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Seaweed Ulva photosynthesis and zero emissions power generation

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ABSTRACT

The present paper is aimed at describing a "closed cycle" power plant schematic (SOFT, Solar Oxygen Fuel Turbine) with macroalgae (seaweed) cultivation in a pond, combustion of its organic matter in a fluidized bed boiler of Rankine cycle and return of the combustion products to the pond to feed algae. The oxygen used for combustion is released to atmosphere in photosynthesis. As a renewable fuel for combustion after drying the seaweed Ulva lactuca is selected. Its growth rate from many experiments (in literature) is 0.1 – 0.2 1/day, heating value of dry weight is 19 MJ/kg, optimal concentration in salty water 1:1000. Energy efficiency is less than in photovoltaics but energy expenditures to construct the pond as solar energy receiver are much less, it gives some economic benefits. The present paper highlights the interest of immediate combustion of the dried biomass fuel without converting it in liquid transportation fuel. The latter is the cause of additional technological problems and energy losses.

Keywords

Seaweed, macroalgae, photocynthesis, solar energy, zero emission.

1.Introduction

Seaweed is not new a thing in the world industry, still limited mostly in food and pharmacy.

Algae cultivation for electricity generation is discussed in the recent decades. All algae have been divided by microalgae (size of t microns) and macroalgae or seaweeds, which are much greater. The photosynthesis is similar in both kinds. At first we will start with microalgae; since the technical problems of cultivation and combustion are different, that is why we then focus on macroalgae only.

First the published results of the use of open ponds with microalgae to convert carbon dioxide from power plants into methane fuel belong to Golueke and Oswald (reported in [1]). They demonstrated a small system, involving microalgae growth, digestion to methane and recycle of nutrients. They tried to catch CO_2 injecting the flue gases into the pond regardless of a very small fraction of CO_2 in flue gases, about 10%. Then especially active was Solar Energy Research Institute SERI (now NERL) in "Aquatic species program". After testing the three outdoor algae facilities in California, Hawaii and New Mexico it was concluded that it is possible to produce microalgae in a large-scale pond at high productivity and relatively low cost. Similar results published by Alexejev et al. [2]from Moscow University (Russia), demonstrating a small microalgae system "Biosolar" with production of 40 g/m^2 dry biomass in a day. The mineralized elements from the tank of produced methane are reused by algae, CO_2 is stored after burning. They stated: *1 Mtce of methane might be produced from 70 km^2 annually.*"

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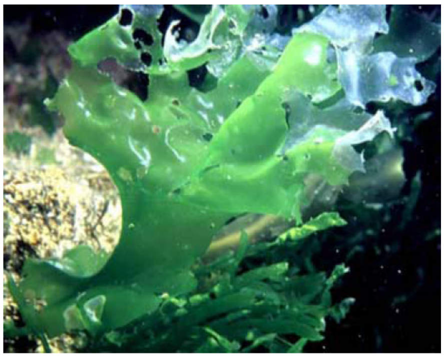
Chemistry of algae pond was described by Brown [3,4] along with the outlook of a raceway-type pond and a paddlewheel to move water. The overall reaction for photosynthesis by cianobacteria, microand macroalgae is as follows:

$$CO_2 + H_2O + \text{light} \Rightarrow CH_2O + O_2 \qquad (1)$$



(a)

(b)

Fig.1: (a) Ulva photo and
(b) distribution around Britain and Ireland [10].

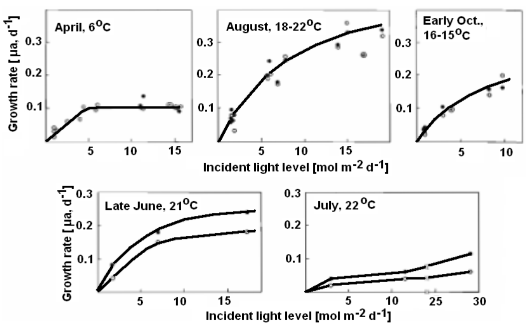


Fig.2: Growth of Ulva lactuca versus insolation [12]: ● with addition of inorganic nitrogen ○ without.

