Technical assessment and thermodynamic analysis of a prime mover Stirling engine in a micro CCHP biomass system for an isolated residence in South-East region of Romania

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Abstract: - The use of renewable energy sources and the assessment of energy economy are the subject of many research studies. Stirling engines have better performances for micro-CHP systems compared with other prime movers as RC, micro-turbine and fuel cell. The paper presents the problem of energy performance and efficiency evaluation of the Stirling prime mover using renewable fuels, in a micro scale combined cooling, heating and power (mCCHP) trigeneration system, for a domestic residence situated in South – East region of Romania.

Key-Words: - Trigeneration system, Stirling engine, renewable fuels, biomass, wood - pellets

1 Introduction

Fossil fuels such as petroleum, coal, and natural gas have become limited resources. In addition, global warming due to carbon dioxide (CO_2) emission has become a serious environmental issue, in recent years. The industrial and demographic development and the production to consumption ratio involve an increase of raw materials consumption and therefore the rise of waste and pollutants [15].

Since current living and economical standards depend strongly on fossil energy sources, it is necessary to realize a new technology that utilizes biomass as a source of energy. Climate change and limited fossil resources call for a reduction of non - renewable primary energy input and greenhouse gas (GHG) emissions by 50 to 80 % by 2050 [2].

The researches in the field of energy generation and consumption are directed applied on the implementation of „clean" technologies: higher efficiency and lower level of pollution [15].

One possible developmental path is decentralization of the electricity system [1]. Distributed power generation in small, decentralized units is expected to help in reducing emissions and saving grid capacity, while also providing opportunities for renewable energy [20]. It could thus form a constituent part of a more sustainable future. This vision of decentralized, and often autonomous, technological systems has been often replicated and has also been applied to energy systems [3, 5]. The trigeneration, as solution for combined cooling, heating and power simultaneously generation, fits the „clean" technologies for energy generation characteristics due to its economic and environmental advantages.

The trigeneration concept refers to the simultaneous production of mechanical power (usually converted to electricity), heat (at low and high temperatures) and cooling (using heat at high temperature) using only one source of primary energy [22]. This source is represented by fossil fuels or by some appropriate types of renewable energy sources (biomass, biogas, solar energy, etc). Since biomass is the only carbon-based renewable fuel, its application becomes more and more important for climate protection [24]. The recovered thermal energy is used to generate heat and cooling thus increasing the overall efficiency of the system with respect to the more conventional separate production of electricity and heating and/or cooling that produce a given saving in primary energy that will depend on the specific technologies and application [16, 17]. In the Energy Performance of Buildings Directive of the European Union, CCHP is seen as a technology to fulfill the energy requirements of buildings [20].

One objective of trigeneration systems is the diversification of energy sources, especially use of renewable ones, accordingly to the geographical location and possibilities [9]. Integrated micro-CCHP system solutions represent an opportunity to address all of the following requirements at once: conservation of scarce energy resources, moderation of pollutant release into our environment, and assured comfort for home-owners [12].

2 The energy demand of the residential consumer

The residential consumers' energy demand is made of the following:

- the heat demand for heating the household
- the hot water household demand
- the electrical demand for the home utilities

The residences energy demand has hourly, daily, monthly and seasonal variability. If we know the hourly variations of heat demand we can determine the daily, weekly, monthly and annually energy consumptions.

2.1 Thermal energy demand of the consumer

The coldest the local climate is and the higher interior temperatures are, the higher the demand for thermal energy to heat the space. Fueling the heating space has to compensate for the losses of heat transmitted through walls and the roof, and also the losses given by the heated air from the mechanical or natural ventilation systems. The external temperature is the most important variable, for explaining the daily influence and the year-to-year variations, the general demand for thermal energy. The specific heat consumptions differ from country to country (climate), but also depend on the residential consumers' comfort level.

2.2 Hot water consumption

Preparing the hot water in household purposes and not only is the second demand of thermal energy as amplitude, after the demand of heat for heating place. This demand for thermal energy is more amplified in the residential sector, comparatively to the industrial sector. A recent informative document or a hot water medium consumption report in the European countries does not exist yet.

