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MICROCONTROLLER DIAGNOSTIC SYSTEM FOR EVALUATION OF STIRLING ENGINE

Summary. *In this paper we present the microcontroller system for the diagnostics and evaluation of the Stirling engine performance. For this purpose the analysis model for the prototype engine has been developed to present the engine's improved benchmarking results. The functioning of this engine has been analysed with the aim to find and optimize the main working parameters. To obtain this goal the Stirling engine has been equipped with different kinds of electronic sensors. A microcontroller testing circuit has been designed, which uses the acquisition of data from the data module.*

Key words: *Stirling engine, heat transfer, regenerator, performance.*

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МІКРОКОНТРОЛЕРНА СИСТЕМА ДІАГНОСТИКИ ДЛЯ ОЦІНЮВАННЯ ДВИГУНА СТІРЛІНГА

Резюме. *Представлено систему вимірювання з мікроконтролером, за допомогою якої здійснюється діагностика та оцінюється ефективність роботи двигуна Стірлінга. В систему заімплементовано модель аналізу прототипу двигуна Стірлінга для знаходження оптимальних значень його основних робочих параметрів. Двигун Стірлінга оснащено сенсорами вимірювання температури за допомогою термопари з матеріалу залізо/константан типу Fe-CuNi/J і давачем тиску. Крім цього, запроектовано пристрій тестування із застосуванням 16-бітного контролера PIC18F для виконання аквізиції даних.*

У зв'язку з тим, що критично важливою частиною двигуна Стірлінга є регенератор, розроблено складну систему електронного керування регулювальних клапанів входу та виходу регенератора. Цю систему створено на основі сучасного мікроконтролера типу PIC24H корпорації Microchip. Систему обладнано оригінальною програмою мовою асемблер, яка покращує роботу двигуна Стірлінга та підвищує його продуктивність шляхом електронного керування клапанами. Електронна система виконує низку вимірювань на головному валу двигуна. Такими є вимірювання частоти обертання, використовуючи давач Холла. Сигнал давача Холла підлягає перетворенню з подальшим обробленням у процесорі PIC24H. Ці імпульси після перетворення в елементі Шотткі застосовуються для керування клапанами та синхронізації блока випередження й регулювання відкриття клапанів.

Система також служить для перевірки потужності двигуна Стірлінга на підставі вимірювання обертового моменту на головному валу. Система характеризується розширеними функціональними можливостями, причому дані з 16-бітного мікроконтролера типу PIC24H обробляється в математичному модулі та, в подальшому, – у мікроконтролері типу ARM11.

Система, окрім вимірювання потужності двигуна Стірлінга, відіграє істотну роль для дослідження характеристик двигуна. Тому побудовано випробувальний стенд, оснащений рядом процесорів для збору даних про частоту обертання і крутний момент. Ці дані використовуються для подальшого аналізу отриманих результатів науково-дослідних експериментів. Вал двигуна Стірлінга з'єднано зі спеціально сконструйованим вимірювальним пристроєм на базі електричного генератора, що дає змогу оцінювати динамічні параметри двигуна Стірлінга. Будова та структура випробувального стенда разом з електронною системою та електричним генератором буде предметом окремої статті.

Introduction. The Stirling engine is a multi energy-sourced engine, as it may use solar energy, combustion energy and heat from old coal refuse heaps. They make considerably less pollution than the traditional engines. The absence of explosive nature in converting heat energy into mechanical one, conveys to silent and cleaner operation. The Stirling engine works in a closed cycle, as shown in Figure 1.

As the working gas here is helium, trapped in the machine undergoes the following transformations: from point $1 \to 2$ isothermal compression, from point $2 \to 3$ isochoric heating, from point $3 \to 4$ isothermal expansion, from point $4 \to 1$ isochoric cooling. The expansion volume is maintained at high temperature, and the compression volume is maintained at low temperature. The theoretical efficiency is equivalent to the Carnot cycle.