He also stated: We may estimate that microalgal biomass production can increase the productivity of desert land 160-fold (6 times that of a tropical rainforest). Microalgae require only 140 -200 lb of water per pound of carbon fixed even in open ponds and this water can be low-quality, highly saline water.

If the pond water is rich with nutrients like wasted municipal water or released from an animal farm the very high figures of dry biomass production have been published: 120 g/m^2 in a day [5] or 175 g/m^{2}day [6]. These figures are translated into 40-50 kg/m^2 annually.

In parallel to the ponds developments some schemes of relevant power plants to use produced biomass as a fuel have been proposed. Patent by Yamada [7] contains the use of dry algae as an addition to the regular fuel. A fraction of flue gases is released to atmosphere by a stack, the rest is directed to an absorption tower to be washed by water, which dissolves CO_2 from the flue gases and returns it to the pond. The sore point of this scheme is rather small fraction of CO_2 in flue gases, where the dominant gas is the inert nitrogen. The separation of CO_2 from nitrogen turned out to be an insurmountable problem.

The radical solution, the separation of nitrogen not after but before combustion has been described by Yantovski [8] as the cycle entitled SOFT (Solar Oxygen Fuel Turbine). Combustion of biomass in the mixture of oxygen and steam or carbon dioxide, gives the flue gases without nitrogen. The CO2 might be returned in the pond to feed algae.

This paper presents the development of the research reported in [9] by Yantovski and Nesterovski.

2. What is ulva?

Crucial data for the SOFT project are productivity of Ulva under natural insolation and by ordinary sea water temperature and chemical composition. There exists some experience of Ulva harvesting in Irish island [11], where it is quite abundant (Fig.1). Aside to Ulva exists a number of similar highly productive seaweeds.

Let us try to evaluate a possible growth rate of macroalgae with dimensions of a branch from one to ten of millimetres. For simplicity assume the form of organic matter particle as a sphere. Its volume $V = 4/3 \cdot \pi \cdot r^3$ and cross-section area $A = \pi \cdot r^2$. As the result of photosynthesis the sphere radius r is increased. Solar energy flow density (insulation) δ = 220 W/m^2. Low heating value of produced organic matter *LHV* = 19 MJ/kg, the biomass density ρ=800 kg/m^3, efficiency of photosynthesis η = 10%. According to standard definition

of the relative growth rate *RGR* = *M′/M*, where *M′* = rate of mass increase in a second or in a day and *M*= mass of organic particle, we have:

$M'/M = RGR = (3/4)\cdot\delta\cdot\eta/\mathrm{H}\cdot\rho\cdot r$

in time increase (2)

$$M(t) = M_0 \exp(t \cdot RGR) \quad (2)$$

Actual problem is the change of *RGR* in time, when Eq. (2) is invalid. In this formula least known are the two quantities, the efficiency of photosynthesis (assume it as 0.1) and the size of a considered particle (r = 1mm). With these rather preliminary assumptions we have:

$M'/M = RGR =$

$(3/4)–220–0.1/(19\cdot10^3\cdot8\cdot105\cdot0.001)=$

$1.08\cdot10^{-6}$ l/s ~ 0.1m^3/day

The result is in agreement with observed data. It is evident: the more is r the less is *RGR*. In some research is indicated the decline of *RGR* after a size of particles is achieved. The direct measurement of Ulva lactuca growth by different insulation in shallow water (40 - 70cm) in the Roskilde Fjord, Denmark has been made by Geertz-Hansen and Sand-Jensen in 1992 [12]. They measured surface area *A* of initially 17 mm diameter Ulva disks. Growth rates denoted μo ere calculated as

$$RGR = \mu_o = \ln(A/Ao)/t \quad (3)$$

where t = days of incubation. Experiments vividly show the conversion of solar energy into chemical energy of Ulva biomass at the rather high latitude of Denmark (Fig. 2).

