CHP and CCHP Systems Today

Review

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Abstract *– The concept of the CCHP system (combined cooling, heating and power - combined cooling, heating and electricity generation) is described in this paper. The development of CCHP systems comes from the CHP system (combined heat and power generation), also known as cogeneration. CHP systems generate electricity from fuel combustion, heat as a by-product may contain even 60% to 80% of the total potential energy, and may be re-used for different applications. CHP is generally defined as the combined production of electricity (or mechanical) energy and useful thermal energy from the same primary energy source. Rated power of most of centralized power plants and industries which use CHP system exceeds 1 MW. Rated power of CCHP systems varies over a wide power range from 1 kW to 500 MW. CCHP systems have high potentials in different forms of energy supply.*

Keywords *– CCHP, CHP, cooling energy, electricity, heating*

1. INTRODUCTION

Insufficient capacities for electricity generation, transmission and distribution, decreased reliability of power systems, possibilities for postponement of large investments in the power sector, price increment of energy forms on the market and the need for heating and cooling energy of modern buildings, impose the idea of an energy independent building equipped with a small-scale energy source. The idea is either to completely fulfill all energy needs all the time (rarely, except for buildings located far away of the present energy networks) or to particularly satisfy its energy needs. Sometimes, or better said during different parts of the day or season, energy transfer is building-network directed and sometimes it is opposite using a power network as energy storage. For example, in the daylight, electricity consumption increases compared with electricity needs at night, so that night surplus electricity is transferred to the electric power network and during peak demand periods the buildings need electricity pooled from the power network. The concept of CCHP systems (combined cooling, heating and power) is developed from CHP (combined heat and power), also known as cogeneration (production of electric energy and useful heat).

CHP is mostly used in district heating power plants controlled by the electric power system. The traditional way of buildings to fulfill electricity needs is to buy electric energy from the power system and to fulfill heating needs by one of combustion fuel techniques.

Efficiency of electricity generation in conventional power plants is 0.2 – 0.4 depending on rated power, technology, thermodynamic parameters of steam, applied materials and the operating point. Efficiency of heating energy is better; it is about 0.5 – 0.8 in domestic applications. CHP systems generate heating energy for a district, or better said, wide town area by the heating pipe network and heating substations, simultaneously generating electricity as a by-product. The simultaneous generation of both electricity and heating power significantly increases efficiency (0.6 – 0.9) depending on system design and continuity of thermal energy needs. There is a question what energy form, electricity or heating energy, is a by-product of the process. Electric power engineering looks at heating energy as secondary energy which remains after turbine energy conversion – heating energy of water steam to mechanical energy, and after that to electricity (electric generator), which is in conventional power plants usually passed to water or air in condenser facilities. But the fact is that the operating point of a CHP utility is determined by heating consumption such that electricity accounts for only a percentage of the total energy generation.

CCHP is similar to CHP, but here cooling energy is also generated for space temperature conditioning, refrigeration processes in industry or for food/drink storage application. CCHP are often small-scale rated power applications in comparison with CHP power plants. Here, electricity is not used for cooling energy production (compressors) but it is forced by heating energy (adsorption process). During summer, all kinds of buildings need electricity, cooling energy (temperature conditioning of internal space) with energy amount dependent on outdoor temperature and small portions of heating energy (to prepare hot water applied in kitchens and baths). During winter, in most cases electricity needs are slightly larger than in summer, cooling energy needs to decrease (only for food/drink refrigerated applications) but heating energy needs to increase. So, the total amount of energy can be compared in different seasons, cooling and heating energies complement each other. CCHP systems can be reduced to a CHP system during the winter, when there is no cooling energy consumption. Or better said, a CHP system presents a CCHP system without any thermally-driven equipment for cooling energy production, although there are some differences between system structures, as in [1].

The distributed CCHP systems come in a wide range of rated power, from 1 kW to 500 MW. Rated power of the majority of centralized cogeneration power plants (CHP) is more than tens of MW. CCHP systems are usually distributed generating systems with rated power less than 1 MW. Rated power of decentralized CCHP systems (trigeneration) ranges between less than 1 kW in residential facilities and more than 10 MW in public buildings, industry, hotels, etc. A CCHP utility can be categorized as "a micro CHP" (S_n < 20 kW), "a mini CHP" (20 kW < S_n < 500 kW) and "a small CHP" (500 kW < S_n < 1000 kW), as in [2].

