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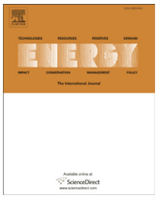

Dynamic modelling and simulation of a heat engine aerobot for atmospheric energy utilization

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ABSTRACT

The low grade heat utilization is not only an inevitable option to solve the energy and environment problems, but also a critical issue for many remote power applications and planetary explorations. In this study, a novel design called a heat engine aerobot which can convert planetary atmospheric energy to electricity is proposed and analysed. A dynamic theoretical model is established and some key issues, such as the thermodynamic performance and conversion efficiency are analysed. It shows that the heat engine aerobot is capable to convert the low grade atmospheric energy to electricity during its self-sustained vertical oscillation movement. Parametric analysis shows that some design parameters, such as the nozzle number, the nozzle outlet diameter, the initial liquid mass and the turbine start height may have significant influence on the energy generation performance.

1. Introduction

The LGH (low grade heat) utilization is not only an inevitable option to solve the energy and environment problems [1], but also a critical issue for many remote power applications [2] and planetary explorations [3]. The ground LGH utilization (solar thermal energy, geothermal energy, biomass energy, and industrial waste heat, etc.) are widely studied by using different conversion methods such as organic Rankine cycle [1], thermal pulse energy harvesting [2], impulse turbine [4], solar chimney [5] and hot air balloon engine [6,7].

Although the upper atmosphere has been used as a low temperature heat sink for ground LGH utilization [5–7], the researches on how to utilize the massive atmospheric LGH is still needed. It is well known that most planets and some moons within our solar system have atmospheres. Due to the combined actions of the solar radiation and the surface heating, the atmosphere temperature decreases with altitude near the planetary surface. For example, the atmosphere temperature decreases from the ground (average about 288.15 K) to the tropopause (average about 216.65 K) of the Earth with a near constant temperature gradient about −6.5 K/km. From the viewpoint of thermodynamics, if we can move a heat engine vertically, the temperature difference between different heights of the atmosphere can be utilized to convert atmospheric LGH to electricity.

We invented a novel heat engine named as a heat engine aerobot [8], which provide a method to convert the atmosphere LGH to electricity. This novel heat engine is based on two technologies: the phase-change balloon [9,10] to realize a self-sustained vertical oscillation, and the impulse turbine for LGH conversion [4,11,12]. Based on our preliminary study of the heat engine aerobot [3], this paper presents our recent work on its working principle, theoretical modelling and simulation results. In addition, the improved design of the heat engine structure to enhance the heat transfers is provided. Based on the proposed theoretical model, some key issues such as the thermodynamic performance and conversion efficiency are analysed.

2. System description and methodology

Fig. 1 shows a typical configuration of a heat engine aerobot, which includes a balloon, a heat engine and a gondola. The balloon is filled with some type of working fluid, which is chosen to be gaseous when below some equilibrium altitude but to condense when above the altitude. The heat engine is installed just below the balloon (Fig. 2) to convert the atmospheric heat to electricity. Different to our previous design [3], a wick layer on the inner wall and fins on the outer side wall of the reservoir are applied to

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Nomenclature

A	area, m^2
C_p	specific heat at constant pressure, J/(kg K)
D	diameter, m
E	energy, J
g	gravitational acceleration, m^2/s
H	height, m
h	specific enthalpy, J/kg
h_{lv}	latent heat, J/kg
k	adiabatic exponent
km	kilometre
L	length, m
m	mass, kg
m_{l0}	initial liquid mass in the reservoir, kg
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number
p	pressure, Pa
P	power, W
Pr	Prandtl number
$\dot{Q}$	heat flux, W
Ra	Rayleigh number
Re	Reynolds number
R_v	gas constant, J/kg
r	radius, m
s	fin spacing, m
t	fin thickness, m
T	temperature, K
T_{tb}	torque of the turbine, N m
ΔT	temperature difference, K
u	specific inner energy, J/kg
U_r	relative gas velocity of the nozzle outlet, m/s
V	volume, m^3
w	height of the fin, m
W	vertical velocity, m/s

