Cogeneration in a large and small scale

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Abstract

Main energy conversion machinery used and to be used in cogeneration systems are described. First, large-scale cogeneration systems used in large power industry are discussed. Then, some assets of distributed generation are pointed out and small-scale cogeneration systems designed for energy units of distributed cogeneration are described.

Introduction

Cogeneration is a simultaneous production of electric energy and heat which leads to a more efficient utilisation of primary energy. Thus, cogeneration brings considerable savings in the final energy production and contributes to decrease the level of emissions into the environment, especially CO_2. The opportunities for cogeneration are however usually determined by the demand on heat, which can very for example seasonally and with the daytime. The complex analysis of a cogeneration unit should take into account the characteristics of the heat receiver.

Sample quantitative gains from cogeneration are displayed in Fig. 1. As seen from the picture, in order to produce 21 units of electric energy and 33 units of heat in cogeneration (assuming the total cogeneration efficiency of 90%) there are 60 units of primary energy required, whereas 97 units of primary energy are needed to produce the same amount of final energies in separate generation.

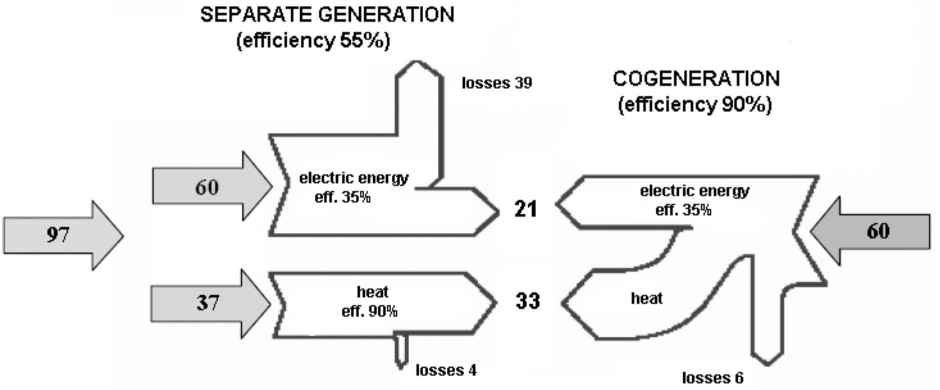

Fig. 1. Production of electric energy and heat in a separate mode and in cogeneration

Cogeneration in a large scale

Prime movers in large CHP systems are first and foremost steam turbines – backpressure or extraction-condensing steam turbines operating in a closed Rankine cycle as well as gas turbines operating in a Bryton cycle [1]. Combined two-fuel steam-gas cycles are also encountered. In a closed cycle of a back-pressure turbine (fig. 2), the production and superheating of steam takes place in a boiler. The superheated vapour expands in a turbine and, from the turbine outlet, is directed to the heat exchanger (condenser) where it gives away its remaining superheat and condensation heat for heating of district net water. One asset of the back-pressure turbine system is its simplicity, another is low demand for cooling water and therefore low heat losses in the condenser. Among a number of disadvantages are a short expansion line (with the region of low pressures and temperatures exempted from the electric energy production) and a large stiffness of the system, that is the dependence of the electric energy production on the demand on heat.

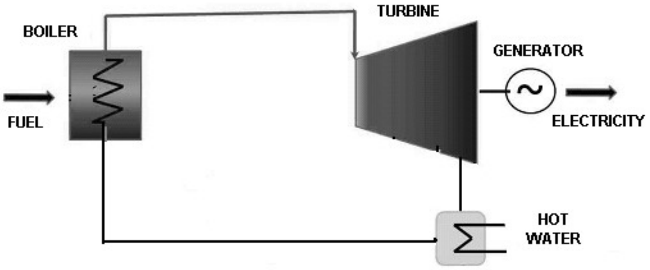

Fig. 2. A cogeneration cycle with a back-pressure turbine

In the extraction-condensing turbine (fig. 3) the steam extraction point is located one, two or more turbine stages upstream of the outlet diffuser. An advantage of this design is the possibility of expansion down to the parameters below 0.1 bar and 40ºC, which is important for the purpose of production of electric energy. Extraction-condensing turbines are met to operate in a power range from a few to a few hundreds of MWe. Truly, the exhaust heat is lost in the condenser in extraction-condensing turbines, but the heat load of the extraction points can, with application of some special designs, change in a wide range with practically little loss to the electric energy production. One way to adapt blading systems of extraction-condensing turbines to variable load operation in the context of cogeneration of electric energy and heat is the adaptive control. The main element of adaptive control is the so-called adaptive stage of flexible geometry located directly downstream of the extraction point. Basically, during extraction of steam to the extraction point this flexible geometry enables reduction of the mass flow rate in the blading system without a reduction of pressure drop in downstream stages. Thus, the full available pressure drop is used in the blading system. Expansions beyond the blading system, involving a loss of turbine power and giving rise to uncertainty in operation of the exit diffuser, are avoided.

