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Underwater striling engine design with modified one-dimensional model

Daijin Li[1], Kan Qin[2] and Kai Luo[1]

[1]*School of Marine Science and Technology, Northwestern Polytechnical University, Xi'an, China*
[2]*School of Mechanical and Mining Engineering, University of Queensland, Australia*

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ABSTRACT: *Stirling engines are regarded as an efficient and promising power system for underwater devices. Currently, many researches on one-dimensional model is used to evaluate thermodynamic performance of Stirling engine, but in which there are still some aspects which cannot be modeled with proper mathematical models such as mechanical loss or auxiliary power. In this paper, a four-cylinder double-acting Stirling engine for Unmanned Underwater Vehicles (UUVs) is discussed. And a one-dimensional model incorporated with empirical equations of mechanical loss and auxiliary power obtained from experiments is derived while referring to the Stirling engine computer model of National Aeronautics and Space Administration (NASA). The P-40 Stirling engine with sufficient testing results from NASA is utilized to validate the accuracy of this one-dimensional model. It shows that the maximum error of output power of theoretical analysis results is less than 18% over testing results, and the maximum error of input power is no more than 9%. Finally, a Stirling engine for UUVs is designed with Schmidt analysis method and the modified one-dimensional model, and the results indicate this designed engine is capable of showing desired output power.*

KEY WORDS: Stirling engine; Unmanned underwater vehicles (UUVs); One-dimensional model; Thermodynamic performance.

NOMENCLATURE

M	mass of working fluid, [kg]
P	pressure of working space, [Pa]
V	volume, [m^3]
T	temperature, [K]
W	mass flow rate, [kg/s]
Q	heat transfer, [W]
$work$	work, [W]
C_p	specific heat at constant pressure, [$J/kg\cdot K$]
C_v	specific heat at constant volume, [$J/kg\cdot K$]
h	heat transfer coefficient, [$W/m^2\cdot K$]
A	heat transfer area, [m^2]
R	gas constant, [$J/kg\cdot K$]
Z	compressibility factor, [-]
W_{ml}	mechanical loss, [kW]
n	engine speed, [rpm]
p_m	mean pressure, [MPa]

Corresponding author: *Daijin Li*, e-mail: *lidaijin@nwpu.edu.cn*

P_{in}	indicated power, $[W]$	Nu	nusselt number, [-]
P_{out}	output power, $[W]$	Re	reynolds number, [-]
W_{aux}	auxiliary power, $[kW]$	φ	phase angle, [*rad*]
t	time, [sec]	α	crank angle, [*rad*]
Δt	time interval, [sec]		

SUBSCRIPTS

w	wall	*	interface
d	design point	*s*	updated value for the change in specific heat
i	index of CV	*sp*	updated value for the change in specific heat and pressure
in	inlet	*spm*	updated value for the change in specific heat and pressure, and mass mixture
out	outlet		
e	expansion space		
c	compression space		

INTRODUCTION

Under the circumstance of limited space for underwater power system, Stirling engines are regarded as an efficient and promising power system for UUVs due to the advantages of compactness, high efficiency and ability to use various heat sources (Wang et al., 2012; Shih et al., 2013). Most importantly, the Stirling engine is an external combustion engine, and thus various types of heat sources can be utilized, including solar energy (Mancini et al., 2003; Kongtragool and Wongwises, 2003; Tlili et al., 2008; Abdullah et al., 2005), waste heat (Shoureshi, 1978; Li et al., 2012; Cullen and McGovern, 2010), or biomass (Waters, 2013). Reader (Reader, 1998) stated that Stirling engines were particularly attractive for marine applications. Mattavi et al. (1969) at General Motors presented basic description of some Stirling engines along with complete maps of performance data and other facts related to their underwater use with closed energy sources, and predicted performance characteristics for power-plant systems combining Stirling engines with heat storage and metal-combustion energy sources. Nilsson (Nilsson, 1983) presented that the United Stirling 4-95 and 4-275 well-known engines had been adapted to underwater operation. Swedish shipbuilder Kockums had built 8 successful Stirling powered submarines since the late 1980s, which were the first submarines in the world to feature Stirling air-independent propulsion, and extended their underwater endurance from a few days to several weeks.

Even though Stirling engines have shown great advantages in underwater environment, the present applications of the Stirling engine to underwater devices only specify to the submarine. To the knowledge of the author, there are few studies about Stirling engines applied to UUV, Bratt (1990) pointed out that Kockums Marine had developed a prototype energy system based on the 4-95 engine for use in an UUV, which coupled with a combustor that burns diesel fuel oxygen. Reader et al. (1998) described the application of the Stirling engine for underwater duties, and in particular the selection, design and development of a Stirling engine powered Drive Propulsion Vehicle (DPV).

Also, during the last several decades, a large number of studies have been done on the development of theoretical methods for the analysis of the thermodynamic performance of different types of Stirling engines, for the use in the design stage and for the prediction of their performance. Various models have been developed and are used for the simulation of the thermodynamic performance of Stirling engines.

Zeroth order analysis

Beale (1969) observed that most modern engines operate under similar conditions of the parametric ratio: dead volume ratio, temperature ratio, swept volume ratio, displacer-piston phase angle advance, and he presented that engine performance could be represented in terms of mean pressure, swept volume and operational frequency.