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Original scientific paper

HVAC&R POLY-GENERATION SYSTEM WITH A GAS ENGINE AND CONVENTIONAL COOLING MACHINES/HEAT PUMPS

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A b s t r a c t: A new concept of poly-generation system for simultaneous production of electricity, heating, and cooling energy for HVAC&R of buildings is presented in this paper. The thermal characteristics of buildings and systems, the performance parameters of the gas engine–electricity generator and of the heating and cooling units (heat pumps/cooling machines) are analyzed. The original purpose of the gas engine–electricity generator is to supply the units for production of heating and cooling energy. Waste heat from the internal combustion engine is used primarily for production of hot water for the central heating system and/or production of sanitary hot water, and secondarily as a heat source in the conventional heat pump. A comparison of the energy (gas) consumption with conventional thermal system is made and high energy efficiency is of the proposed system is confirmed.

Key words: poly-generation thermal systems; energy efficiency; gas engine–electricity generator; heat pump; cooling; heating

ПОЛИГЕНЕРАТИВЕН СИСТЕМ ЗА КЛИМАТИЗАЦИЈА СО ПРИМАРЕН ГАСЕН МОТОР – ЕЛЕКТРОГЕНЕРАТОР, И КОНВЕНЦИОНАЛНИ ЛАДИЛНИ МАШИНИ/ТОПЛИНСКИ ПУМПИ

А п с т р а к т: Во трудот е презентиран нов концепт на полигенеративен систем за производство на електрична, топлинска и ладилна енергија за климатизација на објекти. Анализирани се термичките карактеристики на објектите и системите, работните карактеристики на примарниот мотор – електрогенератор на при роден гас и постројките за греење и ладење (топлински пумпи / ладилни машини). Примарната цел на моторот генератор е задоволување на потребите од електрична енергија на постројките за греење и ладење. Отпадната топлина од моторот со внатрешно согорување првостепено директно се користи за подготовка на циркулациона вода за системот за централно греење и/или за подготовка на санитарна топла вода и второстепено како топлински извор во конвенционална топлинска пумпа. Направена е споредба на потрошувачката на енергија (гас) во однос на класични термички системи, при што е утврдена висока енергетска ефикасност.

Клучни зборови: полигенеративни термички системи; енергетска ефикасност; полигенеративен систем; гасен мотор генератор; термикомпресија; топлинска пумпа; греење; ладење

INTRODUCTION

Development of new concepts of energy-efficient systems, based on dispersed energy production and consumption (electricity, thermal and cooling energy, industrial and technological steam, technological and sanitary hot water, etc.) using natural gas as a cleaner fossil fuel and one of the most reliable primary energy sources as a replacement for the traditionally used fossil fuels (oil, coal, etc.), is a continuous challenge. Optimal application of poly-generation systems for heating, ventilation, air conditioning and refrigeration (HVAC&R) depends on the thermal characteristics of the buildings as well as their energy needs: electricity, energy for heating, cooling and air conditioning, sanitary hot water production [1, 9, 12].

A significant component in the new concept of sustainable development in the energy sector are thermocompression systems and their optimal implementation in thermal technologies with high energy efficiency, as well as thermocompression poly-generation systems for the simultaneous production of electricity, heat energy and cooling energy [5, 6, 8, 9, 16].

The optimal application of heat pumps should be realized in areas of relatively low condensation temperatures, that is, in low-temperature heating systems. The major purpose of the gas engine–electricity generator is to provide electricity to supply the compressors of the heat pump/cooling machine. By using the waste heat energy from the exhaust gas and jacket cooling of the gas engine, relatively high evaporation temperatures are provided, which enables a lower temperature lift and achievement of high values of the thermotransformation coefficient for heating (COPh = 5 – 9). Compared to a classic heat generator – gas boiler, given the high COPh values, the fuel consumption is several times lower [2, 7].

The optimal design of the cooling system comes down to a combined plant with thermal storage. Significant advantages such as reduced installed capacity of the plant, operation in a cheap tariff and at lower temperature regimes (at night) etc., are achieved with the thermal storage. This especially applies to large capacity plants [11].

THERMAL CHARACTERISTICS OF THE BUILDINGS AND THE SYSTEM COMPONENTS

Modern, newly constructed buildings are characterized with high energy efficiency as a consequence of the development in the field of construction engineering and materials. Therefore, the criteria for minimum heat losses/gains are elevated. The energy efficiency of the buildings highly depends on the concept and performance of the heating, cooling, ventilation, air conditioning and refrigeration (HVAC&R) systems. The use of alternative energy sources and heat pumps as dual-purpose units for year-round energy production (thermal energy in winter and cooling energy in summer) represents a permanent challenge [8, 10, 17]. Using the energy from the products of combustion from the gas engine-electricity generator as a heat source of the heat pump is very significant, because it provides a high degree of energy efficiency [3, 4, 5].

