ENERGETSKI EFIKASNE ZGRADE I KOMBINOVANI TERMIČKI SISTEMI ZA PROIZVODNJU ELEKTRIČNE ENERGIJE, GREJANJE, HLAĐENJE I KLIMATIZACIJU

ENERGY EFFICIENT BUILDINGS AND COMBINED THERMAL SYSTEMS FOR ELECTRICITY PRODUCTION, HEATING, REFRIGERATION AND AIR CONDITIONING

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Analizirani su toplotne karakteristike energetski efikasnih zgrada i procenjene su energetske potrebe. Izložen je koncept kombinovanog kompresorsko – ejektorskog termičkog sistema za istovremenu proizvodnju električne energije, grejanja, hlađenja i klimatizacije. Procenjuju se radne karakteristike primarnog motora - električnog generatora na prirodni gas i predložena je optimalna kombinovana kompresorsko – ejektorska rashladna mašina / toplotna pumpa da bi se zadovoljile energetske potrebe za strujom, grejanjem, hlađenjem i klimatizacijom. Izvršene su osnovne termičke proračune, materijalne i energetske bilanse kompletnog termičkog sistema i date su optimizacione procedure za komponente termičkog sistema. Izvršeno je poređenje predloženih termičkih sistema i poređenje potrošnje energije (prirodnog gasa) sa konvencionalnim termičkim sistemima i potrošnje energije za struju, za grejanje (prirodni gas - kotao), za hlađenje (električna energija - kompresorski rashladni sistem) i za klimatizaciju.

Ključne reči: *termički sistemi; simultana proizvodnja; gasni motor; kombinovane kompresorsko – ejektorske jedinice; električna energija; toplota; hlađenje*

Thermal characteristics of energy efficient buildings are analyzed and energy demands are estimated. A concept of combined compressor – ejector thermal system for simultaneous production of electricity, heating, refrigeration and air conditioning is exposed. The performance characteristics of the natural gas prime motor – electric generator are assessed and optimum construction of the combined compressor – ejector refrigeration / heat pump unit is proposed to satisfy the energy demands for electricity, heating, cooling and air conditioning. Basic thermal calculations, material and energy balances of the complete thermal system are carried out and optimizing procedures for the thermal system components are given. A comparison of the proposed thermal systems and energy (natural gas) consumption with the conventional thermal systems and energy consumption for electricity, heating (natural gas - boiler), cooling (electricity – compressor refrigeration system) and air conditioning is made.

Key words: *thermal systems, simultaneous production, natural gas prime motor, combined compressor – ejector unit, electricity, heat, refrigeration;*

1 Introduction

The subject of this paper is analysis of the thermal characteristics and estimation of the energy demands of energy efficient buildings and optimization of combined compressor – ejector thermal systems for simultaneous production of electricity, heating, refrigeration and air conditioning.

Traditional concept of global energetics is based on large electrical power plants (thermal power plants, hydro power plants, nuclear power plants), large district heating systems, central industrial steam boiler facilities, central systems for heating, ventilation and air conditioning (HVAC systems) in residential, administrative, sport, cultural and educational objects, malls, etc. Rapid growth of the world population and the needs for better quality of life, result in significant increase of the energy demands and instant technological and industrial development of the energetic sector. These events entering every aspect of society, cause irreversible global and local environmental impact and climate changes that have negative effect on humanity and a serious threat for the existence of our planet.

Fundamentals for thermal calculations and thermal characteristics of buildings and systems for heating, refrigeration and air conditioning are given in [1]. Summary of research and development activities of cogeneration systems and tri-generation systems (CCHP – combined cooling heating and power systems) is given in [2,3]. Tri – generation technologies based on absorption cooling systems have rather wide application and extensive research activities. Tri - generation technologies that include other technologies, involving ejector cooling systems and Rankine systems, also have extensive research activities [4,5]. Different types of prime movers are used in three-generation systems to obtain

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mechanical work from which electricity is generated in the electric generator. Tri - generation systems with internal combustion engines are suitable in low-capacity applications. These systems are characterized with high energy efficiency. Turbo compressor–turbo expander micro tri–generation systems are an attractive modern research topic.