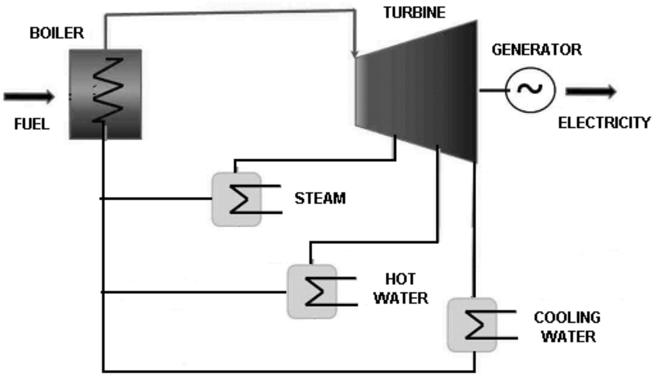

Fig. 3. A heat cycle of the extraction-condensing turbine

In the most typical design the adaptive stage has throttling nozzles that have movable leading edges blocking part of the blade-to-blade passage if necessary, fig. 4 – part A. This construction has been used by LMZ, ABB-Zamech, Alstom Power [2], [3]. Fig. 4 – part B illustrates another design of the adaptive stage nozzles with the same driving mechanism, but with a more complex division line of the stator blade. An interesting design of adaptive stator blade was patented in [4]. The adaptive stage stator has a rotated trailing edge (flap nozzle) which controls the throat. As compared to the design with movable leading edges, this design maintains the smoothness of the profile shape, also for low levels of throat opening, fig. 4 – part C. A similar principle lies behind the system with rotated stator blades, fig. 4 – part D.

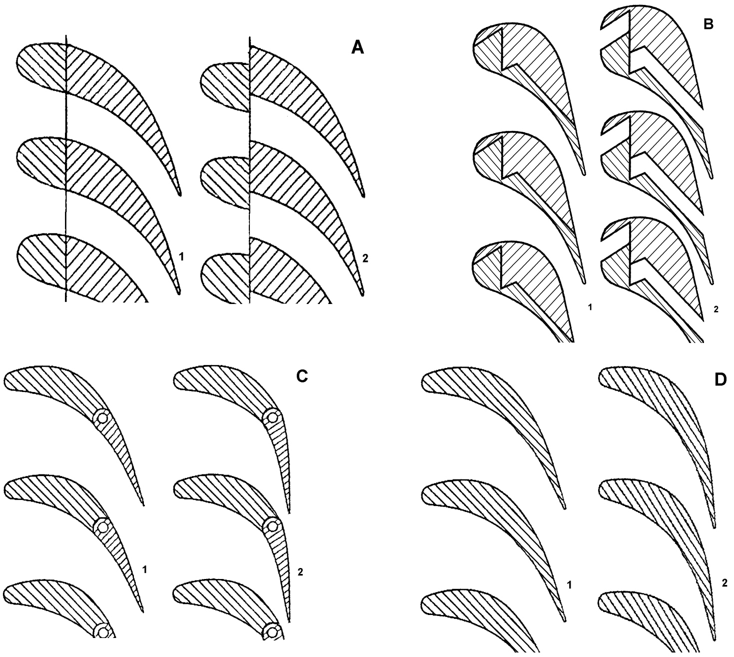

Fig. 4. Adaptive stage nozzles: blade with a movable leading edge (A), blade with a complex division line (B), blade with a rotated trailing edge – flap (C), rotated blade (D); 1 – full opening, 2 – part-load opening

