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Research paper

An alternative observation on the orifice pulse tube cryocooler and analysis through the unified model of cryocoolers

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ABSTRACT

A new observation of the orifice pulse tube (OPT) cryocooler is proposed and analyzed on the ground of the unified model of cryocoolers. The elementary temperature reduction mechanism is modeled and verified through the measurements of Mikulin and others. This analysis refers to the upper limit performance for zero phase shift between the pulses of pressure and flow rate at the cold end. The lowest attainable temperature is formulated and pointed out as central characteristics of an OPT cooler. It dominates the closed form expressions for cooler's cooling capacity, COP and FOM as function of the compression ratio, the size of regenerator, the species of coolant and average flow rate. The so obtained upper limit of COP and FOM is about half of that in literature. Performance is also compared with Solvay and Gifford-MaMahon cryocoolers.

1. The unified model of cryocoolers

1.1. The scope of the model

Any cryocooler is driven by its elementary temperature reduction mechanism (ETRM) that generates a relatively limited reduction (to an extent of δT). This δT is attenuated by the heat load, $\dot{Q}$, and converts to DT. The DT is imposed as a temperature difference between the streams of a counter flow heat exchanger at its cold end (Fig. 1.a). So applied boundary condition pushes further down the temperature at the cold end of the heat exchanger (Fig. 1.b). This is the cooldown process. Consequently, the limited δT is magnified into a larger ΔT_H span below ambient with the magnification index,

$$I_M = (\Delta T_H + DT)/DT \tag{1}$$

A counter flow heat exchanger with such boundary conditions has a growing span of temperatures between the streams in contrast to a traditional counter current heat exchanger of a constant span. To be distinguished it is referred to as an "interchanger". This magnification device was invented by Siemens [1]; he teaches that, ".......the principle of the Invention is adapted to produce an accumulated effect or an *indefinite reduction of temperature*....". It is worthwhile to note that the same principle is also recognized as " A principle of biology" [2] and one of "Some design principles" [3] of general theory of design.

The unified model of coolers is inspired indeed by Siemens as introduced elsewhere [4] and enlightening in its view a variety of coolers [5–7]. In this study it is applied to the OPT cooler. All cryocoolers have in common an interchanger, whether realized in the continuous (DC) version as a recuperator or in the periodic (AC) version as a regenerator.

However, what makes the distinction between the cryocoolers is the particular ETRM's nature, whether isenthalpic/isentropic expansion of compressed coolant, magnetocaloric effect, etc.

It is interesting to note that Mikulin et al., crowned as the inventors of the OPT cryocooler, conducted their study [8] as if implicitly taking for granted the hereby described unified model of coolers. That is enlightened in the Appendix.

1.2. The elementary temperature reduction mechanism

An ETRM is characterized by its ability to generate a limited temperature drop, δT, and its dependence on the level of cooling,

$$\delta T = T_2 - T_3 = \delta T(T_2) = \delta T(\Delta T_H) \tag{2}$$

$$DT = T_2 - T_4 = \delta T(T_2) - \frac{\dot{Q}}{\dot{n} \cdot c_{P,\ L}} \tag{3}$$

The highest temperature along the heat absorption process, T_4, should be regarded as the temperature of cryocooling. The span of cooldown is,

$$\Delta T_H = T_1 - T_2 \tag{4}$$

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Nomenclature

c_P	isobaric heat capacity, J mol^{-1} K^{-1}
$\dot{C}$	capacity rate, $\dot{n}\cdot c_P$, W/K
COP	coefficient of performance
COP$_C$	Carnot's coefficient of performance
FOM	figure of merit
I_M	interchanger's magnification index
K	proportionality factor, $\delta T = K\cdot T_2$
NTU	number of transfer units
NTU$_0$	normalized thermal conductance, Eq. (29)
n	mass, mol
$\dot{n}$	average molar flow rate,mol s^{-1}
P	pressure, Pa
$\dot{Q}$	heat load, cold production rate, W
$\dot{Q}_f$	fractional cooling capacity
r	capacity rates ratio
R	gas constant, 8.314 J mol^{-1} K^{-1}
T	temperature, K
δT	elementary temperature reduction, K
DT	cold end temperature difference, K
ΔT_H	cooldown temperature span, K
UA	thermal conductance, W/K
V	volume, m^3
$\dot{W}_{IN}$	isothermal compression power, W
x	inverse compression ratio, P_L/P_H
Y	non dimensional module, Eq. (36)

