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MICRO-COGENERATION INCLUDING THE CONVERSION OF CHEMICAL ENERGY OF BIOMASS TO ELECTRIC ENERGY AND THE LOW POTENTIAL HEAT

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Abstract
This article deals with combined production of heat and electricity for small premises, such as households, where energy consumption is around few kilowatts. This proposal of micro cogeneration unit uses as a heat source an automatic burner for combustion of wood pellets. Construction of an equipment for the heat transport can be designed using different basic ways of heat transfer. Electricity is produced by the two-stroke steam engine and the generator.

Keywords: cogeneration, two stroke steam engine, heat transfer, heat exchanger, boiler, injection of water

1. Introduction

Biomass plays the key role in reducing the dependence of Slovakia on the natural gas import. Using biomass for electricity and heat production comes to the foreground in a higher extent. Our aim is to use biomass for electricity and heat production using cogeneration. Since cogeneration is currently being promoted mainly for large and medium-sized operations, we focused on its use in small enterprises where the energy consumption is on the level of few kilowatts.

The cogeneration process is carried out in facilities called cogeneration units. It is possible to use electricity to cover own consumption or to sell it to energy supply companies. Heat is used for heating and to heat domestic hot water. Naturally, the final utilization depends on specific conditions. As the cogeneration units operate independently from the network of energy supply companies, they serve also as a back-up power source and they allow the operation also during a blackout.

This paper deals with the research and design of unconventional solution of conversion of biomass heat energy to mechanical energy. To fulfil this objective, this work processes various calculation variants and mainly various variants of design work which would ensure optimal achievement of stated goals?

2. Experimental setup

The main target is to design minimum one suitable way of Micro-cogeneration including the conversion of chemical energy of biomass to electric energy and the low potential heat using analytical-experimental methods. The principal proposal of micro cogeneration unit based on wood pellets combustion is presented in Figure 1 with the energy flow in Figure 2.

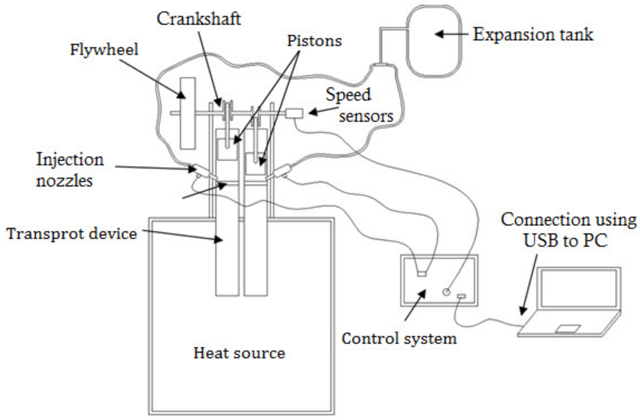


Figure 1: The principal proposal of CHP unit

The micro cogeneration unit consist of following parts:

- Heat source – provides the heat production using biomass combustion
- Heat transport device – ensures heat transport between the fireplace of the boiler and the working area of the engine
- Engine with generator – electricity production using supplied heat and injected water
- Injection and control system – must ensure exact injection intervals as well as an exact amount of the injected water
- Heat exchanger for heat transfer to the heating medium

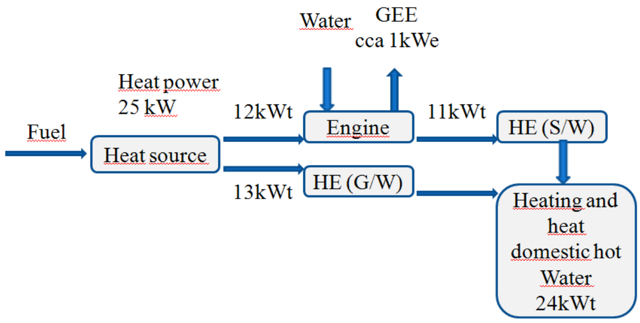


Figure 2: Schema of energy flows in CHP

Heat source

We have used the 25kW boiler for burning pellets with automatic fuel transfer, from the company Kotly Lokca as a heat source. The automatic transport of pellets directly to the fireplace in the boiler enables a continuous flame regulation as well as the possibility to maintain the boiler output at a constant level. It is particularly important for the design of the machine with the cyclic running. The boiler was adapted to set up the two stroke engine and to the option of smoke regulation using welded brackets in the inner part and the 10 mm steel plate (Figure 3).

