Energy Conversion and Management 177 (2018) 280–291

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Thermal analysis of Stirling thermocompressor and its prospect to drive refrigerator by using natural working fluid

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ARTICLE INFO

Keywords:
Thermocompressor
Stirling engine
Oscillating flow
Third order model
Thermoacoustic characteristics

ABSTRACT

The Stirling thermocompressor (STCP), usually working at low frequency (< 5 Hz), is a novel Stirling-type external-combustion machine. It utilizes the temperature difference between the heating temperature and ambient temperature to generate the thermoacoustic power and pressure wave for refrigerators. In order to explore the characteristics of STCP, a detailed thermal analysis based on the third order 1-D finite volume model considering the real gas effect and variable physical properties was proceeded. Three natural fluids, helium, nitrogen and hydrogen are chosen as the working fluids and compared with each other. The parameter effects of pressure fluctuation under no-load operation were studied. To understand the output capacities for refrigerator with using different working fluids, the RC load method is adopt to analysis the STCP's capacity and efficiency of the conversion from heat energy to acoustic energy, also the loss characteristics under different working gas. When the working pressure, frequency and heating temperature are 4 MPa, 4 Hz and 800 K respectively, the STCP using helium as the working fluid could output about 380 W acoustic power for the RC load and relative Carnot efficiency is about 33%.

1. Introduction

The huge energy consumption caused by the rapid development of the world economy makes the fossil energy face an exhaustive risk. The issues including irrational use of energy and large amount of pollutants discharged in the energy conversion process lead to energy waste and environmental pollution [1–4]. The thermal driven refrigerator which can directly convert heat energy into work, is an essential way for fuller usage of energy and reducing environmental pollution. Besides the most common absorption refrigerator, more and more researchers pay attention to the thermal driven Stirling-type machines [5–13]. The traditional Stirling refrigerator (STR) needs an electric motor to drive its piston compressor to generate acoustic power for refrigerator, so it can't use the thermal energy directly [6]. The thermal driven Stirling-type refrigerator (TSTR) is a novel kind of STR, the refrigerator part of TSTR and STR are almost same. Because the relative Carnot efficiency of the ideal Stirling cycle is equal to 1, the thermal driven Stirling-type refrigerator has considerable potential to achieve high efficiency. However, the compressor in TSTR no longer relies on volume variation to generate pressure wave, it can directly use the thermal energy to generate pressure wave and acoustic power.

The thermoacoustic compressor (TACP) is a novel compressor for TSTR and developed in recent years. Instead of the traditional piston, the TACP purely uses gas oscillation to convert thermal energy to acoustic power and pressure wave for refrigerator. For no mechanical moving parts in the system, the TACP has the advantages like simple mechanism, high stability, cheapness and facility to process [4]. To reduce the working frequency, the long resonator tube is usually several meters long, which limits TACP application especially for some occasions with limited geometry [6,7]. In 1989, Radebaugh and Swift first coupled a standing-wave TACP and a pulse tube cryocooler together and achieved a lowest temperature about 90 K [5]. With the development of the thermoacoustic technology, the potential of refrigerator driven by TACP was gradually discovered and the TACP shows great advantages in large-scale application fields [6–13].

However, the large bulk of TACP limits its applications in some constrained areas. If a displacer is introduced into the TACP to control the oscillating flow of working gas, the TACP could no longer use a long resonant tube and have a similar scale with the piston compressor, and become a novel Stirling thermocompressor (STCP), its schematic diagram is shown in Fig. 1(a). The simple structure makes it cheap and easy to manufacture. In Vuilleumier refrigerator, so called thermal-

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https://doi.org/10.1016/j.enconman.2018.09.068
Received 1 August 2018; Received in revised form 18 September 2018; Accepted 20 September 2018

Nomenclature

A	cross-section area, m^2
A_H	heat transfer area between working gas and solid, m^2
A_0	orifice opening area, m^2
C_s	solid specific heat, J/(kg K)
C_P	isobaric specific heat, J/(kg K)
d_h	hydraulic diameter, m
dt	time step, s
f	frequency, Hz
F	friction factor
g	gravity acceleration, m/s^2
h	heat transfer coefficient, $W/(m^2 K)$
i	node number
k	thermal conductivity, W/(m K)
L	length, m
m	mass, kg
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
Q	heat, W
R	gas constant, J/(kg K)
Re	Reynolds number
t	time, s
T	temperature, K
u	velocity, m
V	volume, m^3
W_{ac}	acoustic power, W
X	longitude coordinate, m
Z	compressibility factor