The last informative newsletter available and used is the report (Eurostat, 1999) about the energy consumed in EU15 households and some CEE countries.

The medium hot water consumption is estimated to 50/liters/day/person.

2.3 The estimate electric consumption demand

The electrical demand of the residential consumer is dependent on the endowment of electrical devices in the house.

The standard monthly consumption of a Romanian residence is (100-300) kWh and can be considered constant for a residence.

3 A micro CCHP System

At the moment, new small scaled combined heat and power systems are emerging on the market especially for individual houses and small building blocks. Small scaled combined heat and power is however quite expensive and not enough diffuse in Europe.

A comparison of residential micro CHP technologies focused on prime mover, made versus separate heat and power, where the needed separate heat and power (SHP), indicates that the overall system efficiency has the best value for Stirling micro-CCHP technology as well as for thermal/electric ratio [4, 19].

One of the most recent and promising alternatives for the biomass use are the m-CCHP (Combined Cooling, Heating and Power small-scale <1 MWe) plants. In such systems, there are no important resources requirements and the seasonal efficiency of the conversion is increased thanks to the high efficiency of the overall system and the large operation period.

A CCHP system (figure 1) indicates large-scale technologies that contain both improved conventional approaches, like steam turbines, engines, combustion turbines and electric chillers, as well as relatively new technologies such as fuel cells, micro turbines, Stirling engines, absorption chillers and dehumidifiers [22]. Although steam turbine, reciprocating internal combustion engine and gas turbine that can be considered as the conventional prime movers still make up most of the gross capacity being installed, micro gas turbine, Stirling engine and fuel cell present a promising future for prime movers in CCHP system.

The trigeneration technology is a very good solution to supply energy to the building sector (residential houses, offices, hotels) [7, 14].

In industrial applications the energy demand is very regular across the year, but in buildings the energy demand is highly variable due to the external ambient conditions, the occupancy, the different building uses, etc. The flexibility of a trigeneration equipment is able to adapt to the customer's service requirements, despite the high variability in energy demand characteristic of building applications [19].

Successful development of a micro-CCHP system for residential applications has the potential to provide significant benefits to users, customers, manufacturers and suppliers of such systems [12].The benefits of the CCHP system include significantly increased energy efficiency, reduced consumption of fossil fuels, by using renewables, reduced pollutants and CO_2 emissions from power generation.

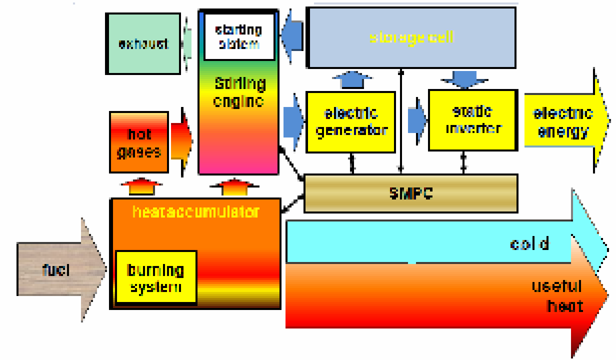

Fig.1 – A micro - CCHP unit

The design and operation of combined cooling, heating and power (CCHP) systems are dependent upon the seasonal atmospheric conditions, which determine thermal and power demands of buildings. Trigeneration system applied to residences cover the usual electrical power needs < 5 kW(e) and for the thermal needs <25 kW(th) [4, 9]. The fundamental requirement for a trigeneration micro-CCHP system is to provide full services and comfort for the dwelling occupants with or without external supply of power while utilizing electricity and fuel in the most efficient manner through heat recovery and other integrated system solutions.

The target customers are people with houses located outside the utility's distribution lines or in areas with unreliable electric grid service. (figure 2).

