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Simultaneous heating and cooling production devices composed by reverse cycle systems under variable loads

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ABSTRACT

Energy and exergy analysis leads to integrated solutions for process design. However, if the overall process design is optimized its robustness and its operability could be major weaknesses. This paper focuses on an integrated process where a reverse cycle system answers both heating and cooling demands. For variable heat demands, the aforementioned reverse cycle system may be inadequate. Therefore, one option is to add flexibility to the device by splitting it into two systems. In this paper, in addition to the initial reverse cycle system, five more solutions are proposed and studied: three uncoupled and two partially coupled solutions. First, simplified models are used to compare the different proposed solutions for several nominal operating points. Then, more detailed models are used to consider heating or cooling demand variation. Results show that the flexible solutions designed can be relevant options when heating or cooling demands vary.

Dispositifs de production simultanée de chauffage et de froid composés de systèmes à cycle inversé sous des charges variables

Mots clés : Pompe à chaleur ; Variation de charge ; Flexibilité ; Intégration d'énergie ; Controle ; Conception ; Systèmes thermodynamiques

1. Introduction

In order to reduce energy consumption in industry, energy and exergy analysis are coupled with the pinch analysis method. This coupling leads to integrated solutions for process design or process retrofit. This efficient design is generally composed by a heat exchanger network and integrated thermodynamic systems, such as heat pumps. These methods were developed initially by Linnhoff (Linnhoff,

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Nomenclature

C_v	Coefficient of flow restriction (m^2)
Cp	Specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
Ex	Exergy (J)
KS	Overall heat transfer coefficient ($W\ K^{-1}$)
P	Pressure (Pa)
T	Temperature (K)
$\Delta\tilde{T}$	Entropic mean temperature difference (K)
$\dot{Ex}$	Exergy flow (W)
$\dot{H}$	Enthalpy flow (W)
$\dot{Q}$	Heat (W)
$\dot{S}$	Entropy flow ($W\ K^{-1}$)
$\dot{W}$	Electrical power (W)
$\dot{m}$	Mass flow rate ($kg\ s^{-1}$)
$\dot{v}$	Flow rate ($m^3\ s^{-1}$)
f	Frequency (Hz)
h	Specific enthalpy ($J\ kg^{-1}$)
s	Specific entropy ($J\ kg^{-1}\ K^{-1}$)
Acronym	
COP	Coefficient of performance (–)
HPS	Heat Pump for Simultaneous heating and cooling
Greek letters	
α	Surface restriction (%)
η	Cycle efficiency (–)
ρ	Density ($kg\ m^{-3}$)
Subscripts	
c	Cold
comp	Compressor
cond	Condenser
d	Destroyed
ev	Expansion valve
evap	Evaporator
h	Hot
he	Heat exchanger
i	In
is	Isentropic
o	Out
sat	Saturated
u	Useful
Carnot	Carnot

March, 1998) to find the optimal design for an oil refining process. For decades, scientists and engineers have been improving this methodology and using it for many applications (Feng and Zhu, 1997; Savulescu et al., 2002; Hallale, 2002).

This methodology requires the identification of heating and cooling needs of the process. It also allows finding one or several optimal solution(s) for a unique nominal operating point. For some cases, heating and cooling requirements are variable. Therefore, the design must be able to adapt efficiently to variations that can be due to:

- specified several operating points (process planification),
- heating and/or cooling demand variations due to a varying mass flow rate for instance,
- performance degradation due to heat exchangers fouling, usually observed in industry and which can cause a low speed variation of an operating point,
- a difference between expected and real performance of one component or one thermodynamic system.

All these phenomena cause energy demand variations. In other words, the composite curves proposed by Linnhoff become time-dependent. The literature contains several works covering heat integration for time-dependent problems. Most often the solutions have resulted in a heat exchanger network scheduling optimization (Al-Mutairi and El-Halwagi, 2009). Alternatively, the implementation of energy storage at different temperature levels is used (Kemp, 2007).

All these methodologies have a common point: hot and cold utilities are considered available and capable to deliver the required load. Thus, the objective is to minimize cost or exergy consumption. Sometimes, for one operating point, the heating and cooling needs could be provided simultaneously by heat pumping, in that case a thermofrigopump can be used; and additional hot and cold utilities are excluded. A heat pump can be designed and optimised for one operating point by choosing the thermodynamic architecture, the refrigerant and each component: compressor, expansion valve, and heat exchangers. However this equipment can become inadequate when energy demand varies. Indeed, a heat pump cannot adjust its operating parameters in order to provide heating and cooling capacities simultaneously. Thus a control issue appears. For instance, a heat pump in heating mode using a variable-frequency driven compressor adjusts its frequency to provide heating needs; cooling needs become a consequence of this control. Therefore, the designed heat pump could become inefficient because the solution is not enough flexible.

To introduce flexibility some authors worked on a non-standard heat pump with an intermediate heat exchanger which releases heat or absorbs heat from the ambiance (Byrne et al., 2009; Byrne et al., 2011a; Byrne et al., 2011b). Thus this device, called Heat Pump for Simultaneous heating and cooling (HPS), is capable to operate in three modes: heating, cooling or simultaneous modes. The switch between these three modes is realised by a valve control. Although this equipment presents better performance than a classical heat pump into the studied area, this equipment presents one disadvantage: HPS cannot adapt both cold and hot utilities to meet a varying demand.

In the residential field, multi-heat pump has been improved to operate in cooling or heating mode but also in both cooling and heating mode (Kang et al., 2009). These equipments could be used for instance in winter to provide cooling capacity for data center and heating capacity for thermal comfort. This device is composed by several indoor heat exchangers which can switch between heating and cooling modes using a mode change unit and several electronic expansion valves. One outdoor heat exchanger operates as a condenser when the cooling service exceeds the heating one and operating as an evaporator when the heating load is the main service. This device has been also challenged in partial conditions which lead to large imbalance between the cooling and the heating capacities (Joo