
INTEGRATED SOLAR ENERGY POWER PLANT BASED ON PARABOLIC CONCENTRATOR AND ALPHA STIRLING SYSTEM FOR ENERGY GENERATION

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Abstract: *This paper presents a case study on a solar system for the production of heat and electricity, which was developed and implemented within a research project development. The energy system consists mainly of a parabolic concentrator combined with an alpha sterling system that uses solar energy that is free and clean, to produce heat and electricity through cogeneration process.*

This system provides an annual period of about five months, during the summer, providing heat and electricity from renewable sources such as solar energy, providing electricity storage over an extended period in the form of chemical energy expects by storing hydrogen obtained by the electrolysis of water, and its use to generate energy when weather conditions are not favourable.

Keywords: *alpha sterling, integrated solar energy, power plant, parabolic concentrator, cogeneration process*

1. Introduction

Robert Stirling invented Stirling engine in 1816. Robert Stirling not only developed and built heat engines but was also a reversed in the church of Scotland. Engines based on his invention were built in many forms and sizes. The new materials, developments, and models are the keys of the success for this engine. The increased interest in Stirling engines is due to several important advantages over the classical engines. Stirling engines are simple in design, easily operated and externally heated. They operate on a closed regenerative thermodynamic cycle using compressed gases [1].

Combined cycle power plants (CCPP) utilize the exhaust heat from the gas turbine engine to increase power plant output and boost overall efficiency up to 50%. Recently, exergy analysis, which is based on the second law of thermodynamics, has been found to be a potential tool for enhancing the understanding of system performance by determining the amount of irreversibility for each component and providing better insight into system design [1].

If the fuel combustion is considered as the fueling heat for this engine, the Stirling engine appears to be more clean and efficient engine, because the combustion is performed externally and the possibility of controlling the amount of oxygen will result in getting a complete combustion, and less fuel consumption with lower pollution [2].

Dish-Stirling technology development began in the late 1970's as a U.S. Department of Energy sponsored Solar Dish Electric Program with Jet Propulsion Laboratory. Currently, the technology is being developed in several locations worldwide. The most unique characteristic of this technology is the prime mover, known as a Stirling engine. The high temperatures achievable with concentrated solar energy make Stirling engines a prime candidate for solar thermal electric energy conversion, due to their high operating efficiency and emission free operation. The technology has demonstrated operating success, achieving the world's record for solar-togrid energy conversion efficiency. Megawatt rated plants are now online, with plants rated for several hundred megawatts nearing construction [3].

2. System overview

An example of a dish-Stirling unit is shown in Fig. 1. The main components of interest are the concentrator, receiver, Stirling engine, and generator, where the power conversion unit (PCU) contains the Stirling engine, generator, receiver, and various control systems. The concentrator consists of mirrors arranged in the shape of a paraboloid, with the focal point at the opening of the receiver. The receiver acts as a thermal interface between the concentrated sunlight and the PCU. Conductors from the PCU generator are connected to the utility through underground cables. Rated power output of systems to date range from 8 kW to 25 kW at an irradiance level of 1000 W/m² [4].

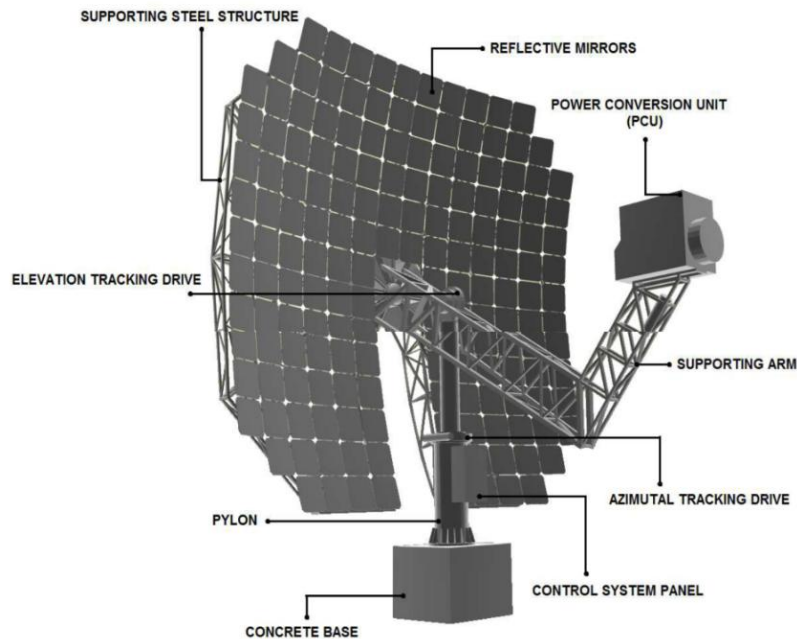


Fig. 1. Dish-Stirling system with labeled components [5]