Characteristics of combined thermal systems for simultaneous production of electricity, heat and refrigeration with natural gas engine – electric generator and compressor and/or ejector refrigeration / heat pump and thermal vapor compression are presented in [6]. Waste heat from the internal combustion engine is utilized motive heat in the compressor – ejector cooling machine / heat pump system for production of heat energy for heating and refrigeration. Fundamental theory of thermal transformation is applied in the analysis of the compressor – ejector cooling machine / heat pump systems.

Thermo-transforming technologies are presented in [7,8] where technical and economic potentials of these systems are analyzed and different industrial processes are discussed with their working temperatures, as a potential low temperature heat sources.

Implementation of the concept of dispersed production of electrical energy with the implementation of the proposed poly – generation systems [9] together with the dispersed production of electrical energy with photovoltaic solar collectors, represents a fundamental structure for sustainable development of the energetic sector, and a key component in the overcoming of global ecological problems related to global warming and ozone layer depletion.

The main purpose of this paper is designing a procedure for determination of optimal capacity of compressor – ejector poly-generation systems for simultaneous production of electricity, heating, refrigeration and air conditioning of residential buildings, administrative buildings, educational buildings, theatres, malls, etc. Optimal implementation of the proposed poly - generation systems results in significant technical, economic and environmental effects.

2 Analysis of the thermal characteristics of buildings

Optimized application and conception of the combined compressor – ejector poly-generation systems depend on the thermal characteristics of buildings and their energy demands for electrical energy, heating energy, energy for refrigeration and air conditioning and energy for production of sanitary (domestic) hot water.

Architectural and thermal properties of buildings (residential and private buildings, administrative, cultural and educational buildings, cinemas, malls, etc.) along with the outside weather conditions and the desired inside conditions define the heat loss (winter months) or heat gains (summer months) working conditions. Latest tendencies for construction of energy efficient buildings, and latest technologies in the construction materials industry, have led to application of criteria for minimal heat loss / heat gains of buildings and construction of buildings with appropriate thermal insulation and completely energy efficient cover.

Energy efficiency of buildings strongly depends on the conception and the performance of the HVAC system:

- the performance of the pipeline network,
- the balancing of the pipeline network and the regulation of the system,
- the performance of the heat recovery system,
- the concept of performance of the system and the energy source for heating / cooling,
- system operation, maintenance and management, etc.

The use of solar energy systems, low temperature waste heat, geothermal energy systems, heat pump systems, etc., as an alternative to the usual concepts of energy systems with fossil fuel boiler and refrigeration unit, is an important component for the construction of energy efficient buildings.

Basic standardized procedures are used to calculate the nominal heat losses / gains of the building [1]. Thermal energy for heating during the heating season, defined by the heating energy diagram (Fig. 1), depends on the weather conditions. For conditions of humid continental climate (Republic of Macedonia) the heating diagram is characterized by a sharp peak, i.e. a short period of time with extremely low outside temperatures (close to the design temperatures).

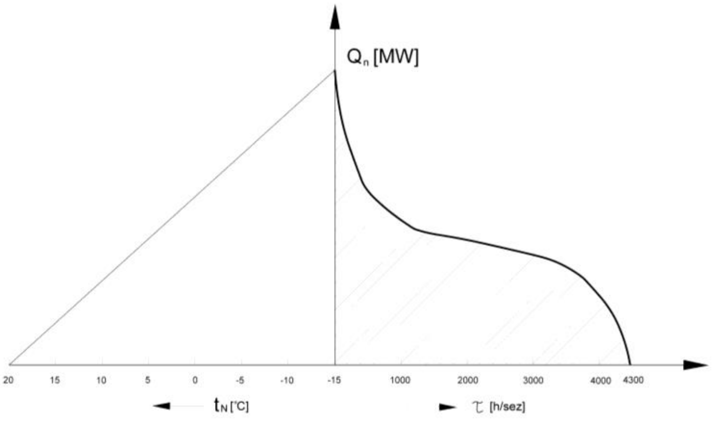

Figure 1 Diagram for heating energy calculation

It is very important when designing complex combined heating systems with heat pumps or designing combined poly-generation systems to cover the base heat energy with the system, which would result in less installed power or lower investment.