Figure 3: 25kW boiler burning the pellets

Figure 4: Removable lid with holes on the top side of the boiler

On the top side of boiler we have constructed a removable lid with holes. It is possible to clap the equipment for heat transport through them, directly over the fireplace of the burner (Figure 4). All modifications are executed in order not to affect the boiler power.

The great advantage of this boiler is the simplicity of its operation. The user ensures the fuel tank filling by the prescribed fuel. The fuel is served out from the reservoir to the burner by the screw transporter. The whole process is controlled by the control unit. The fan blows air to the burner to ensure the fuel combustion. The fuel combustion and the creation of thermal energy are in progress in the burner. This energy in the form of hot exhaust gases is transmitted in the tube directly into the engine and in the heat exchanger to the water of heating system. In the same time is the old burned fuel in the burner pushed out by the new fuel to the direction of retort's outer edge. Emerging ash forfeits through the edge of the burner to the ashtray. This whole cycle takes place automatically without user intervention. The only duty of the operator is to add the fuel to the fuel tank and to remove the ash.

Figure 5: Burner in boiler

3. The steam engine

A piston steam engine with a generator has been designed for the transformation of heat energy to electricity on the Figure 6.The engine together with the generator serve for electricity production. The principle of thermal energy transformation to electricity is based on injecting steam through the nozzles to the evaporative surface in the workspace of the engine. After injecting water to the front surface, the rise of the enthalpy of water evaporation and changes of its state will be used for the piston movement. After the expansion the steam leaves the working area of the engine.

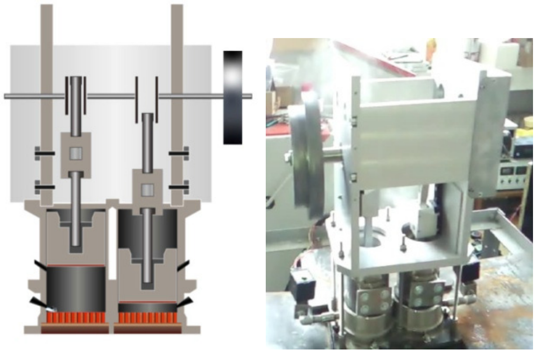


Figure 6: Steam engine

The injection is enabled through the nozzles that contain 22° angle with the evaporative surface. The steam discharge is controlled by two electromagnetic valves placed on the harmful engine surface level.

For the correct operation of the engine, we had to ensure constant pressure of water, which is being injected through the nozzles into the working area of the engine directly to the evaporative surface. To achieve constant high pressure the resource of the power water has been designed with the help of an expansion tank.

4. Transport equipment using the heat transport by conduction

The transport equipment for the heat transfer in the micro cogeneration unit from the combustion chamber area into the working area of the two stroke steam engine, which uses the heat transport by conduction, was designed using a 3 mm thick cooper plate to which cooper rods with various diameters and with various configurations were attached, figure 1. The choice of the material for the heat transport device construction was made mainly for its high thermal conductivity. These rods should serve for the transfer and the accumulation of heat in the combination with a ceramic plate placed on the head of the steam engine cylinder. This accumulated heat should serve for the evaporation of the injected water in the cylinder space on a ceramic plate.

For the transport system proposed by us, calculations were made for the heat transport from the burning chamber area in the case of using a heat source with the estimated 25kW thermal power. We have used CFD methods for calculation. The volume of exhaust gas per hour and subsequently the velocity of flowing around the rods exchanger were calculated using stochiometric equations. We took into consideration that the rods will be placed in the flue with dimensions 10x20x10mm where the velocity of smoke will be 2,15 meters per second and with the exhaust temperature 800 degrees. The aim was to determine if it is possible to get the necessary amount of heat to the cooper plate surface by the heat transfer from the boiler chamber using the outflow gases.