Potential energy produced by distributed generation (CCHP included) is significant in the world today. But there are still too many problems connected with outdated ideas of design engineers, misunderstandings of CCHP techniques by potential users, as well as constant regulation obstacles that very often refer to non-existent feeding tariffs.

2. BASIC CHP SYSTEM DESIGN CONFIGURATIONS

District heating power plants are conventional CHP systems with installed large-scale rated power. There are three CHP configurations: steam turbine design (Figure 1), gas turbine design (Figure 2) and combined cycle – both gas and steam turbine included design (Figure 3).

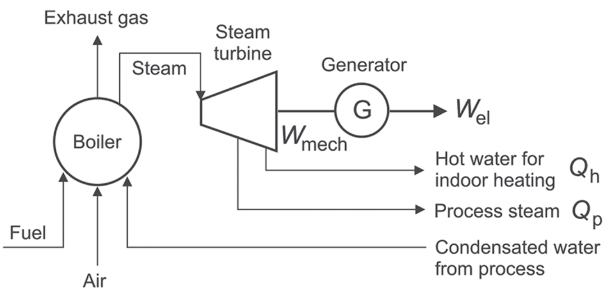

Fig. 1. Steam turbine CHP system design

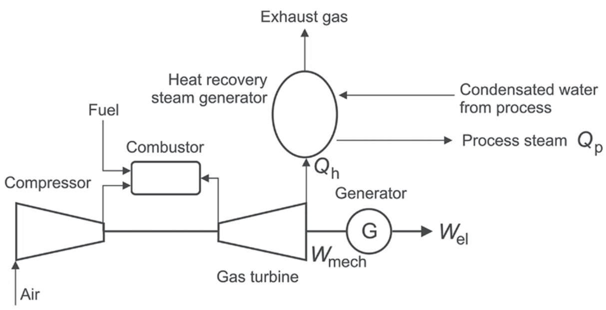

Fig. 2. Gas turbine CHP system design

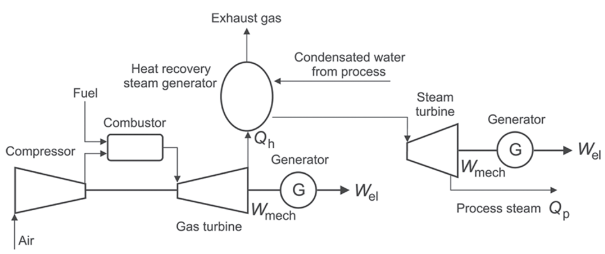

Fig. 3. Combined cycle CHP system design

A steam turbine CHP system consists of a steam boiler unit, a steam turbine and an electric generator as main parts, Figure 1. A steam boiler needs fuel and air input to produce high pressure steam which is fed to the steam turbine. By steam expansion in the steam turbine, part of thermal steam energy is transformed into mechanical energy. The rotor of the electric generator is connected to the same turbine shaft, so there mechanical energy is transformed into electric energy. Output steam from the turbine is used to satisfy the technological process or indoor heating system needs, as in [3] and [4]. If there is no heating consumption of full output steam capacity, a waste part of steam thermal energy comes to the condenser unit and gives its thermal energy to ambient air or water. There are improved steam turbine CHP systems with additional steam overheating between high pressured and low pressured turbine units and regenerative feed water heating. While energy efficiency of conventional power plants with the steam turbine is 0.35 – 0.44, energy efficiency of district heating power plants - CHP systems with the steam turbine is 0.7 – 0.8 - as described in [3] and [4].