The main parts of the concentration solar plant:

- Power conversion unit (PCU): The unit with Stirling engine generating power;
- Mirror area: 168 pieces of parabolic mirrors reflecting solar radiation to the PCU located in the focal point;
- Steel structure: Consisting of a pylon, supporting mirror frame and supporting arm of PCU;
- Tracking drive: AC motors with gear controlling slew drives in two axes – azimuthal and elevation direction; and Control system panel: Contains control elements to control the solar plant [5].

The units use two-axis tracking of the sun throughout the day, returning to a stow-away position in the evening when irradiance levels become too low to produce power. Two methods for controlling the receiver temperature are currently implemented, namely, variable stroke and variable pressure control. Variable pressure control is more common and is therefore used in this analysis. Detailed technical specifications on component dimensions and operating characteristics can be found in for several different dish-Stirling systems [6].

3. General description of concentrating solar power plant

Concentrating solar power plant CSP DISH STIRLING represents an unique energetic and ecological device, which effectively uses renewable sources of energy.

This power plant is built on modern technologies, which are able to use concentrated solar radiation.

This principle, efficiency and power output overcomes the possibilities of wide range of other devices using renewable sources of energy.

Parabolic concentrator with mirror surface reflects solar radiation to the focal point where is the PCU - power conversion unit (aggregate).

A main part of the PCU is Stirling engine which converts thermal energy gained from solar radiation to mechanical energy and then to the electrical energy via generator.

This system also allows effective take-off of unused thermal energy and waste heat, so that the solar power plant can be used even for making heat and cold.

This system features fully automatic controlling and positioning of the concentrator in two axis and meets the requirements in order to be built and engaged in harsh conditions. The output electricity can be sold or used for immediate consumption [7].

Solar conversion unit consists of the following sub-systems:

- Conversion unit base frame on which all parts of the unit are mounted.
- Thermal insulation of the front shield protects the front part of the unit against concentrated solar radiation. Metal covers of the unit muffle noise generated by the unit operation and prevent the effects of weather (rain, wind) from affecting it directly. Safety curtain of the front shield immediately screens engine from solar radiation in case of failure.
- Stirling engine, located in the front part of the power conversion unit.
- An electric generator connected to the engine. There is a refill bottle of the medium on the right side of the device.
- On the sides and at the rear part of the unit, there are coolers which absorb thermal power output generated by the unit. To increase the cooling output of the coolers, there is a bladed fan installed at the rear of the unit which increases the flow of cooling air through the cooling surfaces of coolers.
- In the left side of PCU there are parts of cooling circulation – pump and expansion tank. There is also a manometer.

In Figure 2 is represented the basic construction of Power Conversion Unit with heat Stirling engine. PCU allows simple basic maintenance and service, and design allows fast exchangeability. Stirling engine does not need water for electricity generation or cooling cycles (closed circuit) [7].

