EFFICIENT HEAT PUMPS AND TERMINALS
FOR DIFFERENT CLIMATE ZONES

Ruzhu WANG
Shanghai Jiao Tong University

The 8th International Conference
on Compressor and Refrigeration
Xi’an, July 20-22, 2017
Outline

1. Introduction

2. The definition of climate zone in China

3. Hot-summer and cold-winter zone

4. Cold region

5. Severe cold region

6. Conclusions and perspectives
Introduction

Since the establishment of PR. China, the space heating technologies in China has been developed rapidly.

The 1950s
Learned from USSR

In 1975
The first draft of heating and ventilation design specification

The 1980s
Rapid development period of district heating

21st century
A lot of new technologies and new products

There are more than 300 cities in China with district heating facilities, and more than 500 large and medium-sized thermal energy companies.
Introduction

The applications of new technologies

- power plants with high parameter and large capacity
- the condensing power plant was reformed to thermal power plant
- the steam supply system changed into hot water heating system
- the wide use of prefabricated heating pipes
- development of huge boiler for large heating area
- comprehensive application of automatic control technology
Introduction

- The latest version of "Code for design of heating, ventilation and air conditioning for civil buildings (GB50736-2012)" was released in 2012.

- The new technologies includes heat and power cogeneration, household boiler, distributed heating, solar heating, heat pump technology.

- Space heating mainly depended on heat and power cogeneration, supplemented by centralized boiler, gradually replaced by other advanced and efficient heating methods.

- The central and local levels of government have made great efforts to adjust the energy structure, promote diversified heating methods and realize sustainable development.
**Introduction: development stages**

1. **the heat carrier is steam**; concrete ducts, steam traps, and compensators; replace individual boilers to reduce the risk of boiler explosions

2. **supply water temperature is over 100°C**; large tube-and-shell heat exchangers and heavy valves; achieve fuel savings and better comfort by utilizing CHP

3. **hot water temperatures is below 100°C**; prefabricated components, pre-insulated pipes; replacing oil with various cheaper fuels: coal, biomass and waste

4. **lower distribution temperature**; thermal grids with smart control; higher energy efficiency; assembly-oriented components; various renewable energy
Introduction

In China: Clean heating from coal to electric

- Fog Haze .......... “煤改电”政策
- ASHP for heating, a new market was born!
Outline

1. Introduction

2. The definition of climate zone in China

3. Hot-summer and cold-winter zone

4. Cold region

5. Severe cold region

6. Conclusions and perspectives
The climate zone in China

1) Harbin for SC, Beijing for C, Shanghai for HSCW, Guangzhou for HSWW and Kunming for M.

2) In January, outdoor temperature in Harbin is 35°C lower than that in Guangzhou.

3) In July, Guangzhou is no more than 10°C warmer than Harbin.

China Meteorological Administration, Tsinghua University, Meteorological Data for Built Thermal Environment Analysis in China, China Architecture &Building Press, Beijing, China, 2005 (in Chinese).
The climate zone in China

- A big challenge to develop the space heating systems for different climate zones
  - district heating
  - household base heating
  - individual heating
- How do the local people select the most efficient heat pump and terminals
  - single stage compression
  - vapor injection
  - multi-stage, cascade heat pump
  - transcritical CO$_2$ system
- Seldom studies focusing on the comparison between climatic zones (especially for winter condition) conducted in China
Outline

1. Introduction

2. The definition of climate zone in China

3. Hot-summer and cold-winter zone

4. Cold region

5. Severe cold region

6. Conclusions and perspectives
Single-stage vapor compression cycle consists of a compressor, an expansion valve and two heat exchangers served as evaporator and condenser, respectively.

Single stage compression HP (a) Schematic diagram; (b) $p-h$ diagram
Hot-summer and cold-winter zone