Thermodynamic cycle of the Stirling engine. In this cycle a constant mass of helium is alternately: relaxed, cooled, compressed and warmed. The processes of heating and cooling are improved by using a regenerator. The regenerator is generally a metal cylinder constituted by an annular unit. Matrix for the regenerator is based on 0,14 mm steel wire. It works as a thermal sponge, which alternatively absorbs and releases heat.

The objective of the research was to study the Alfa type Stirling engine, which has been developed in order to perform modernization and to make a benchmark of it efficiency. The Alfa engine shown in Figure 2 consists of two separate cylinders, and each one has its own piston.
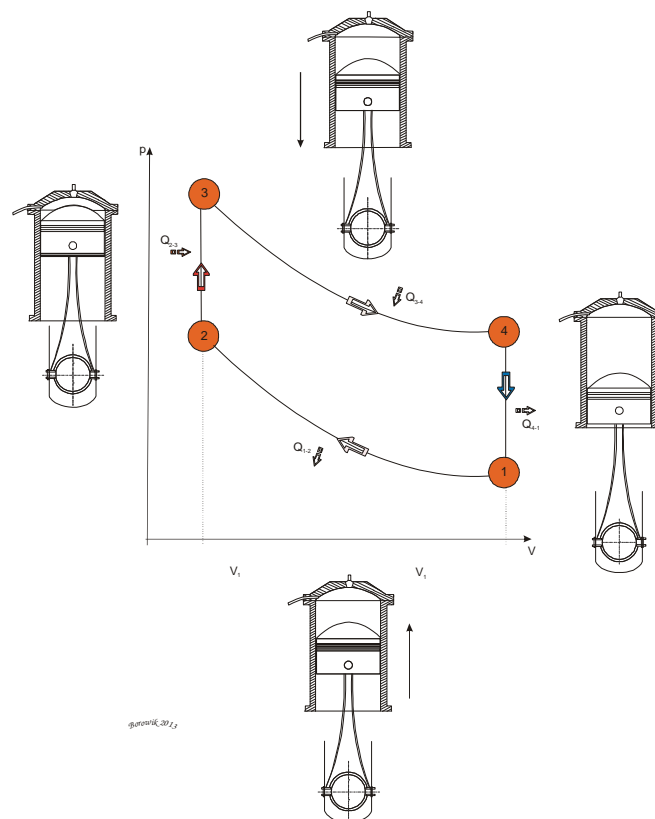

Figure 1. Thermodynamic cycle of the Stirling engine.

The Stirling engine with Ross Yoke linkage. The power output is produced by the separate motions of the individual pistons. Drive mechanism poses some problems for the Alfa type Stirling engine, since discontinuous motion is required to achieve the volumetric changes that result in a net power output. For this reason, in this engine for transferring dual piston motion into rotational motion - the Ross yoke mechanism has been implemented. The

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Ross yoke mechanism does not produce sinusoidal volume variations and has the advantage over the traditional system by minimizing lateral forces acting on the pistons and leading to a more efficient and compact design.

The objectives of the test bench are mainly to characterize the performance of Stirling engines and to evaluate different control strategies for engines, which operate with variable heat sources. With respect to the thermal metrology conditions, the engine is equipped with 8 thermocouples, 4 pressure transducers and volume transducers. The microcontroller based system measures Torque and RPM (Revolutions per minute) on the main shaft. Using this data volume a transducer will determine the total air volume trapped in the two rooms, as well as in the regenerator. It delivers the signal of continuous tension. Its maximum corresponds to $V_{max} = 230$ cm^3 and the minimum corresponds to $V_{min} = 120$ cm^3. Voltage delivered by this transducer is proportional to the volume of gas shunt in the Stirling engine, as shown in Figure 3.