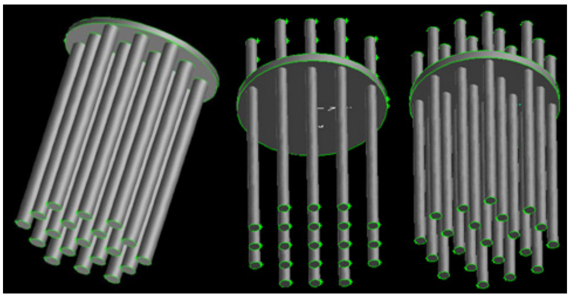


Figure 7: The mathematical model with used tetra-hybrid mash

3D models with rod diameters 4, 6 and 8 mm in different amounts and in ordering one after another and chequerwise were drawn in Gambit. The height of rods is 100 mm so they fill in the entire space in the flue. The tetra-hybrid mesh was used for the meshing. The number of elements ranged from 5 to 8,5 million elements according to the chosen model.

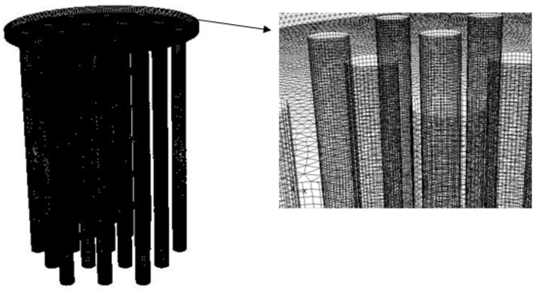


Figure 8: Heat profiles of various orderings

The continuity equations, the Navier – Stokes equations and the energy balance equations were used for the simulation calculation.

Continuity equation

The mass conservation equation of the gas phase is written as:

$$\nabla(\rho\bar{v}) = 0 \qquad (1)$$

where ρ is the fluid density and $\bar{\upsilon}$ is its ensemble-averaged velocity vector defined on a 3D domain.

Momentum equations

The Navier-Stokes (~momentum) conservation equations are defined as:

$$\frac{\partial}{\partial t}(\rho U_i) + \frac{\partial}{\partial x_j}(\rho U_i U_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho f_i \qquad (2)$$

where f_i are the sum of external forces and τ_{ij} is the viscous stress tensor described by the Newton law:

$$\tau_{ij} = \mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \frac{2}{3}\mu\delta_{ij}\frac{\partial U_l}{\partial x_l} \qquad (3)$$

whereδ_{ij} is the Kronecker symbol and μ is the molecular viscosity depending on the fluid properties.

Energy equation

When considering heat transfer within the fluid or solid regions of the domain, the software covers also the general form of the energy equation written below:

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_i}(\rho h U_i) - \tau_{ij}\frac{\partial U_i}{\partial x_j} + \frac{\partial q_i}{\partial x_i} = \rho U_i f_i + S_h \qquad (4)$$

where h is the total specific enthalpy and which for a multi component medium takes the following form:

$$h = \Sigma Y_i h_i \qquad (5)$$

whereY_i is the mass fraction of the species i in the mixture and h_i is its total enthalpy written as:

$$h_i = h^0_{Tref,i} + \int_{Tref}^{T} Cp_i(T)dt \qquad (6)$$

where h^0, T_{ref} and $C_{p,i}(T)$ are the formation enthalpy, the reference temperature and the specific heat at constant pressure, respectively.

Species transport equations

Finally, the behavior of the species i will be solved by the following equation:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla(\rho\vec{v}Y_i) = -\nabla\vec{J_i} + R_i + S_i \qquad (7)$$

where S_i is the rate of creation by the addition from the dispersed phase plus any user-defined sources, $R_i$is the net rate of production of species i by chemical reaction and $\vec{J_i}$is the mass transfer rate. The finite volume method to solve the governing flow equations described above is applied.

