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Attainability of the Carnot efficiency with real gases in the regenerator of the refrigeration cycle

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HIGHLIGHTS

- Real gas effects degrade the coefficient of performance of regenerators seriously.
- The heat input or removal approach for improving the COP is proposed and analyzed.
- Attainability of the Carnot efficiency of the refrigeration cycle is affirmed.
- A simplified approach is effective to reach 90% of the Carnot efficiency.

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ABSTRACT

Improving efficiency is an enduring effort for all work-heat conversion cycles. Ideal regenerators working with ideal gases bring about a lossless work and heat transfer over a temperature gradient, but real gases give rise to an "intrinsic" heat loss in regenerators because of the time-averaged enthalpy flow associated with the pressure dependence. Real gas effects play a vital role on the coefficient of performance (COP) of regenerators of refrigeration cycles working at the temperatures close to or below the critical point. The "intrinsic" heat loss of real gases degrades the theoretical COP of regenerators to as low as 1% of the Carnot efficiency. In this paper, an approach of heat input or removal aiming to improve the COP is proposed. The theoretical analysis of this approach reveals the underlying mechanism. It is shown that the theoretical COP of an ideal regenerator working with a real gas applying this approach is identical to the Carnot efficiency. A simplified approach of heat input is further analyzed. The Carnot efficiency can be attained under certain circumstances, and it is possible to obtain over 90% of the Carnot efficiency with a discrete method. The theory of improving the COP with the approach of heat input in discrete regenerator locations is supported by the experiment results found in the relevant literature. This new approach provides a potential way to significantly improve the efficiency of the regenerator of the refrigeration cycle working at the temperatures close to or below the critical point. This approach may further provide a reference for studies of the heat pump cycle and the engine cycle working with real gases.

1. Introduction

Improving efficiency is an enduring effort for all work-heat conversion cycles [1–7]. The derivation for the theoretical efficiency reveals the working mechanism and sets a target for real devices, so it is prior work for a new cycle and for a new condition [8–11]. The refrigeration cycle is a reverse work-heat conversion cycle that removes the heat from a low-temperature reservoir with a work input. Efficient regenerative refrigerators are important for fulfilling the refrigeration requirement of industrial gas liquefaction [12–15], superconducting devices [16–20], infrared detectors [18,21], and so on. The function of the regenerator in the refrigeration cycle is to transport the work over the temperature gradient from the hot end to the cold end with the least work and heat losses possible in the oscillation flow. Ideal regenerators working with ideal gases bring about a lossless work and heat transfer over a temperature gradient. The refrigeration cycle applying an ideal regenerator and ideal pistons at the hot end and cold end, such as the Stirling refrigeration cycle, reaches the Carnot efficiency [22]. The pulse tube refrigerator works without pistons at the cold end, and it dissipates the work in the phase shifter, thus its theoretical COP is equal to (T_c/T_h) [22–24]. Recent investigations on the mass-spring (or gas spring) feedback [25–30], step piston [31], cascade style [32–34], etc., realize a recovery of the dissipated work, thus the COP is improved significantly. In fact, the theoretical COP of these improved

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Nomenclature

A	availability (W)
COP	coefficient of performance
$\langle \dot{H}_p \rangle$	pressure-induced enthalpy flow (W)
$\langle \dot{H}_T \rangle$	temperature-related enthalpy flow (W)
p_r	reduced pressure
$\langle p\dot{V} \rangle$	pressure-volumetric power (W)
$\dot{Q}$	heat input or removal (W)
$\dot{Q}_c$	refrigeration power (W)
$\dot{Q}_{tot}$	total heat flow (W)
$rCOP$	relative Carnot COP
T	temperature (K)
x	position (m)
Z	compressibility factor

Greek letters

β	volume expansivity (1/K)

Subscripts

c	cold end
h	hot end
i	index number
n	total index number
T	temperature related

refrigerators is equal to the Carnot efficiency.

However, the theoretical COP is challenged if a real gas is used as the working fluid. The enthalpy flow associated with the pressure dependence, abbreviated as the pressure-induced enthalpy flow, which is a significant property of real gases, gives rise to an energy imbalance. This imbalance is generally solved by generating an enthalpy flow associated with imperfect heat transfer and limited matrix heat capacity in the regenerator, abbreviated as the heat-associated enthalpy flow [35,36]. But the heat-associated enthalpy flow is actually an “intrinsic” heat loss of the regenerator, so the COP of the cycles working with such regenerators cannot reach the Carnot efficiency [37–40]. The theoretical COP of such regenerators that work close to or below the critical point is usually lower than 30% of the Carnot efficiency, and it gets even smaller if the refrigeration temperature goes lower [37–40]. This means that over 70% of the availability gets lost in such situations. The loss mechanism caused by real gas effects has been analyzed in previous studies [35,40–42], and the expression of the COP of the regenerator and the pulse tube cryocooler has been derived.