The numerical analysis of effects of adaptive control in a group of stages of a large power LP turbine (as in fig. 5) based on the rotated blade design is presented in [5]. Fig. 6 exhibits changes of power in a group of two exit stages (last and last-but-one stage) as a function of mass flow rate during extraction of steam to the extraction point. Changes of power are plotted for different stator blade stagger angles (coloured solid lines) and for different pressure drops through the stage group (coloured dashed lines). Several point are marked to help to estimate the advantages of adaptive control. They are: N – nominal operation point; A – sample operation point under conditions of extraction of additional 10% of the turbine mass flow rate to the extraction point, and A' – the same point of operation after adaptive control. The aim of adaptive control is to take advantage of the full pressure drop available and to bring the expansion back to the turbine blading system. It follows from fig. 6, this can be achieved by closing last-but-one stator throats and rotating the blades by 2°. Point A is then moved to point A' that lies on the line of nominal pressure drop in the stage group from 0.39 to 0.10 bar. A significant reduction of flow losses especially in the last stage can be achieved as a result of that. It was calculated that for a considered extraction-condensing turbine of power 50 MW, under conditions of a 10% mass flow rate extraction to the extraction point located upstream of a group of two exit stages, power gains reach on average 2.5 MW per stage. The stage group power is then lower by about 11% than the power before the steam extraction (6,5 MW), and is practically decreased by the decreased mass flow rate through the blading system. Note that for a 50MW turbine the power increase obtained from the adaptive control amounts to about 10% of the turbine power.

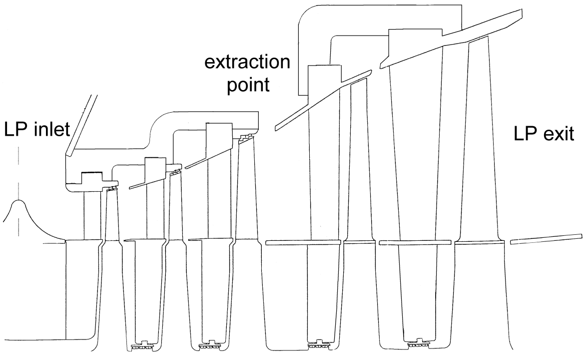

Fig.5. Geometry of the flow system of the LP extraction-condensing turbine in meridional view

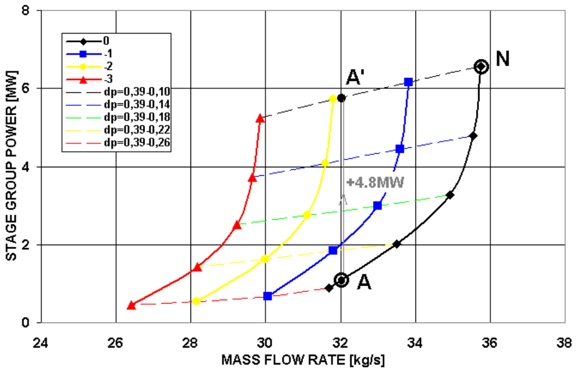

Fig. 6. Changes of stage group power as a function of mass flow rate

In large cogeneration systems also gas turbines are often used. A sample cogeneration cycle with a gas turbine operating in an open cycle is illustrated in fig. 7. Compressed air is fed to the combustion chamber where the fuel is burned under constant pressure. Heat is passed to the flue gases which expand in the turbine driving a generator. The exhaust gases from the turbine of temperature still in the region of 400-600°C first go to the recuperator, then to the heat exchanger where the district net water is heated. Due to a relatively high temperature of exhaust gases, gas-steam heat cycles with cogeneration can also be build. Among advantages of gas turbines as prime movers in cogeneration systems are large efficiency of energy production and a relatively quick start-up to the nominal operation. The electric power of gas turbines usually does not exceed 100 MWe.