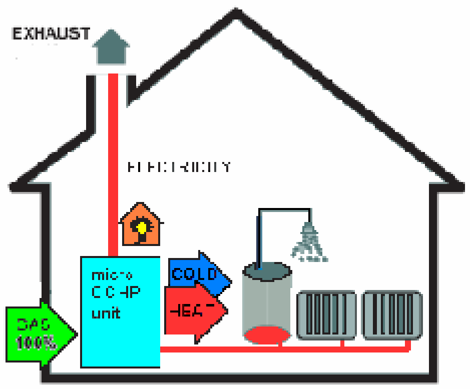

Fig. 2 - Schematic residential building with mCCHP

The proposed micro-CCHP systems comprise a prime mover, which generates electricity, and the heat recovery and utilization components which use the heat rejected by the prime mover provide space heating, hot water, and cooling [10].

3 Prime movers

A prime mover in a micro-CCHP system generates electricity and the waste heat is recovered downstream [12, 15]. The prime movers to be evaluated include:
- reciprocating engines;
- micro steam and gas turbines;
- fuel cell systems;
- Stirling engines.

3.1 Reciprocating engines

In micro-CHP systems with reciprocating engines, the conventional internal combustion engines (ICE) are coupled with a generator and heat exchangers to recover the heat of the exhaust gas and the cooling water and oil [9, 10].

For micro - CCHP applications, typically, spark ignition engines are used, due to their heat recovery system producing up to 160 ^{0}C hot water or 20 bar steam output compared to diesel engines where the temperature is often lower, usually 85°C maximum.

Reciprocating engines have several advantages for micro-CHP [12]:
- It is a mature and well-understood technology.
- It can be designed for different fuels including gasoline, diesel, natural gas or landfill gas, etc.
- The efficiency of the ICE is around 25-45%, which is higher than current Stirling engines.
- A short startup time than external combustion engines.

Some limitations of ICE are [9, 12]:
- Frequent maintenance.
- Noise and emissions are two issues for the reciprocating engines. The NO_x emissions of small engines are fairly low, but still higher than the other technologies.

3.2 Rankine cycle engine and micro gas turbines

Typical Rankine cycle (RC) systems are in the order of MW or above, but some small scale systems have capacity as low as 50 kWe [15]. The RC for micro-CHP is less expensive than most other prime mover technologies and is likely to be a competitive prime mover technology. There haven't been any RC engines in commercial sales for micro-CHP and more testing data are needed to really evaluate this promising technology [15].

The major disadvantage of the RC engines is that the efficiency is low (around 10%) [15].

Micro gas turbines are small gas turbines belonging to the group of turbo machines up to an electric power output of 300 kWe [15].

The electric capacity of current micro-turbines, usually 25 kW or above, is too high to be in a residential micro-CHP unit. Research is ongoing for systems with capacities less than 25 kW, e.g. 1 and 10 kW, which will be suitable for the single-family residential buildings [5, 14].

For cogeneration applications, an overall efficiency of 80% and above can be achieved [20]. However, in the lower power ranges, reciprocating ICE have higher efficiency.

Micro - turbines offer a number of advantages when compared to reciprocating internal combustion engine based cogeneration systems:

- Fast response.
- Compact size, low weight and lower noise.
- Lower NO_x emission.
- Low maintenance requirements.

Micro-turbines can use different fuels, including natural gas, hydrogen, propane or diesel and other biobased liquid and gas fuels.

The major disadvantages of this technology include the high cost and relatively shorter life.

The efficiency of micro-turbines is not very high, although this is enough or more than enough for residential micro-CHP because of the high thermal/electric load ratio.

3.3 Fuel cells

Fuel cells are electrochemical energy converters similar to primary batteries [15]. Fuel cell micro-CHP systems are either based on the low temperature proton exchange membrane fuel cell (PEMFC) which operate at about 80 ^{0}C, or on high temperature solid oxide fuel cells (SOFC) working at around 800 – 1000 ^{0}C [15].

Fuel cells normally run on hydrogen, but can also be used with natural gas or other fuels by external or internal reforming [5].

Fuel cells have several benefits [9, 12, 15]:

- Higher efficiency, up to 45% electric.
- Emissions are essentially absent producing negligible amounts of pollution.
- The fuel cells are very quiet.

Fuel cells are still in the R&D stage [15]. The major problem of fuel cells is the short lifetime of the membrane and their cost is very high. There are no fuel cell based micro-CHP systems commercially available at this moment.

