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SUPERFINE WATER CLEANING SYSTEM WITH “NET ZERO” POWER CONSUMPTION AS A RENEWABLE POWER SOURCE

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ABSTRACT

A rational nature management advanced by the United Nations Industrial Development Organization UNIDO gives impetus to proliferation of all that is associated with the «green industry» concept, namely ecology, power effectiveness, environmental protection against industrial pollution, in particular, protection of the water reserves and their rational usage [1].

The need in the fastest realization of the like developments is connected with not only purely ecological issues but, also, with more and more common man-made catastrophes causing lengthy breaks of the power and heat supply to utilities, small enterprises, medical institutions, all types of transport, etc. The like situation contributes to development of independent power micro systems (IPMs) on the basis of many concepts (from Stirling engines and solar batteries to micro turbines and fuel cells [2-7]), on one hand, and the most environmentally friendly and power saving independent water cleaning systems [8-12], on the other hand

The paper includes results of:

- development of a superfine water cleaning system where all the power required for the system’s operating is generated directly in the process of cleaning;
- researches over designed and built main parts of the system – lab devices:
  - **the power saving** five-step **cleaning system with the exit water quality** meeting requirements to water utilized at fish-breeding and **with production of the gaseous fuel** in amount sufficient to generate the electric and heat power, when IPMs of the electric efficiency not below 28% and the total efficiency not less 80% are applied;
  - the micro gas turbine engine (μGTE) with the electric efficiency of (28±1)% and the total efficiency over 80%.

INTRODUCTION

In 2010, the Daikin Europe company launched a Net Zero Energy Project , while the Japanese Misawa company started its serial production of similar “living” houses. Officially, this status was awarded to the first two “the greenest” buildings in the USA built of non-toxic, safe to handle materials, these buildings equipped with power generation systems based on renewable sources and sewage cleaning with no use of harmful chemicals, and they operate the whole year round [1]. It is just reasonable that the like approach with introduction of a cleaning system **that meets its own needs in power** and which is, at the same time, an IPM, becomes, also, an optimum for industrial, agriculture, and domestic sewage treatment. Realization of such technology is practicable provided there is a balance between the energy required to operate a cleaning system and the energy generated at firing of the gaseous fuel released during the cleaning process.

To attain this balance, it is first necessary:

- to achieve the 2-4 times increase in the process effectiveness for the slowest “filtering” steps; this will enable an adequate increasing of the amount of the gaseous fuel released in the fine biological cleaning process;
- to arrange the process chain for the biological and chemical cleaning steps in such a way that they could employ fully all the flow of carbon oxides released at the gaseous fuel firing;
- to develop a green ($NOx \rightarrow 0\%$) and high efficiency (electric efficiency of 28±1%) micro engine that will provide all the required volume of the electric and heat power for the superfine cleaning process.

A solution of all these issues is just the objective of the presented study.

MAIN CHARACTERISTICS OF SUPERFINE WATER CLEANING SYSTEM AS RENEWABLE POWER SOURCE

The schematic diagram for the superfine sewage cleaning process is shown in Fig. 1.