A gas turbine CHP system consists of a compressor unit, a combustor unit, a gas turbine, a heat recovery steam generator and an electric generator, Figure 2. Compressed air and fuel are put to the combustor unit, from where high pressure and high temperature gases are fed to the gas turbine unit where thermal energy is transformed to mechanical energy. The rotor of the electric generator is connected to the same gas turbine shaft, so there mechanical energy is transformed into electric energy. Exhaust gases are put in the heat recovery steam generator unit where their thermal energy is transformed on hot water/steam to satisfy process steam or heating system needs. Energy efficiency of the gas turbine CHP system is less than in the steam turbine CHP system, and the cost of generated energy in the steam turbine is also cheaper than in the gas turbine (fuel nature and efficiency). But the fact is that most of the recent investments in conventional power generating units around the world are gas turbine CHP systems because of their advantages, i.e. lower costs of investments, a shorter construction period, a faster response to a required change of electric power load (peak power plants), lower costs of starting and stopping, and more environmentally friendly – gas turbine CHP systems emit smaller amounts of harmful gases.

A CCGT system (combined cycle gas turbine), has both a gas turbine unit and a steam turbine unit, Figure 3. It is the best design solution applied today in large-scale centralized district heating power plants using advantages of both steam and gas turbine CHP systems. A district heating power plant Osijek, Croatia, with the total installed 89 MW rated electric power, 139 MW rated thermal output power and 50 t/h steam production, may be mentioned as a good example, [5].

Last year (i.e. in 2010), a steam turbine unit of 45 MW was operating 4390,31 hours. The district heating power plant generated 97,517 MWh of electricity on the grid, 199,395 MWh of thermal energy and 73,085 t of process steam, [5] and [6]. It is very important to have thermal consumption uniformly distributed during the whole year (process steam) to reach the maximum energy efficiency possible (η = 0.88).

3. BASIC CCHP SYSTEM DESIGN CONFIGURATIONS

CCHP system design depends on energy user demands, available fuel for basic aggregate, connections to the power network, available space for system installing and limitations regarding local regulations.

The CCHP system has five basic components: the basic aggregate, an electric generator, a heat recuperation subsystem, a thermally-driven unit and a management/ control subsystem. Basic aggregates can be selected from steam turbines, combustion gas turbines, the internal combustion engine, microturbines, fuel cells and Stirling engines. The basic aggregate is chosen to satisfy different needs and adjustments to the local regulation limits, especially local heat and electric demand models, regionally allowed emission, as well as noise regulation and assembly constraints. An electric generator is selected according to a prime mover (fuel cells – a direct current system, and others - usually an alternating current system), according to the voltage level of electric installation inside the building and the voltage level of the connection to the power network, the required operating point of the generator (rated power, power factor, etc.). A heat recuperation subsystem improves energy efficiency of the process. A thermally-driven unit is selected from current technologies like absorption devices, adsorption devices and dehumidifiers, and it provides a cooling or dehumidification process.

CCHP systems have great potential in distributed energy generation, with small-scale rated power units. Although energy efficiency of CCHP is lower than in large-scale CHP systems, there are several important advantages of CCHP systems: a low emission rate, higher efficiency than in the classical approach (electricity produced in power plants and distributed to consumers, refrigeration units for air-condition devices fed by electric energy and a classic boiler for heating energy) and successful low-grade thermal energy recovery. Today, internal combustion engines, gas turbines and microturbines as basic aggregates, and electric refrigerators and absorption refrigerators as thermally-driven units dominate as design solutions for trigeneration systems.

System design of the CCHP system based on the internal combustion engine as a prime mover is presented in Figure 4, similarly to [7]. Here, cold water is used to limit the operating temperature of the engine (heat exchanger engine oil - water and engine jacket - water) and it takes thermal energy in the heat exchanger from exhaust gases to become hot water or steam, applied to internal space heating. It is more often to produce cooling energy by electric refrigerators, but there are also system design solutions with cooling energy generation by adsorption refrigerators driven by thermal energy fed by the internal combustion engine.

CCHP system design with microturbines is commercially developed at the beginning of the 21st century. Microturbines are ideal primary aggregates for decentralized CCHP systems with small-scale rated power, Figure 5, similarly to [8]. The main advantage of microturbines is in their modular connection system what enables peak power increment of the installed CCHP system or combines the exact number of modules to work simultaneously to meet actual energy needs.

