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<tr>
<th>$T_{HT}$  (heat sink)</th>
<th>60 °C (hot water)</th>
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<tbody>
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<td>$T_{MT}$  (2\textsuperscript{nd} heat source)</td>
<td>30°C (waste heat)</td>
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<td>$T_{LT}$  (1\textsuperscript{st} heat source)</td>
<td>0°C (brine)</td>
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#### Ratio of the two heat sources
\[
\beta = \frac{\dot{Q}_{MT}}{\dot{Q}_{MT} + \dot{Q}_{LT}}
\]

#### COP cycle
\[
COP_{cycle} = \frac{\dot{Q}_{HT}}{W_{el,1} + W_{el,2}}
\]

#### Efficiency 2nd
\[
\eta_{2nd} = \frac{COP_{cycle}}{COP_{Carnot}}
\]

#### COP Carnot
\[
COP_{Carnot} = f(\beta, COP_{Carnot,LT}, COP_{Carnot,MT})
\]
Simulation Results - First and Second Law Efficiencies

\[ \beta = \frac{\dot{Q}_{MT}}{\dot{Q}_{MT} + \dot{Q}_{LT}} \]

heat supply ratio across the LT and MT evaporators

Heating Application
\( T_{HT} = 60^\circ C, T_{MT} = 30^\circ C, T_{LT} = 0^\circ C \)

Ref Reference cycle (two parallel heat pumps)
MC 1 Multi-stage compressor cycle with subcooler
MC 2 with open economizer
MC 3 with closed economizer
MC 4 with booster system
CAS Cascade cycle
EXV Expansion valve cycle
EJ Ejector cycle
Conclusions

1. **Design strategies for multi-temperature heat pumps:**
   - Multi-stage compressors, cascades (with secondary loops), expansion valves, (multiple) ejectors, and separated gas coolers
   - Most heat pump designs use two heat sources and one heat sink

2. **Multi-temperature applications**
   - Major part in refrigeration (supermarket, households)
   - Domestic space heating and hot water production

3. **Simulation of COP and 2nd Law efficiency - cycle comparison**
   - Multi-stage compressor > cascade > ref > ejector > expansion valve cycles

4. **Outlook – current R&D efforts**
   - Multiple ejectors in transcritical CO2 cycles (efficiency improvement)
   - Multi-stage compressors with better capacity control and intercooling
   - Oil-free compressors
   - Natural refrigerants with low ODP and GWP
Thank you for your attention!

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WEBLINK