However, the investigations dealing with the real gas effects are not sufficient. Systematical methods of increasing the COP of the refrigerators working with real gases have not been proposed. Although a practical method of benefiting from the “intrinsic” losses, i.e. gathering the “intermediate refrigeration power” (described as “excess cooling power” [43,44] or “free cooling power” [45,46]), has been proposed and investigated in previous studies [43–46], the theoretical value of the “intermediate refrigeration power” and the theoretical COP of the regenerator taking account of the “intermediate refrigeration power” have not been analyzed yet. The term “intermediate refrigeration power” is used in this manuscript because it can explain the physical essence and describe the temperature range better. It has been found that an “intermediate refrigeration power” can be extracted in the middle section of a regenerator, leading to none or little degradation on the refrigeration performance at the cold end [43–48]. This “intermediate refrigeration power” method has been numerically and experimentally studied in cryocoolers working down to 4 K [43–48]. Such “intermediate refrigeration power” can be used to increase the liquefaction rate [44,47], and to increase the cold-end cooling power of the cryocooler itself [43] by precooling the pulse tube, the radiation shield, and through other means. It has also been pointed out that the regenerator loss could be decreased and the efficiency of the cryocooler could be improved by the “intermediate refrigeration power” method [43,46].

An approach of heat input or removal is proposed to decrease the real gas losses and to improve the COP of refrigerators in this manuscript. The heat input or removal is the heat inputted or removed from an external system to the refrigeration system at intermediate temperatures [49]. The working gas of the refrigeration system absorbs the external heat and it is turned to the enthalpy of the gas in the case of heat input, and the working gas turns its enthalpy to heat and the heat is transferred to the external heat sink in the case of heat removal. In brief, the heat input or removal superimposes a finite time-averaged enthalpy flow in the regenerator. The heat input is actually one kind of refrigeration power (or heat sink) at intermediate temperatures, but the heat removal is one kind of heat load (or heat source) at intermediate temperatures. Because the heat input or removal takes place in a temperature range rather than a temperature point, a series of micro refrigeration cycles should be applied to realize the process.

The ideal regenerator is one-dimensional, as assumed in the theoretical thermodynamic derivation, so the heat input or removal at a discrete location or at a certain temperature affects the corresponding section evenly.

Although the theory of heat input or removal has been proposed in the previous study, the real gas effects have not been taken into account [49]. The working fluid was assumed to be an ideal gas in that important pioneering work. The conclusion was that the regenerator working with a finite enthalpy loss is able to absorb or remove a certain amount of external heat. The influence of the heat input or removal to the temperature profile and the energy flow was analyzed and simulated.

This paper will systematically investigate the attainability of the

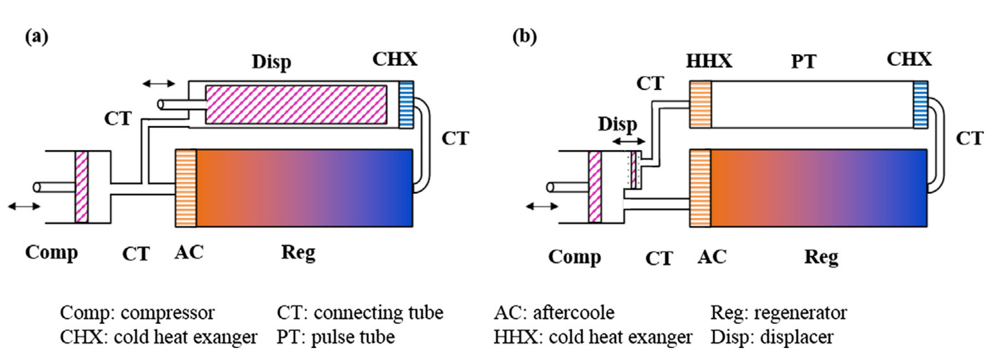

Fig. 1. Schematics of two typical regenerative refrigerators, a Stirling refrigerator (a) and a pulse tube refrigerator with a displacer (b).