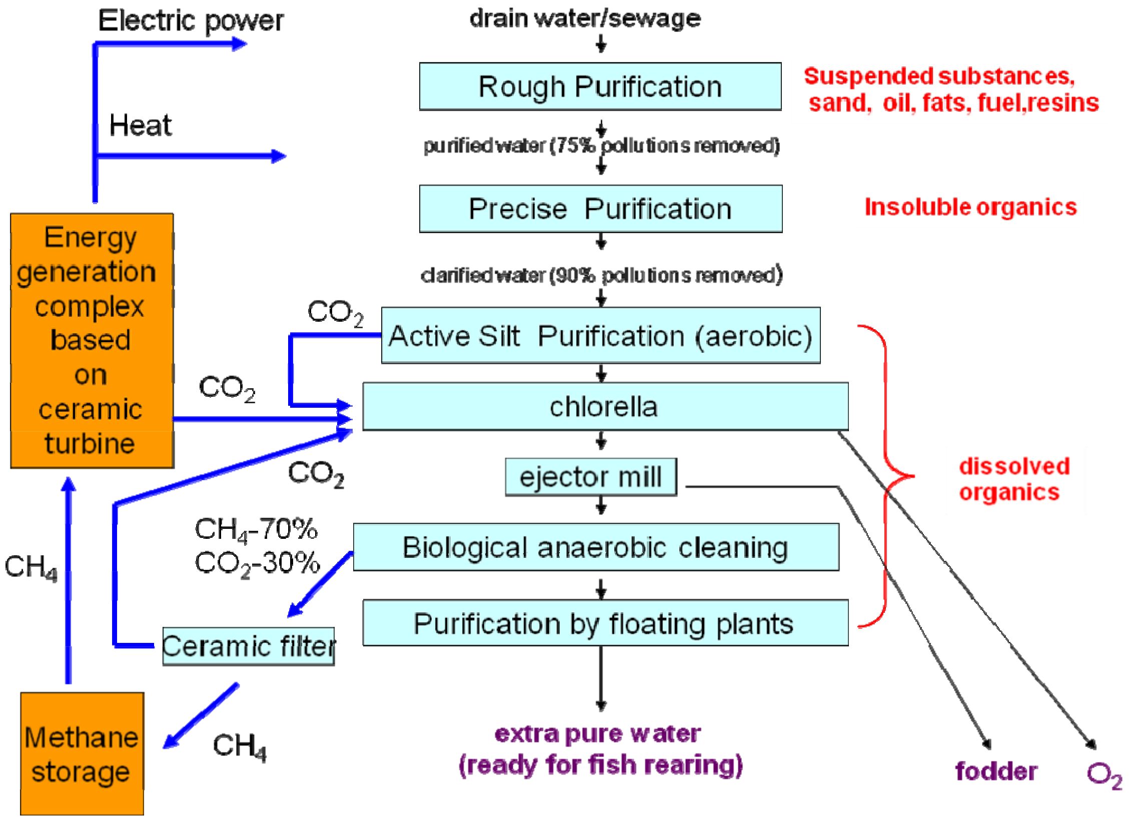


Figure 1. Schematic diagram of sewage superfine cleaning process

The sewage supplied to a plant is subjected to 5 cleaning steps sequentially:

1. **A coarse cleaning**, when weighed solid substances and, also, sand, oils, fats, fuel and resins making up ~75% of all admixtures contained in the sewage are removed.
2. **A fine cleaning** when unsolved organics are removed.
3. **A biological aerobic cleaning**, intended to remove the soluble organics, is implemented using an «active silt» based on micro organisms that feed on the oxygen solved in the water and release the carbon dioxide which is a feed of the one-celled micro algae “chlorella”. This algae increases its mass intensively (nearly two-fold increase of the algae mass for a day) under certain lighting conditions and in a sufficient amount of CO$_2$ solved in water).
4. The chlorella micron crushed to 2 microns size enters a capacity with **anaerobic micro organisms**, feeding on the bio-mass with release of the gases mixture (70%CH$_4$+30%CO$_2$). As at the earlier stage, these organisms are to be used for the water cleaning from the soluble organics. The gases mixture enters ceramic filters through which CO$_2$ is carried away into a tank with chlorella, while methane is removed into a fuel tank of the ceramic micro gas turbine engine (μCGTE) that generates the heat and electric power thereby ensuring operation of the entire compressor, pump, fan, and heat exchange hardware of the system. It should be also emphasized that the μCGTE is green since the carbon dioxide from its exhaust is discharged into the tank with chlorella, while the nitrogen emissions in the process of combustion in the ceramic μCGTE combustor are NOx≤5 ppm.
5. **Bio-pond** is the next step of the solved organics removal from water using water plants. It finalizes the superfine cleaning process. Then the water that outflows from it is of a quality suitable for the **fish - breeding**.

DESIGN OF PLANT FOR SUPERFINE WATER CLEANING

Projects of plants incorporated into the system were made on the basis of the schematic diagram for the water cleaning system that fulfils its own needs for power. It is shown in Fig. 1. In conformity with the initial project, the operating **model water cleaning plant was built** (II-V, Fig.2; and Fig.3).