In conditions of pronounced strategies for the construction of buildings with high energy efficiency, the requirements, and criteria for high internal comfort (temperature, relative humidity, temperature uniformity, air purity, amount of fresh air, air speed, noise, etc.) are also increasing.

The thermal energy needs for heating and cooling are fundamental for the optimal design of the combined thermocompression poly-generation system and the choice of the gas engine–electricity generator. The electricity produced in the gas engine-electricity generator will be used to supply the heat pump units, to meet the energy demands of the residential building, and possible surpluses will be delivered to the electric distribution network [13, 14, 15].

The concept of complex poly-generation systems for heating with heat pumps is based on covering the basic heat load with a heat pump (as a generator of cheap heat energy), and the peak heat load with a cheap heat generator (shown in the heating diagram in Figure 1). With installed power of the base heat generator (the heat pump) in the amount of 60% of the design heat load, 90% of the required heat energy is covered. The peak energy will be covered by a cheap heat generator (40% of the installed power, design heat load), producing only 10% relatively expensive heating energy. The choice of heat pump power as part of the poly-generation system is a subject of complex techno-economic optimization, which also includes other components of the system.

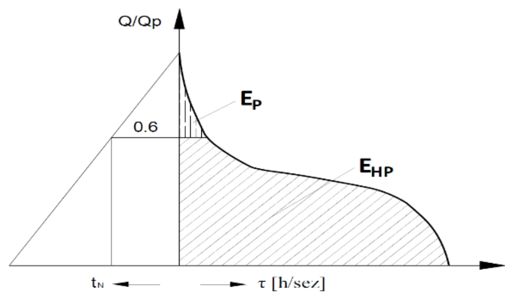


Fig. 1. Diagram for heating energy calculation

Design cooling load (summer mode) refers to a certain period of the day with high outside temperature, high intensity of solar radiation and other sources of heat gains. The installed power of the cooling unit should be significantly lower (20–50% of the design heat gains), which leads to a series of advantages: significantly lower investment, lower administrative costs for fees for hired electric power, lower operating costs for hired electric power, relief of the electric power system, etc. The complete coverage of heat gains is realized by introducing a cooling storage system. This leads to additional benefits: continuous operation of the refrigerating unit during the day (24 hours), operation of the refrigerating unit during the night period at lower outside temperatures, which results in a higher cooling factor (COP_c), operation of the refrigerating unit at night – during on a cheap electricity tariff, etc. This especially applies to plants with a large capacity, where the consumption of electricity is high.

Scheme of a single-stage compressor plant, as well as the thermal *T-s* (temperature – enthalpy) and *p-h* (pressure – enthalpy) diagrams are presented in Figure 2.