4 Stirling engine as a prime mover

Since the invention of Robert Stirling in 1816, the Stirling cycle engines have always been of great importance for the engineers to generate mechanical or electrical power more efficiently or to reduce the energy consumption of the refrigeration devices [8, 18]. Stirling engines can be used for primary power generation and as a bottoming cycle utilizing waste heat for power generation. The most outstanding feature of the Stirling engine is its ability to work at low temperatures, and thus it can use low temperature energy sources that are widespread in nature: the hot water from flat solar collectors, geothermal water, and hot industrial wastes. Stirling engine can also use all fossil fuels and biomass, to realize an environmentally friendly electrical energy production.

The problems concerning utilisation of biomass fuels in connection with a Stirling engine are concentrated on transferring the heat from the combustion of the fuel into the working gas. The temperature must be high in order to obtain an acceptable specific power output and efficiency, and the heat exchanger must be designed so that problems with fouling are minimized [15].

Compared to conventional internal combustion engine, Stirling engine is an external combustion device [21, 23]. It produces power by an external heat source and not by explosive internal combustion. Stirling engines closely couple a burner to a heater-head heat exchanger that induces harmonic oscillations in a piston inside a hermetically sealed container [13].

Main parts of engine are crank mechanism, heater, cooler and a regenerator. There are about 280 configurations for this engine based on drive mechanism, type and location of heat exchangers and working fluid [23].

The Stirling engine itself is a heat recovery device, like the steam turbine [9, 23]. Two main types of Stirling engines show potential for residential trigeneration:

- kinematic Stirling
- free-piston Stirling [6, 8].

The free-piston Stirling has fewer moving parts, does not need for a lubricant, it has low maintenance costs and a longer life. Heat exchangers in a Stirling engine play a main role on performance parameters of the engine so improving the design and construction of heat exchangers cause to improvement in engine performance [23].

Stirling engines generally are small in size, ranging from 1-25 kW although some can be up to 500 kW [18, 21]. The Stirling engines are 15 - 30% efficient in converting heat energy to electricity, with many reporting a range of 25 to 30% [19]. The efficiency of modern Stirling generators is more than 40% [10]. Stirling engines are expected to run 50000 hours between overhauls, and free-piston Stirling engines may last up to 100000 hours [19]. The cost of 1 kWh of power from a cogeneration system is 3 – 4 times less than for centralized power systems, and the heat generated is essentially free [9].

4.1 Mathematical model analysis of Stirling engine

In the ideal Stirling engine cycle, a working gas is alternately heated and cooled as it is compressed and expanded [7, 13, 18]. The ideal Stirling cycle combines four processes, two constant-temperature processes and two constant-volume processes (figure 3). The engine works between two temperatures T_H and T_C, theoretically the thermal efficiency of the engine is equal to Carnot, which is the highest possible of all heat engines. Alternative compression and expansion of working gas under isothermal process produces work [23].

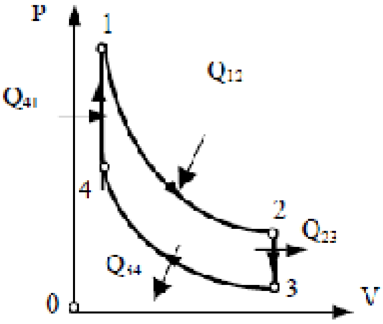

Fig.3

The study presents the thermodynamic analysis of a Stirling engine with two separate V cylinders. (figure 4).

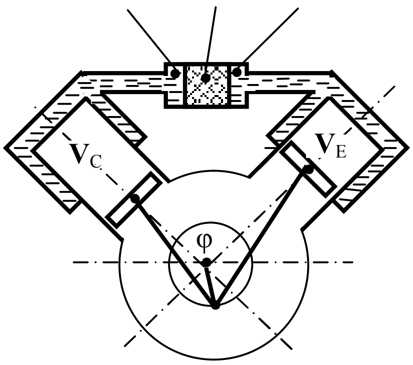

Fig. 4

V_E – expansion volume, V_C – compression volume, H – heater, C – chiller, R – regenerator

The two pistons generate the compression and the expansion spaces and the regenerator is on the connecting pipe between the two variable volumes.