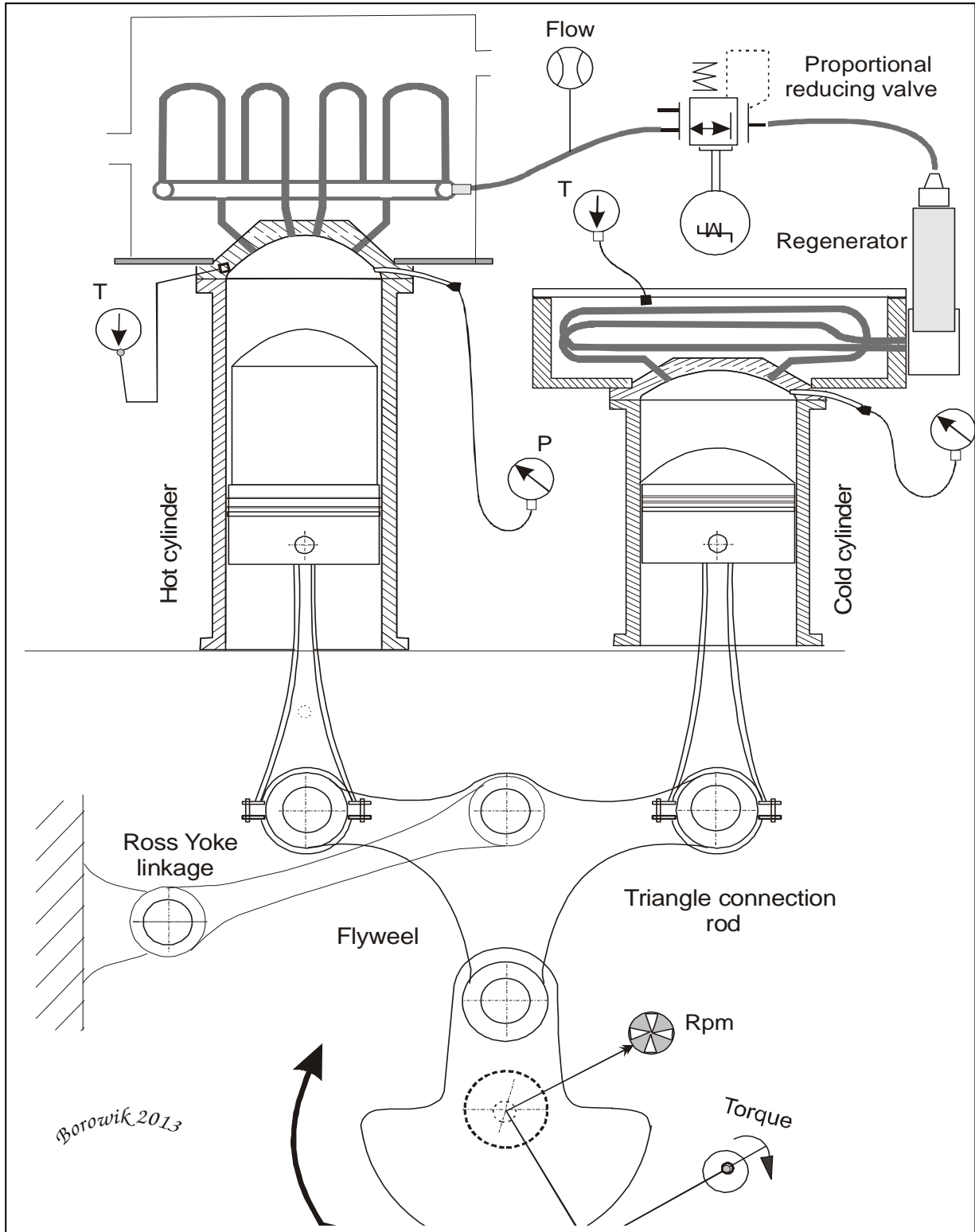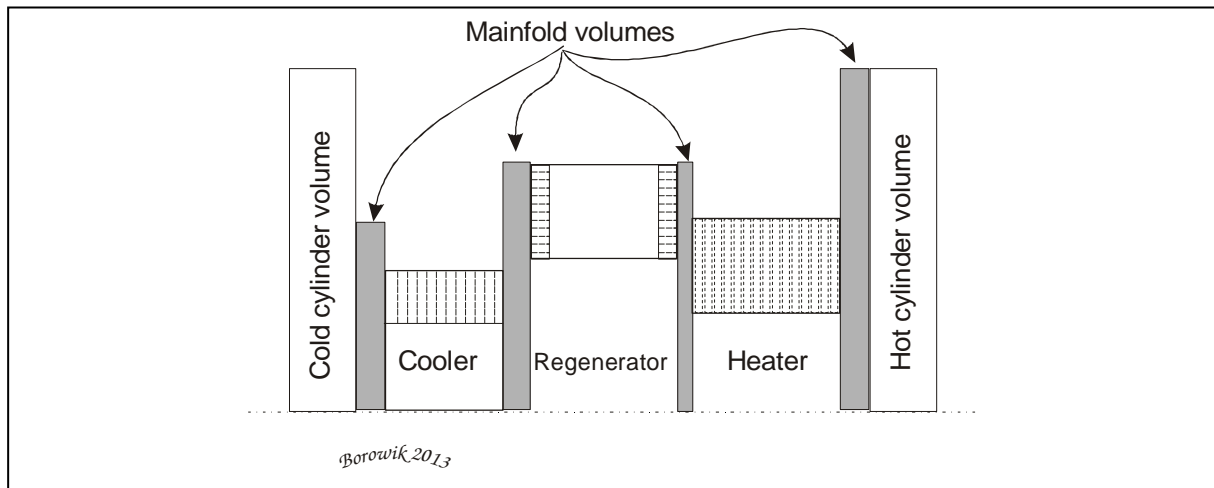**Figure 2.** The Stirling engine with Ross Yoke linkage.