A total of 5 graphs are presented RGR in unit 1/day versus local isolation in mol/m^2·day. The last unit should be converted in our convenient units W/m^2. Here mol = mole of photons = 1 einstein = 210 kJ, and day =86400 s, hence 10 mol/m^2·day= 24.3 W/m^2. The most important data are rather high growth rate (up to 0.3 1/day) in natural conditions of 55 grad of latitude by modest isolation and real temperatures. In other countries it might be much higher due to warm winters. Most productive seaweed Ulva is working already for water cleaning (denitrification). The experience is of value for SOFT cycle. As the depth of ponds here is 1 m, the dry weight of Ulva biomass is 1.5 kg/m^3 of water and growth rate 0.1/day. Daily produced biomass is 1200 kg (case B) =13.8 g/s. If assume the *LHV* of biomass is equal to 19MJ/kg the energy flow in biomass as a fuel is 262.2 kW. Assuming a realistic efficiency of fuel into power conversion as 25% (even in small units like a microturbines or piston engines), the produced power from such pond of 0.8 ha surface is 65.5 kW or 100 kW from 1.22 ha. In the subsequent calculations the same power needs 4 ha due to much less assumed biomass productivity. It is possible, and the photosynthesis in denitrification is more productive than in sea water without nitrides.

A role of nitrides mentioned in earlier work: We recorded specific growth rates (NGR) ranging from 0.025 to 0.081 d^{-1} for a period up to two months in the repeated short-term experiments performed at relatively low initial algal densities (300–500 g AFDW m^{-3}). These NGR resul- ted significantly related to dissolved inorganic nitrogen (DIN) in the water column. Tissue concentrations of total nitrogen (TN) were almost constant, while extractable nitrate decreased in a similar manner to DIN in the water column. Total phosphorus showed considerable variation, probably linked to pulsed freshwater inflow.

In the long-term incubation experiment, NGR of Ulva was inversely related to density. Internal concentrations of both total P and TN reached maximum values after one month; thereafter concentration P remained almost constant, while TN decreased below 2% w/w (by dry weight). The TN decrease was also accompanied by an abrupt decrease in nitrate tissue concentration. The biomass incubated over the two month period suffered a progressive N limitation as shown by a decreasing NY ratio (49.4 to 14.6). The reciprocal control of Ulva against biogeochemical environment and vice versa is a key factor in explaining both resource competition and successional stages in primary producer communities dominated by Ulva. However, when the biomass exceeds a critical threshold level, approximately 1kg AFDW m-3, the macroalgal community switches from active production to rapid decomposition, probably as a result of self-shading, biomass density and development of anaerobic conditions within the macroalgal beds.

Systematic measurements of Ulva growth in natural conditions of a coastal lagoon Sacca di Goro, Adriatic Sea, has been made by Viaroli et al. [15]. On the area 26 km^2 by average depth about 1.5m by observed different chemical content of water they recorded RGR of Ulva about 0.05-0.15 1/day. This is a renewable source of fuel for the SOFT cycle of about gigawatt range.

3. Macroalgae as a renewable fuel

Having looked at the growth rate of about *RGR*= 0.08– 0.23 in literature and fantastic "calibrate value" *RGR* = 0.4509, we need to learn the main property of any fuel – the heating value (sometimes called "calorific value" when measured in calories). In literature one may see rather different values from 10 to 19 MJ/kg. The thing is what means this kg, dry or wet, with ash or without. The most comprehensive seems to be the work by Lamare and King [17] (Fig. 3). Here dry algae samples are disintegrated and combusted in a bomb. Extrapolating to 0% ash, we see 4.7 kcal/g dry W_t = 19.64 MJ/kg which might be accepted for all organic matter of different algae. By 10% of ash it is about 19 MJ/kg which is selected for forthcoming energy conversion calculations. As inorganic substance is absorbed from water solutions without photosynthesis it seems to be out of energy balance.

Heating value of algae depends on a season of growth (Fig. 4).

In this measurements the heating value of Ulva seems to be a little less than 19MJ/kg. However we will use just this figure as more statistically proven.

Let us present some data based on Mediterranean experience [16]. There were in 1998 three raceway-type ponds, each surface of 1500m2 with the paddle-wheel sea water circulation. CO_2 is supplied by a tank on a lorry and injected into water by perforated tubes. The depth of water 0.4 m, hydrogen factor pH=7. The firm figures were obtained for seaweed Gracilaria only. The stable productivity of dry mass from a pond was 12 t/year or 8 $kg/m^2 \cdot$year. Using seaweed Ulva the expected productivity is doubled. These ponds are located near to the sea shore, from where the sea water is pumped into ponds. Still the produced biomass is used as raw material for chemicals and pharmaceutics. Recently some headway in seaweed cultivation had made Noritech-Seaweed Biotechnologies Ltd. In Italy the main practical interest in Ulva seems to be concentrated in water cleaning and denitrification [13,14,18,19] where much research have been done in Genova, Venice and Parma Universities. Their active work gives an opportunity to use the SOFT cycle also as an incinerator, deflecting extra nitrides, heavy metals and other contaminants in fuel separation device to dispose it of; perhaps underground in some depth.