4.1.1 Volumes

Compression and expansion instantaneous volumes are defined according to crankshaft angle.

- Instantaneous expansion volume:

$$V_E = V_{EM}(1+\cos\alpha)/2 \qquad (1)$$

- Instantaneous compression volume:

$$V_{C_1} = k \cdot V_{DM}[1+\cos(\alpha-\varphi)]/2 \qquad (2)$$

α – rotation angle of the crankshaft

φ – angle between cylinders; usually, $\varphi = 90^0$

- Overall instantaneous volume:

$$V_T = V_E + V_C = V_{EM}\begin{bmatrix} 1+k+\cos\alpha + \\ +k\cos(\alpha-\varphi) \end{bmatrix}/2 \qquad (3)$$

- Maximum overall volume:

$$V_{TM} = V_{EM} + V_{CM} = (1+k)V_{EM} \qquad (4)$$

- Constant "dead" volume:

$$V_M = X \cdot V_{EM} \qquad (5)$$

4.1.2 Pressures

The total gas mass is the sum of instantaneous mass of the considered volumes:

$$m_T = \frac{pV_{EM}}{2RT_E}(1+\cos\alpha) + \frac{k}{2}\frac{pV_{EM}}{RT_C}[1+\cos(\alpha-\varphi)] + \frac{pV_M}{RT_M} \qquad (6)$$

Using the notations [11]:

$$K = 2\frac{RT_C}{V_{EM}} m_T = \text{ct.} \quad S = X\frac{T_C}{T_M} = \frac{2x\tau}{1+\tau} \qquad (7)$$

Relation (6) becomes:

$$\frac{K}{p} = \tau(1+\cos\alpha) + k(1+\cos(\alpha-\varphi)) + 2S \qquad (8)$$

We use the notations:

$$A = \left(k^2 + \tau^2 + 2k\tau\cos\varphi\right)^{1/2}, \; B = \tau + k + 2S \qquad (9)$$

$$C = A/B \quad \theta = \text{arctg}(k\sin\varphi(\tau + k\cos\varphi)) \qquad (10)$$

$$\tau = T_C/T_E, \; k = V_{CM}/V_{EM} \qquad (11)$$

And the instantaneous pressure is:

$$p = \overline{K}(1 + C\cos(\alpha-\tau))/B \qquad (12)$$

- Average pressure is:

$$p_a = \int_0^{2\pi} p\,d(\alpha-\theta) = \sqrt{p_{min}\,p_{max}} = \tag{13}$$
$$= p_{max}\sqrt{\frac{1-C}{1+C}}$$

Where:

$$p_{min} = \overline{K}(1+C)/B \tag{14}$$

$$p_{max} = \overline{K}(1-C)/B \tag{15}$$

$$p = p_a\left(1-C^2\right)^{1/2} / [1 + C(\alpha-\theta)] \tag{16}$$

4.1.3 Energy analysis

The expansion heat $Q_E>0$ and compression heat $Q_C<0$ are considered to be isothermal and they are equal to the work.

- At the expansion space:

$$Q_E = W_E = \int_0^{2\pi} p\,dV_E = \tag{17}$$
$$= \pi p_a V_E C \sin\theta \Big/ \left[1 + \left(1-C^2\right)^{1/2}\right]$$

- At the compression space:

$$Q_C = W_C = -\int_0^{2\pi} p\,dV_C = \tag{18}$$
$$= \pi p_a k V_C C \sin(\theta-\varphi) \Big/ \left[1 + \left(1-C^2\right)^{1/2}\right]$$

- Exchange heat ratio:

$$Q_C / Q_E = -\tau \tag{19}$$

- Overall work of the cycle:

$$W_T = W_E + W_C = (1-\tau) Q_E \tag{20}$$

4.1.4 Efficiency of Stirling cycle

-Stirling engine cycle efficiency is:

$$\eta = \frac{W_T}{Q_E} = 1 - \tau = 1 - \frac{T_C}{T_E} = \eta_{max} \tag{21}$$

4.1.5 Mass of the agent

The mass of the agent in Stirling engine is obtained from relation (1), (2) and (16).