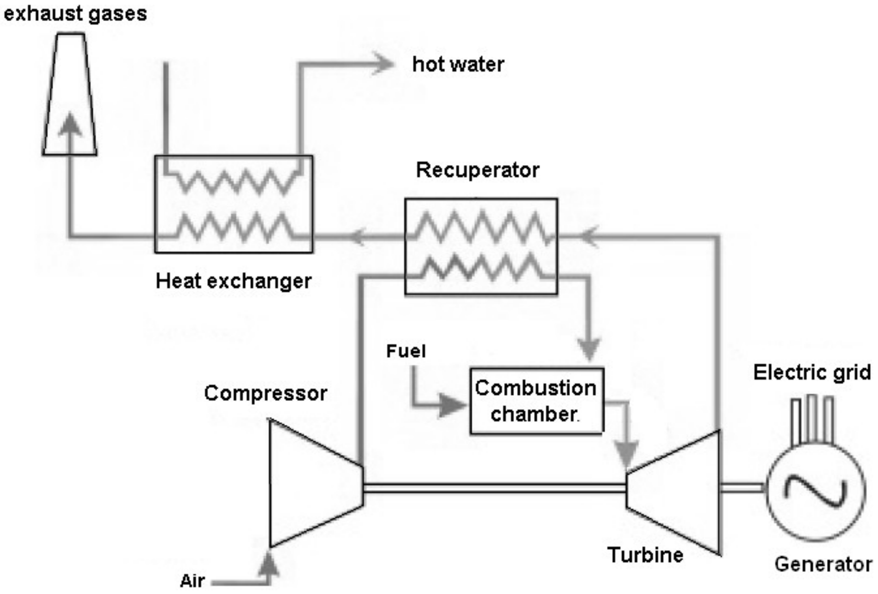

Fig. 7. A cogeneration cycle with a gas turbine

Distributed generation

Cogeneration as a simultaneous production of electric energy and heat can especially be applied in small power units of distributed generation systems [6], [7]. The development of these small power units is not centrally planned. Classification of distributed generation units refers mainly to electric power units with the possibility of heat generation. Probably the most adequate division of distributed generation units according to the generated power is as follows:

- micro distributed generation (up to 5 kW),
- small distributed generation (5 kW – 5 MW),
- medium distributed generation (5 MW – 50 MW),
- large distributed generation (50 MW – 100 or 150 MW).

There are many different technologies of generation of electric energy and heat in distributed sources. Distributed generation units can be small conventional power plants, small coal-based heat or heat and power stations, biomass heat stations, hydro power plants, wind farms, off-shore wind farms, solar stations, fuel cells and energy storage systems, biogas and biorafinery stations, fig. 8. In the latter, a simultaneous production of fuels, electric energy and heat can take place. Although the upper power limit for the distributed generation units has been set about 100-150 MW, we will further refer to small and micro distributed generation systems of power not exceeding 5 MWe.

In small and micro distributed generation systems, the produced energy goes first to local communities. One can mention here the energy generation for households, residence buildings, large farms, public buildings or small and medium enterprises. The surplus of electric energy goes to the power network, heat surplus goes to local district heating networks, whereas the surplus of fuel can be used for transportation or compressed into a gas network.