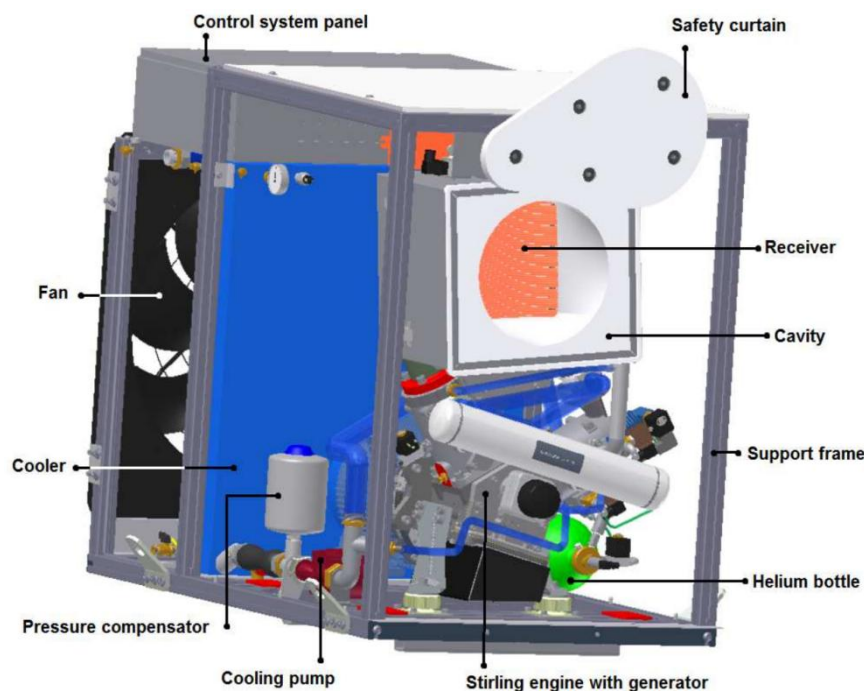


Fig. 2. Power Conversion Unit with heat Stirling engine [7]

Stirling engine is a confined system in which the working gas operating at high pressure is heated and cooled. The higher the pressure, the higher is the output. Working gas comes to the two cylinders of the engine, passes through the heater, called in the solar application "hot bulb receiver", regenerator and gas cooler. The working cycle is defined by pressures and temperatures in expansion and compression pistons. After heating in a receiver, the working gas expands and pushes the piston in expansion cylinder. The expanding hot gas flows back through regenerator and cooler, wherein the regenerator stores the thermal energy against cooling. The compression piston is used to transfer cooled gas back to the expansion part where the gas is reheated, expands and a new cycle begins. The mechanical force on pistons connected to the crankshaft drives an electric generator which generates electrical power.

In Figure 3 is represented the Stirling engine parts and working cycle.

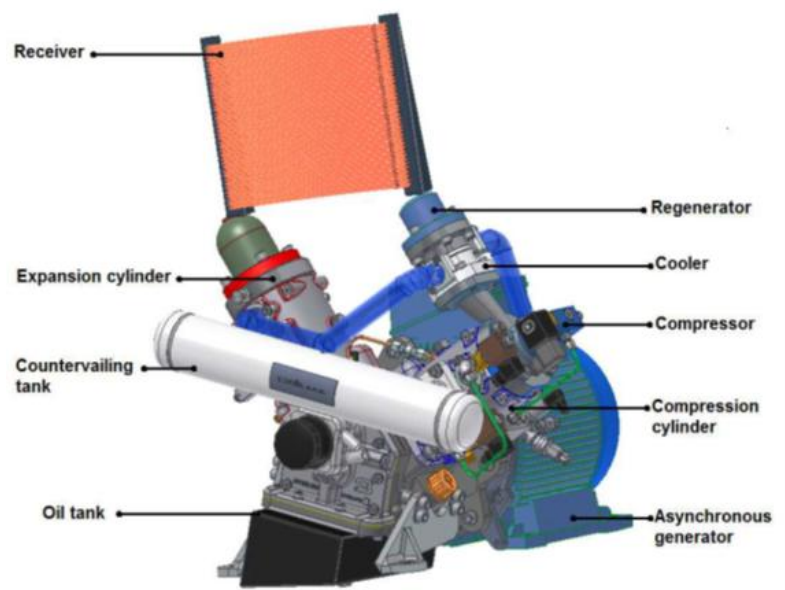


Fig. 3. Stirling engine parts [8]

3.1. Cooling system

In Figure 4 we present, as specified manufacturer, the cooling system that provides the cold source which it transfers its heat and is recovered by the heat exchanger, providing up to 9-25 kW.