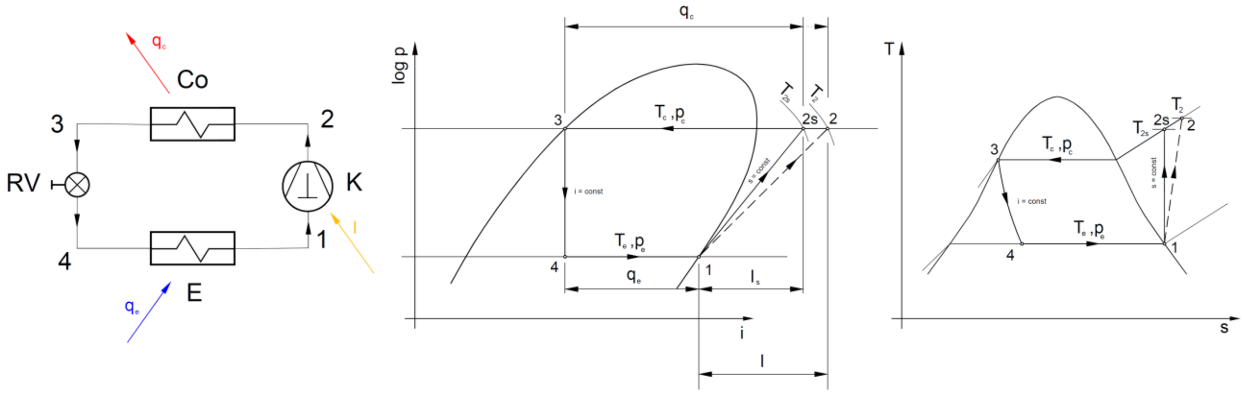
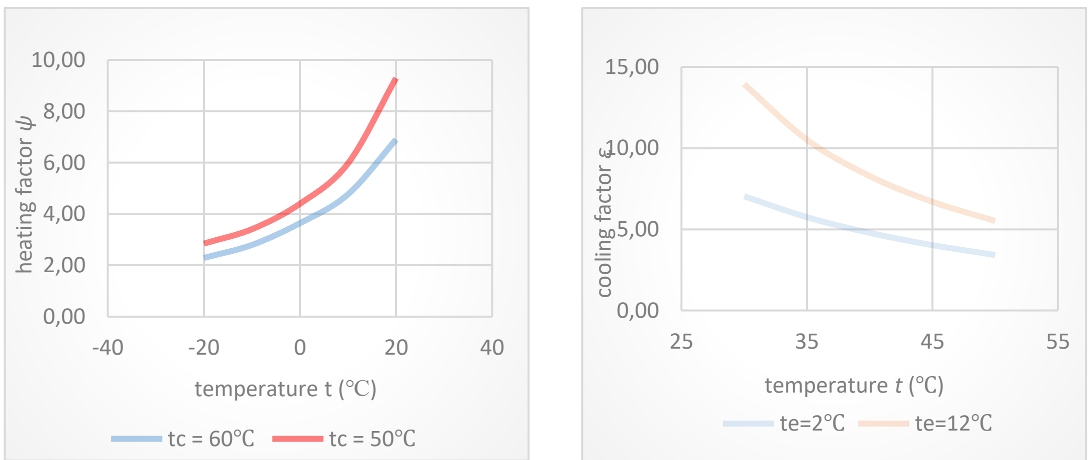


Fig. 2. Single-stage compressor plant scheme with thermal *T*-s, and *p-h* diagrams

A basic indicator of the efficiency of thermotransformation in the heat pump/cooling machine is the coefficient of thermotransformation – the heating factor ψ or $COP_h = qc/l$, which represents the ratio between the received thermal energy and the consumed electrical energy to supply the compressor, i.e., the cooling factor ε or $COP_c = q_e/l$ which represents the ratio between the obtained cooling energy and the consumed electrical energy in the compressor.

Calculated values of the thermal transformation coefficient COP for different operating conditions, i.e., temperatures of condensation t_c and evaporation t_e, in different operating modes of the unit, with R134a as a refrigerant are given in in Figure 3. The efficiency factor of the compressor is $\eta = 0.8$.

For realization of the thermal cycle, the heat pumps/cooling machines use electricity to supply the electric motor of the compressor. In the proposed poly-generation systems, the use of a gas engine – electricity generator for the production of electricity is proposed.



Heat pump Cooling machine

Fig. 3. COP of heat pump/cooling machine for different operating conditions

Intensive research and development of internal combustion engines has led to improvement of their construction and achievement of high performance and high efficiency coefficients. The thermal efficiency coefficient of internal combustion engines reaches values G_{up} to 45% (relative to the lower heating value of the fuel). Production of large series of parts for internal combustion engines contributes to reduction of their price, which is an advantage compared to turbo-expander units. The extensive range of design powers for different versions of internal combustion engines (from tens of kW to several hundreds of kW) contributes to their optimal application in the proposed concept of combined compressor poly-generation systems for the simultaneous production of electricity and energy for heating and cooling.

Scheme of a gas engine–electricity generator unit with energy balance is given in Figure 4.