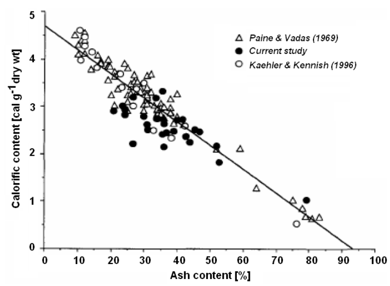


Fig.3: Correlation line for many algae: heating value versus ash content [17].

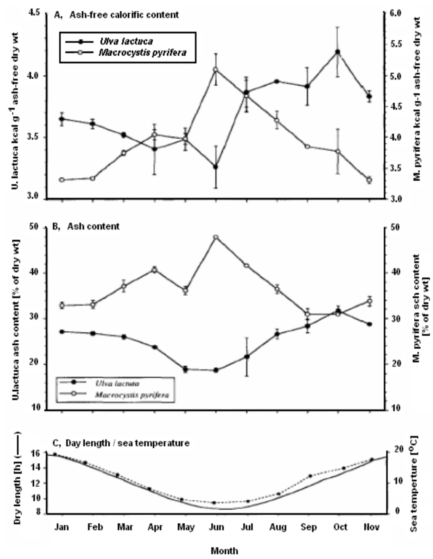


Fig.4: Heating value variation in a year (New Zeland winter is in May-August).

Table 1. Ulva production in denitrification ponds [13].

A) Phytoteatmeat pond average condition		B) Phytoreatment pond average condition	
Ulva biomass (Kg fw m^2)	1,5	Ulva biomass (Kg fw m^2)	1,5
Water depth (m)	1,0	Water depth (m)	1,0
Temperature range (C°)	15-30	Temperature range (C°)	15-30
Light Intensity range (uEm^2s^4)	500-2000	Light Intensity range (uEm^2s^4)	500-2000
pH range	7-8	pH range	7-8
Experimental measurements		**Experimental measurements**	
Ulva Growth rate (d^4)	0,1	Ulva Growth rate (d^4)	0,1
Ulva assimilation ratos (unol Nd^{-1} m^{-2})	40000,0	Ulva assimilation ratos (unol Nd^{-1} m^{-2})	40000,0
INPUT	**INPUT**	**INPUT**	**INPUT**
Pond Area (m^2)	1300,0	Pond Area (m^2)	8000,0
Water Flow ($1s^{-1}$)	250,0	Water Flow ($1s^{-1}$)	140,0
Ammonia in ialet water (uM)	179,0	Ammonia in ialet water (uM)	61,0
Nitrate in pond Water (uM)	6,0	Nitrate in pond Water (uM)	6,0
Output		**Output**	
Biomass to be removed daily (Kg fw d^{-1})	195,0	Biomass to be removed daily (Kg fw d^{-1})	1200,0
Be nitrified nitrogen (%)	0.04	Be nitrified nitrogen (%)	1,21
Assimilated nitrogen (%)	1,3	Assimilated nitrogen (%)	43,4
Total nitrogen removal (%)	1,4	Total nitrogen removal (%)	44,6
Ammonia in outlet water (uM)	176,5	Ammonia in outlet water (uM)	33,8

Table 2. Growth rates of algae and rates of decay [14].

