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Trapezoid Cycles and Extended Pinch Analysis

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ARTICLE INFO

Article history:
Received 2 July 2014
Received in revised form
30 September 2014
Accepted 1 October 2014
Available online 12 October 2014

Keywords:
Trapezoid Cycles
Pinch Analysis
Vapour compression cycles
Storage devices
Waste heat recovery
Heat pump

ABSTRACT

Trapezoid Cycles are thermodynamic cycles, mainly vapour compression cycles, which simply spoken adapt to the heat source curve and the heat sink curve in the temperature – entropy – diagram (T-S-diagram). The name of the cycles refers to the case of sensible heat, where the shapes of these cycles is similar to trapezoids. It was shown before that trapezoid cycles are feasible by adding storage devices to the cycle setup.

In this article exact and simplified theoretic equations for the calculation of the COP of different cases of Trapezoid Cycles both with and without influence of dissipation are presented. These equations allow a mathematically simple prediction of the COP with very small error.

Further the use of Trapezoid Cycles in the well-known Pinch Analysis is derived on a graphical basis (T-S-diagram). Heat which is usually lost in the Pinch Analysis will become usable with the highest thermodynamic possible efficiency.

Cycles trapézoïdes et analyse étendue de Pinch

Mots clés : Cycles trapézoïdes ; Analyse de Pinch ; Cycles à compression de vapeur ; Dispositifs d'accumulation ; Chaleur récupérée ; Pompe à chaleur

1. Introduction

Vapour compression cycles mainly consist of an evaporator, a compressor, a condenser and an expansion valve. With mainly storage devices and zone valves added to the condenser and/or to the evaporator, Trapezoid Cycles are feasible and allow drastic improvements of the COP, especially when the temperature spread of the heat sink or the heat source are large. COP improvements of 30 %–50 % were measured in a prototype setup. The measurement results were presented in (Löffler and Griessbaum, 2014; Löffler, 2012a), at the European Symposium on Applied Thermodynamics (Löffler, 2012b) and in the Seminar of the Institute of Thermodynamics and Refrigeration at KIT (Karlsruhe Institute of Technology) in December 2012.

In the most industrial entities like factories or production plants, there are waste heat sources and heat sinks at different temperature levels. It is a major topic in science and

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http://dx.doi.org/10.1016/j.ijrefrig.2014.10.002

Nomenclature

$COP_{trap,i}$	Ideal coefficient of performance of trapezoid cycle
$COP_{trap,r}$	Real coefficient of performance of trapezoid cycle
$COP_{trap,s}$	Simplified coefficient of performance of trapezoid cycle
i	Ideal
Q	Thermal energy in Ws
$\dot{Q}$	Thermal power in W
Q_0	Reference thermal energy in Ws
r	Real
S	Entropy in WsK^{-1}
S_0	Reference entropy in WsK^{-1}
$T_1..T_4$	Temperatures in K
T_1	End temperature of heat sink fluid in K
T_2	Start temperature of heat sink fluid in K
T_3	Start temperature of heat source fluid in K
T_4	End temperature of heat source fluid in K
T_a	Ambient temperature in K
trap	Trapezoid
ΔT_{diss}	Temperature difference describing dissipative losses in K

industry to save energy costs by using waste heat potentials. Publications show the potential of heat sources and the requirement of the heat sinks, the temperature levels in the industrial sectors and the technology steps in case of refrigerants (e.g. Lambauer et al., 2012; Wolf et al., 2012).

The Pinch Analysis (VDI, 2006; Linnhoff, 1998; Ludwig, Jens, 2012) helps to use locally available heat sources (offer) in order to feed locally existing heat sinks (demand). Storage tanks for heat or cold help to overcome different time scales of heat offer and heat demand (Krummenacher, Pierre, 2001). As a result of the Pinch Analysis, a part of the heat offered can be transferred to the heat sinks by means of heat exchanger networks (Meier Daniel and Raymond, 2007). The use of heat pumps with common heat pump cycles (Carnot-type cycles) is also described in the Pinch Analysis (Linnhoff, 1998, p. 28–30, Kemp, 2007, p. 163, Welling, Beat et al., p. 109, Zogg, Martin, 1999).

In the present article, an overview of calculation models for the COP of Trapezoid Cycles is shown, including simplified equations with small errors when compared to the mathematically exact equations.

Integrating the Trapezoid Cycles into the Pinch Analysis, two options in case of the heat source are investigated. First, ambient heat sources provide the required heat. Second, the unused waste heat sources provide the required heat, which may lead to higher COPs.

2. Theoretic background

2.1. Calculation of COP of Trapezoid Cycles

Trapezoid Cycles are mainly based on vapour compression cycles. Vapour compression cycles usually contain a heat source and a heat sink. Fig. 1 shows the heat source curve and the heat sink curve in the T-S-diagram.[1] The temperature levels T_1 to T_4 are defined in Fig. 1. The heat sink is heated up from T_2 to T_1, the heat source is chilled from T_3 to T_4.

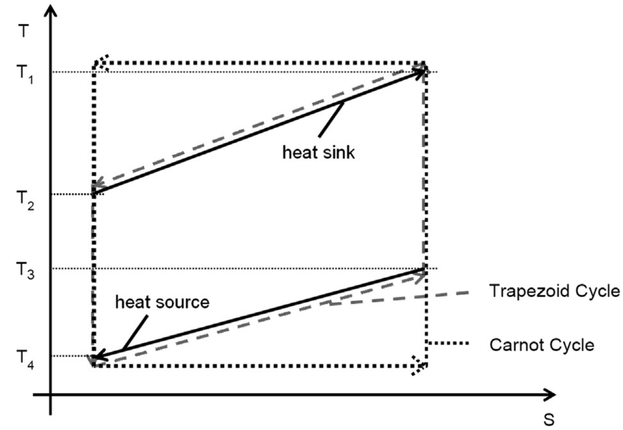

Fig. 1 – Thermodynamic cycles, heat source and heat sink and definition of temperature levels T_1 to T_4.

An ideal trapezoid shaped thermodynamic cycle is adapted to the heat source line and the heat sink line. The striped line in Fig. 1 shows the line of a Trapezoid Cycle.

Usual vapour compression cycles approximate a rectangle in the T-S-diagram. This type of cycle is called Carnot cycle. The cycle line of a usual vapour compression cycle is shown as a dotted cycle in Fig. 1.

Referring to Löffler (2012a) the COP of ideal trapezoid cycles can be calculated by the equations listed in the following Table 1 for three cases:

- Case 1 is defined by a heat source with small temperature spread and a heat sink with large temperature spread.
- Case 2 is defined by a heat source with large temperature spread and a heat sink with small temperature spread.
- Case 3 is defined by that both of the temperature spreads are large.

The shown pictograms roughly indicate the shape of the Trapezoid Cycles in the T-S-diagram.

Measurements and theoretic examinations carried out by Löffler (2012a) show that by introducing a term reflecting the dissipation, the real COP of Trapezoid Cycles can be calculated by the equations in Table 2 (see also Löffler and Griessbaum, 2014). The dissipation of the heat pump is represented by ΔT_{diss}.

2.2. The Pinch Analysis

The Pinch Analysis is used to indicate usable heat sources in an industrial plant (VDI, 2006). Some percentage of industrial

[1] Instead of the specific entropy s the absolute entropy S is used. This method results from the fact, that Trapezoid Cycles are realized by an unsteady process. Additionally absolute Entropy S is used here in order to include the entropies of the heat transfer liquid in the same diagram as the refrigerant. Consequently, instead of the thermal power $\dot{Q}$ the thermal energy Q is used.