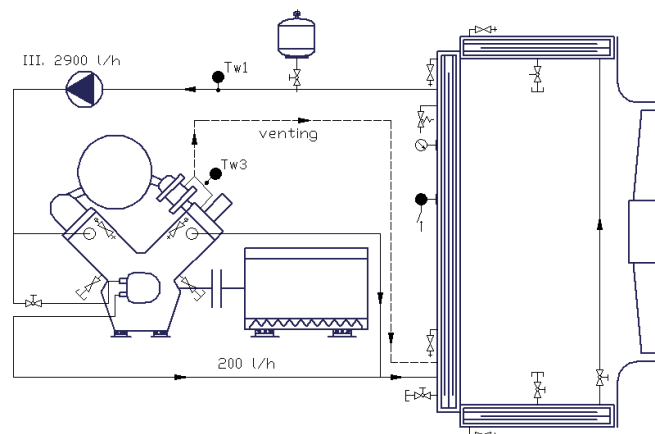


Fig. 4. Scheme of the cooling system [8]

3.2. Working gas system

Since the loss during the heat cycle varies between 3 and 15 cc/min, the working gas refilling, He, is supported with a valve from a storage tank. Refill valve regulates the working gas supplied from the refill bottle and increases the pressure to the required value according to the regulation temperature at the receiver. Working gas is led from the engine and returned to the refill bottle using a piston compressor and pump-off valve.

The total amount of working gas in the engine and the refill bottle is monitored by a controlling system and compared with two levels. If the amount is not sufficient to achieve the maximum operating pressure in the engine (first level), the control system automatically replenishes from external refill bottle at the beginning of the operation. If the amount is below the second level, operation is not possible. Replenishing is done by trained service technicians in the service mode of controlling system from the external refill bottle [8].

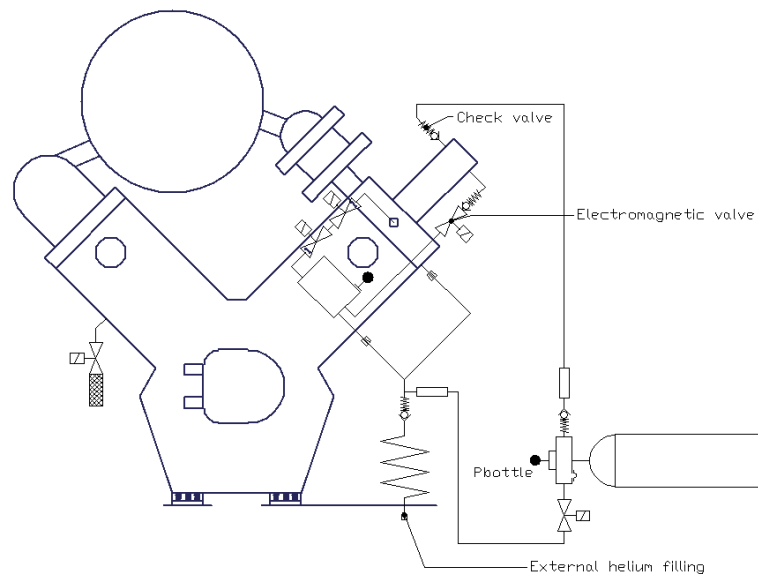


Fig. 5. Scheme of helium system [9]

3.3. Unit power output

The power output of the unit depends on the temperature on the receiver which regulates pressure level in the engine. If the temperature is too high, the pressure of helium increases and so does the electric power output.

Increasing of the pressure decreases the temperature on the receiver to the required range. At too low temperature, helium is pumped off by compressor section of the engine, thereby lowering the pressure. That lead to an increase of temperature on the receiver but decreasing pressure lowers the electrical power output of the unit.

The maximum working pressure of the engine is 130 bar and the minimum pressure during operation is 30 bar. Optimum operation is between 60 to 100 bar. With the engine off, the working gas pressure in the engine is lower than 30 bar, but the pressure of switched-off engine should not be lower than 10 bars. The pressure in the refill bottle is then approximately 170-200 bar. Maximum output depends on the temperature of the input coolant [9].

3.4. Control panel of the controlling system

Controlling of the device takes place in three independent control panel.

In Figure 6 is represented the Control panel of the controlling system and location of control panels.