Parameter	Meaning	Units	Literature value	Calibrated value
$\mu\max 04$	Ammonification rate	day^{-1}	0.045	0.1263 ± 0.0251
$\mu\max 42$	Nitrification rate	day^{-1}	0.011	0.0010 ± 0.000785
$\mu\max 23$	Nitrification rate	day^{-1}	0.046	0.1323 ± 0.0147
μ denit	Denitrificationrate	day^{-1}	0.37	0.8329 ± 0.0948
$\mu\max$	Macrolgae maximum growth rate	day^{-1}	0.23	0.4509 ± 0.0312
Ω_m	Macroalgae decay rate	day^{-1}	0.03	0.0594 ± 0.062
SR	Ruppia decay rate	day^{-1}	0.041	0.0675 ± 0.0043
$\rho\max$	Ruppia maximum growth rate	day^{-1}	0.17	0.3780 ± 0.0235

4. Energy flow concentration

The main obstacle of solar energy capture is its very low current density, especially annually averaged. In Mediterranean coast for example, it is about 220 W/m^2, only 16% of the solar constant 1368 W/m^2. In central Europe it is a half. Thus the energy expenditure and cost of incidental energy absorber is of primary importance. In case of photovoltaics with rather high efficiency (in laboratory about 30%, in practice a half) the pure silicon absorber takes by manufacturing lots of energy and money. That is why solar cells up to now are rather expensive. As it will be shown later, the efficiency of the solar energy conversion into electricity through algae pond is much less, about 3-5%.

But the energy expenditure of absorber-pond is hundred times less than that of silicon. Having been absorbed by algae the solar energy in chemical form is concentrated by water flow much better than by optical concentrator. The concentration factor of a paraboloid concave mirror is about 500, it means the averaged focal spot energy current density is about 500·220= 110 kW/m^2. Energy flow in the pipe from algae pond to processing is about

$$\alpha\cdot\rho\cdot V\cdot H = 0.001\cdot1000\cdot1\cdot19\cdot10^6=19000\ \mathrm{kW/m^2} \quad (4)$$

here α = 0.001 = mass fraction of biomass in water,
ρ =1000 kg/m3 = water density, V = 1m/s = water velocity, H = 19 MJ/kg =dry biomass heating value.

It is evident that energy current density in the pipe is hundred times more than that in the focal point of optical concentrator (hydrodynamic concentration). It means the equipment size for the subsequent energy conversion processes should be rather small. It is more important than large size of solar energy absorber.

5. Power unit outlook

Schematic is presented on Fig.5. Water with algae 6 from the pond 4 is going to the water separation unit 12, from where the pure water without algae is used as a circulating water to cool condenser 14 and absorb CO_2 in 16. Wet organic matter is dried in 18 by heat of flue gases. Relatively dry fuel is directed to the fluidized bed combustor 8. After combustion in the artificial air (the mixture of oxygen and carbon dioxide), flue gases go in the cyclone separator 20, the deflected ash is returned into the pond CO_2 with some steam go through heat exchanger 19 and fuel drier 18 to a separation point, from where a major part is mixed with oxygen, forming artificial air for fluidizer and a minor part is directed to absorber 16 to be dissolved in circulation water and returned to the pond. This minor fraction of CO_2 flow is exactly equal to CO_2 appeared in combustion. Oxygen is produced from air at the cryogenic or Ion Transport Membrane unit 10. Water from condenser 14 goes by a feed water pump through heat exchangers 18 and 19 into tubes of the fluidised bed combustor 8 (boiler). Produced steam expands in the turbine 22, driving generator. Low pressure steam is condensed in 14. Actually it is the ordinary Rankine cycle.

Some words on the chemicals production. It is unwise to combust the crude seaweed at power plant in the same sense as it is unwise such use of crude oil. A small mass fraction of seaweeds contains very useful organic chemicals which should be deflected along with water separation before the fuel combustion. There exist lots of methods of high organics separation, which is far from the scope of the present paper. In any case the chemicals production could improve economics of the SOFT cycle.

Let us take for a numerical example the decentralized power supply by a small power plant of 100 kW [20]. In order to get the reliable figures we make rather modest assumptions:

- Fuel is wet (50% water content)
- ASU power consumption by 98% oxygen purity
  0.22 $\mathrm{kWh/kgO_2}$
- Superheated steam before turbine 130 bar, 540ºC
- 0.75
- Seaweed productivity 16 $\mathrm{kg/m^2}$ year or 10 $\mathrm{W(th)/m^2}$
- Photosynthesis efficiency 4.6%

- **CALCULATED RESULTS:**

- Heat input 425.5 kW(th)
- Net output 107.3 kW (el)
- Cycle efficiency 25.2%
- Pond surface 4 hectar.