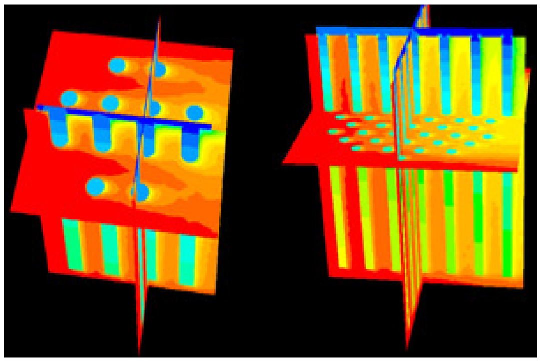


Figure 9: Comparison of different kind of thermal models with different ordering

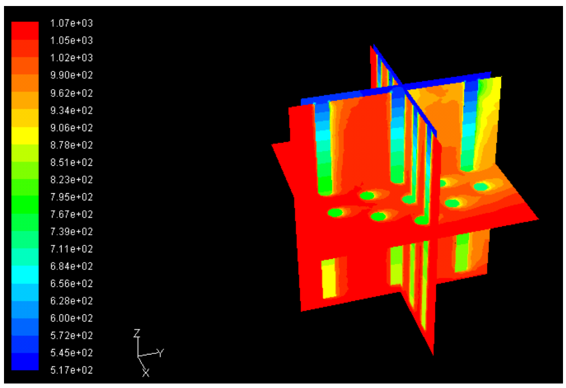


Figure 10: The heat profile of optimal ordering

To optimize the parameters for the experimental device the mathematical model was simulated in the Fluent software package. Based on all input parameters different variants of rod

dimensions and ordering were calculated (Figure 9). The calculation was applied for the turbulent flow, the k-epsilon Standard and for the k-epsilon RNG low Re numbers.
These mathematical models showed that with the help of the heat transfer through the copper rods we are able to achieve, using an adequate arrangement, the sufficient heat flux/flow and the sufficiently high temperature to vaporize water regardless the small size of the evaporative surface. The model with chequerwise arranged 19 tubes with 6 mm thickness was proved as suitable (Figure10).

5. The transport device using the heat transfer by the heat pipe

Another alternative which we have dealt with in terms of heat transport from the combustion chamber area to the area in the piston steam engine was the proposal of the transport equipment using the heat transport with help of heat pipes.
The heat pipe is the technology serving for the heat transport and the heat power while maintaining a small temperature difference. The heat transfer is ensured by the evaporation and the subsequent condensation. Using this technology it is possible to transfer a large amount of heat at a small size device. The device has not any moving parts, it does not require any maintenance and it has a very long working life.

The principle of the heat pipe working

The heat pipe is hermetically closed pipe containing sodium or other working medium at a defined pressure. In the longitudinal direction the heat pipe is made up of an evaporator section and a condenser section. Heating of one tube end and cooling of the second tube end will cause that the working medium in the vaporization section of the tube starts to evaporate. Steams pass through the tube into the condensing section. They condense here back to liquid and because of gravity and climbing through the absorbing material the liquid passes back into the vaporization part. It will evaporate here again. These results in a forced circulation of the working medium associated with the heat transfer. The device operates only with the temperature gradient, thus only if there is a difference between temperatures at the ends of the heat pipe. The bigger the difference is, the bigger is the efficiency of the heat transfer. Used medium depends on the temperature range of pipe at which occurs the evaporation and the condensation of the working medium, ambient pressure and the pressure inside the tube.

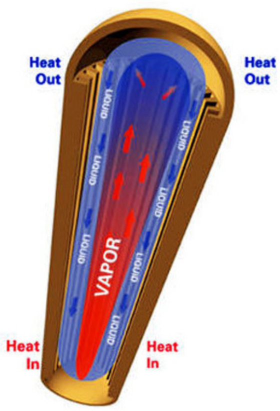
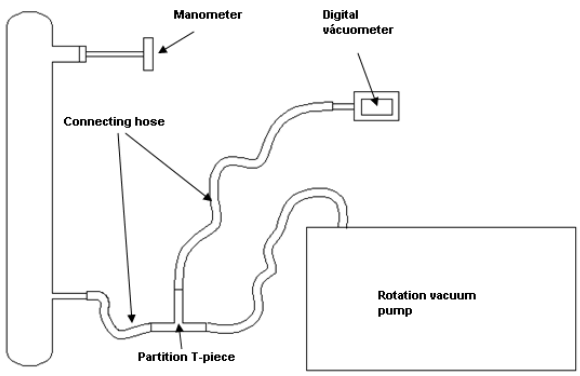


Figure 11: The heat pipe

In our workplace we decided to design and to produce a transport device for the heat transfer from the fireplace to the working area of a steam engine using the gravitational heat pipe with sodium as a working fluid.