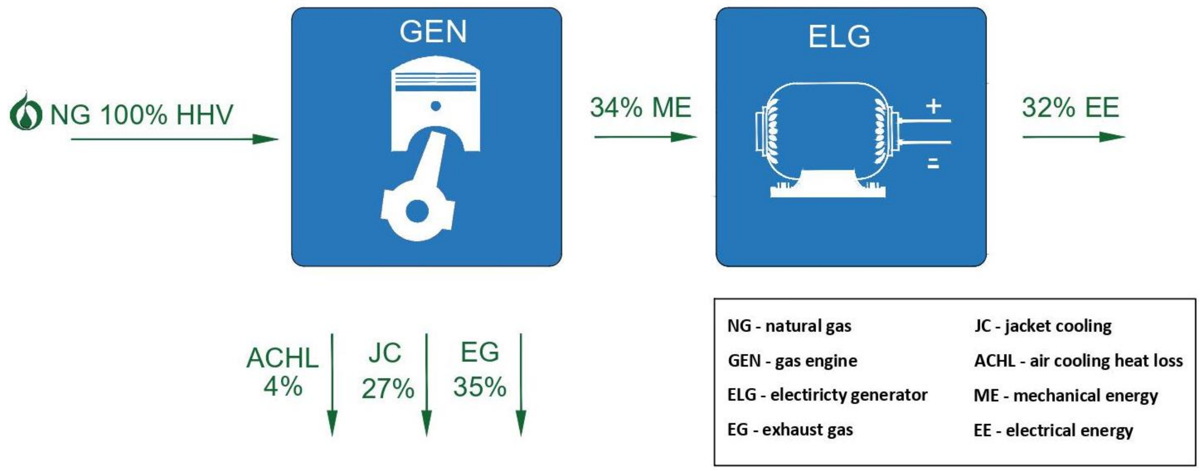


Fig. 4. Energy balance of gas engine–electricity generator unit

Natural gas is used as a fuel in the internal combustion engine. The Russian natural gas is a clean fossil fuel, without impurities and mainly consists of methane (CH_4). The lower heating value of natural gas is typically in the range of LHV = 33.5 – 35.0 MJm_n^{-3} and the higher heating HHV = 37.2 – 8.8 MJm_n^{-3}.

In the poly-generation systems for production of electricity, thermal energy for heating and energy for cooling, internal combustion gas engines are used to obtain mechanical work, from which electricity is obtained in the electric generator. The waste heat from the internal combustion engine is primarily used directly for preparation of circulating water for the central heating system or for preparation of sanitary hot water and secondarily as a heat source in a conventional heat pump.

The produced electricity is used to drive the compressors of the conventional compressor refrigeration machines/heat pumps for central preparation of circulating water for cooling/heating of buildings. When designing this system, the priority is the heating mode when the system works as a heat pump.

In cooling mode, circulating water (7/12°C) is prepared in the evaporators of the cooling machines/heat pumps. Flowing water (ground water, river water, lake water) is used in the condensers. The condensing temperature depends on the condenser water temperature.

In heating mode, the circulating water (60/50°C, low-temperature heating) is prepared in the condensers of the cooling machines/heat pumps. Waste heat from the gas engine-electricity generator is used as a heat source in the first heat pump, and flowing water (ground water, river water, lake water) is used in the second heat pump/cooling machine. The evaporation temperature depends on the temperature of the water used as a heat source.

ANALYSIS OF THE THERMAL CHARACTERISTICS OF THE POLY-GENERATION SYSTEM

Basic thermal calculations, material and heat balances are performed for the complete system and for the subsystems: gas engine – electricity generator; compressor heat pump for utilizing the heat of the exhaust gases and compressor heat pump/

cooling machine when the heat source is water (underground water, river water, lake water). Cascading connection of the heat pumps would enable a lower temperature lift of the heat pumps and the achievement of higher COPs.

Poly-generation system for the production of electricity, thermal energy for heating, energy for cooling and preparation of sanitary hot water, with a gas engine–electricity generator and conventional compressor cooling machines/heat pumps, with the basic material and energy balances and temperature conditions is presented in Figure 5.

In the gas engine (GEN) 34% of the input energy of natural gas (NG) (100% HHV – higher heating value of natural gas) is transformed into mechanical energy (power). According to the analysis of the performance of gas engines and the data of the manufacturers of gas engine units the efficiency coefficient is in the range of 32 to 35 % (of HHV). The efficiency coefficient of the electric generator is estimated to be 95%. In the electric generator (ELG) 32% of the input energy of the natural gas is transformed into electricity (power).