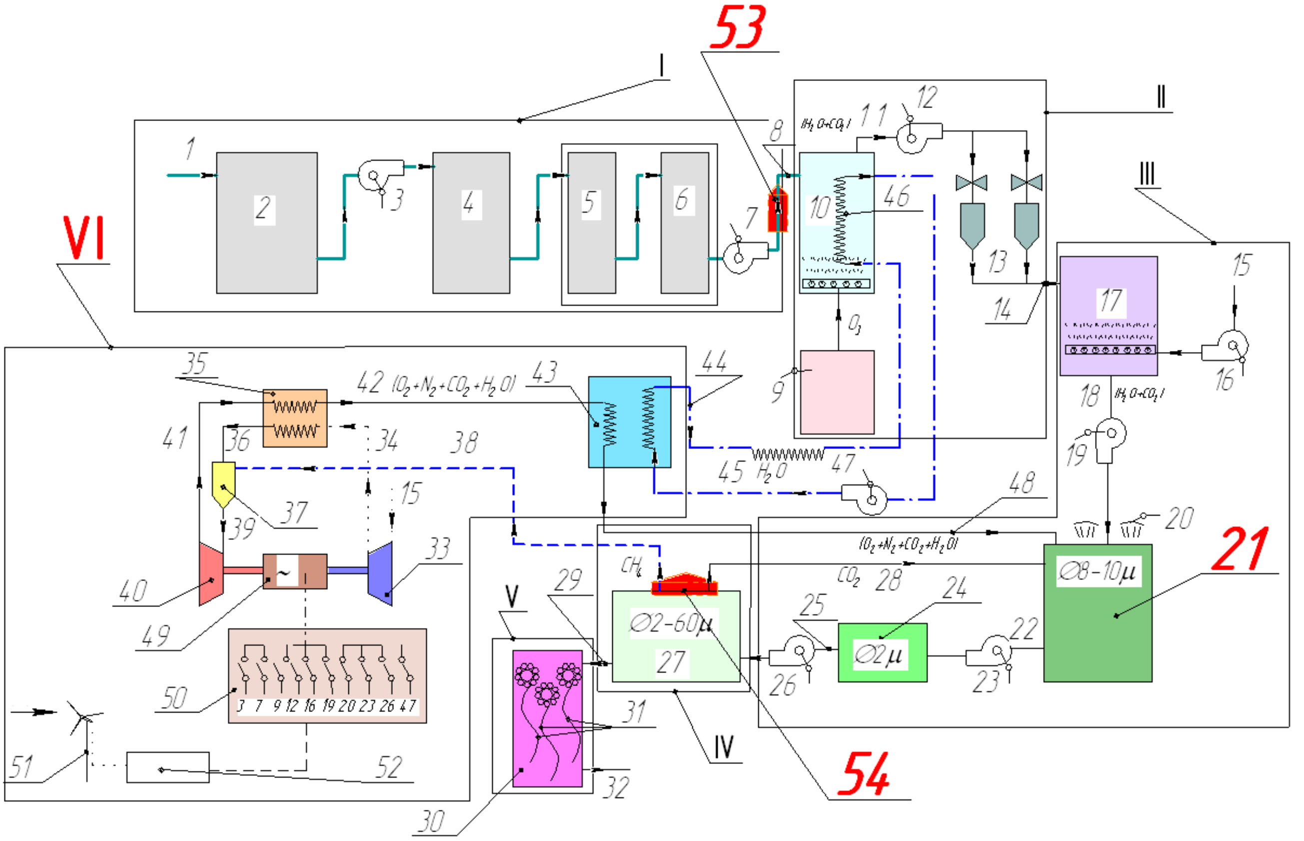


Figure 2. Superfine sewage cleaning system that fulfils its own needs for power

I – coarse sewage cleaning system: 1 – sewage inflow, 2 – settling tank , 3 – sewage pump, 4 – sand trap, 5,6 – fat and fuel traps (2nd step), 7 – pump, 8 – clarified water (cleaning value 90%).

II – fine sewage cleaning system: 8 – inflow into ozonization tank, 9 – ozonizer, 10 – CO_2 generator, 11 – CO_2 solution in H_2O, 12 – pump.

III, IV, V – biological aftercleaning system: 13 – filters, 14 – (CO_2+H_2O) inflow into active silt tank (oxitank), 15 – air, 16 – pump, 17 – active silt tank, 18 – CO_2 solution in H_2O, 19 – pump, 20 – irradiators, 21 – photobioreactor (PBR), 22 – water suspension for chlorella of 8-10µ size, 23 – pump, 24 – mill, 25 – water suspension for crushing of chlorella (up to ≤2 micron size), 26 – pump, 27 – anaerobic fermentation capacity (methatank), 28 – CO_2 removal from metatank into PBR, 29 – removal of purified water into biopond, 30 – biopond, 31 – eihhornia, 32 – drinking warer outflow.

VI – power supply unit: 33 – compressor, 34 – compressed air, 35 – air heater, 36 – heated compressed air, 37 – combustor, 38 – methane supply to combustor, 39 – working gas supply to turbine, 40 – turbine, 41 – heating gas supply, 42 – heating gas discharge, 43 – water boiler, 44 – hot disctrict heating water, 45 – return (cold) water, 46 – mixtire (H_2O+ CO_2) heater, 47 – disctric heating water pump, 48 – exhaust mixture (O_2+N_2+ CO_2+H_2O), supply to PBR, 49 – electric generator, 50 – power supply board for pumps, irradiators, ozonizer, etc, 51 – wind generator of 2 kW power, 52 – accumulator.