Figure 3. Representation of working volume in the Stirling engine

The thermocouple circuit for temperature monitoring in the Stirling engine. To reach those objectives the system has been equipped with sensors, actuators and management software that allow a flexible operation. The test platform is composed of different subsystems: heating and cooling subsystem, electric subsystem, management and control subsystem. The platform allows testing the Stirling engine under different filling pressures, shaft speeds and hot heat exchanger temperatures. Related to the last one, a temperature control loop implemented in the hot air generator controller (independent from the engine operating conditions) allows the hot heat exchanger temperature, fixing whatever engine control system employed.

The management software permits running semi automatic tests at different operating conditions, and with its manual version, testing new strategies for start and stop procedures. The temperature of the engine is subject to thermal regime conditions.

In the conducted testing we used transducers such as thermocouple type TTJ/KE-361 as thermoelectric sensor Fe-CuNi/J/ class 1, shown in the schematic diagram on Figure 4.
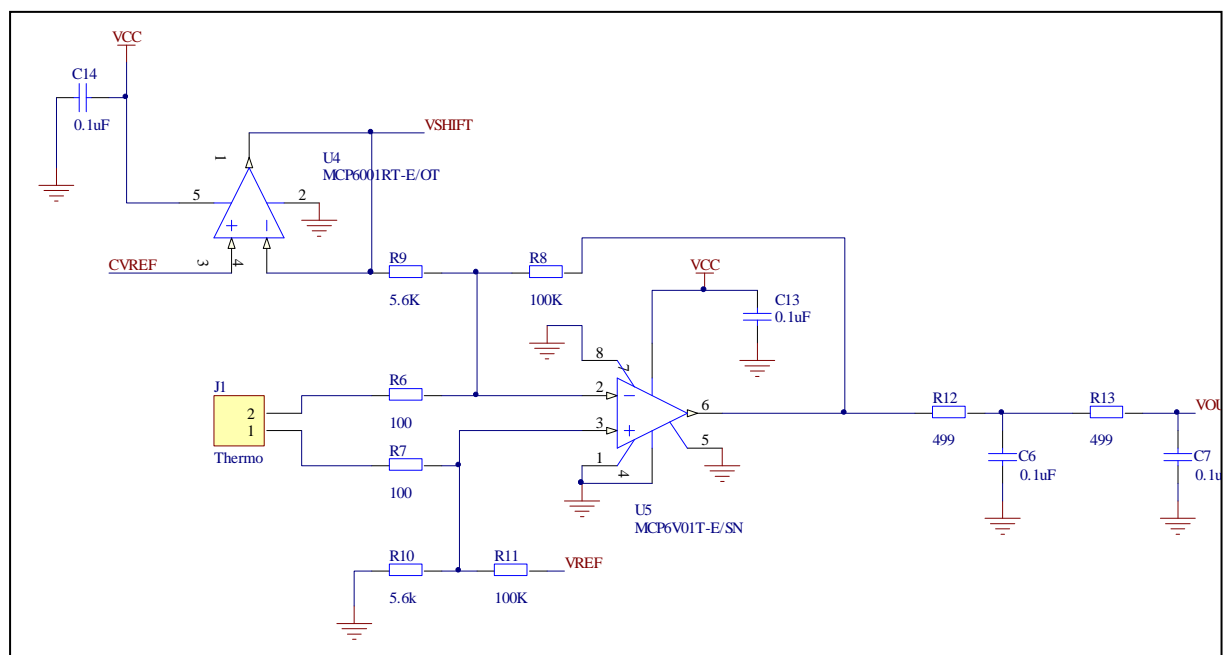