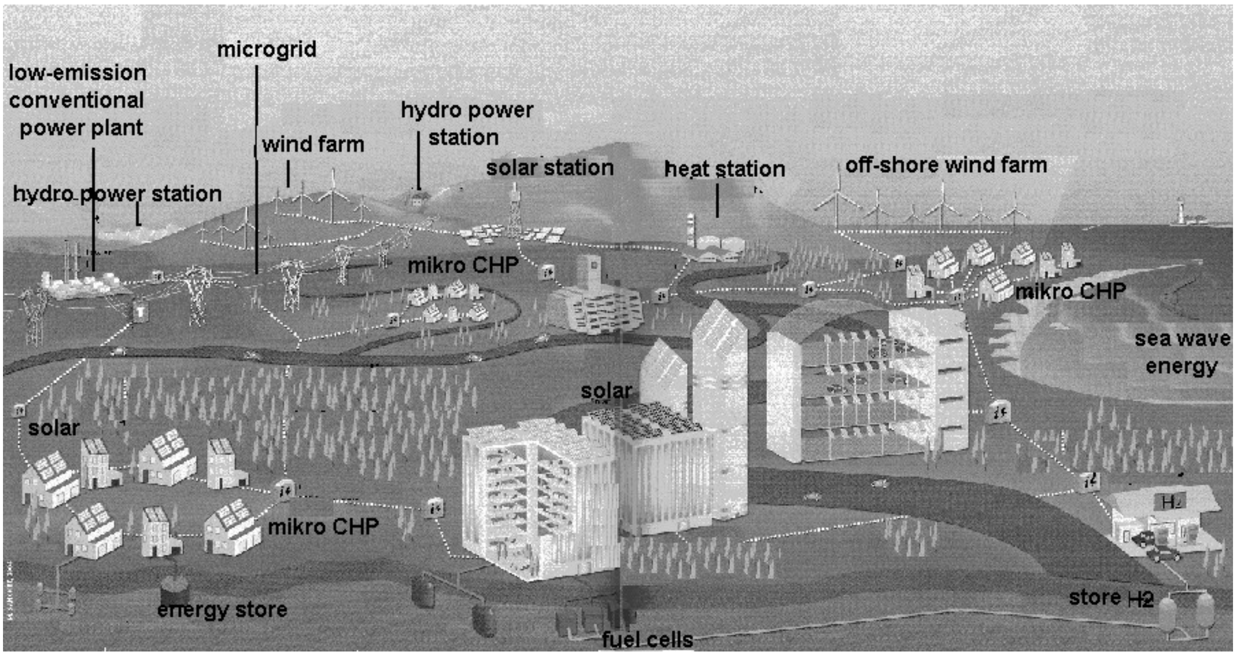

Fig. 8. Model of distributed generation

There are several advantages of distributed generation such as:

- possibility of utilisation of local energy resources, especially renewable energy sources,
- production of different forms of final energy in cogeneration,

- avoiding excessive installed power in a single location,
- reduction of peak load,
- reduction of transmission losses,
- increasing energy safety by diversification of energy sources,
- reduction of green-house gas emissions (cogeneration, renewable energy sources).

Among disadvantages of distributed generation one can mention:

- uncertainty of energy production from some sources (wind farms, solar units) and the necessity to keep power reserves,
- high initial investment costs,
- high costs of energy measurement and billing per unit of produced power,

The policy of European Union is favourable for distributed generation and renewable energy sources, only to mention:

- directive 2004/8/EU in point of cogeneration,
- directive 2003/87/EU in point of trading limits in green-house gases emission,
- directive 2003/96/EU in point of taxation of energy products and electric energy,
- directive 2001/77/EU concerning the share of renewable energy in the energy balance of membering countries.

The profitability of energy production in distributed generation units can be increased due to a programme of economic incentives such as green certificates for energy from renewable resources, red certificates for cogeneration, certificates for energy efficiency or low charges for entry to network connections.

There are also a number of regulations that can act either in favour or against distributed generation, for example:

- regulations concerning entry of distributed generation units to network connections,
- environmental regulations concerning emissions of green-house gases and other harmful emissions (SO_2, NO_x), dust pollutions, noise emissions, landscape deterioration or other bad impact on the environment,
- regulations concerning security and safe operation.

Cogeneration in a small scale

Primary movers for cogeneration units operating within the distributed generation systems are ignition (spark and diesel) engines. Power units based on ignition engine cycles topped with a recovery heat node are main components of cogeneration systems integrated with the production of fuels from biomass in biogas and biorafinery stations. Equipped with appropriate feeding and ignition systems can burn both gas and liquid fuels, also less caloric fuels such as biogas from fermentation biogas stations, gas obtained from pyrolytic gasification, liquid products of fermentation and pyrolysis or products of estrification of animal fat. A basic power range for ignition engines is from a dozen kWe to a few MWe.

A cogeneration cycle for ignition engines is illustrated in Fig. 9. The piston ignition engine drives a generator of electric energy. Heat from the cooling and lubrication cycle can be used for heating net water. Heat recovered from exhaust gases can be used for the production of technological steam and also for district heating.

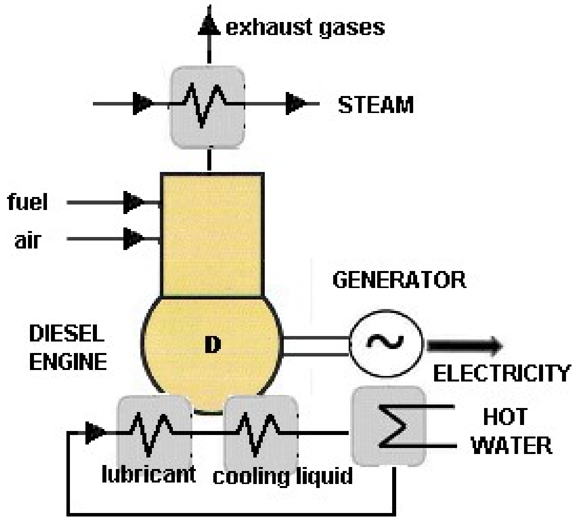

Fig. 9. A cogeneration cycle for the piston ignition engine

Main advantages of small power stations based on piston ignition engines are:
- high efficiency of electric energy production, also during low load operation,
- possibility of quick start-up to the nominal operation conditions,
- possibility of operation in places distant from entry to the distribution network and as an emergency supply,
- variable fuel supply,
- relatively low investment costs.