The main part of this heat transport equipment is a heat pipe. Its lower part is heated from the fireplace which temperature is known from the used type of fuel. The temperature range of the fireplace using briquettes and pellets is from 600 to 1200 degrees. Sodium was chosen as a working medium due to the low boiling point as well as due to the low vapour pressure.
A draft of this heat pipe was based on the requirement to ensure the possibility of its inserting into the engine´s working area as well as into the combustion chamber area of the heat source.
Production of the heat pipe is quite complicated since the sodium is the working medium and it has some dangerous properties. A high vacuum must be achieved and a sufficient cleanliness of pipe´s inner parts must be ensured in the heat pipe area. From the aspect of the research, it is necessary to enable the heat pipe designed in this way a pressure measurement in the heat pipe area also at relatively high temperatures about 750 degrees. To



produce a heat pipe a device on the Figure 6 was designed.
Figure 12:The vacuum equipment of sodium heat pipe

It is necessary to install a pressure gauge to examine for vapour pressure at different temperatures. A thin pipe must be welded on the pipe as well. It will be connected to the vacuum pump. This thin pipe helps to create a vacuum in the heat pipe. All welds necessary for the heat pipe construction must be done in a good quality in order to tighten and to maintain created vacuum.

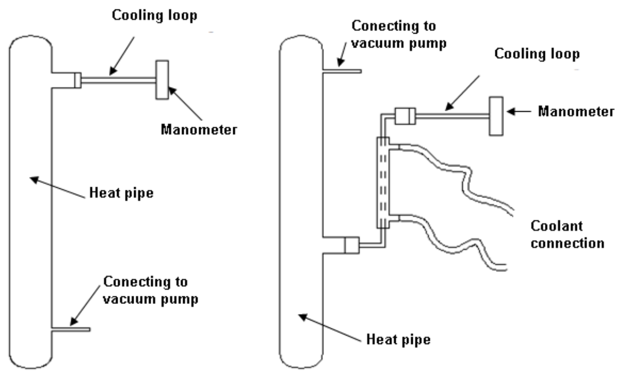


Figure 13: Proposal of pressure measurement in the sodium heat pipe

The heat pipe for the heat transport from the combustion chamber of a boiler to the working area of a steam engine, we have constructed for this experiment, is made of fireproof steel AISI 310S-W with diameter 90 mm, with pipe wall thickness 2,5 mm and height 625 mm (Figure 14).
A cover of a half-round shape was welded on the pipe. A manometer was installed on the pipe prototype to examine the increase of sodium vapor pressure. The pressure gauge was installed to the heat pipe with the help of a welding piece with the inner thread and the cooling loop (Figure 13). The biggest

complications by the construction were caused while the choice of a suitable sealing. As suitable solution for the high temperature application seemed to be talc sealing circles but during the pressure experiments the seal bond was leaking.

Figure 14: The heat resistant stainless pipe

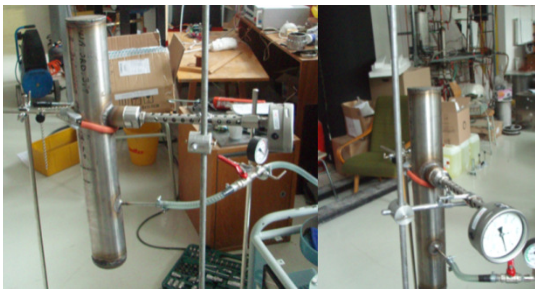


Figure 15: Sodium heat pipe with manometre

To create vacuum we have welded a ¼´´ stainless tube on a heat pipe. With the help of a rubber hose a force pump was connected to the tube. It was relatively difficult to create a vacuum using a stainless heat pipe because it is very difficult to press even a thin stainless tube so that it would maintain the vacuum. In comparison to closing a copper pipe, even after heavy pressing a stainless tube it releases back and it enables a re-sucking of an air.

