Applied Thermal Engineering 50 (2013) 1543–1548

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Valorisation of low-temperature heat: Impact of the heat sink on performance and economics☆

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ARTICLE INFO

Article history:
Received 17 June 2011
Accepted 3 October 2011
Available online 14 October 2011

Keywords:
First cost
Operating cost
Thermodynamics
Temperature
Characteristic equation

ABSTRACT

Low-grade heat is available everywhere; consequently, the valorisation of this heat seems to be attractive in terms of economics. However, irrespective of the form of energy which is produced, any valorisation comes along with the production of another stream of waste heat with even lower value. The dumping of this reject heat often turns out to be the issue which determines cost.

This presentation will elaborate on the influence of the heat sink temperature both on conversion efficiency and cost. It first will give a frame on a very generic level. It is easy to reproduce the well-known fact that the change in COP of a compression heat pump with heat sink or source temperatures is in the order of some %/K. The same order of magnitude holds for all generic cycles with one important exception: the influence of the heat sink temperature on the COP of a thermally driven cooling machine is about twice the impact of the other temperatures. In addition, simple equations to account for the cost of heat exchange are presented. They show that heat pumps, be it work driven or heat driven, exhibit the best efficiency-to-cost ratio.

In order to leave the generic level, a more detailed analysis is given for an absorption cooling system. It is confirmed that the impact of the heat sink temperature on capacity and COP is significantly larger than that of the other temperatures; in the nominal point a rise in heat sink temperature reduces the cooling capacity by over 10%/K.

Finally, the influence of the humidity of the ambient air on performance is presented in a first order approach, also.

1. Introduction

Valorisation of low-temperature heat is a broad area. It covers heat recovery by compression heat pumps, sorption heat pumps, and heat transformers, as well as conversion into cold or mechanical energy. The means to do so are abundant as well: conventional conversion systems use thermodynamic mono-fluid cycles (closed steam cycles, open steam cycles, or even gas cycles), or dual-fluid cycles such as sorption cooling processes or sorption power processes. Some options which are state of the art, or technically feasible, or at least in discussion, are listed in Table 1.

The numbers (#1, 2, etc.) which are listed in Table 1, refer to Fig. 1, in which the nature of the duty to be fulfilled by these cycles is depicted on a temperature scale.

The first aim of this paper is to give an order to the said options and then to elaborate on the impact of the heat sink, and that of the other temperatures, too. It has to be distinguished between the impact on power density, efficiency, and cost. This will be done using generic equations. In a more technical approach, absorption chillers will be discussed in detail.

2. Generic thermodynamic approach

2.1. Options for revalorisation

These options could be discussed in terms of exergy, but we keep using energy and temperature as describing parameters.

First two definitions or clarifications are in order: low-temperature heat is heat with a temperature above ambient (at least two times the temperature gradient across a heat exchanger!). The heat sink is defined by the ambient, as well. It may include humidity, so it may be the dry bulb temperature or the wet bulb temperature. In order not to complicate things, in the first part of the paper we do not distinguish this.

☆ A large part of this paper has been published before at the 2nd European Conference on Polygeneration, March 30th–April 1st 2011, Tarragona, Spain.

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doi:10.1016/j.applthermaleng.2011.10.002

Table 1
Options for valorisation of low-temperature heat.

Mono-fluid		Multi-fluid		No fluid	
Air cycle	#1	Absorption cycle	#2, 4, 5	Peltier cooler	#1
				Magnetocaloric cooler	#1
				Thermoelectric generator	#3
Rankine cycle	#3	Adsorption cycle	#2, 4, 5		
Steam jet cycle	#2, 5	Chemical cycle	#2, 4, 5		
Stirling cycle	#1, 3	Hybrid sorption cycle	#1		
Vapor compression cycle	#1	Rankine sorption cycle	#3		
Vuilleumier cycle	#2, 4, 5				

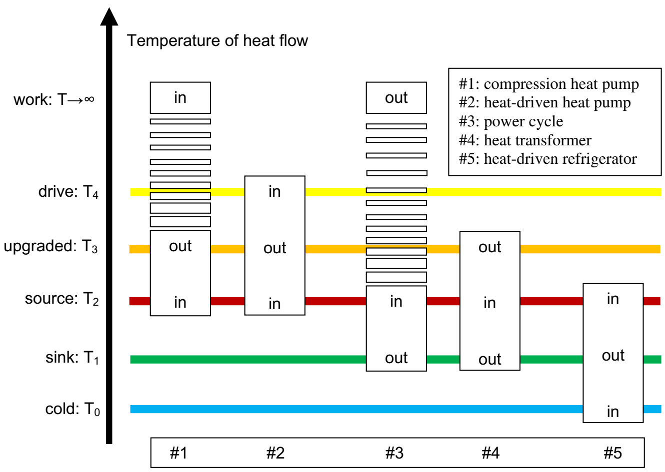

Fig. 1. Generic options to valorise heat of temperature T_2.