Figure 4. The thermocouple circuit for temperature monitoring in the Stirling engine.

The thermocouple matches the characteristic of type J (Iron-Constantan) and is trimmed for type K (Chromel-Alumel) inputs. Thermocouple amplifiers represent shown in fig.2 calibration accuracies ± 1 °C, working with cold Junction Compensation and High Impedance Differential Input. It combines an ice point reference with a prefabricated amplifier to produce a high level (equal to 10mV/°C) output directory from a thermocouple signal.

It can be used to amplify its compensation voltages directly, thereby converting it to a stand alone Celsius transducer, with a low impedance voltage output. It includes Reference temperature U_3 MCP9800A0T digital temperature sensor. The register setting allows for user selectable 12-bit temperature resolution measurements. The sensor works in industry standard I2C. To reduce the amount of circuitry the application monitors only four signal channels, but any number of channels supported by the PIC18F2550 microcontroller could be monitored (fig.5).
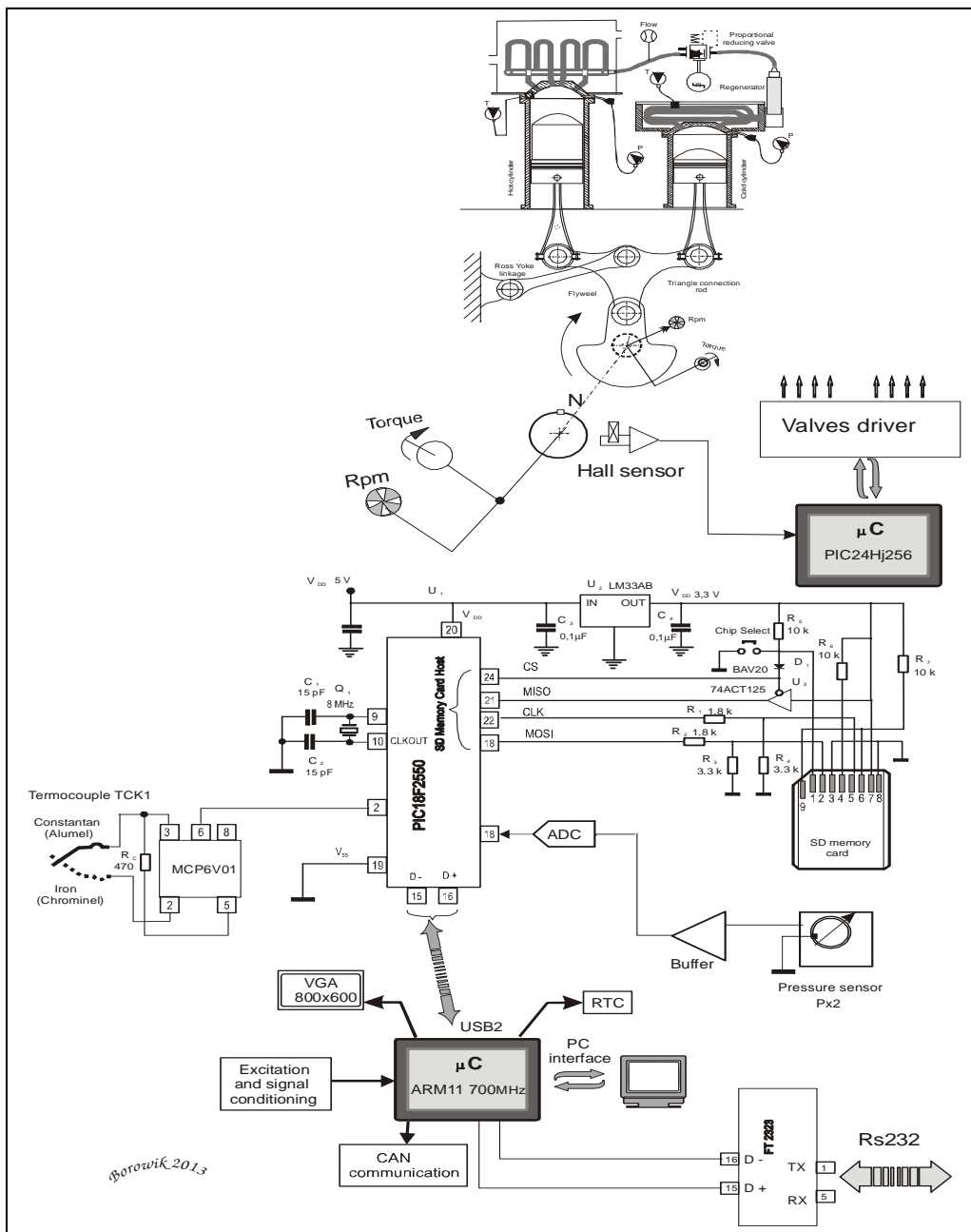