The heat capacity of the system (Q_h) is determined using the values for the nominal heat capacity (Q_n) calculated for nominal (design) outside temperature (t_n), and the conditions of heating defined by the medium outside temperature (t_{mout}) and the inside temperature (t_{in})

$$Q_h = Q_n \cdot \frac{t_{in} - t_{mout}}{t_{in} - t_n}$$

The reliance of the heat capacity of the system (Q_h) from the medium outside temperature (t_{mout}) given in %, adopting nominal heat capacity 100 % for design temperature t_n = -15 °C is given in Fig. 2.

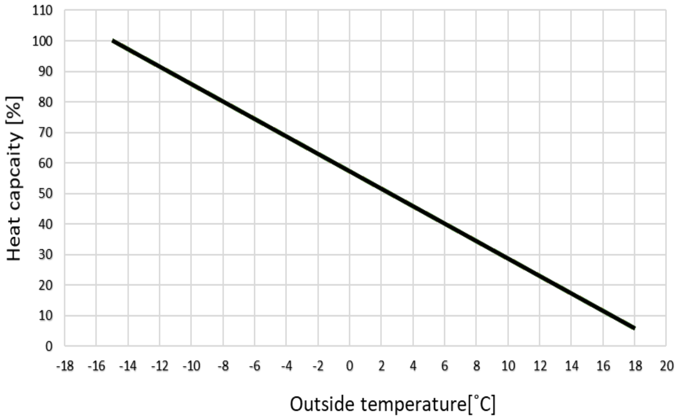

Figure 2 Heat capacity for different outside temperatures

For example, system with 60 % of the nominal power will be able cover 92% of the required heating energy. The peak energy for minimal outside temperatures will be covered by a top heat generator (40% of the installed power) producing 8% of expensive thermal energy for heating. The optimal choice of power of the poly-generation system is subject to complex techno-economic optimization, which includes other components of the poly-generation system.

Nominal heat gains (summer mode) refer to a certain period of the day with high outdoor temperature, high intensity of solar radiation and other sources of heat gains. The installed capacity of the refrigeration unit should be significantly lower (20 - 25% of the nominal heat gains) which leads to a number of benefits: significantly lower investment, lower administrative costs for fees for engaged electricity, lower operating costs for engaged electricity, load reduction of the power system etc.

Full coverage of heat gains is realized by introducing a cooling storage system. This leads to additional benefits: continuous operation of the refrigeration unit during the day (24 hours), operation of the refrigeration unit at night at lower outdoor temperatures, operation of the refrigeration unit with higher cooling factor (COP), operation of the refrigeration unit during the period of low price electricity, etc.

In a period of strongly developed strategies for construction of energy efficient buildings, modern requirements and criteria for better quality of life are increasing. In this context, the requirements and criteria for the parameters of internal comfort that should be provided by the HVAC system (temperature, relative humidity, heat balance, air purity, amount of fresh air, air velocity, air temperature and distribution, noise, etc.) are increasing. Additionally, the needs and requirements for the quality and quantity of sanitary hot water are also increasing. Depending on the daily dynamics for the needs of sanitary hot water, appropriate thermal storage is predicted, i.e. an appropriate fluid tank. With the implementation of the concept of construction of energy efficient buildings, the thermal energy for the preparation of sanitary hot water becomes an increasingly important component in the total needs for heating energy of the buildings.

Obtained information for heating, cooling and sanitary hot water production capacities are implemented in the concept of the combined compressor-ejector system. Calculated demands for thermal energy for heating and cooling are utilized as basic information for optimal techno-economic conception of the combined compressor-ejector system.

Electrical power produced in the prime mover - electric generator unit will be used to satisfy the needs for electricity of the residential building. Problems with sufficient amounts of produced electrical energy and deficiency of electrical energy will be solved by interconnection of the combined thermal poly-generation system with the electrical distribution system.