Figure 16: Equipment for pressing stainless tube

The construction of a heat pipe for the heat transport from the combustion area of a boiler to the working area of a two stroke steam engine was very complicated as sodium was a working medium. We had to ensure safety while constructing this heat pipe because while using sodium the working temperature is around 750 degrees. Very important role plays the quality of welds because after filling the pipe with sodium with the help of a force pump these welds had to resist high temperatures and changes of pressure.

Production of gravitational heat pipe with sodium for the micro cogeneration unit requires sophisticated technology in comparison with the original heat pipe.

For proper function of the micro-cogeneration unit plays an important role the evaporative surface (figure 18) on the head of steam engine, which is either part of the heat pipe or in contact with it.

The material of evaporating area is very important as well as forming. This area must provide the best and fastest heat transfer to the working substance, its warming and subsequent evaporation. For development of the micro-cogeneration unit were used ceramic and metallic materials.

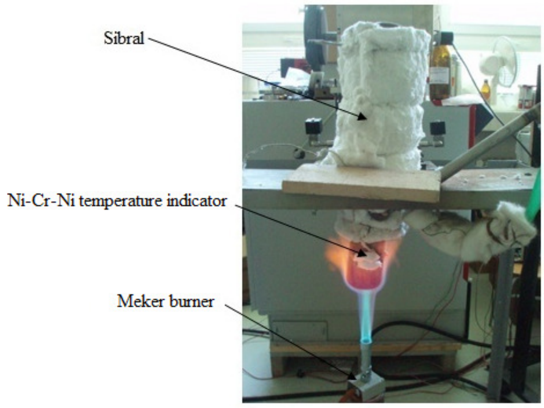


Figure 17: Sodium heat pipe

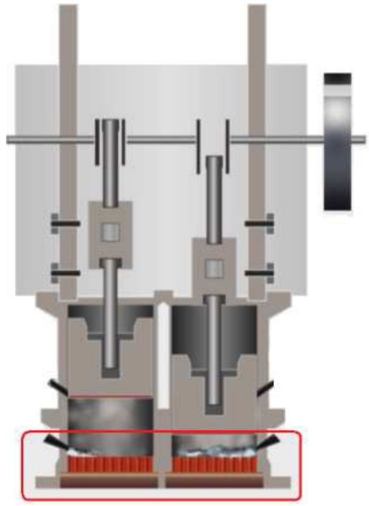


Figure 18: Evaporative surface

The advantage of ceramic materials is their porosity, which increases the evaporating surface and have good accumulation capacity. Disadvantage is that the change of state inside the pores creates the internal tension and its low thermal conductivity. Therefore, emphasis is placed on the strength of materials. In the case of metallic materials is great advantage the high thermal conductivity.

Production of ceramic plate for evaporation of water in the working area in two stroke engine was evolved in collaboration with the Institute of Inorganic Chemistry in Bratislava. Composition of ceramic engine parts (regenerator) was optimized based on the results of corrosion tests. The corrosion tests compared the three dense ceramic materials: Si_3N_4 (Si_3N_4 + 5 m% Yb_2O_3 + 2 m% MgO), SiC (SiC + 5% AlN + 2 m% Yb_2O_3) and SiAlON ($Si_{6-z}AlzOzN_{6-z}$, with value z = 3,8). The corrosion tests showed that material based on SiC has better resistance to water vapour at 280 ° C and a pressure of 70 atmospheres as Si_3N_4. Much better results were obtained form a terials based on b-sialon. The disadvantage of this material (SiAlON) is lower thermal conductivity (17-20 W/m×K) in comparison with Si3N4 and SiC (80 and 104 W/m×K). Good thermal conductivity is necessary in applications where the material is subjected to thermal shock. Based on the results of corrosion tests and measurement of thermal conductivity of silicon carbide (SiC) was chosen as a matrix of ceramic regenerator (UACH SAV).