- Instantaneous mass in expansion space:

$$m_E = \frac{1}{2}\frac{p_a V_{EM}}{RT_E}\frac{(1+\cos\alpha)\left(1-C^2\right)^{1/2}}{1 + C\cos(\alpha-\theta_1)} \tag{22}$$

- Instantaneous mass in compression space:

$$m_C = \frac{k}{2}\frac{p_a V_{EM}}{RT_C}\frac{(1+\cos(\alpha-\varphi))\left(1-C^2\right)^{1/2}}{1 + C\cos(\alpha-\varphi)} \tag{23}$$

- Instantaneous mass in regenerator dead space:

$$m_M = X\frac{p_a V_{EM}}{RT_M}\frac{\left(1-C^2\right)^{1/2}}{1 + C\ \cos(\alpha-\theta)} \tag{24}$$

Total mass is the sum of instantaneous mass of considered volumes. Using relations (22)…(24), and $\alpha = 0$, it results:

$$m_T = \frac{p_a T_{EM}}{RT_C}\frac{\left(1-C^2\right)^{1/2}}{1 + C\cos\theta}[\tau + k(1+\cos\varphi)/2 + S] \tag{25}$$

4.1.6 Dimensionless heat parameters

In order to compare micro CCHP systems two dimensionless parameters are considered:

- Overall expansion input heat related to total mass:

$$\overline{Q}_E^m = \frac{Q_E}{m_T R T_C} = \tag{26}$$
$$= \frac{\pi C \sin\theta(1 + C\cos\theta)}{(1-C)^{1/2}\left[1 + \left(1-C^2\right)^{1/2}\right][\tau + k(1+\cos\varphi)/2 + S]}$$

- Overall expansion input heat related to maximum pressure of the cycle:

$$\overline{Q}_E^{max} = \frac{Q_E}{p_{max} V_{TM}} = \tag{27}$$
$$= \frac{\pi C \sin\theta\left(1-C^2\right)^{1/2}}{(1+C)^2\left[1 + \left(1-C^2\right)^{1/2}\right](1+k)}$$

- Dimensionless overall work:

$$\overline{W}_T = (1-\tau)\overline{Q}_E \tag{28}$$

The overall work of the cycle W_T depends of some parameters: τ, k, X and φ. [18, 25].

Usually, the following values are considered:

$T_C = 300$ K, $T_E = 300 - 1700$ K, $X = 0 - 2$
$k = 0 - 5$ $\varphi = 0 - 180^0$

The influence of ratio τ on the overall work is shown in figure 5.

The influence of k on overall work is shown in figure 6.

The influence of ratio X on the overall work is shown in figure 7.

The influence of φ^0 on overall work is shown in figure 8.