3 Combined thermal poly – generation systems for electricity production, heating, refrigeration and air conditioning

Conventionally, the cogeneration systems for electrical power production and heating contain a gas engine, or a diesel engine or a turbo expander – turbo compressor engine and an electrical generator. The waste heat is utilized for heating hot water production. Usually, in tri-generation systems, the waste heat is utilized for chilling water production using an absorption refrigeration system. Turbo compressor - turbo expander micro–tri-generation systems recently are an attractive topic of investigations.

The subject of investigation in this paper are the poly-generation systems with natural gas engines (prime movers; internal combustion motors) and electrical generator, for electrical energy generation, and turbo compressor and/or ejector heat pumps / cooling machines for heating, refrigeration and air conditioning application.

Original schematic diagrams of different thermal systems along with temperature conditions of the working fluids are given in Figures 3 and 4, using recent development achievements in the field of high temperature heat pumps and thermal transforming technologies [11,12,13], as well as in the field of high speed high pressure ratio transonic centrifugal compressors [10,14,15,16,17] and in the field of supersonic ejectors [10]. Basic thermal calculations, material and heat (energy) balances have been realized and results are given in the schematic diagrams: Gas engine – electrical generator: natural gas consumption; air quantity for combustion process; content and quantity of combustion (exhausted) gas; material and heat (energy) balances; mechanical power generation; electrical power generation; jacket cooling (waste) heat generation; exhausted gas (waste) heat generation and multi stage heat exchanger exhausted gas utilization for generating motive vapor in the combined compressor - ejector; exhausted gas cooling and utilization of HHV (higher heating value) of natural gas; electrical generator 95 – 97 %.

Current development in the field of internal combustion engines result in achievement of high efficiency (up to 50% mechanical efficiency of LHV – lower heating value of natural gas). However, in this paper the mechanical efficiency of the gas engine is taken 32 – 35 % of HHV, considering ecological and other influencing and optimizing reasons.

3.1 Poly – generation with combined compressor-ejector refrigeration / heat pump system

A combined poly-generation system for production of electricity, chilling water, heating hot water and sanitary hot water, which consists a natural gas engine (G EN), an electric generator (EL G) and a combined compressor – ejector refrigeration / heat pump system for utilization of the waste heat from the gas engine is given in Fig. 3. The main estimated thermal parameters and power balances (in %) are also given in the Fig. 3, according to the higher heating value (HHV) of natural gas (NG) input (taken as 100%).

In the gas engine (G EN) 34% of input natural gas (NG) energy (100% HHV – higher heating value) is transformed to mechanical energy (power). According to analysis of performance characteristics of natural gas engines and data of producers of gas engine aggregates the efficiency of natural gas engines is in the range 32 – 35%. The efficiency of the electric generator is estimated to be 95%. In the electric generator (EL G) 32% of input natural gas energy is transformed to electrical energy (power).

The waste heat of the gas engine jacket cooling (JC) is estimated to be 27% and the waste heat of the gas engine exhaust gas (EG) is 35%. About 4% are turbocharger intercooler heat losses (ACHL). The waste heat of the gas engine is utilized as a motive power for the ejector stage of the combined compressor – ejector refrigeration system.

With heat exchangers (EX1 – 14% and EX2 – 14%) the waste heat of the exhaust gas is transferred to the circulating water and then to the refrigerant in the generator section G1 and G4. The exhaust gas is cooled below 70°C to provide condition for condensation of the water vapor contained and to use natural gas higher heating value.

The waste heat of the gas engine jacket cooling (JC) is used in the generator section G2 and G3. Four-section generator is structured to utilize larger part of the waste heat. The exhaust gas exit heat loss (EGE) is 7%. The evaporation of the refrigerant in the generator is at 85°C and 110°C.

A combined compressor – ejector refrigeration / heat pump system is applied for utilization of the waste heat from the gas engine. Two-stage compression is introduced in the combined refrigeration cycle: first mechanical compression (C) and second vapor ejector compression (EJv1 and EJv2). An economizer (EC) is installed between the stages. Two throttling valves are proposed: first one between the condenser (Co) and the economizer (EC) and second one between the economizer (EC) and the evaporator (E), which is suitable for COP increase.