In small or micro distributed cogeneration systems gas turbines or microturbines can also be applied. The idea of cogeneration cycle is the same as for large power objects (fig. 7). Gas turbines are characterised by a significantly longer exploitation time as compared to piston engines and require less frequent maintenance services. The efficiency of electric energy production however is usually by a few per cent lower than that of the ignition piston engines in the considered range of power. Initial investment costs are also higher.

The counterparts of large power turbines in distributed generation are small steam turbines or microturbines that operate in an organic Rankine cycle (ORC) whose schematic is presented in fig. 10. Main components of this CHP station are ecological boiler fit to combust different kinds of biomass or biofuels, intermediate heat cycle to extract heat from flue gases to thermal oil as a heat carrier, evaporator, turbine with a low boiling liquid as a working medium, generator, condenser and circulating pumps for the working medium and thermal oil [8], [9]. In the presented heat cycle, electric energy is a by-product and forms only about 10-20% of the total heat. The remaining superheat and condensation heat of the working medium is used for heating net water. The solution offers a possibility to apply low temperature heat sources, allows utilisation of different types of fuels and modular construction, which facilitates adaptation of the CHP unit to the required power range. Micro CHP units dedicated for individual households of total heat capacity up to 20kWt and electric power up to 4kWe as well as small CHP modules dedicated for communal energy centres of total heat capacity 1000kWt and electric power 200kWe (maximum up to 5 MWt and 1 MWe respectively) are currently being elaborated at IMP PAN. In the power range of a few or a dozen kWe one can also consider cogeneration units with a Stirling engine (with external combustion) or based on a fuel cells system.

Aiming at the development of cogeneration technologies integrated with systems of production of fuels from biomass which are characterised by a high efficiency of electric

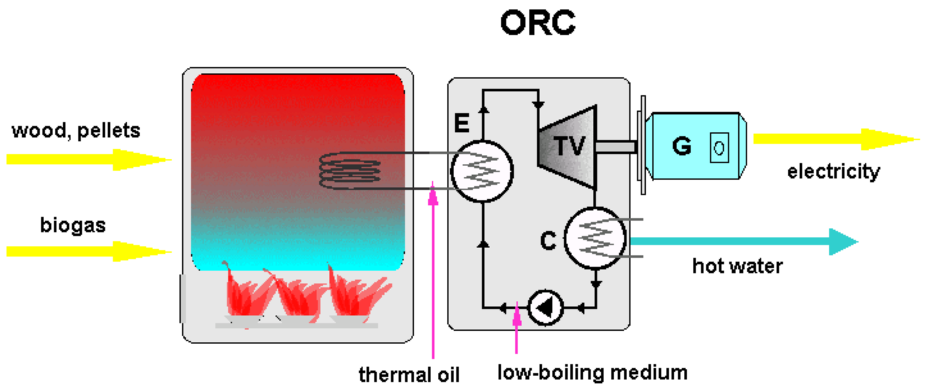

Fig. 10. Cogeneration unit with ORC;
E – evaporator, TV – steam turbine, C – condenser, G – generator.