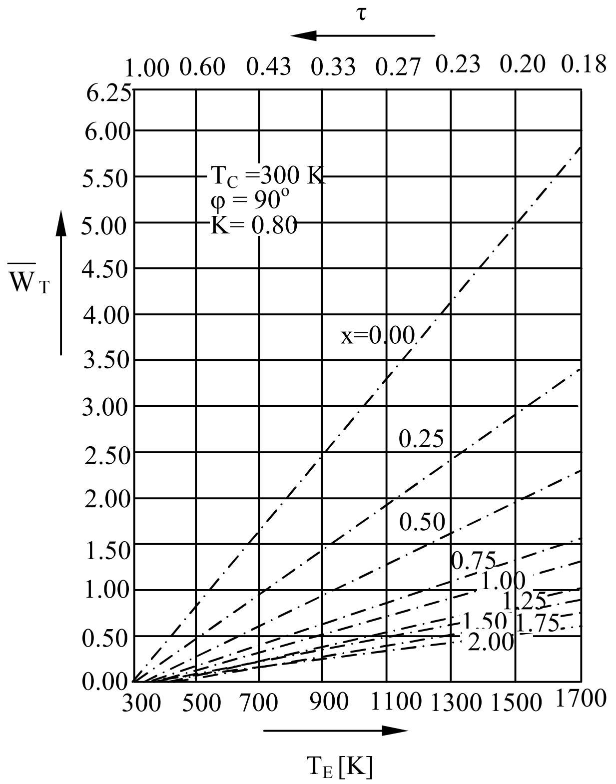

Fig. 5 - The influence of ratio τ on the overall work

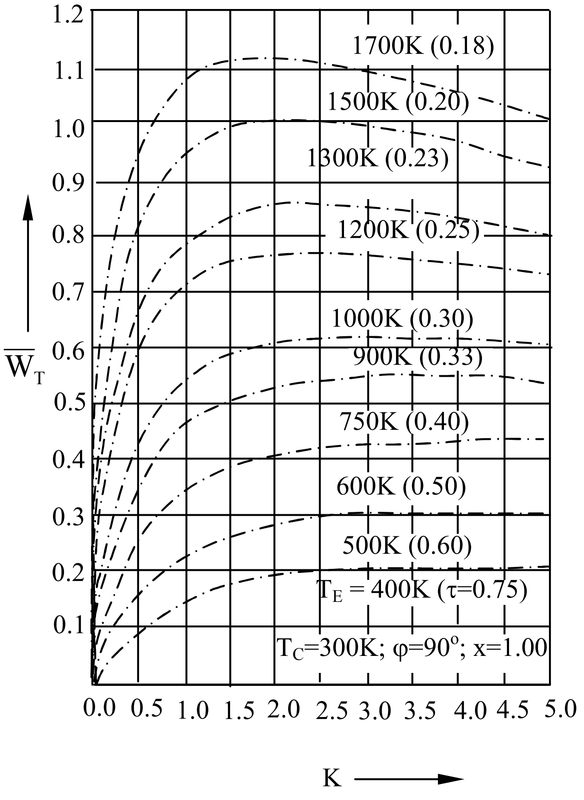

Fig 6 - The influence of k on overall work

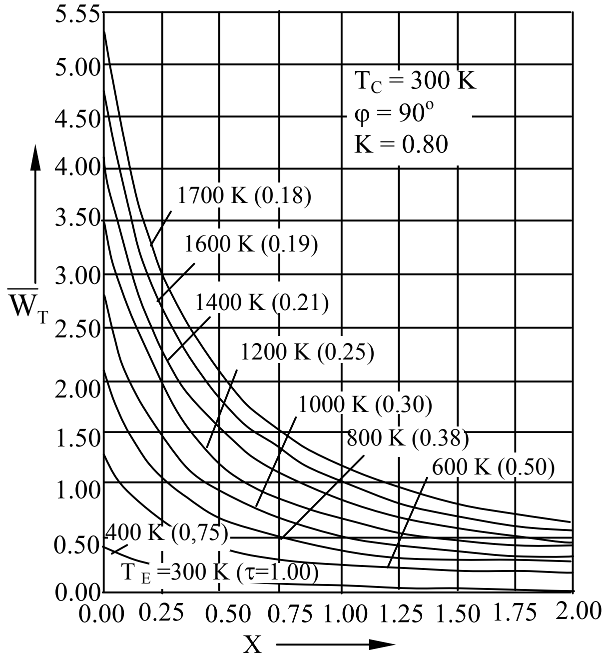

Fig. 7 - The influence of X on overall work

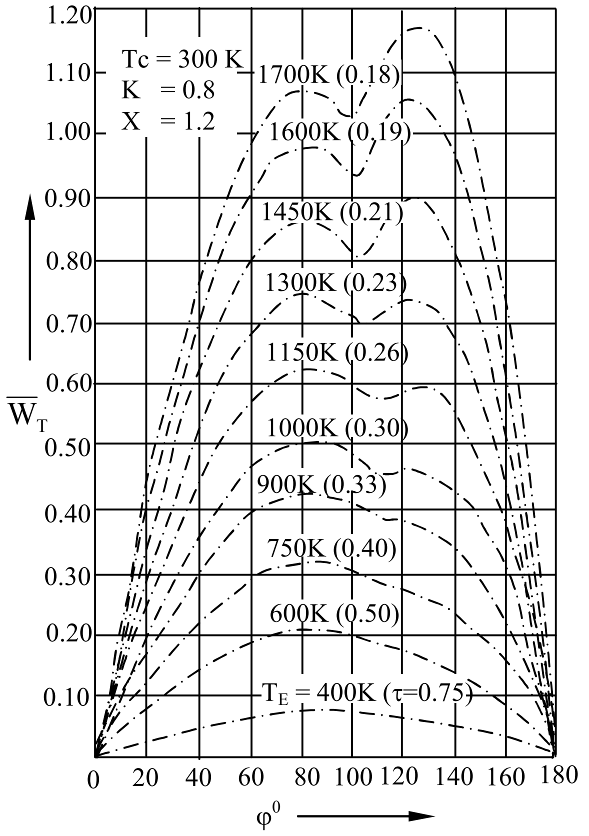

Fig. 8 - The influence of φ angle on overall work

5 A case study

The development of sustainable energy systems for the future is the combined production of electricity heating and cooling in small units that are directly embedded in the buildings where the heat, cold and electricity are to be used. Implementation in the experimental building on the University "Dunarea de Jos" of Galati campus of a micro CCHP experimental system, using renewable energy available in the South-Eastern region of Romania and meet the specific climatic conditions, has the purpose to validate the theoretical developments and to provide the basis for the generalization of results for the entire region. [25]. Therefore, after a brief overview of the South Eastern region of Romania

- Climatic conditions of the region, and
- Energy resources, especially renewable ones, available in the region were identified and analyzed.

The climatic parameters that influence the construction of a building are temperature, humidity, wind speed and sunshine.

From the analysis of statistical data about these parameters the climatic conditions for space heating and the specific heat needed were determined.

From the analysis of urban and rural conditions for space heating and the potential of renewable energy in the South-Eastern region it was identified the type of renewable energy that can be used to achieve a mCCHP system, namely biomass pellets and solar panels.

The simplified model of the residence meets the current standards for a living area and space volume needed for a 4-member family while keeping the particulars of the South East region of Romania.

The architectural sketch of the residence is given in figure 9. In terms of construction and functionality, the residence consists of three areas: attic, basement and inhabited area.

Fig.9