Figure 5. The Stirling engine testing facilities.
The Stirling engine testing facilities. In order to monitor the Stirling engine

performance some temperature sensors have been mounted. Measuring the temperature in the Stirling engine is not a simple matter because of the small volumes involved in the exchangers and the fast changes of the temperature of the working gas during the thermodynamic cycle. So only the average temperature can be measured during a single cycle. The engine has been equipped with 5 temperature sensors inside the regenerator, one inside a tube of the hot heat exchanger, one inside a tube of the cold one, and two inside the compression chamber. Other temperature sensors were mounted in the water circuit, in the carter and in the exhaust gas circuit. The compression chamber pressure also has been monitored, together with the rotational speed of the crankshaft and the output electric power generator. Figure 5 shows a measuring system for the cold energy used in the Stirling engine. Working gas temperature and pressure are measured at the three points, which are: the compression space, the expansion space, and the buffer space. Wall temperature of the cold side heat exchanger is measured at the top and the bottom side.

Conclusions. Through this test bench we can carry out experimental analysis of the α Stirling engine, which allow us to investigate the importance of applying the correct buffer volume pressure in order to obtain advantages in term of the power to the shaft. Taking into account the resulting energy dissipation leads to severe limitations on the maximum attainable thermal efficiency, and non-dimensional power output P. These limitations are independent of the regenerator conductance C_r. The maximum value of the power output P can be calculated from the formula:

$$P_{\max} = \frac{\left(\sqrt{\frac{T_h}{T_c}} - \sqrt{\frac{T_c}{T_h}} \right)^2}{4},$$

where: T_h – denotes a hot head temperature,

T_c denotes a cold head temperature.

The value of the thermal efficiency equals the following: $\dfrac{\left(1 - \dfrac{T_c}{T_h} \right)}{2}$, what further equals the half of the Carnot value.

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