Problems caused by air conditioner heating

1. The poor temperature distribution in heating room

2. Repeated defrosting makes COP lower, room uncomfortable
3. Low COP for heating: high pressure ratio in winter

<table>
<thead>
<tr>
<th>Condition</th>
<th>Shanghai Summer</th>
<th>Shanghai Winter</th>
<th>Nanjing Summer</th>
<th>Nanjing Winter</th>
<th>Wuhan Summer</th>
<th>Wuhan Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor aver temp/°C</td>
<td>30</td>
<td>1.5</td>
<td>28.1</td>
<td>-0.1</td>
<td>28.9</td>
<td>0.7</td>
</tr>
<tr>
<td>Room temp/°C</td>
<td>25</td>
<td>20</td>
<td>25</td>
<td>20</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>Evap temp/°C</td>
<td>5</td>
<td>-8.5</td>
<td>5</td>
<td>-10.1</td>
<td>5</td>
<td>-9.3</td>
</tr>
<tr>
<td>Cond temp/°C</td>
<td>40</td>
<td>50</td>
<td>38.1</td>
<td>50</td>
<td>38.9</td>
<td>50</td>
</tr>
<tr>
<td>R22 P ratio</td>
<td>3.19</td>
<td>5.21</td>
<td>3.06</td>
<td>5.66</td>
<td>3.1</td>
<td>5.5</td>
</tr>
<tr>
<td>R410a P ratio</td>
<td>2.59</td>
<td>5.08</td>
<td>2.47</td>
<td>5.33</td>
<td>2.52</td>
<td>5.15</td>
</tr>
</tbody>
</table>

Deviation of design condition and operating conditions

(GB 18430) “力不从心” (Statistics) “大材小用” (GB 18430)

7°C Conventional HP 1.5°C Low temperature HP -12°C
Hot-summer and cold-winter zone

Schematic diagram of the single-stage compression heat pump [13]
Hot-summer and cold-winter zone

- Compared with the conventional air conditioner, the heat pump system is equipped with a 4-way valve which can switch the flow direction in the system to operate in heating mode or cooling mode.
- There are also two expansion valves and one-way valves for heating or cooling, respectively.
- There is a receiver in the system to balance the difference of the refrigerant.
- A suction line accumulator is added to prevent the compressor from exposing to liquid drops.
Hot-summer and cold-winter zone

Typical applications of heat pump for hot water, heating and cooling
Hot-summer and cold-winter zone

New products based on comfort and high efficient heating
Hot-summer and cold-winter zone

Small temperature difference fan-coil unit

NFCU

Air: 38-21°C
Water: 45-40°C

STDFCU

Air: 32-21°C
Water: 35-32°C
The supplied hot water temp from the ASHP

7°C ambient

The 8th International Conference on Compressors and Refrigeration, 2017
Development of small temperature difference fan-coil unit

**Structure parameters**
- \( L: 1.24 \text{m} \)
- \( W: 0.13 \text{m} \)
- \( H: 0.41 \text{m} \)

**Typical heating conditioning**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat trans Area m(^2)</td>
<td>4.2</td>
</tr>
<tr>
<td>Delta T °C</td>
<td>7.8</td>
</tr>
<tr>
<td>Air flow rate m(^3)/h</td>
<td>450</td>
</tr>
<tr>
<td>Water flow rate L/s</td>
<td>0.11</td>
</tr>
<tr>
<td>Air inlet T °C</td>
<td>21</td>
</tr>
<tr>
<td>Air outlet T °C</td>
<td>36</td>
</tr>
<tr>
<td>Water inlet T °C</td>
<td>40</td>
</tr>
<tr>
<td>Water outlet T °C</td>
<td>35.2</td>
</tr>
<tr>
<td>Heating power W</td>
<td>2190</td>
</tr>
</tbody>
</table>
The system includes: an ASHP unit with rated heating capacity of 9.5 kW, a 150 L water tank and small temperature difference fan-coil units.
Hot-summer and cold-winter zone

✓ An ASHP is installed in a 92m² apartment in SJTU.
✓ The ASHP unit’s heating capacity in this experiment is 9500W and power is 2370W.
The average outdoor temperatures are 8.8°C, 7.3°C, 6.4°C, respectively.

The return water temperatures are set to 30°C, 35°C, 40°C, respectively.

Average air temperature in different rooms during the test/ °C

<table>
<thead>
<tr>
<th></th>
<th>Living</th>
<th>Dining</th>
<th>Kitchen</th>
<th>North Bed</th>
<th>South Bed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day1</td>
<td>19.5</td>
<td>19.2</td>
<td>18.5</td>
<td>20.1</td>
<td>21.8</td>
</tr>
<tr>
<td>Day2</td>
<td>19.9</td>
<td>20.0</td>
<td>19.2</td>
<td>21.3</td>
<td>23.3</td>
</tr>
<tr>
<td>Day3</td>
<td>19.8</td>
<td>20.2</td>
<td>19.5</td>
<td>21.5</td>
<td>23.6</td>
</tr>
</tbody>
</table>
Hot-summer and cold-winter zone

Energy consumption and COP of ASHP with STDFCU at different supplying hot water temp for heating
### ASHP heating at the extremely cold conditions in Shanghai in Jan.2016