Fig. 1 schematically shows the thermodynamic options [1]; the only scale used is a temperature scale with temperature rising from bottom to top.

Each box denotes another generic conversion process. The words "in" or "out" are related to the energy flow on the respective temperature level, entering or leaving the device. Box #1 depicts a compression heat pump which upgrades heat from T_2 to T_3 with input of mechanical work. Process #2 does the same upgrading, albeit with using heat of temperature T_4 as drive. It depicts a heat driven heat pump.

Box #3 stands for a power cycle which works between T_2 and T_1. Box #4 represents a heat transformer cycle which upgrades heat from T_2 to T_3 with degrading part of the heat to the heat sink at T_1. Box #5, finally, shows a heat driven refrigerator. So, summarising, #1, #2, and #4 are heat pumps of different nature.

In any case, the low-temperature heat source at T_2 conveys heat into the box. Energy flows out at a higher level (#1–4) or flows in at a lower level (#5). The focus of this paper is on the processes #3 to #5 because they have to reject heat to a heat sink at a temperature T_1. However, we will discuss processes #1 and #2 also shortly.

Table 2
Performance of generic valorisation processes.

		Efficiency	Example
#1	Work-driven heat pump	$COP = \frac{Q_3}{W} = g\frac{T_3}{T_3 - T_2}$	$COP = 4.9$
#2	Heat-driven heat pump	$COP = \frac{Q_3}{Q_4} = g\frac{T_3}{T_4}\frac{T_4 - T_2}{T_3 - T_2}$	$COP = 1.1$
#3	Power cycle	$\eta = \frac{W}{Q_2} = g\frac{T_2 - T_1}{T_2}$	$\eta = 0.06$
#4	Heat transformer	$COP = \frac{Q_3}{Q_2} = g\frac{T_3}{T_2}\frac{T_2 - T_1}{T_3 - T_1}$	$COP = 0.29$
#5	Heat-driven refrigerator	$COP = \frac{Q_0}{Q_2} = g\frac{T_0}{T_2}\frac{T_2 - T_1}{T_1 - T_0}$	$COP = 0.43$

2.2. Performance

Table 2 gives the definition of efficiency or COP and an equation to determine it in the most simple way, which is to calculate the reversible limit and multiply this with a rough measure for thermodynamic quality, g. This is done often although it is not really correct: irreversibilities, of course, change with temperature and, especially, with temperature differences. In order not to prolong this paper we will stick to a simple numerical example, just for orientation. This example uses the temperatures from Table 3 and a constant quality of $g = 0.5$.

All these equations are well-known from textbooks (e.g. [1],) or can be derived easily, so they will not be discussed here. The sensitivity of the efficiencies on the temperatures will be investigated by using the derivatives. Table 4 gives the derivatives with respect to all the relevant temperatures, normalised with the respective efficiency.

From these equations it is obvious that, e.g., the impact of the source temperature, T_2, on the heat pump COP is always somewhat larger than that of the sink, T_3, in the work driven case (#1) because $1 > T_2/T_3$, whereas it is smaller in the heat driven case #2 because $(T_4\text{-}T_3)/(T_4\text{-}T_2) < T_2/T_3$ under realistic circumstances. For a power plant (#3) the impact of the heat sink, T_1, always is somewhat larger than that of the heat source, T_2 because $1 > T_1/T_2$. In the case of the heat transformer (#4) it is the other way round, again. This is understood easily, as a shift in the intermediate temperature T_2 changes temperature lift and temperature thrust of the process at the same time. For the same reason, the impact of the heat sink in the case of refrigeration (#5) is the largest one.

In order to quantify these findings, the derivatives according to Table 4 are plotted against the heat sink temperature for a set of other temperatures (see Table 3) in Figs. 2 to 6. The absolute value of the relative (normalised) derivatives is shown. The dashed lines display negative derivatives.

The impact of the temperatures on the COP of a compression heat pump (#1, Fig. 2) between T_2 and T_3 is the larger, the smaller the temperature lift, $(T_3\text{-}T_2)$, to be accomplished is. It is in the order of some %/K for realistic temperatures. The difference between the impact of the two temperatures is marginal.

For heat driven heat pumps (#2, Fig. 3), the impact of the temperatures on the COP is in the same order of magnitude as for compression heat pumps. However, the influence of the driving temperature T_4 is the smallest and it varies slightly only. For moderate temperatures, the impact of the sink T_3 is the strongest, as discussed before.

For a power station which is operated by low-temperature heat (#3, Fig. 4), the impact of the temperatures is reverse as compared to Fig. 2, naturally.

Table 3
Set temperatures according to Fig. 1.

Temperature level	T_4	T_3	T_2	T_1	T_0
Value [°C]	180	120	80	35	−5