Innovative developments: 21 – one-celled algae «chlorella» - assimilates 7-10% of solar energy (usually-<1%), **mass doubling for 24 hrs**, for 24 hrs suspension liter produces 10 liters of O_2; ***53*** – ceramic filter – 20-fold reduction of power consumption, 3-fold increase in filtration efficiency, 10-fold increase in filter service life; ***54*** – ceramic filter for CH_4 and CO_2 separation, 3-fold increase in filtration efficiency, 10-fold increase in filter service life;***VI*** – power co-generation plant of 6 mW power of 3 ceramic micro turbines of 2 kW power (NO_x≤5ppm, CO<5ppm, actually no CO_2 exhaust into atmosphere, electric efficiency 28±1%, total efficiency is not over 85% of power – renewable).

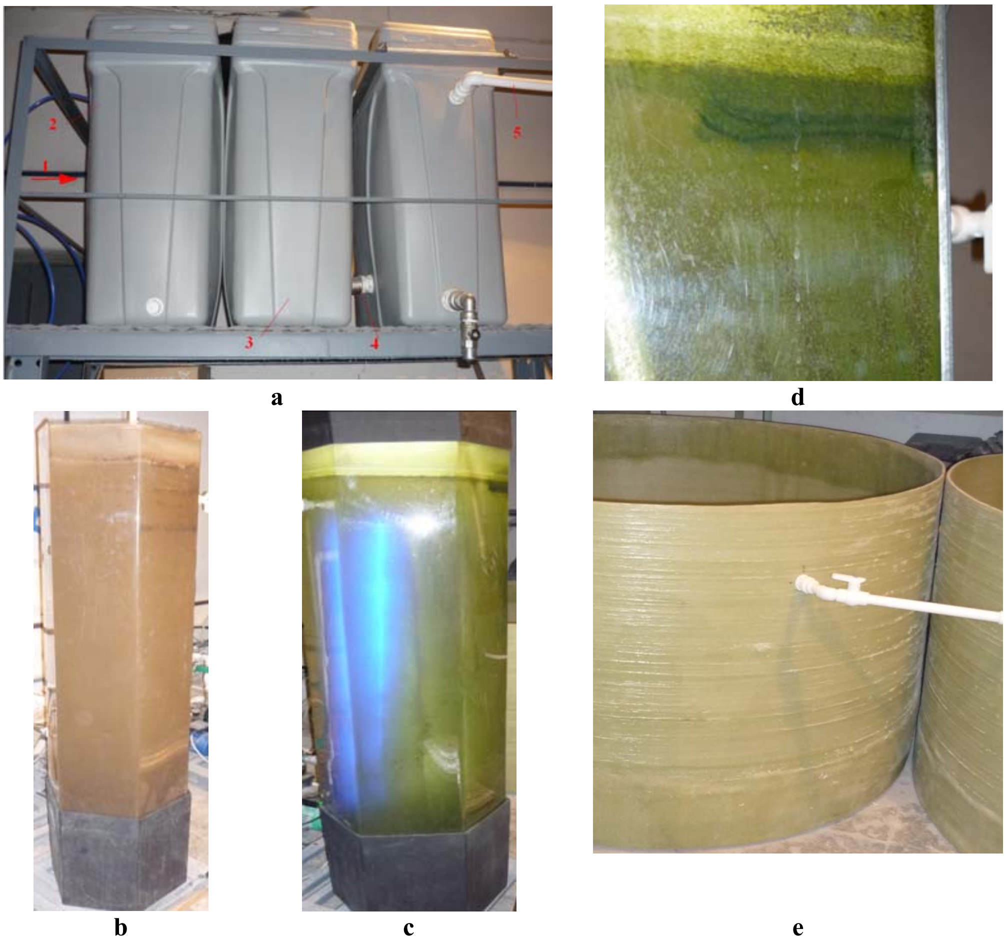


Figure 3. Components of water cleaning unit

a) Coarse cleaning: 1 – sewage , 2 – sand trap (capacity 120 liters), 3 – two-step fat- and fuel trap (2 capacities of 120 liters each.), 4 – purified water bypass, 5 – water discharge after coarse cleaning.

b) Capacity with active silt (capacity (150 liters) for generation of active silt and carbon dioxide (oxitank).

c-d) Photobioreactor: c – water with solved CO_2 + chlorella ∅8-10µ for fine water cleaning and bio-mass growth by CO_2 absorption, d – wall of photobioreformer capacity with chlorella suspension flowing around.

e) Bio-pond (volume not $<3m^3$ each) – for superfine water cleaning using water flowers (in this present case, it is eihhornias).

Main parameters of the plant are in the Table 1.