See the graph of efficiency vs. fuel moisture in Fig.6. For quite possible figures of Rankine cycle with reheat and efficiency of 35% the needed surface of the pond is 3 ha. A local power plant of 10 MW by cycle efficiency 40% and photosynthesis efficiency 6% the specific power per square meter is about 5W (220·0.4·0.06=5.28) and pond size is about 2 $\mathrm{km^2}$. By the order of magnitude it is comparable with Yatir – reservoir in the desert Negev near to Beer Sheva. There is a project [21] to build 100 water reservoirs in the next fife years. One of these might be used for the SOFT demonstration. Finally, for the national power demand of 10 GW (about 2 kW pro capita) in Mediterranean area a reasonable extrapolation is possible: expecting specific power of 10 $\mathrm{W/m^2}$ due to the increase of the cycle efficiency and photosynthesis one. It means the needed pond surface is about 1000 $\mathrm{km^2}$. The surface of the Dead Sea is just the same (exactly 980 $\mathrm{km^2}$). If in some future a Life Sea (with the normal, not deadly salt concentration for seaweed) would appear in the desert, not too far from the Dead one, it could give the country full electrical power along with lots of fresh water and organic chemicals. There would be no emission of combustion flue gases and no net consumption of oxygen, which is consumed in combustion but released in photosynthesis. The only need is solar energy and a piece of a desert. The Life Sea might be a useful consumer of the transferred water at the middle of the pipeline.

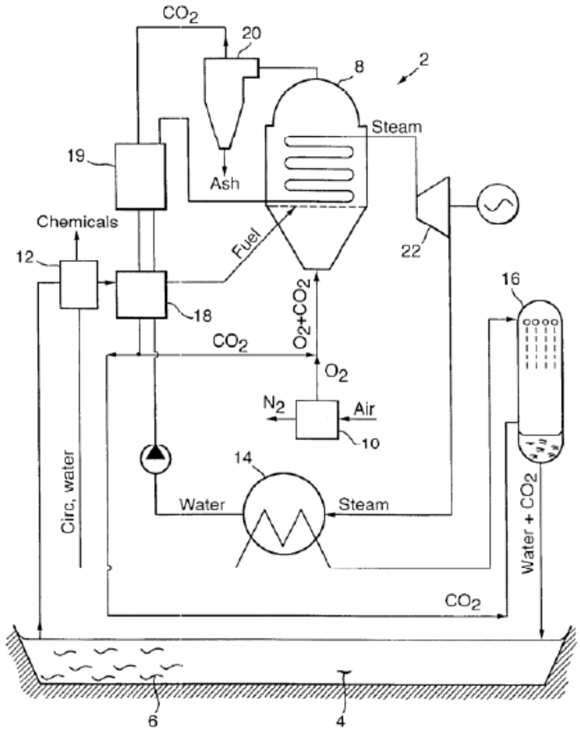


Fig.5: Schematic of the SOFT cycle [22].

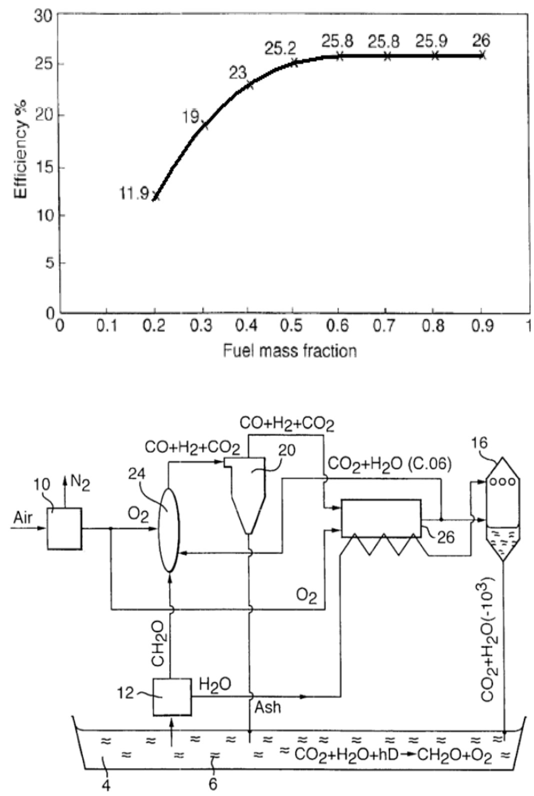


Fig.6: The efficiency versus fuel wetness and a version of the SOFT cycle with fuel gasification [22].