Greek symbols

α	heat transfer coefficient, W/(m^2 K)
β	bulk expansion coefficient, 1/K
ω	angular velocity, rad/s
ε	porosity of the wick
η	efficiency
λ	thermal conductivity, W/(m K)
μ	dynamic viscosity, Pa s
ν	kinetic viscosity, m^2/s
ρ	density, kg/m^3

Subscripts and superscripts

a	atmosphere
b	balloon
bs	base
cd	condensation
eff	effective
ev	evaporation
f	fluid
fc	forced convection
fin	fin
i	inner
l	liquid
nc	natural convection
o	outer
rs	reservoir
s	saturate
t	total
tb	turbine
v	vapour
w	wall
wi	wick

enhance the evaporation process. The scientific mission payloads and the secondary batteries are installed inside the gondola beneath the heat engine.

Fig. 3 illustrates the basic principle of the heat engine aerobot. The intersection of the thermodynamic property line of the atmosphere and the saturated line of the working fluid yields the equilibrium point (point 0) at the equilibrium height (H_0), where the working fluid in the heat engine aerobot is thermodynamic equilibrium with the atmosphere, that is,

$$T_{f0} = T_{a0}, \quad p_{f0} = p_s(T_{a0}) = p_{a0} \tag{1}$$

When the aerobot goes below the equilibrium altitude, it works at an evaporation mode. The atmospheric temperature is higher than the saturate temperature of the working fluid at the ambient pressure, and thus the liquefied fluid is evaporated in the reservoir. Considering an operation point at H_1 bellow H_0, if the working fluid inside the reservoir is thermally balanced with the ambient atmosphere, the pressure of the fluid is higher than that of the atmosphere (point $f1$ in Fig. 3),

$$T_{f1} = T_{a1}, \quad p_{f1} = p_s(T_{a1}) > p_{a1} \tag{2}$$

Since the vapour pressure in the reservoir is higher than that inside the balloon which is in equilibrium with the ambient pressure, the vapour flows through the turbine and converts the heat energy to the kinetic energy and finally to electricity by the generator. Actually, due to the thermal resistance and finite time and area of the heat transfers, there is a temperature difference between the inner working fluid and the outer atmosphere, and the real evaporating temperature of the fluid $T_{f1'}$ should less than T_{f1} and the corresponding saturation pressure $p_{f1'}$ is lower than p_{f1}

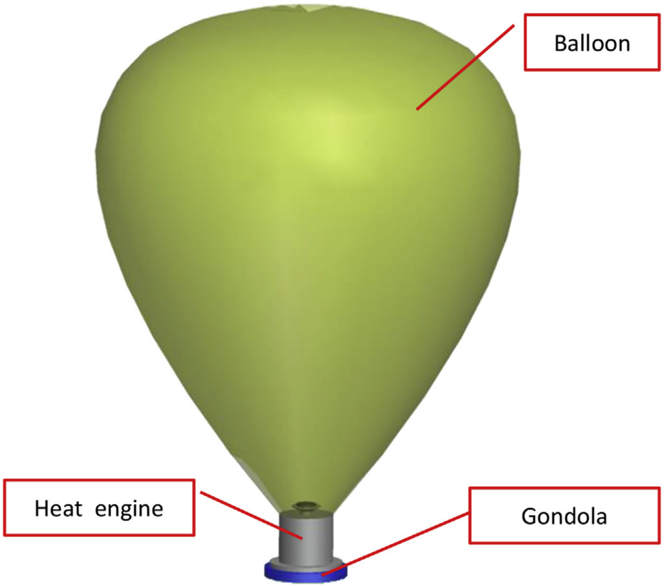

Fig. 1. A typical configuration of a heat engine aerobot.