Table 1. Main technical data on operating water cleaning unit model

№	Name	Dimension	Value
1	Total volume of dry chlorella at methatank entry	kg/h	5.0
2	Required amount of methane (70%)	kg/h	2.7
3	Amount of CO_2 in biogas	kg/h	1.16
4	Total amount of biogas required at methatank exit.	kg/h	3.86
5	Required capacity volume to produce a target amount of dry substance (24 hours) at output of 100 gr./l dry substance.	l	1200.0
6	Electric power supply	kW/h	7
7	Heat power supply	kW/h	16.5

The data demonstrates that the superfine sewage cleaning plant:

- can be adapted to any sewage type – industrial, agricultural, domestic;
- releases the gaseous fuel in amount allowing to produce not less 85% of power required for operation at the power supply unit efficiency of 28±1%;
- provides a high water quality at the plant exit that meets requirements to water applied at fish - breeding;
- reduces CO_2 exhaust with gas applied to increase the produced bio-mass;
- enables production (if required) of by-products (as function of sewage), i.e. bio-manure, feed, and cattle;

POWER PLANT DESIGN

A co-generation ceramic micro gas turbine engine (μCGTE) was designed to supply the heat and electric power to the water cleaning system. The main objective of the design was to ensure a high electric efficiency (not less 28±1%). This efficiency level can be provided only if the working media temperature at the turbine inlet is not lower 1350°C. This demand implies impracticability of use of metal materials for manufacture of components and parts of the high temperature path of the engine.

It is known that a miniaturization of the regenerative GTE leads to decreasing of its efficiency. This raises importance of realization of concept of uncooled ceramic tunnel turbomachines [13,14]; application of structural and composite materials (SCMs) such as non-shrinkage corundum-carbide-silicon-boron-nitride (K3BNK) ceramics that adapt easily to machining and welding [15]; introduction of arrangements with location of the rotor and stator portions of the electric generator (μEG) in between the corresponding micro turbocompressor (μTC) devices. All these measures enable to raise the initial gas temperature at the turbine inlet considerably with an appropriate increase of the efficiency of the plant as a whole.

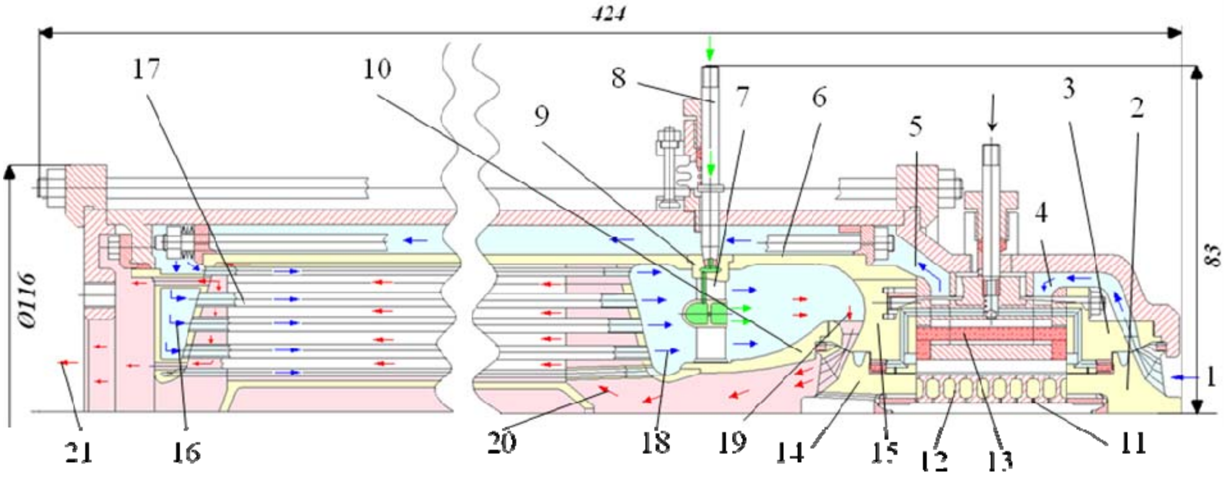
Application of μCGTE with tunnel ceramic turbomachines will allow to alleviate the adverse effect imposed by reduction of absolute sizes. As a result, **the following can be achieved**:

- provision of a **reliable operation** of the engine under high temperature conditions without use of cooling;
- **reduction** of internal **losses** in stage due to leaks of the working media over gaps;
- increasing **the adaptability to manufacture and decreasing the cost** of manufacture compared to conventional turbomachines designs.