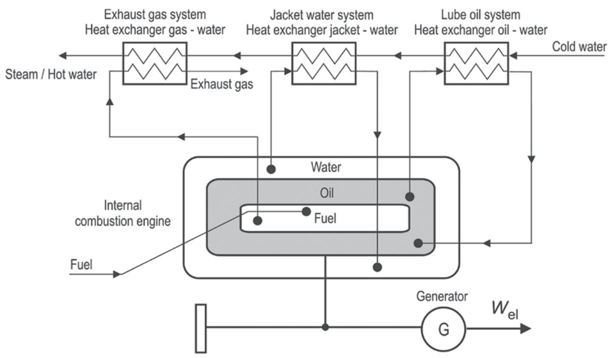

Fig. 4. CCHP system design with the internal combustion engine as a basic aggregate

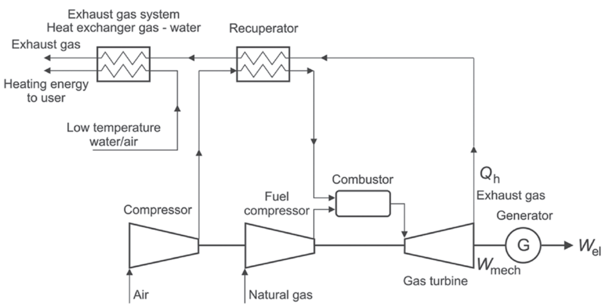

Fig. 5. CCHP system design with a microturbine as a basic aggregate

CCHP system design with the Stirling engine as a primary aggregate is considered to be applicable in small commercial and residential energy sources because of their low emission rate, a low noise level and a relatively low waste heat flow to ambient, Figure 6.

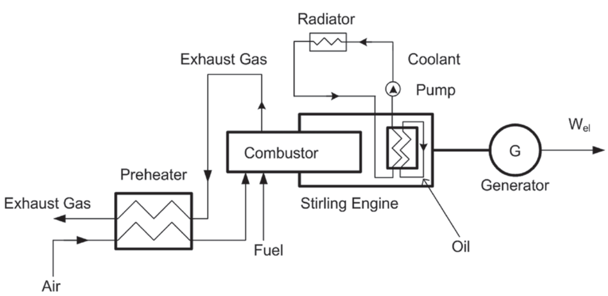

Fig. 6. CCHP system design with the Stirling engine as a basic aggregate

CCHP system design with a fuel cell as a primary aggregate is promising in the forthcoming period because of their potential in direct generation of electricity and thermal energy. Although there are several different numbers of fuel cell types, a lot of money is expected to be invested in development of a commercial fuel cell with required reliability.

4. DEVELOPMENT OF CHP AND CCHP TODAY

4.1. CHP AND CCHP IN THE UNITED STATES OF AMERICA

The Public Utility Regulatory Policy Act (PURPA) was declared in 1978 laying the foundations of CCHP application in the USA. According the Act, public utilities had to buy all electric energy generated at small-scale power producers (renewable energy, CHP and CCHP power plants). In the next 20 years there were 46 GW installed CCHP systems.

After that, the US government adopted several measures to re-stimulate the CCHP development. First, DOE (US Department of Energy) in collaboration with EPA (Environmental Protection Agency) and CHPA (Combined Heat & Power Association) launched the CHP Challenge in 1998. In the next 12 years there were 92 GW installed CCHP systems. Also, expected plans were made to apply the CCHP technology to new and existing building construction [9].

The National Energy Policy Development Group (NEPD) and the National Energy Policy (2001) contain guidelines for an increase of cleaner and more efficient technologies in CHP and CCHP projects by shortening the amortization periods or by insuring the investment taxes on loans, i.e. discount on investment tax. The CCHP market in the USA significantly grew in 2002, but after that it suddenly slowed down due to high natural gas prices and regulatory barriers, as described in [10].

4.2. CHP AND CCHP IN THE EUROPEAN UNION

The Cogeneration Directive, the Emissions Trading Directive, the New Electricity and Gas Directives, the Energy Performance of Buildings and the Taxation of Energy Products Directives are most important legislative documents connected with the energy market and CHP/CCHP systems in the European Union. EU energy policy set goals of installed CHP and CCHP systems and tried to promote cogeneration and trigeneration technology. Denmark, the Netherlands, Finland and Austria are the four leading countries in CHP/CCHP application in the EU, according to [11].