Estimations have been conducted with R245fa as a suitable refrigerant for these operating conditions using calculating procedure for the ejector flow field optimization and performance characteristics (Chapter 3, [10]), and traditional calculating procedures for real mechanical compressor cycles.

The evaporating temperature is 5°C. The evaporator (E) is with 45% refrigeration effect. The compressor (C) power consumption is 3% (9.4% of electrical power production) in cooling mode or 6.5% (20.3% of electrical power production) in heat pump mode. With the ejector (EJ1 and EJ2) second stage compression the heat is transformed up to condensing pressure, corresponded to condensing temperature 35°C in cooling mode (103%) or to 50°C in heating mode (106%). The COPs of the combined compressor–ejector refrigeration / heat pump system are:

- refrigeration mode (CM), COP_{th} = Qe / Qg=0.82; COP_{mech}=Qe / P_{mech} =15;
- heat pump mode (HM), $COP_{th\ hp}$=Qc /Qg =1.93; COPmech hp =Qc /P mech = 16.3

Using the concept of multi-section generators (four in Fig. 3) and multi-segment ejector units (two in Fig. 3) working in different generating and condensing temperatures, the heat transfer irreversibility and temperature degradation of the heat of exhaust gas in the generating subsystem and in the condensing subsystem can be decreased, the generating temperature in some segments can be increased and condensing temperature in some segments can be decreased, which leads to increment of the COPs of poly-generation combined compressor – ejector systems.

According to an analysis of numerous published studies and results obtained using calculating procedure it can be exposed that with appropriate choice of refrigerant, with optimally structured system (using multi-section generator and multi-segment ejector unit concept) and with optimal design of the ejector flow field elements the ejector thermo-compression systems can be successfully applied in various poly-generation systems and in combined (hybrid) thermal systems for utilization of low temperature heat, geothermal energy, solar energy and waste heat.

