INTERNATIONAL JOURNAL OF REFRIGERATION 54 (2015) 142–150

Available online at www.sciencedirect.com

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Trapezoid vapour compression heat pump cycles and pinch point analysis

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ARTICLE INFO

Article history:
Received 19 December 2014
Received in revised form
19 February 2015
Accepted 2 March 2015
Available online 10 March 2015

Keywords:
Trapezoid cycles
Pinch analysis
Vapour compression cycles
Heat exchangers
Waste heat recovery
Heat pump

ABSTRACT

Trapezoid Cycles are thermodynamic cycles, which basically adapt to the heat source curve and the heat sink curve in a temperature–entropy diagram (T–S-diagram). The name trapezoid cycle refers to the shape of these cycles in the T–S-diagram describing heat sources with sensible heat. It was shown earlier that trapezoid cycles are feasible when storage devices are added to the cycle setup. Two cases of an improved pinch analysis are shown in which trapezoid cycles can be implemented in plants for heat recovery. This methods lead to drastic improvement of cycle efficiency.

In this article, the valve, heat exchanger and storage tank setup are derived for an example plant. The two methods of extended pinch analysis are described and compared to each other. For both methods the storage tank setup is derived.

The second method differs from the first through an innovative integration of heat pumps in pinch analysis and consequently offers improved efficiency.

Cycles trapézoidaux à compression de vapeur d'une pompe à chaleur et analyse de pinch

Mots-clés : Cycles trapézoidaux ; Analyse de pinch ; Cycles à compression de vapeur ; Echangeurs de chaleur ; Recuperation de chaleur ; Pompe à chaleur

1. Introduction

Vapour compression cycles consist mainly of an evaporator, a compressor, a condenser and an expansion valve. The addition of storage devices and zone valves to the condenser and/or to the evaporator allow for the implementation of trapezoid cycles. This yields drastic improvements in the coefficient of performance (COP), especially in the case of a large temperature spread in the heat sink or the heat source or both. COP improvements of 30 %–50 % of the heat pump were measured in a prototype (Löffler and Griessbaum, 2014; Löffler, 2012a, 2012b).

In most industrial settings like factories or production plants, waste heat sources and heat sinks occur at different temperature levels, thus energy efficient use of waste heat is a

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http://dx.doi.org/10.1016/j.ijrefrig.2015.03.003

Nomenclature

$COP_{trap,i}$	Ideal coefficient of performance of trapezoid cycle
$COP_{trap,r}$	Real coefficient of performance of trapezoid cycle
i	Ideal
P2	Water pump
r	Real
R1, R2	Check valves
S	Entropy in WsK^{-1}
S_0	Reference entropy in WsK^{-1}
S1, S2	Storage tanks
T_a	Ambient temperature in K
$T_{b,l}$	Temperature at the bottom of the left storage tank
$T_{b,r}$	Temperature at the bottom of the right storage tank
$T_{t,l}$	Temperature at the top of the left storage tank
$T_{t,r}$	Temperature at the top of the right storage tank
trap	Trapezoid
V1..V4	Valves
ΔT_1, ΔT_2	Temperature differences
ΔT_{diss}	Temperature difference describing dissipative losses in K
ΔT_{pinch}	Pinch temperature in K
η_C	Carnot factor

major concern for industry and in research. The potential of using heat sources and the requirement of heat sinks, the temperature levels in the industrial sectors and the technology steps in case of refrigerants have been discussed (e.g. Lambauer et al., 2012; Wolf et al., 2012).

The standard pinch analysis (VDI, 2006; Linnhoff, 1998) helps to use local heat sources (supply) in order to feed local heat sinks (demand) in industrial processes for example (Ludwig, 2012). Storage tanks for heat or cold help to overcome the time difference between heat supply and heat demand (Krummenacher, Pierre, 2001). As a result of pinch analysis, part of the heat supplied can be transferred to the heat sinks through heat exchanger networks (Meier Daniel, 2007). The use of heat pumps with common heat pump cycles (Carnot-type cycles) is also described in pinch analysis (Linnhoff, 1998, p. 28–30, Kemp, 2007, p. 163, Welling, Beat et al., p. 109, Zogg, Martin, 1999). The first scientific investigation into integrating trapezoid cycles into pinch analysis has already been presented (Löffler, 2015).

The combination of pinch analysis and exergetic analysis was described by Feng and Zhu (1997) and Staine and Favrat (1996) and was designed to integrate dissipative processes, like heat engines, into pinch analyses. The Carnot factor η_C was introduced in order to reflect the temperature level of the heat. In the Carnot factor, the ambient temperature T_0 is taken as reference. Marechal and Favrat (2005) carried out a sound exergy concept based on a pinch analysis focused on integrating heat pumps and using the Carnot factor as an indicator for exergy. Thus, sources and sinks with ambient temperatures are considered. The focus of this paper is the integration of rectangles in the grand composite curve, which stands for Carnot type heat pump cycles.

This article presents two methods of pinch analysis and two setups for integrating trapezoid cycles. Both approaches lead to higher COP when compared to Carnot type setups. The article refers to previous articles about trapezoid cycles (Löffler and Griessbaum, 2014; Löffler, 2015).

2. Pinch analysis: methods and setup with trapezoid cycles

2.1. *Source, sink and storage tank setup*

Pinch analysis is a method that indicates usable heat sources in industrial plants and is used to establish heat exchanger setups. The method is well known in the fields of research and education (VDI, 2006). A percentage of industrial waste heat can be reused in new locations while other waste heat cannot be used elsewhere. However, insufficient waste heat can be supplemented by additional heat from conventional means.

Ambient heat sources or heat sinks can be used in vapour compression cycles and it is also possible to use waste heat as heat source (Linnhoff, 1998).

Table 1 shows an example composed of multiple heat sources. The temperature levels in this example are chosen arbitrarily because the method is the focus of this work. “High temperature” refers to the temperature of the hot feedwater, “low temperature” refers to the return water temperature.

Conversely, Table 2 shows an example composed of two heat sinks. Here “high temperature” means the temperature of the return water and “low temperature” means the temperature of the colder feedwater.

According to basic thermodynamic equations (Löffler, 2015) the entropy of the sources and sinks are added together. Fig. 1 shows the described heat sources and heat sinks in the T–S-diagram and the composite curves which is an aggregation in S-direction of the three heat source and the two heat sink curves.

The hot composite curve contains 5 sections:

1. 10 °C–40 °C: only source 1 contributes heat
2. 40 °C–50 °C: sources 1 and 2 contribute heat
3. 50 °C–80 °C: only source 2 contributes heat
4. 80 °C: only source 3 contributes heat
5. 80 °C–90 °C: only source 2 contributes heat

The cold composite curve contains 3 sections:

1. 70 °C–60 °C: only sink 1 takes heat
2. 60 °C–50 °C: sinks 1 and 2 take heat
3. 50 °C–40 °C: only sink 2 takes heat

It is presumed that all heat sinks and heat sources with sensible heat use water as heat transfer medium therefore the water from sources and sinks can be mixed. However, condensation from the latent heat source (source 2) cannot be mixed with the water from the other heat sources.