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Indicated diagrams of low temperature differential Stirling engines with channel-shaped heat exchangers

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ABSTRACT

The low temperature differential Stirling engine with channel-shaped heat exchangers and regenerators achieved approximately 5 times the indicated power per a stroke volume of displacer of the cases using flat-shaped heat exchangers. The ratio of the maximum fluctuation of ensemble averaged working fluid temperatures, which is the ratio of the internal energy fluctuation to the heat capacity of the working fluid, to the temperature difference between the two heat exchangers in cases using flat-shaped heat exchangers was 0.08–0.09, that in cases using channel-shaped heat exchangers was 0.10–0.17, and that in case using channel-shaped heat exchangers and regenerators was 0.21. The improvement in the experiments is lower than the estimation by the CFD. In terms of the polytropic index, low temperature differential Stirling engines with channel-shaped heat exchangers and regenerators obtained a higher value than low temperature differential Stirling engines with flat-shaped heat exchangers before the displacer reached the dead center.

1. Introduction

The aim of this study is the development of a low temperature differential (LTD) Stirling engine (SE) with a heat source temperature below 100 °C for a personal-use application. A LTDSE can generate brake power from a low-exergy heat source. A non-fuel combustion heat source is available, although LTDSEs can receive only part of the energy from such a heat source. Therefore, it is difficult to define the energy supply in the discussion of thermal efficiency. However, the problem to solve is power, not thermal efficiency. The poor power output discourages the practical use of LTDSEs.

The first low-temperature differential Stirling engine was presented at the International University Center in Dubrovnik in 1983 [1]. Ohyagi et al. [2] reported experimental data from a LTDSE that utilized atmospheric air as the working fluid and operated with an approximately 18 °C temperature difference between the heat source and the heat sink. Kongtragool and Wongwises [3] reported the experimentally determined effect of some parameters on brake power. Karabulut et al. [4] reported that a beta configuration SE could operate with a hot end temperature of 93 °C. There are some reports that practical LTDSEs have generated watt-level power with a heat source temperature of approximately 100 °C. Schleder and Zoppke [5] developed a practical LTDSE called "Sunwell50". This SE worked as a water pump, and the energy source was sunlight. Hoshino and Yoshihara [6] developed two free piston beta SEs with an expansion space temperature of 100 °C. One of the engines that Hoshino and Yoshihara developed is based on the test models of a free piston SE converter, which was developed for the demonstration of solar heat energy utilization for future aerospace applications. In another engine that they developed, the working fluid was helium with a mean pressure of 0.5 MPa. According to their report, the piston power output, the difference between the indicated power and the work required to move the displacer, was 11.8 W, although the electrical power output from the mismatched linear alternator was approximately 1 or 2 W. In this case, the frequency of the piston and the displacer may be 35 Hz with strokes of 8 mm; the expansion space temperature was 100 °C, and the coolant temperature was 20 °C. These reports suggest that LTDSEs for practical use can be realized.

Table 1 shows the evaluations of LTDSEs from previous works. Takeuchi et al. [7] reported their SE operated by 300 °C- oil as a LTDSE. Tavakolpour et al. [8] reported LTDSE heated by solar collector. Kato [9] reported indicated diagrams. The West number W_N [10] is defined by Eq. (1), where The Beale number B_N is expressed

Abbreviations: CFD, Computational fluid dynamics; LTD, Low temperature differential; SE, Stirling engine; MFEAWFT, the maximum fluctuation of ensemble averaged working fluid temperature.