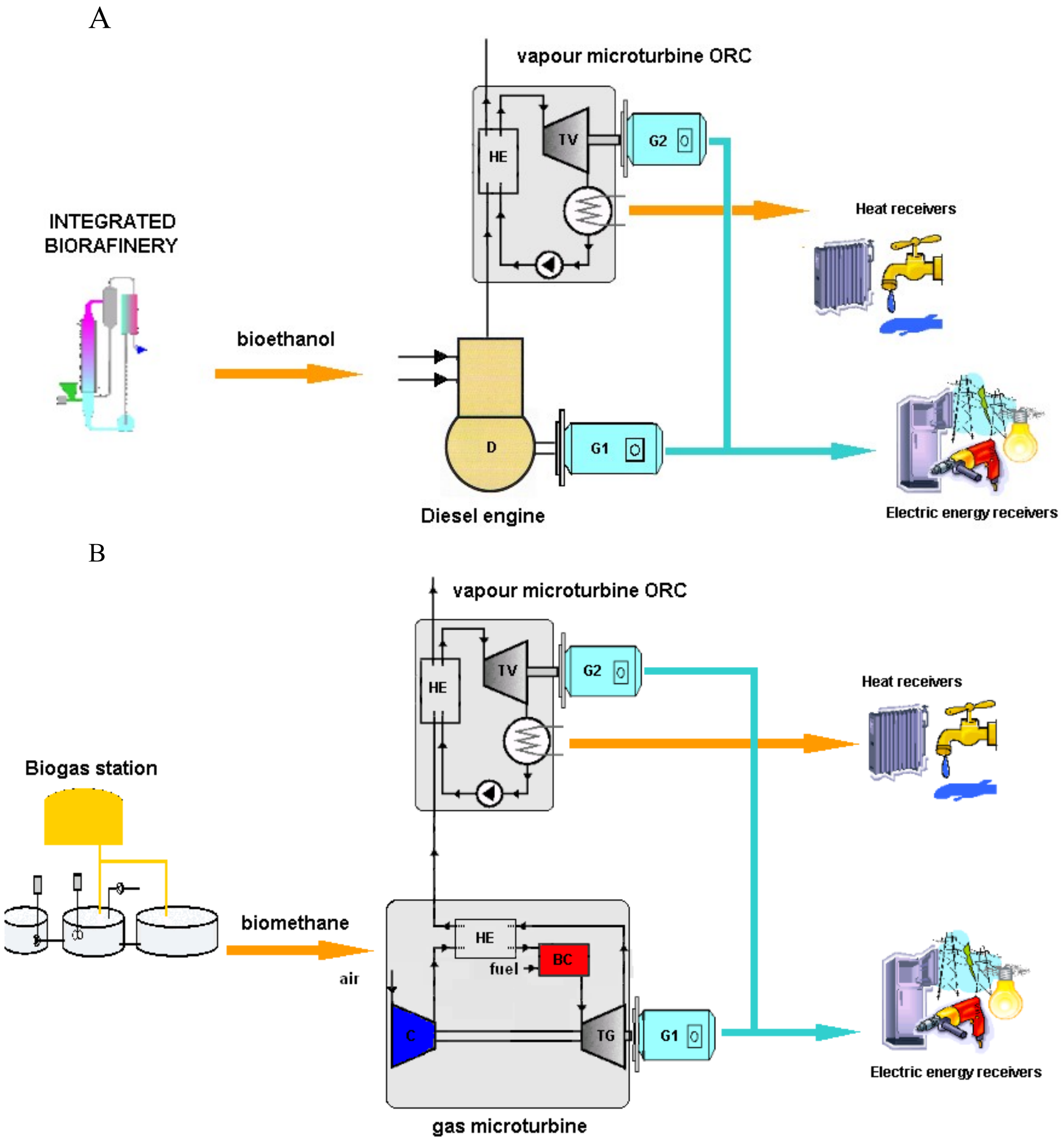

Fig. 11. Schemes of cogeneration units in a combined cycle: A – diesel engine + ORC cycle; B – gas turbine + ORC cycle; TV – steam turbine, TG – gas turbine, G1, G2 – generators, C – compressor, BC – gas turbine combustion chamber,
HE – heat exchangers.

energy production (40-45%), works on combined steam/gas cycles illustrated schematically in fig. 11 are in progress at IMP PAN. It seems that cogeneration units of electric power 0.5-1MWe will most often be used. The main heat cycle is that of the ignition engine or gas turbine, where the generator is driven by the ignition engine or gas turbine. An additional heat cycle in a steam ORC cycle working based on heat recovered from engine/gas turbine exhaust gases or cooling systems. The steam turbine drives another generator which produces additional amount of electric power. The remaining superheat and condensation heat of the working medium in the ORC cycle is then used for heating net water.

Summary

Main CHP technologies used in large power industry and distributed generation were presented. As for large CHP units particular attention was paid to extraction-condensing turbines. Advantages of adaptive control, which allows changes of heat load of extraction points with little detriment to the production of electric energy, were illustrated. The assets of distributed generation and a number of CHP technologies suitable for distributed generation units were also discussed. The paper was focused on CHP stations equipped with ORC modules. It seems that in the years to come many machines of this type will be applied in distributed generation units based on biomass. They are:

- micro CHP stations of heat capacity up to a few dozens kWc and electric power up to a few or a dozen kWe dedicated for individual households (Household CHP stations),
- small CHP stations of heat capacity up to 5 MWc and electric power up to 1 MWe dedicated for local communities (Communal Energy Centres),
- small CHP stations in a combined steam/gas cycle integrated with systems of production of fuels from biomass and characterised by a high efficiency of electric energy production within a power range of 0.5-1MWe.

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