<table>
<thead>
<tr>
<th>Exp. On 3 days</th>
<th>Return hot water T, °C</th>
<th>FCU set room air, °C</th>
<th>Out door air Average T, °C</th>
<th>Fan Coil Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-1</td>
<td>40</td>
<td>22</td>
<td>-4.8</td>
<td>Automatic gear</td>
</tr>
<tr>
<td>8-1</td>
<td>35</td>
<td>22</td>
<td>2.5</td>
<td>Automatic gear</td>
</tr>
<tr>
<td>9-1</td>
<td>30</td>
<td>22</td>
<td>-4</td>
<td>Automatic gear</td>
</tr>
</tbody>
</table>

![Graph showing space temperature](image.png)

System COP=3.0
Hot-summer and cold-winter zone

Further test in SJTU-GEL

装有不同类型末端的实验室
1. Normal FCU
2. Small deltaT FCU
3. Floor heating

中意绿色能源楼
Sino-Italian GEL
Hot-summer and cold-winter zone Test System
Hot-summer and cold-winter zone

Research Results

- Comfortable
- High efficiency
- Economic
- Comfortable cooling option
- Low initial investment
- Option to make hot water
Outline

1. Introduction
2. The definition of climate zone in China
3. Hot-summer and cold-winter zone
4. Cold region
5. Severe cold region
6. Conclusions and perspectives
Cold region

- **Vapor injection cycle**

![Diagram of vapor injection cycle with labeled components: Condenser, Compressor, Evaporator, IHE, and Expansion devise.]

(a) internal heat exchanger
Cold region

Vapor injection cycle

- Condenser
- Expansion device
- Compressor
- Evaporator

(b) Flash tank
Cold region

EVI compressor: low temperature application

Outlet water temperature (°C)

Ambient temperature (°C)

EVI heat pump
Cold region

Cold region

- COP increases a lot with outdoor air temperature increasing.
- Defrost energy consume is also considered in the frosting zone.
- Lower the condensation temperature can improve the COP greatly.

Heating COP under different outdoor air temperature

To make the water supply temperature as low as possible, the more suitable terminals in cold region of China are radiant floor heating or STDFCU.
Cold region

Radiant floor heating (Underfloor heating) is a form of central or distributed heating terminal which achieves indoor climate control for thermal comfort using heat conduction, radiation and convection.
Advantages of radiant floor heating:

- The temperature distribution from floor to ceiling is uniform, which could provide an acceptable thermal environment.
- It is more efficient than baseboard heating and usually more efficient than forced-air heating because it eliminates duct losses.
- The supply hot water and return water temperature for underfloor radiator is 45°C and 35°C, or even lower.
Cold region

(a) COP as a function of outdoor temperature ($t_o$) and water production temperature ($t_p$); (b) Part load operation (Edwards and Finn).


Cold region

- the unit COP can be greatly improved with water production temperature decreasing for the same outdoor air temperature.
- when the outdoor air temperature is \(-15^\circ C\), the unit COP is about 1.6 with the 50\(^\circ C\) hot water produced. However, the unit COP can be increased to 2.1 with the 35\(^\circ C\) hot water produced.
- the radiant floor heating with low temperature water supply can be adopted to satisfy the heating demand and keep the ASHP unit operating with high efficiency.

Cold region


Schematic diagram of EVI-ASHP and radiant floor heating system
The 8th International Conference on Compressors and Refrigeration, 2017

Cold region

Dry-bulb temperature and relative humidity

The predicted and measured COP

- The COP of heat pump in December 1\textsuperscript{st} in Lanzhou is above 2.5.
- Water inlet temperature in double-pipe heat exchanger is 40\textdegree C.
- The experimental COP is lower than predicted ones because of the lower environmental temperature.
Cold region

EVI-ASHP and floor heating system/STDFCU
Outline

1. Introduction
2. The definition of climate zone in China
3. Hot-summer and cold-winter zone
4. Cold region
5. Severe cold region
6. Conclusions and perspectives
Severe cold region

Efficient heat pump systems

Compression efficiency

Two stage compression

Three stage compression

Cascade heat pump system

Combined heat pump system

System performance

Large temperature lift

Lower outdoor temperature
Severe cold region

Two stage compression cycle

- Subcooler
- Condenser
- Flash tank
- Evaporator

Diagram showing the process:

1. Evaporator
2. Subcooler
3. Condenser
4. Flash tank
5. Stage II
6. Stage I

Thermodynamic diagrams with variables:

- $T$ vs $S$
- $p$ vs $h$
- $p_c$, $p_m$, $p_e$
Severe cold region

- Three stage compression cycle

- Condenser
- Flash tank
- Subcooler
- Stage III
- Stage Π
- Stage I
- Evaporator

- T Diagram:
- p Diagram:
- h Diagram:
Severe cold region

Centrifugal heat pump with multi-stage compression

➢ The hot water supply and return temperatures were 45.1 °C and 35.6 °C respectively.