Greek notation

ε	heat exchanger's effectiveness
κ	isobaric/isochoric heat capacities ratio
Θ	normalized temperature, T/T_1
ρ	density, mol m^{-3}
Π	compression ratio, P_L/P_H

Subscript

1 to 5	Coolant's states in a cryocooler (Fig. 1)
L	low pressure stream
H	high pressure stream

Superscript

IDEAL	ideal cooler,$UA \to \infty$
MIN	minimum value
MAX	maximum value
OPTM	optimum value

Abbreviations

ETRM	elementary temperature reduction mechanism
GM	Gifford-McMahon
BPT	basic pulse tube
OPT	orifice pulse tube
PT	pulse tube
rB	reverse Brayton
SO	solvay

Notation

$\bar{T}$	average of T

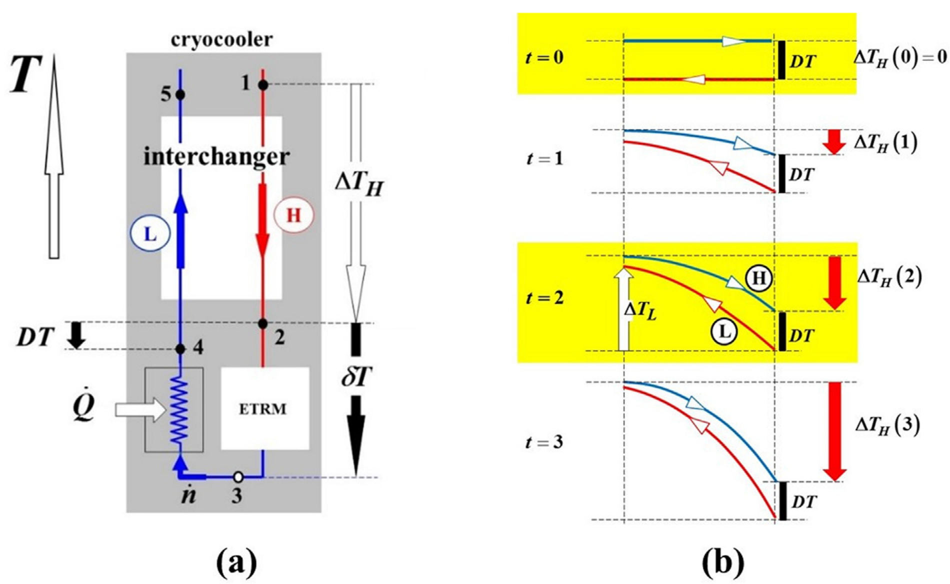

Fig. 1. (a) The unified model of cryocoolers comprises an elementary temperature reduction mechanism (ETRM) that generates aδT, and a magnifying element which is the interchanger. (b) The evolution of the interchanging process; magnifying DT to get a growingΔT_H.

1.3. The interchanger

The behavior of an interchanger and the evolution of ΔT_H is governed by the general relations of a counter flow heat exchanger based on the capacity rates of each stream, $\dot{C}_L = \dot{n}_L\cdot c_{P,L}$ and $\dot{C}_H = \dot{n}_H\cdot c_{P,H}$; let the ratio between the smaller and larger be,

$$r = \dot{C}^{MIN}/\dot{C}^{MAX} \leqslant 1 \tag{5}$$

$$\text{NTU} = UA/\dot{C}^{MIN} \tag{6}$$

$$I_M(\dot{C}_H \geqslant \dot{C}_L) = \frac{1}{1-\varepsilon} \quad \text{and } I_M(\dot{C}_H \leqslant \dot{C}_L) = \frac{1}{1-r\cdot\varepsilon} \tag{7}$$

$$\varepsilon = [1-e^{-\text{NTU}\cdot(1-r)}]/[1-r\cdot e^{-\text{NTU}\cdot(1-r)}] \tag{8}$$