On the basis of a sustained search for optimum design approaches for each component, the following was done:

- the electroturbocompressor (ETC) with tunnel turbomachines was designed, this turbocompressor ensuring a reliable operation under all operation conditions;
- a rigid rotor design was embodied by μTC and μEG integrating;
- an μEG cooling system was developed, this system using all the cycle air flow that supplies from the μTC blower thereby increasing the μCGTE efficiency.

The longitudinal section of the optimum μCGTE version is shown in Fig. 4.



Working media parameters	№	1	4	18	19	20	21
Pressure	MPa	0.1013	0.2520	0.2440	0.2380	0.1064	0.1013
Temperature	°C(K)	15(288)	133(406)	1004(1277)	1350(1623)	1144(1417)	299(572)

Figure 4. Ceramic micro gas turbine plant

Designations: 1 – air inlet (**16.7 g/s**); 2 – compressor impeller μC (**23,0000 rpm**); 3 – diffuser μC (**π_k=2.5**); 4,5 – air μEG inlet-outlet; 6, 7 – outer and inner liners of μCC; 8,9,10 – μCC devices: 8 – dome, 9 – fuel supply (0.160 g/s), 10 – igniter; 11,12 – metal parts and permanent magnets for μEG rotor; 13 – μEG stator; 14 – μT wheel; 15 – μT nozzle vanes; 16,18 – μAH air inlet-outlet; 17 – μAH heat exchange matrix elements, (**E_r=86%, ΔP_Σ=6%**); 19 – μT gas inlet; 20,21 – μBΠ gas inlet-outlet; 22 – air supply for bearing floating at startup.

A normal electro-magnetic interaction is utilized in this rotor version since the outer titanium shell with the cross inner baffles forms a truss type support metal system. Outer and inner cylinders thereat serve as the basis for the system. At minimum deformations, the truss bears the target centrifugal loads. It transfers the torque to the µEG rotor from the µTC rotor since the truss cylinders are connected by their bayonet devices with end faces of solid discs of µTC impellers and µEG wheels.

At rated conditions, the magnet core of the µEG rotor operated under compressive stresses (-120 MPa) and at a maximum stress value of 578 MPa in the titanium shells of the magnets, while the stress in ceramic discs of turbomachines is 190 MPa (Fig. 5).

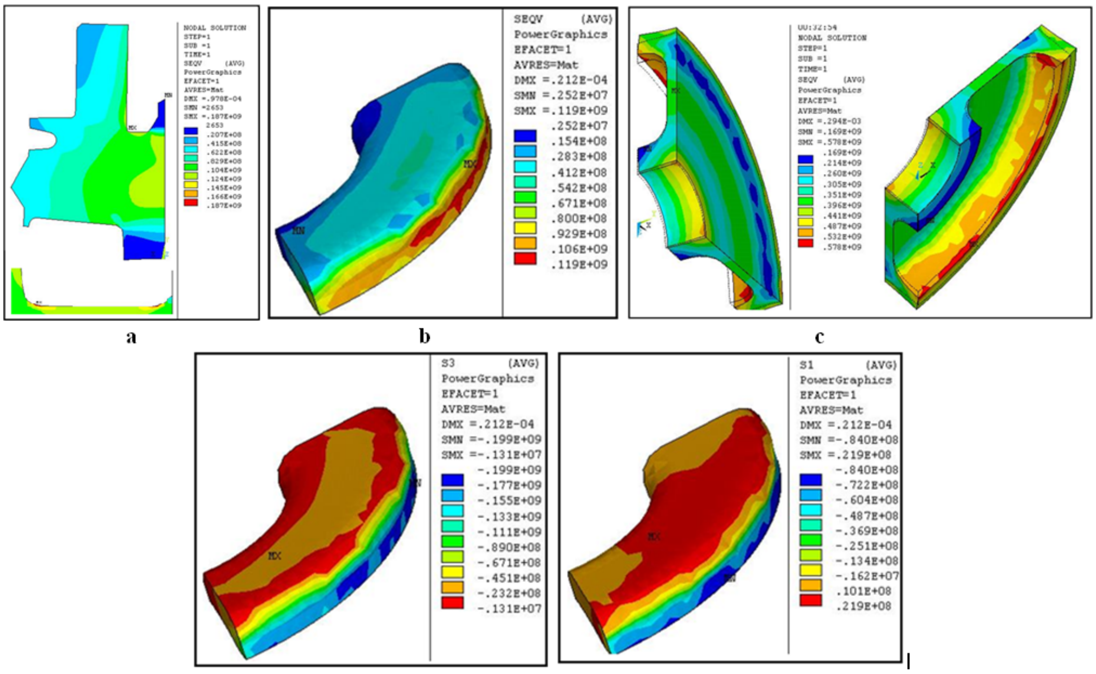
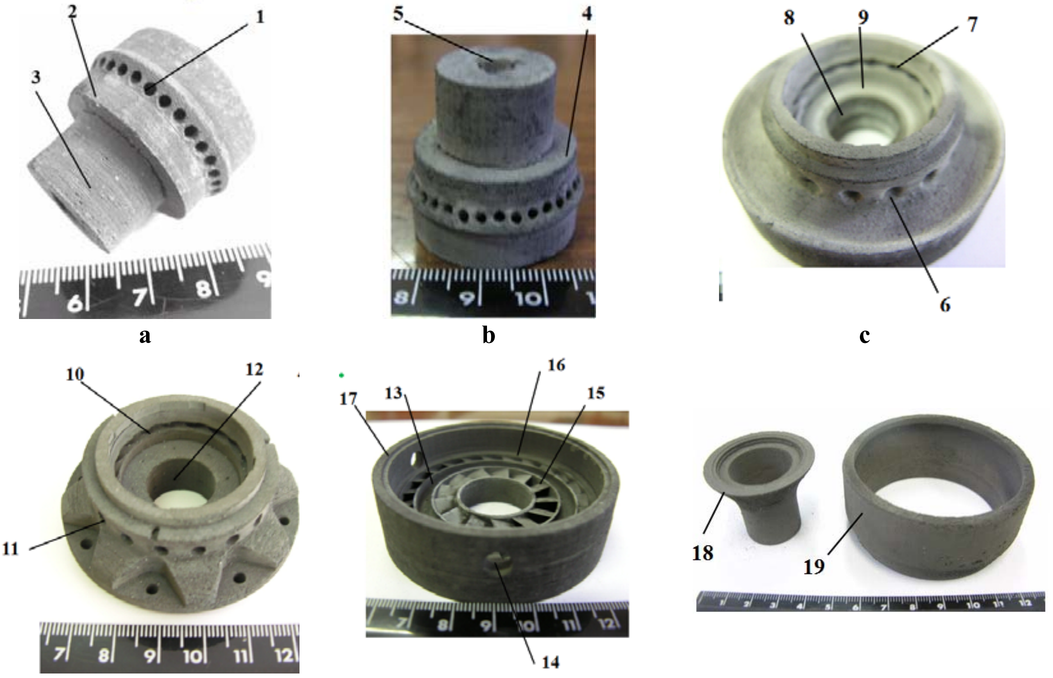