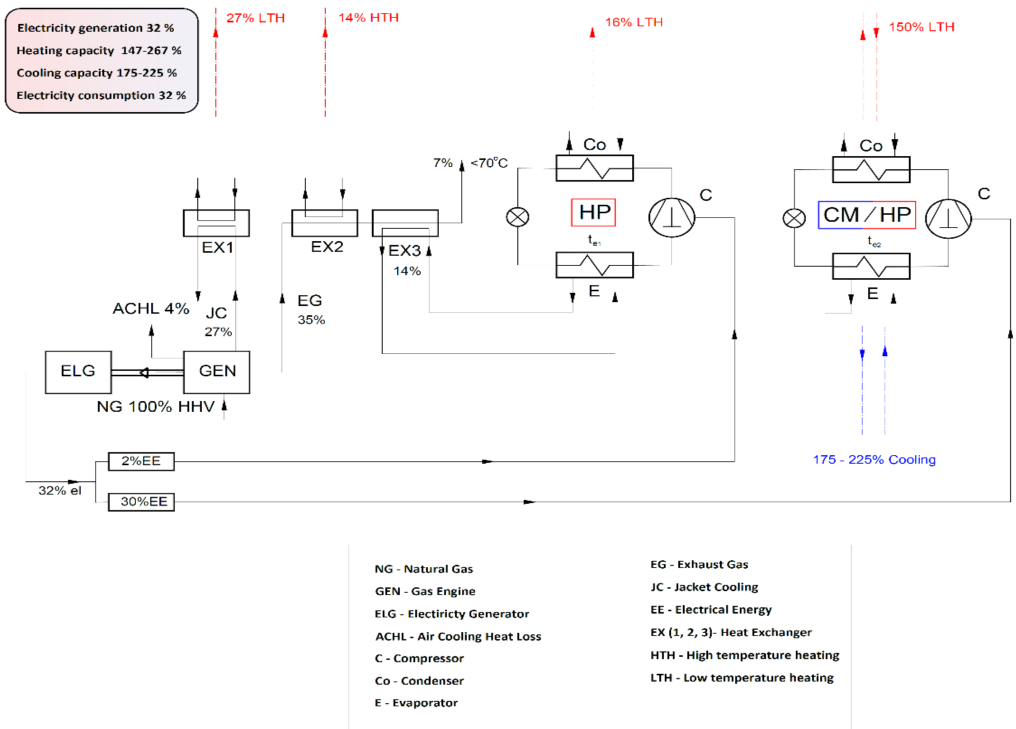


Fig. 5. Poly-generation system for production of electricity and conventional heat pumps [9]

Waste heat from engine jacket cooling (JC) is estimated to be 27% of HHV, and engine exhaust gas waste heat (EG) 35%. About 4% are heat losses in the environment and heat losses in the turbocharger-intercooler (ACHL). In the heat exchanger EX1, the waste heat from jacket cooling (27% of HHV) is used for heating the circulating water from the heating system and for preparation of domestic hot water. In the heat exchanger EX2, the waste heat from the exhaust gases (14% of HHV) is directly used to heat the circulating water from the heating system. Additional use of the waste heat from the exhaust gases (14% of HHV) is carried out in the heat exchanger EX3, where the exhaust gases serve as a heat source for the heat pump.

Calculations of the poly-generation system for the temperature conditions (given in the Figure) have been carried out, with R134a as a suitable refrigerant for compressor refrigeration systems for air conditioning applications, using a traditional calculation procedure for mechanical compressor refrigeration/heat pump cycles, as well as traditional thermal procedures for material and energy balances for the heat exchangers and for the elements of the poly-generation system. The calculations were performed for an energy efficiency coefficient of the compressor $\eta = 0.8$.

The produced electricity (32% of HHV) is used to supply the compressors of the cascade connected water-water heat pumps. The electric power consumption of the compressors is 2% of HHV in the first, and 30% of HHV in the second heat pump. With two cascade connected heat pumps (with evaporation temperatures t_{e1} = 30°C and t_{e2}=10°C, condensation temperature t_{c1} = t_{c2} = 65°C), in winter mode (heating), the heat factor is: COP_{h1} = 8 and COP_{h2} = 6, and the thermal power for heating 237% of HHV.

In summer mode (cooling), at a condensation temperature of t_c = 30°C and an evaporation temperature t_e = 5°C, the cooling factor is COP_c = 6.5, and the cooling power is 221% of HHV.

For comparison, in conventional heating system (without the possibility of cooling in the summer period), with a conventional natural gas boiler, the heat power produced for heating is 81% of HHV (at the boiler's efficiency coefficient η_b = 0.9). This means that the fuel consumption of the proposed system is 2.9 times lower. The proposed system is at a modern, high technical-technological level. Investment costs are higher. However, high energy efficiency and several times lower fuel consumption result in significant technical, economic, and environmental benefits.

CONCLUSIONS

The thermal characteristics of a poly-generation system with a gas engine – electricity generator of natural gas and conventional – compressor heat pumps have been analyzed in this paper. Generated electricity in the gas engine – electricity generator is used to supply the compressors of the heat pumps/ cooling machines where energy for heating, cooling, air conditioning and refrigeration (HVAC/R) of buildings is produced. The analysis indicates high degree of energy efficiency. At coefficient of performance COP_{h1} = 8 and COP_{h2} = 6, the heat output for heating is 237% of HHV. In summer mode (cooling), at a condensation temperature of t_{c1} = t_{c2} = 30°C and evaporation temperatures t_{e1} = t_{e2} = 5°C, the cooling factor is COP_c = 6.5, and the cooling power is 221% of HHV. It can be stated that the consumption of fuel (natural gas) is significantly lower compared to classic heating and cooling systems.

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