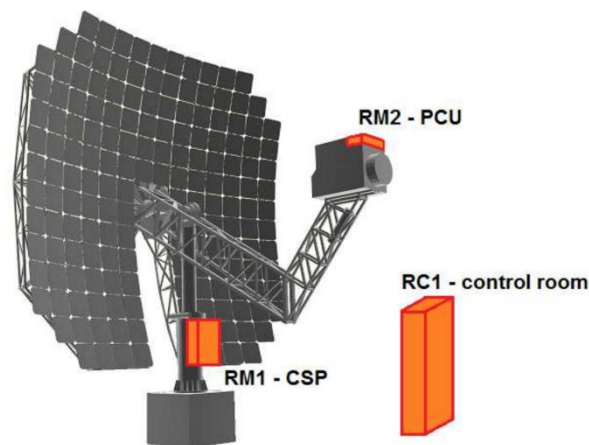


Fig. 6. Location of control panels. RM3 panel is located in the control room. [8, 9]

1. Control panel in PCU unit (RM2) – ensuring the distribution of electrical controls and collection of signals from sensors necessary for the operation and regulation of the conversion unit which generates electricity power.
2. Control panel on the pylon of the solar power plant (RM1 or RM1.1; RM1.2) – RM1.1 part includes autonomous controlling system on the basis of PLC with monochromatic control. The system is equipped by communication interface Ethernet for connecting the system to the superior controlling system. Power electrical installation in RM1.2 part used for leading electrical power output of the unit in the local power grid, comprising the main fuse with excess voltage fuses for the entire system.
3. Control panel in control room (RC1) – this control panel ensures communication between the power plants and PC.

4. Technical data and basic information

Welded and tilt-up steel construction placed on reinforced concrete base:

- Robust and resistant concentrator's construction diameter 8,5 m;
- Designed and verified by static and engineer's office according to relevant standards.

Parabolic concentrator (50kW/DNI>1000 W/m²) with reflective surface Concentrator's axis height above the ground level 5,3 m. Finished steel construction - zinc coated. CSP unit total weight: 5 000 Kg.

- Raw concentrator surface is 58m². Geometric concentration ratio is 1150. Focal length is 6 m.
- Segment specially shaped highly reflectance precise mirrors . Mirrors are resistant to a harsh climate conditions and are tested according to appropriate standards. Positioning of the concentrator and operating conditions position according to wind velocity.
 - Maximum elevation positioning range -20° to 90°, azimuthal 30° to 330°. Variable stabilized (parking).
 - Positioning meets the requirements for safe operating in very demanding conditions.
 - Maximal allowed wind speed during operation is 65 kmph (optionally 75 kmph) in stable position is 130 kmph (opt. 150 kmph). Power Conversion Unit (PCU 35) 35 kW with Stirling Engine SBT V-183 efficiency 25%. The 100% relative humidity, temperature -20°C to + 50°C, resists water, snow, icing, sand and dust.
 - Stirling heat engine 10 kWe (1500 rpm), single action α modification, swept volume 183 cm³, maximum efficiency is 25%.
 - Max output 10kWe + 25kWh (on DNI 1000 W/m²), ~400V AC/50Hz/3 phases, IP55, min coolant temp.
 - Working gas temperature 600-700°C, max. mean pressure 15 MPa, working gas Helium, volume of motor oil 2 litres. PCU weight: 500 kg. Control system with remote access 50°C, output heat water 60°C.

- Automatic and manual control. Controlling, monitoring and archiving of basic states of control
- Switch-board and communication array for remote control, monitoring, service and maintenance.

The control system allows sharing of information and conditions with remote workstations [9,10].

5. Performances and utilization

Depending on a power plant modification and customer's specifications, output possibilities, parameters and linkages can be combined and custom modified. Primary output is clean electrical energy with parameters allowing direct connection to the transmission network or direct consumption of this energy for common or technological needs. Secondary output is thermal energy, which can be accumulated and then used for a number of purposes. Among the main ways of utilization, production of cold for technological or processional purposes or desalination of sea water can be placed.

Individual concentrating solar power plants can be connected and used as standalone systems or can be integrated into big groups with power plant output ranging from tens of kw to tens of MW. On grid and off-grid solution is possible. Dish Stirling can be installed on terrain with high slope tolerance [8, 9,10].

In Figure 7 is represented the dependence of electrical efficiency and electricity power output on mean pressure of working gas.

