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Application of the Stirling engine driven with cryogenic exergy of LNG (liquefied natural gas) for the production of electricity

Ireneusz Szczygieł*, Wojciech Stanek, Jan Szargut

Silesian University of Technology, Gliwice, Konarskiego 22, Poland

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ABSTRACT

LNG (liquefied natural gas) delivered by means of sea-ships is pressurized and then regasified before its introduction to the system of pipelines. The utilization of cryogenic exergy of LNG for electricity production without combustion of any its portion is analyzed. For the conversion of LNG cryogenic exergy into electricity, the Stirling engine is proposed to be applied. The theoretical thermodynamic model of Stirling engine has been applied. This model is used to investigate the influence of pinch temperature in heat exchangers, engine compression ratio and dead volumes ratios on the thermodynamic parameters of the Stirling engine. The results of simulation represent the input data for investigations of thermodynamic performance of the proposed system.

In order to evaluate the thermodynamic performance of the proposed process, an exergy analysis has been applied. The exergy efficiency and influence of design and operational parameters on exergy losses are determined for each of the proposed system configurations. The obtained results represent the background for advanced exergy-based analyses, including thermo-ecological cost.

1. Introduction

LNG (liquefied natural gas) delivered by means of sea-ships is pressurized and then regasified before its introduction to the system of pipelines. The possibilities of the utilization of cryogenic exergy of LNG for electricity production without additional combustion of any its portion, have been analyzed. For the LNG exergy conversion to the electricity the Stirling engine is proposed. LNG (liquefied natural gas) delivered by sea-ships contains considerable cryogenic exergy which can be utilized for electricity production before its regasification and introduction into the system of pipelines. The liquefaction of natural gas consumes a considerable amount of exergy. This exergy is completely lost when the regasification powered by ambient heat is employed. Some part of the LNG exergy may be recovered by means of a thermal device utilizing the cryogenic exergy of LNG. The simplest method of that utilization might be based on the principle of a cold Rankine cycle absorbing the regasification heat from the environment and rejecting the heat of condensation to preheat and evaporate LNG [15]. Such solution was proposed by Szargut and Szczygieł [1]. Similar attempt was shown by Lu et al. [2], where the ammonia–water power system was investigated. Tsatsaronis and Morosouk [3,4] shown exergy analysis on CHP system driven by the cryogenic exergy of LNG. The ammonia–water based cycle in new configuration was also presented by Wang et al. [5]. Technical realization of Rankine cycle is a challenge from technological point of view and, in effect, is a very expensive solution. In the paper the simpler cycle is proposed: Stirling engine. The simplified analysis of employing Stirling engine for the LNG exergy recovering was shown by Dong et al. [6]. In the paper the ideal Stirling cycle was investigated. The Stirling engine was constructed by Robert Stirling in 1816. The Stirling cycle consist of four thermodynamic processes of closed medium: two isothermic and two isochoric processes (Fig. 1). Very important part of Stirling cycle engine is a heat recovery, which brings the Stirling cycle to the Carnot cycle. When the heat regenerator works perfectly, namely when $q_{R1} = q_{R2}$ (Fig. 1), the efficiency of the Stirling cycle is equal to the efficiency of the Carnot one:

$$\eta_s = 1 - \frac{T_C}{T_H} \tag{1}$$

where T_C, T_H stand for the temperatures of upper and lower heat sources, respectively.

* Corresponding author.
E-mail address: ireneusz.szczygiel@polsl.pl (I. Szczygieł).

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Nomenclature

b	specific exergy, kJ/kg
c_v	isochoric heat capacity, kJ/(kg K)
B	exergy, kJ
h	specific enthalpy, kJ/kg
H	enthalpy, kJ
k	relative size of dead volume
L	work, kJ
m	mass, kg
p	pressure, kPa
q	specific heat, kJ/kg
Q	heat, kJ
R	individual gas constant, kJ/(kg K)
T	temperature, K
v	specific volume, m^3/kg
V	volume, m^3