Figure 5. Static strength of main components for optimum µETC
a) turbomachine impeller, **b)** magnet element – equivalent stresses, **c)** element of annular titanium shell, **d)** element of magnet – compressive stresses, **e)** element of magnet – tensile stresses.

Calculations of the natural frequencies and forms of oscillations for the aligned design of the µETC rotor identified only two natural oscillations for the tie, namely 4537.1 and 4548.5 Hz (corresponding to the speed of 272,220 and 272,910 rpm), lying much over the rated load speed value.

It follows from the µETC optimum version that the developed design of micro engine ensures its reliable operation at the peripheral velocities up to 365 m/s (230,000 rpm). This is verified by the admissible stress level in all rotor elements, absence of limit velocities within the operation conditions range, optimum temperature values at the µEG running.

Some main components and parts of the engine are already built (Fig.6) and in the process of preparations for testing.



a b c

d e f

Figure 6. Elements of high temperature ceramic path for μCGTE
a) Turbine rotor: 1-working media inflow into tunnel channels, 2-surface to be treated at turbocompressor balancing, 3-rotor portion of journal bearing. **b)** Compressor rotor: 4-rotor portion of thrust bearing, 5-bypass joint with electric generator rotor.
c) Nozzle vanes for turbine: 6-working media inflow into nozzle channels, 7-working media outflow from nozzle channels, 8-stator portion of journal bearing, 9-stator portion of thrust bearing.
d) Compressor diffuser**:** 10-air inlet, 11-air outlet, 12-s tator portion of journal bearing.
e) LowNOx emission combustor**:** 13-flame holder, 14-hole to admit igniter, 15-outer air swirler, 16-inside air swirler, 17-fuel holes.
f) Inside (18) and outside (19)combustion chamber liner (μCC).
g) 20 – ceramic matrix recuperator

R&D works accomplished within the energy area of the water cleaning system verified practicability of:

- manufacture of ceramic μGTE with efficiency on the level of 28±1%;
- provision of low NOx and CO emissions and the noise level acceptability;
- efficiency increase for micro electric generator up to 98-99%, due to:
  - application of **SCMs** to all high temperature path elements,
  - **integration** of μTC and μEG into a monolithyc design device,
  - **optimization** of the temperature **conditions** for **μEG operation**,
  - development of a "green" **μCC** with **«cold» flame**.