4.3. CHP AND CCHP IN THE REPUBLIC OF CROATIA

According to the Strategy of Energy Development in the Republic of Croatia, 100 MW micro and mini cogeneration CCHP systems and at least 300 MW cogeneration CHP systems are expected to be installed by the year 2020. The main intention is to reduce CO2 emissions and energy dependence, to have more energy efficient energy sources, to dynamically improve private investments in the energy sector, to increase security of energy supply and to reduce power losses in electric power transmission and distribution. One of the important targets is to employ domestic industry in development and manufacturing of cogeneration and trigeneration units, similarly to [12].

5. CONCLUSION

Cogeneration and trigeneration systems improve energy efficiency, reduce CO2 emissions, develop small-scale rated power applications and employ domestic manufacturers, designers and maintenance companies. It is special benefit when it is possible to combine CCHP with renewable energy sources, e.g. biogas or wood. As the standard of life is increasing and simultaneously climate changes are causing increment of average daily temperature, cooling energy generation potential of CHP and CCHP systems should not be neglected. These systems have to be installed wherever there are heating, cooling and electric needs. Generally, the problem existing in the Republic of Croatia is a lack of investments in the energy and industry sectors, decreased production capacities in the existing industry companies and undefined regulation and legislation without feeding tariffs refining in heating energy generation. The problem also exists as to insufficient knowledge in the field of technology and its advantages on energy independence, security of energy supply, delayed investments in the public energy sector and reduction of power losses in distribution and transmission of the electric power subsystem.

6. REFERENCES

[1] D.W. Wu, R.Z. Wang, "Combined Cooling, Heating and Power: A Review"; Progress in Energy and Combustion Science, Vol. 32, pp. 459-495, 2006.

[2] COGEN Europe, A guide to cogeneration, www.energymanagertraining.com/CHPMaterial/12-V, (August 2011).

[3] Energy and Environmental Analysis, Inc., Natural gas impacts of increased CHP, www.chpcentermw.org/bchp/pdfs/0310-chp_gas_report.pdf, (August 2011).

[4] M. Šunić, "Djelotvornost kogeneracijskih postrojenja, EGE – energetika – gospodarstvo – ekologija – etika", Energetika marketing, Zagreb, 129(12), pp. 28-31, 1995.

[5] Hrvatska elektroprivreda, HEP Proizvodnja, Termoelektrane, www.hep.hr/proizvodnja/osnovni/termoelektrane/osijek.aspx, (August 2011).

[6] Hrvatska energetska regulatorna agencija, www.hera.hr, (August 2011).

[7] The National Renewable Energy Laboratory, The Department of Energy, Office of Energy Efficiency and Renewable Energy and the Gas Research Institute, Gas-fired distributed energy resource technology characterization, www.nrel.gov/docs/fy04osti/34783.pdf, (August 2011).

[8] Resource Dynamics Corporation, Cooling heating and power for industry: a market assessment, www.nrel.gov/analysis/tech_infra_analysis.html, (August 2011).

[9] P. Lemar, E.J. Honton, Resource Dynamics Corporation, High natural gas prices and the updated market for CHP, http://www.distributed-generation.com/Library/WEEC_2004.pdf, (August 2011).

[10] R.L. Bamberger, M.E. Holt, Bush Energy Policy: Overview of Major Proposals and Legislative Action, www.nationalaglawcenter.org/assets/crs/RL31096.pdf, (August 2011).

[11] W. Jörß, T. Wehnert, P. Löfler, M.M. Nortes, M. Uyterlinde, E. Sambeek, B. Groenendal, H. Schwarzenbohler, M. Wagner, Decentralised Generation Technologies, Potentials, Success Factors and Impacts in the Liberalised EU Energy Markets, IZT, COGEN Europe, RISO, ECN, Jenbacher AG, www.izt.de/pdfs/decent/DECENT_Final_Report.pdf, (August 2011).

[12] D. Kreković, H. Petrić, "Kogeneracijski sustavi u Hrvatskoj - racionalno gospodarenje s energijom", Hrvatska stručna udruga za plin, Zagreb, Croatia, 2005.