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Review

Multi-temperature heat pumps: A literature review

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ARTICLE INFO

Article history:
Received 24 March 2016
Received in revised form 24 May 2016
Accepted 24 May 2016
Available online 30 May 2016

Keywords:
Multi-temperature
Multi-stage
Heat pump
Refrigeration
COP
Second law efficiency

ABSTRACT

This review highlights the major advantages and challenges of mechanically driven heat pumps and refrigeration systems with focus on multi-temperature applications. Different design strategies are presented, including cycles with multi-stage compressors, ejectors, expansion valves, cascades, and separated gas coolers.

Most multi-temperature heat pump cycles use two heat sources and one heat sink. In supermarket applications, multi-stage compressor cycles with transcritical CO2 is an established key technology. Cascades with secondary loops are another frequently applied type of system. Expansion valve cycles are applied in household refrigeration and air conditioning. Cycles with ejectors seem to be a promising modification for system performance improvement. Separated gas coolers for space heating and hot water production have recently attracted attention due to the possible combination with supercritical CO2 cycles.

Thermodynamic simulations reveal that multi-stage compressor cycles have the highest COPs and second law efficiencies, followed by cascade, ejector, and expansion valve cycles. The baseline cycle consisting of two single-stage heat pumps in parallel shows lower second law efficiency than the multi-stage compressor and cascade cycles, and higher efficiency than the ejector and expansion valve cycles.

Pompes à chaleur à multiples températures: Une synthèse de la littérature

Mots clés : Températures multiples ; Multi-étagé ; Pompe à chaleur ; Froid ; COP ; Rendement exergétique

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http://dx.doi.org/10.1016/j.ijrefrig.2016.05.014

Nomenclature

CAS	cascade
COP	coefficient of performance [–]
EJ	ejector
EXV	expansion valve
h	specific enthalpy [kJ kg^{-1}]
HT	high temperature
HFC	hydrocarbon refrigerant
INT	intermediate
LT	low temperature
MC	multi-stage compressor
MEJ	multiple ejector
MT	middle temperature
$\dot{m}$	mass flow rate [kg s^{-1}]
p	pressure [kPa]
$\dot{Q}$	heat rate [kW]
Ref	reference
s	specific entropy [J kg^{-1} K^{-1}]
SC	subcooling
SGC	separated gas cooler
SH	superheating
T	temperature [K]
v	velocity [m s^{-1}]
W	compressor power [kW]
x	vapor quality [–]
I	subcycle 1 with LT evaporator
II	subcycle 2 with MT evaporator
1 . . . 12	numbering of states in p–h diagrams

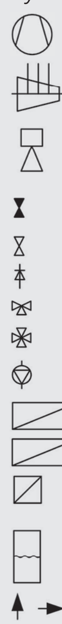
Greek symbols

β	heat source ratio [–]
η	efficiency [–]

Subscripts

c	compressor
C	cooling application
Carnot	Carnot cycle, theoretical maximum
cycle	cycle
diff	diffusor [ejector]
el	electrical power
H	heating application
LT	low temperature
MT	middle temperature
HT	high temperature
INT	intermediate
tot	total
mn	motive nozzle [ejector]
sn	suction nozzle [ejector]
2nd law	second law

Symbols used to draw the schematics



compressor
multi-stage compressor
ejector
expansion valve
shut-off valve
check valve
three-way valve
four-way valve
liquid pump
condenser, gas cooler
evaporator
subcooler, internal heat exchanger, closed economizer
open economizer, flash tank, liquid-vapor separator
heat flows (source, sink)

HT	high temperature
MT	middle temperature
LT	low temperature

1. Introduction

Heat pumps are highly attractive energy conversion devices for the industry, since they offer efficient means to reduce primary energy consumption by utilizing heat recovery (Jung et al., 2000).

In residential buildings, heat pumps are already widely used for space heating and hot water production, in particular in Europe and Japan. More and more, they also spread into the industrial sector, especially for waste heat recovery, heat upgrading, cooling and refrigeration in processes or for heating and cooling of industrial buildings (IEA, 2012).

As presented by the International Energy Agency (IEA, 2012), there is a diverse demand for heating and cooling at different temperature levels. In the 27 EU countries, a high demand for low exergy heat is found between 60 °C and 100 °C, mainly in the pulp and paper and food and tobacco industries. Rather than providing this heat through the combustion of fossil fuels, a more efficient way of providing this service is by using heat pump technology. There are large amounts of recoverable industrial waste heat, which can be used as heat sources to generate process heat through heat pumps.

Fig. 1 illustrates such promising heat sources and sinks in industrial heat pump applications.

Potential heat sinks in industry are for space heating (>35 °C), drying processes (>70 °C) or process heat (120 to 150 °C) (IEA, 2014).

In Switzerland, major heat sources for heat pumps are available from production processes. Many processes utilize air of 20 °C to 50 °C (i.e. cooling air, waste gas, exhaust air) or liquids of 15 °C to 40 °C (i.e. cooling water, oil, cooling lubricants) (Wellig et al., 2012).

In the German market (Fig. 2), the range of typical working temperatures of industrial heat pumps ranges from 15 °C to 82 °C with average temperature lifts of about 31 °C (Wolf et al., 2014).