"GREEN" HOUSE

All that was outlined above could be applied to build an environmentally friendly house (Fig. 7) that would provide comfortable living conditions with no demand for external power savings.

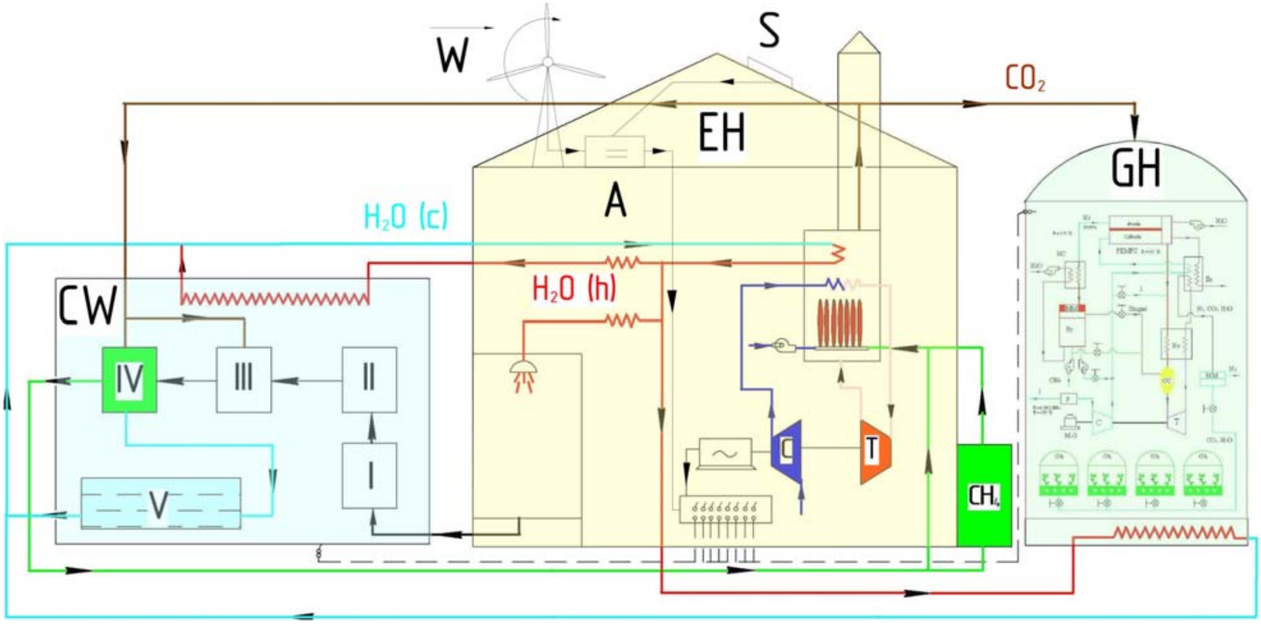


Figure 7. Multi-generation (electricity+heat+hot bed+pure water+ CO_2 absorption) «green" house system that fulfils its own needs for power.

Designations: EN – "green" house: H_2O (h) – hot water, C – compressor, T – turbine; W – wind engine;S – solar battery; A –accumulator; ***CW – pure water:*** I – sewage coarse cleaning system, II – sewage fine cleaning system, III, IV, V – biological aftercleaning system; ***GH – hot bed;*** H_2O(c) – cold water, CH_4 – methane, CO_2 – carbon dioxide.

━━━ sewage; ━ ━ electric power

CONCLUSION

1. A practical feasibility of development of **a superfine sewage system that fulfils its own needs for power** was shown.
2. A system model project of two plants – water cleaning and co-generation units- was completed.
3. **Water cleaning unit**:
   - Provides the pure water quality which is on the level of requirements to fish - breeding; it carries out processing at the speed three times the conventional one, produces fuel for the power co-generation unit operation;
   - Processes its exhaust gases.
4. **The co-generation unit** supplies the heat and electric power to the water cleaning system; it is green, and operates with a high electric efficiency (28±1%), thereby working with the gaseous fuel that was released by the unit. The unit includes:
   - three µGTEs of 2 kW power (total electric power of three µGTEs is **6 kW**),
   - three water boilers of 5.5 kW heat output each (total heat output of three boilers is **16.5 kW**),
   - central heating water system,
   - exhaust pipe,
   - complex water cleaning device,
   - **micro wind generator** (µWG) of **1 kW power**, e.g. of the type presented in [16],
   - accumulator.

The total electric power of the co-generation unit is 8 kW. The electric µGTE power is 6 kW. The heat output of three boilers is 16.5 kW.

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