➢ COP of centrifugal heat pump were 6.95.

Severe cold region

- **Cascade heat pump system**

  - Condenser
  - High stage compressor
  - Expansion devise
  - Cascade heat exchanger
  - Low stage compressor
  - Expansion devise
  - Evaporator

Graphs showing temperature and pressure changes in the system.
Severe cold region

- Combined transcritical CO₂ and R134a heat pump

- R134a subsystem

- Transcritical CO₂ heat pump
Severe cold region

Heat pump system with two-stage variable volume ratio compressor

Air source heat pump with two-stage variable volume ratio compressor. [Link](http://news.ehvacr.com/people/2016/1121/99877.html)
The two-stage variable volume ratio compressor has three cylinders (high pressure cylinder, low pressure cylinder 1 and low pressure cylinder 2).

The compressor can operate in a wide-range of ambient temperature (-35°C to 54°C).

When the outdoor air temperature is -20°C, the heating COP of such two-stage heat pump is 6.5% higher than conventional two-stage heat pumps.

The heating COP of such two-stage heat pump can be kept at 1.5 when the outdoor air temperature is -30°C.
Severe cold region

Heating COP of GREE and conventional two-stage heat pumps

![Graph showing heating COP at different outdoor air temperatures for GREE and conventional two-stage heat pumps with hot water temperatures of 41°C and 55°C.](image)
Severe cold region

A new kind of bimetal radiator

- High efficiency
- Excellent heat convection
- Stability
- Combined with ASHP
- Anti-corrosion
- Good heat conductivity
Severe cold region

(a) A picture of bimetal radiator

(b) Structure of bimetal radiator

A new kind of Unbeatable bimetal radiator

- Both natural and forced convection heat transfer are adapted.
- The supply water temperature can be as low as 40°C.
- Maximize the heating output by heat conduction and convection.

Severe cold region

XJTU:
Schematic of the combined R134a and transcritical CO₂ heat pump (CRTCHP)

Severe cold region

System performance of CRTCHP with the feed and supply water temp. of 50 and 70°C

- Heating capacity and power consumption decreased by 26% and 12% when ambient temperature decreased from 0 to -20°C.
- The heating capacity decreases slower than total power consumption.

Severe cold region

- An application case is located in Shunyi district of Beijing.
- The original heating method is coal-fired boiler combined radiator.
- The coal-fired boiler is replaced with the combined R134a and transcritical CO₂ heat pump.
- Radiators and heating pipeline inside the building is kept.
- Suitable defrosting method is necessary in operating.

Outline

1. Introduction
2. The definition of climate zone in China
3. Hot-summer and cold-winter zone
4. Cold region
5. Severe cold region
6. Conclusions and perspectives
Conclusions and perspectives

Climate Zones

- HSCW zone
- Cold region
- Severe cold region

Efficient Heat Pumps and Terminals

- Conventional heat pump with STDFCU
- Vapor injection heat pump and radiant floor heating/STDFCU
- Two stage heat pump and new bimetal radiator/radiant floor heating terminals, cascade heat pump or combined R134a and transcritical CO₂ heat pump
Conclusions and perspectives

COP of favorable heat pump system for different climate zone
Conclusions and perspectives

- For hot-summer and cold-winter zone, the conventional heat pump can meet the requirement of heating in winter and cooling in summer as long as the suitable terminal is selected, such as STDFCU.

- In cold region, vapor injection heat pump and radiant floor heating/STDFCU is the best heating combination.

- For severe cold region, the two-stage heat pump and new bimetal radiator may be a promising heating method.

- The cascade heat pump or combined R134a and transcritical CO₂ heat pump with radiator is also an competitive solution for north China.
Acknowledgements

• This work was supported by: National key research & development program of China (2016YFB0601200). The authors are grateful of GREE Electric Appliances, INC for offering the test data.

• Other contributors

<table>
<thead>
<tr>
<th>LiWei Wang</th>
<th>Bin Hu</th>
<th>Long Jiang</th>
<th>Shuai Du</th>
<th>ZhenYuan Xu</th>
<th>QuanWen Pan</th>
</tr>
</thead>
</table>

Thank you!