For a good choice of the system to be implemented by the project, it is necessary to know the structures, used worldwide for the energy -heat-cold production systems. Implementation of optimal solution – particular climate conditions and construction and functional particulars of buildings in the South East of Romania – calls for a comprehensive comparative analysis of the multitude of existing solutions to achieve these systems. Precisely because of this variety, it was necessary to organize the structural-functional analysis, according to different criteria:

- according to the type of primary mover;
- according to how refrigeration cycle is carried out;
- according to the type of the electric generator employed.

At the basis of this project lies the integration of Stirling engine (fueled with wood- pellets) with an electric generator and their interfacing with an electronic module that has a programmed logical (IT) for monitoring, protection and control (MPCS).

In this case, we choose the Stirling engine (figure 10) from Sunmachine (Germany) with characteristics:

- Stirling engine 2 single acting - pistons in V type arrangements
- Wood pellets as fuel
- Electrical output capacity: 1.5 – 3 [kW]
- Thermal output capacity: 4.5 – 10 [kW]
- Cost of unit: 23000 €
- Specific cost of unit (€/kWe): 7670

Fig. 10

Wood pellets to fuel the Stirling engine have the characteristics:

- diameter: 6 mm
- length: 4 - 15 mm
- density: 1300 kg/m^3
- humidity: 3.6 %
- ash content: 0.8 %
- calorific power: 18200 kJ/kg.

6 Conclusion

From the point of view of energy economy and use of renewable fuels (wood pellets), the Stirling engine draws attention of the engineers for its advantages.

The evaluation of various micro-CCHP systems, regarding the prime mover technology for producing electricity, heat and cooling for residential use, indicated that the micro-CCHP units with Stirling engines are more appropriate for the micro-CCHP having the best value for overall system efficiency.

A market study focused on producers and conversion techniques with a high development status pointed out that in the case of the micro-CCHP units with Stirling engines, there can be generated savings of 10% of the energy costs using it in existing one-family-houses.

The major disadvantage of the Stirling engines is the high cost of the equipment. Installation costs should be reduced by 50% before CCHP systems become interesting for residential use.

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