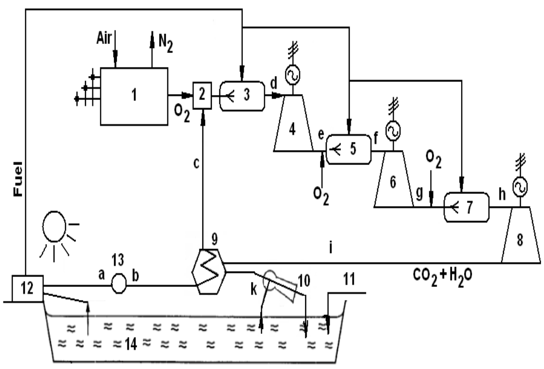


Fig.7: First version of the SOFT cycle (1991).

6. Gasification

In the proper energy mix not only electricity, but also gaseous or liquid fuels are needed. In the SOFT cycle it is attainable by a small modification (Fig.6). The difference is the gasification in the fluidised bed reactor (gasifier 24). Biomass gasification is well documented [22].

Fluidized bed gasification experiments with the sugarcane bagassa were described by Gomez [23]. Produced gaseous fuel mixture consists of carbon monoxide, hydrogen and carbon dioxide. After cleaning in 20 it is used in a piston engine or turbine 26, producing mechanical power. The same fuel gas mixture might be converted into a liquid fuel like methanol or even gasoline. After combustion in 26 the flue gases are absorbed by circulated water and returned to the pond 4 to feed seaweed 6.

7. Water desalination

Let us consider what might the SOFT cycle do for water desalination: is it possible to use low-grade heat after the turbine expansion to evaporate of a fraction of the circulating salty water (sea water) with the subsequent condensation of vapor for the fresh water production (desalination). Assume an evaporator of a minor fraction of circulating water after turbine. Cooling and condensing this vapor by the major part of circulating water gives fresh water as condensate.

How large is its flowrate? Assume the turbine as of back-pressure type, by exit steam pressure 1.2 bar. If in a modern high temperature steam turbine inlet is 1000 K by 200 bar, the enthalpy is 3874 kJ/kg. After expansion the steam is at 450 K and 2830 kJ/kg. For water evaporation by 1 bar the enthalpy drop of 2500 kJ/kg is enough. In a small power unit of 100 kW the mass flowrate of cycle water of Rankine cycle is $100/0.25 \cdot 1044 = 0.4$ kg/s. The mass flowrate of desalinated water is the same 0.4 kg/s. For a small demonstration plant the pictures are:

- Pond surface 4 ha (40 000 m^2)
- Power 100 kW
- Dry fuel flow 0.021 kg/s
- Chemicals (4%) 1 g/s
- Fresh water 0.4 kg/s

Specific dry fuel consumption is 756 g/kWh. It is about twice in excess of standard fuel consumption in microturbine power units due to lower heating value and low efficiency.

In a 1GW power plant with cycle efficiency 40% and pond surface 10-20 km the flowrate of produced fresh water is 4 t/s or 14400t/h. Assuming 7000h/year operation the yield of water annually is about 0.1 km^3. It is evident, that if the SOFT cycle with water desalination would be used in full scale, it might meet all the water demand. Contemporary practice of the use of 18 power generating and desalinating plants at the West bank of Persian Gulf [24] giving 15 GW of power and 1.9 km^3 of desalinated water annually, confirms the above guesses. In case of applicability the experimental results of Italian researchers.

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11. Biographies

Evgeni Yantovski was born on 13 May 1929 in Kharkov, Ukraine.
Graduated in Kharkov Aviation Institute (Ukraine) on 1951, Doctor of Science 1973, Professor in 1989. Since 1990 lectureship in many European and American universities. His main areas of interest are magnetohydrodynamic generators and pumps, heat pumps, zero emission power plants with membrane oxygen for combustion, energy and exergy currents, and exergonomics

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