Greek symbols

η	efficiency
κ	isentropic exponent
ε	compression ratio

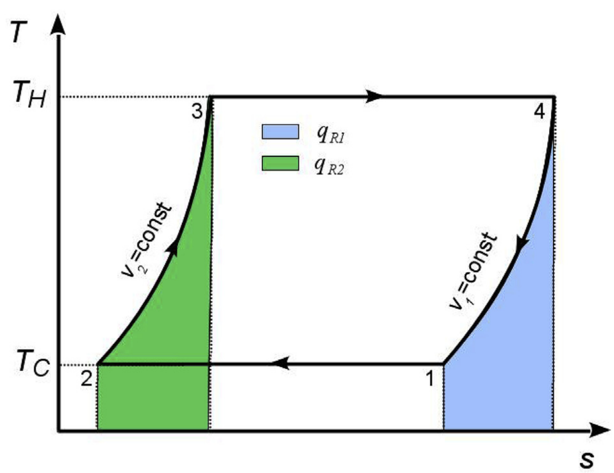

Fig. 1. Temperature-entropy diagram of Stirling cycle.

When the real regenerator is concerned, the efficiency of the Stirling cycle drops down, and depends on the compression ratio $\varepsilon = v_1/v_2$ and the regenerator efficiency η_{HE}:

$$\eta_s = \frac{(\kappa-1)\left(1-\frac{T_C}{T_H}\right)\ln\varepsilon}{(\kappa-1)\ln\varepsilon + \left(1-\frac{T_C}{T_H}\right)(1-\eta_{HE})} \quad (2)$$

The regenerator energy efficiency is defined as the fraction of actual regeneration heat (q_R) and the total isochoric heat (q_{R1} or q_{R2}, Fig. 1) $\eta_{HE} = q_R/q_{R1}$.

2. Description of Stirling engine

The principle of operation as well as the construction of Stirling engine is much simpler when comparing to Rankine cycle which should result in the investments costs reduction.

Principle of operation of the Stirling engine corresponding to T-s diagram (Fig. 1) is shown in Fig. 2.

The real cycle differs from the theoretical one. The source of these differences can be sought in all the irreversibilities: during expansion, compression and during isochoric processes. Additionally, the physical realization of the cycle is connected with dead volumes of the expansion and compression cylinders as well as with dead volume of the heat regenerator. These dead volumes significantly decrease the theoretical efficiency of the engine. The example real cycle is shown in Fig. 3. The Stirling engines have numerous advantages which can be summarized as:

- auxiliary heat source,
- no phase change,
- continuous burning (silent) can be applied,
- low noise emission,
- sealings and bearings on the cold side,
- no valves,
- easy start-up.

The engine disadvantages can be itemized as:

- high size/power ratio,
- expensive and large heat exchangers,
- slow start up.

The application field of Stirling engines is very wide. Nowadays the engines can be found, among others, in cooling and heating processes, CHP systems for recovering waste energy, utilization of solar energy, drive of submarines, cooling of electronic devices, cryogenics. Due to the point of the paper, it is worth to notice that the Stirling cooler is used in the process of LNG liquefaction or re-liquefaction.

3. Mathematical model of Stirling cycle

Parameters of Stirling engine operation can be evaluated in two ways: thermodynamic analysis and CFD (computational fluid dynamics) modeling. Many papers have been devoted to thermodynamic analysis of various concepts of Stirling cycle. Bancha et al., in 2003 [7] have presented a literature review on solar powered Stirling engines and low temperature differential Stirling engines technology. A number of research papers is discussed in that work. In 2005 Bancha et al. [8] have shown the thermodynamic analysis

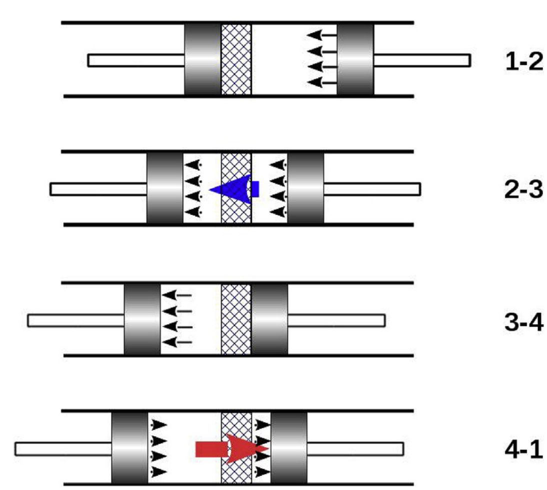

Fig. 2. Principle of operation of Stirling engine.