In an experimental test of evaporation from the surface of ceramics has been found that this material is capable of rapid evaporation. The disadvantage of the material is the sensitivity to rapid changes in temperature and the ceramic plate bursts after a while the water injection on material (Figure 19).

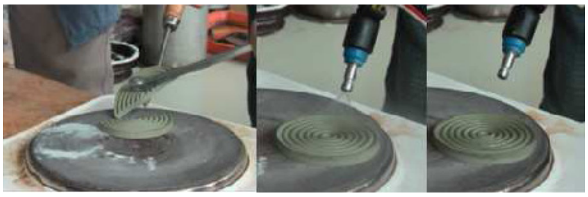


Figure.19: Test of evaporation from the surface of the ceramic plate

As a further material was tested plate made of stainless steel. Neither this material is not suitable alternative, because during the injection was created the film boiling.The drops of water did not evaporate from the surface, but were collected into one whole and were jumping on the surface (Figure 20).

Figure20: Test of evaporation from the surface of stainless material

When testing different materials has proved very good solution to use material from cast iron (Figure21). It has high thermal conductivity and high evaporation capacity.

Figure 21: Test of evaporation from the surface electric cooker (cast iron)

The best material was cooper instead of iron. The Figure 22 shows that the accumulated heat in the copper plate in a second can transform large amounts of water vapor. This material was used for production of the frontal evaporation surface in a steam engine.

Figure 22: Test of evaporation from the surface of copper plate

To transform heat into electricity has been designed piston steam engine. The principle of transformation of thermal energy to electricity is based on injecting water through the nozzles to evaporative surface in the workspace of the engine. Using the heat supplied by heat transfer surface from the boiler, the injected water turns to steam. When water evaporates, its volume increases and expands. After the expansion steam leaves engine.
Water injection was carried out through the nozzle, which were connected to a source of constant water pressure. Opening and closing of the nozzle was realized by the control system. When running a piston steam engine played a very important proposal from the control (Figure 23) system and control algorithm.

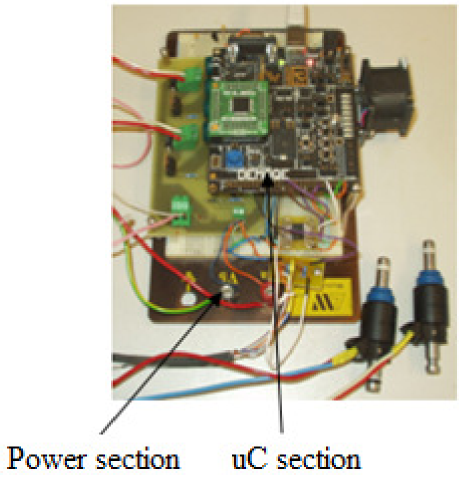


Figure 23: Control system

Different time injection intervals were tested, what is directly in proportion to the amount of water.

6. Conclusions

With the help of designing and modifying the steam piston engine for the micro cogeneration unit we were able to bring the proposed steam engine into operation. Using the injection and the control system, we eliminated forces that operated against the engine movement. This control system has played a very important role in putting the steam engine into operation. The various injection intervals were detected, what is directly in proportion to the amount of water. These experiments showed that the injection time has a minor effect to the speed. The speed of the piston was gradually set up to the cycle, which was due to evaporation speed. The engine moved in range from 90 to 130 revolutions per minute. This implies that the evaporated water in the form of steam has enough big energy to expand and to rotate the crank shaft 360 degrees. It was not possible to measure the output because of low speed. The largest power expansion of the engine was developed soon after the injection on the copper evaporating surface. This implies that an increase in the output can be achieved by reducing the height of lift, through which the biggest energy and the expansion of steam will be used. By increasing the piston diameter the piston area, on which steam exerts its pressure, would increase. As well the evaporative surface would increase and this could increase the engine performance.

7. Acknowledgements

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