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Nomenclature

B_N	Beale number [W/(bar·cc·Hz)]
C	Specific heat [J/(kg·K)]
C_1	Coefficient
C_2	Coefficient
C_μ	Coefficient
E	Coefficient
h	Ratio of temperature differences
h_C	Ratio of temperature differences in cold side
h_H	Ratio of temperature differences in hot side
k	Turbulent kinetic energy
m	Mass of working fluid [kg]
n	Engine speed[Hz]
p	Pressure [Pa]
p_1	Pressure [Pa]
p_2	Pressure [Pa]
p_3	Pressure [Pa]
P'_m	Mean pressure used for the estimation by the Beale number [bar]
Q_{Cin}	Internal energy contained by the working fluid flowing from the cold side to the regenerator
Q_{Cout}	Internal energy contained by the working fluid flowing from the regenerator to the cold side
Q_{Hin}	Internal energy contained by the working fluid flowing from the hot side to the regenerator
Q_{Hout}	Internal energy contained by the working fluid flowing from the regenerator to the hot side
R	Gas constant [J/(kg·K)]
S_D	Cross-sectional area of the displacer chamber [m^2]
T_1	Temperature [K]
T_2	Temperature [K]
T_3	Temperature [K]
$T_{average}$	Ensemble averaged temperatures in the section below the displacer [K]
$(\Delta T_{average})_{max}$	Maximum fluctuation of ensemble averaged working fluid temperature [K]
T_c	The cold side temperature [K]
$\overline{T_C}$	Ensemble averaged temperatures of the cold side section in the displacer chamber [K]
T_{Cin}	Temperature of the working fluid flowing into the cold side section in the displacer chamber [K]
T_{Cw}	Heat exchanger temperature of the cold side section in the displacer chamber [K]
T_h	The hot side temperature [K]
$\overline{T_H}$	Ensemble averaged temperatures in the hot side section of the displacer chamber [K]
T_{Hin}	Temperature of the working fluid flowing into the hot side section in the displacer chamber [K]
T_{Hw}	Heat exchanger temperature of the hot side section in the displacer chamber [K]
U	Time averaged velocity in the horizontal direction [m/s]
u_τ	Friction velocity [m/s]
ΔU	Internal energy fluctuation of the working fluid during one cycle [J]
V	Volume [m^3]
V_1	Volume [m^3]
V_2	Volume [m^3]
V_3	Volume [m^3]
V'	Volume used for the estimation by the Beale number [cc]
W_N	West number
W_{out}	Brake power used for the estimation by the Beale number [W]
x_{stD}	Stroke of the displacer [m]
y^+	Dimensionless length [−]
α	Phase angle, which is difference between the phase angle of a displacer oscillation and the phase angle of a power piston oscillation
η_R	Regenerator efficiency [−]
φ	Phase angle of power piston oscillation in a calculation. The volume is minimum when $\varphi = 0$
σ_ε	Coefficient [−]
σ_k	Coefficient [−]
τ	T_c/T_h [−]

by Eq. (2). The performance difference shown in Table 1 is significant. In terms of West number W_N, the maximum value is 83 times of minimum value in Table 1. The difference of West number W_N causes the difference of power, as engine speed, mean pressure and stroke volume effect on an engine power. However, the reason for the difference is not clarified. Therefore, a discussion based on a basic mechanical engineering is required.

$$W_N = 10B_N\frac{1+\tau}{1-\tau} \tag{1}$$

Table 1
West numbers of LTDSEs from previous works.

	W_N	W_{out} [W]	n [Hz]	$V' = S_D x_{stD}$ [$\times 10^{-3}$ m^3]	P'_m [kPa]	T_h [°C]	T_c [°C]
Ref. [7]	1.2×10^{-1}	1.0×10^{4}	15	28.51	600	300	20
Ref. [3]	1.5×10^{-2}	9.0×10^{-1}	0.7	6.39	100	126	34
Ref. [8]	1.8×10^{-3}	1.5×10^{-1}	0.5	14.52	100	110	25
Ref. [2]	1.4×10^{-3}	1.0×10^{-3}	0.2	1.15	100	22	4
Ref. [9]	4.1×10^{-3}	3.3×10^{-3}	0.8	0.24	100	56	28
Ref. [9]	5.2×10^{-3}	2.2×10^{-3}	0.6	0.24	100	44	25

$$W_{out} = B_N P'_m V' n \tag{2}$$

Kato [9] suggested that the indicated work of a conventional LTDSE was much lower than the thermodynamic upper limit. Fig. 1 shows the schematic views of the tested LTDSE, a conventional LTDSE. The shape of the heat exchangers was flat. The heat exchangers are installed on both the top and bottom of the displacer

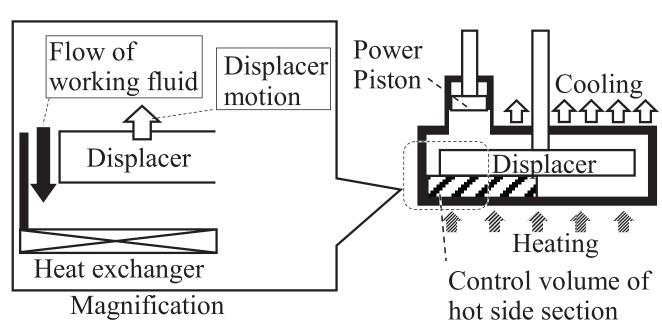

Fig. 1. Schematic views of a LTDSE with flat-shaped heat exchangers.