Greek symbols

β	volumetric expansion coefficient, 1/K
γ	adiabatic index
λ	conductivity factor
ω	angular frequency, rad/s
μ	viscosity, Pa s
φ	porosity
η	efficiency
η_C	relative carnot efficiency
θ	phase angle, rad/s
ρ	density, kg/m^3
ν	specific volume, m^3/kg
Δx	control volume length, m
δx	node distance, m

Subscripts

0	average
c	cold cavity
CV	control volume
$deadc$	dead volume of cold cavity
$deadh$	dead volume of hot cavity
f	interface between control volumes
h	hot cavity
i	node number
o	orifice
R	gas reservoir
s	solid

Superscripts

n	time layer
· (dot)	time derivative

Abbreviations

TACP	thermoacoustic compressor
TSTR	thermal driven Stirling-type refrigerator
STR	Stirling type refrigerator
STCP	Stirling thermocompressor
VM	Vuilleumier
TDMA	Tri-Diagonal Matrix Algorithm
PDMA	Panta-Diagonal Matrix Algorithm
HC	hot cavity
HHE	hot heat exchanger
REG	regenerator
CHE	cold heat exchanger
CC	cold cavity

driven Stirling refrigerator, STCP can utilize the temperature difference between two temperature sources to generate acoustic power to the refrigerator [14,15]. Different from the piston, the function of displacer is only to move the gas into different temperature sources, so there is no obvious pressure difference between two sides of the displacer, which ensures its high stability in operation. The STCP can be driven by various heat sources, for example, the combustion heat, electrical heat, solar energy and waste heat from automobile exhaust. For often using natural working fluids like helium, the STCP is very friendly to the environment [15,16]. Compared with the TACP, the STCP has good stability, and is easier to achieve larger pressure ratio and more compact for introducing the displacer to control the motion of gas. The theoretical efficiencies of TACP and STCP are all 1 due to belonging to the Stirling-type machine. All these advantages ensure that the STCP is very suitable to recover the waste heat from the exhaust of mobile vehicle and then drive a refrigerator to condense these exhaust [15], even in some bad conditions. Also, it can also be used in the medical field [17].

The initial concept of STCP was introduced by Vuilleumier in his patent in 1918 [18]. In 1960s, a VM refrigerator driven by STCP was applied successfully for space cooling [19]. The Vuilleumier (VM) refrigerator or VM heat pump is in fact a displacer-type expander driven by a STCP and had been tested for residential heating [20,21]. As more and more attentions are paid to the compressor using natural fluids, the STCP is gradually studied individually. Wu built a second-order thermodynamic model to estimate the temperature and mass flow fluctuation in two cavities under no load operation [22]. In 2011, Xue et al. measured the no-load characteristics of the STCP using helium as the working fluid under different pressure and heating temperature. He also used a simple isothermal model for the STCP to predict the relationship between pressure ratio and temperature ratio [16]. Wu et al. designed a STCP driven by linear motor in 2013 and estimated its performance using wire gap regenerator by experiments and they presented the hydrodynamic radius of the gap regenerator needs to match the thermal penetration depth [23]. Lin and Wu et al. studied the heat transfer process through a second-order model and test the output acoustic power of STCP by experiments [24]. Ji et al. studied the coupling characteristics of STCP and pulse tube cryocoolers using helium as the working fluid. Three pulse tube cryocoolers with different structures driven by their STCP were introduced in experiments [15]. In 2016, to replace the conventional mechanical compressor in a CO2 heat pump for the residential heating, Rabah et al. reported a valve-type STCP for supercritical CO2 heat pump from boostHEAT Company [25]. They pointed the gap leakage between the displacer seal and cylinder is very important for the performance of STCP. Also, they used a second order model to predict the temperature and pressure fluctuation in no-load