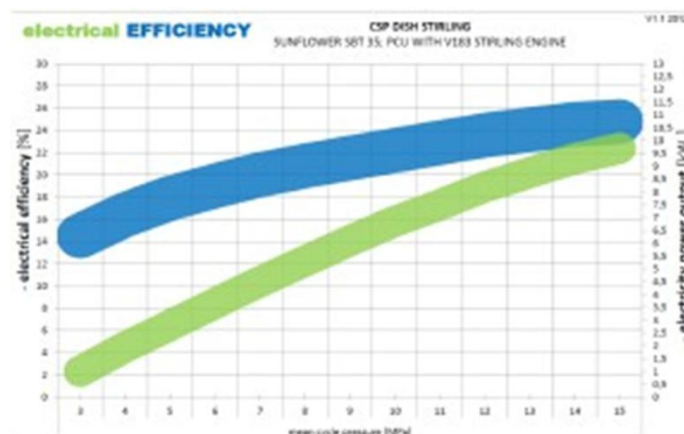


Fig. 7. Dependence of electrical efficiency and electricity power output on mean pressure of working gas. [7]

In Figure 8 is represented the dependence of electricity power output on direct normal irradiation (DNI) system.

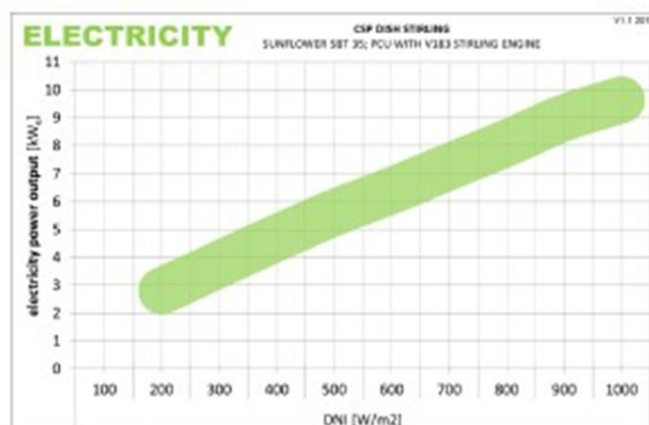


Fig. 8. Dependence of electricity power output on direct normal irradiation (DNI) system.[7]

6. Conclusions

This paper presents a case study of a research project that has been implemented, and which has as main objective the development of an integrated system to produce electricity and heat from renewable energy sources with low levels of pollution such as solar energy.

In recent years the use of food resources, water and energy have become a key issue, especially in rural areas where the vast majority have no possibility to connect to electricity, water or gas, but with a potential of renewables very good, especially solar, wind and biomass.

The case study analyzed in this paper reveals that the development of such a concept of energy system, consisting mainly of a solar concentrator coupled with a Stirling engine, and is entirely based on solar energy, can bring significant benefits on insurance energy in various remote areas, increase security of supply and environmental protection.

Acknowledgments

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References

- [1] M. Tarawneh, F. Al-Ghathianb, M. A. Nawafleh, and N. Al-Kloubd, "Numerical Simulation and Performance Evaluation of Stirling Engine Cycle", *JJMIE*, vol.4, 2010;
- [2] Masoud Ziabasharhagh and Mostafa Mahmoodi, "Numerical Solution of Beta-type Stirling Engine by Optimizing Heat Regenerator for Increasing Output Power and Efficiency", *J. Basic. Appl. Sci. Res.*, 2(2)1395-1406, 2012;
- [3] "Tessera Solar and Stirling Energy Systems Unveil World's First Commercial Scale Suncatcher™ Plant, Maricopa Solar, with Utility Partner Salt River Project," Press Release, Tessera Solar, January 22, 2010. URL- http://tesseractosolar.com/north-america/pdf/2010_01_22.pdf;
- [4] T. Mancini, P. Heller, B. Butler, et. al, "Dish-Stirling Systems: An Overview of Development and Status", *ASME, Journal of Solar Energy Engineering*, vol. 125, pp. 135-151, May 2003;
- [5] Sunflower 35 Concentration Solar Plant – Instruction Manual - Strojírny Bohdalice, a.s., 2013;
- [6] William B. Stine and Richard B. Diver, "A Compendium of Solar Dish/Stirling Technology." Sandia National Laboratories, Report SAND93-7026 UC-236, January 1994;
- [7] www.concentrating.eu;
- [8] Sunflower 35 CONCENTRATION SOLAR PLANT, Instruction manual, Manufacturer Strojírny Bohdalice, a.s, Bohdalice 63, 683 41 Bohdalice, Czech Republic, 2014;
- [9] www.concentrating.cz;
- [10] www.strobo.cz.