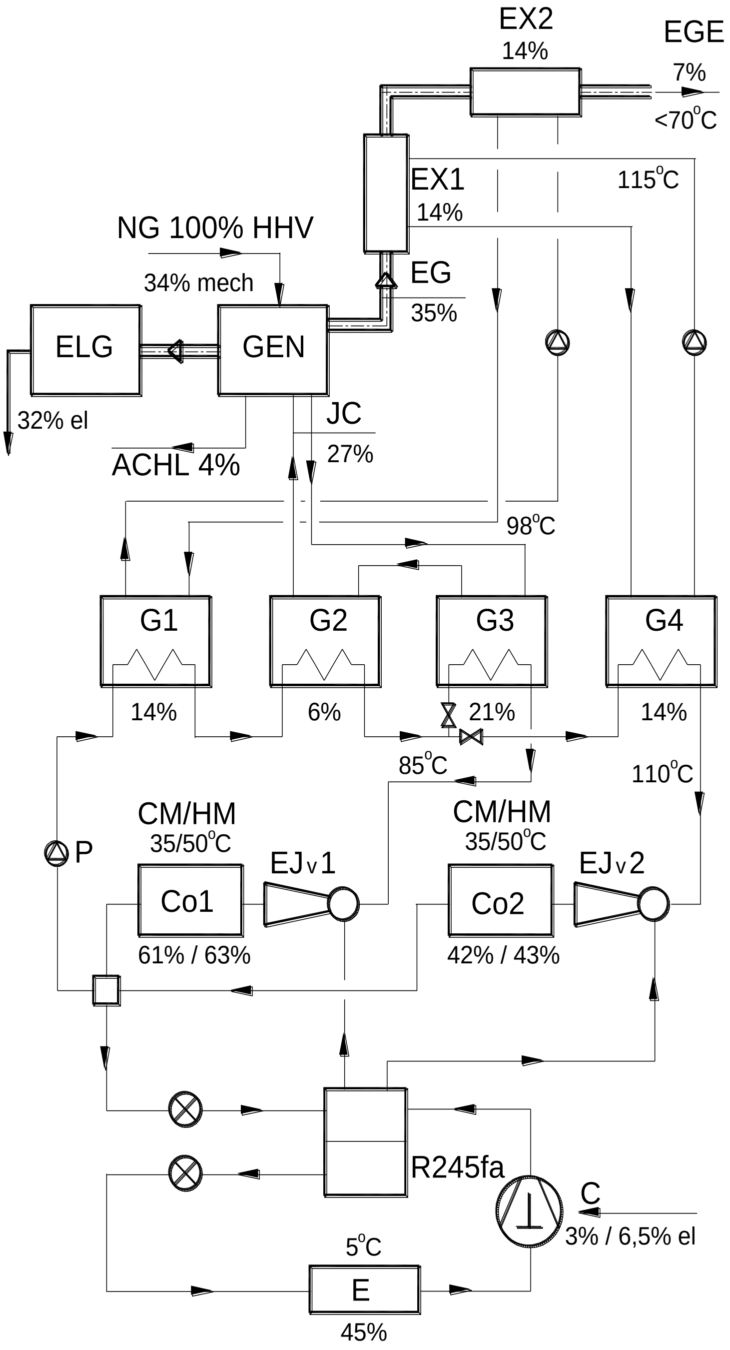

Figure 3 Poly-generation system with combined compressor-ejector refrigeration / heat pump system

3.2 Poly–generation with compressor refrigeration / heat pump system

A combined poly-generation system for application in HVAC&R systems for production of electricity, chilling water, heating hot water and sanitary hot water, which consists a natural gas engine (G EN), an electric generator (EL G) and a compressor refrigeration / heat pump system for utilization of the waste heat from the gas engine is given in Fig. 4. The main estimated thermal parameters and power balances (in %) are also given in the Fig. 4., according to the higher heating value (HHV) of natural gas (NG) input (taken as 100%).

In the gas engine (G EN) 34% of input natural gas (NG) energy (100% HHV – higher heating value) is transformed to mechanical energy (power). According to analysis of performance characteristics of natural gas engines and data of producers of gas engine aggregates the efficiency of natural gas engines is in the range 32 – 35%. The efficiency of the electric generator is estimated to be 95%. In the electric generator (EL G) 32% of input natural gas energy is transformed to electrical energy (power).

Heat energy is generated using the waste heat from the combustion process in the gas engine (JC – jacket cooling; EG – exhaust gas). Low temperature waste heat from the jacket cooling is used to produce hot water in EX1 for low temperature heating (45 – 55 °C, 27%). Exhaust gas waste heat is used to generate hot water for high temperature heating in EX2 (80 – 90 °C, 14%) and warm water in EX3 (30 – 40 °C, 14%) which is to be used as a heat source in the evaporator of the heat pump.

The total amount of produced electricity is consumed in the compressor of the heat pump (HP) (7%) and in the compressor of the (CM/HP) cooling machine – summer mode, or heat pump – winter mode (25%).

The heat pump (HP) is used for low temperature heating (45 – 55 °C) or domestic sanitary hot water production during the whole year. High values of the COP at the HP are reached; $\Psi = COP_h = Q_c / P$ = (9–12), for temperature lift ΔT = 5 - 10 K. Heating capacity of the heat pump (HP) is (63 – 84) %.

CM/HP in cooling mode (t_e = 5°C) is used for preparation of chilling water for air conditioning. The condenser uses well underground water with temperature t_w = 14-17 °C. High values of refrigeration $\varepsilon = COP_r$ can be reached (7 – 9). It means that CM/HP cooling capacity is (175 – 225) %. CM/HP in heating mode (t_e = 5 – 7 °C) is used for preparation of heating water for low temperature heating (45 – 55 °C). The condensing temperature is (50 – 60) °C. The heat pump COP is estimated to be (3.0 – 4.0). It means that CM/HP heating capacity is (75 – 100) %.

According to the previous analysis it can be summarized from 1 kW input energy of the natural gas the total amount of the obtained energy for heating is (1.79 – 2.25) kW. The obtained cooling energy is (1.75 – 2.25) kW in the summer mode. The traditional heating system with natural gas boiler (η_b = 0.85 – 0.90) can obtain (0.85 – 0.90) kW heating energy from 1 kW input energy which is much lower compared to the thermal system with cascade compressor heat pumps / cooling machines.

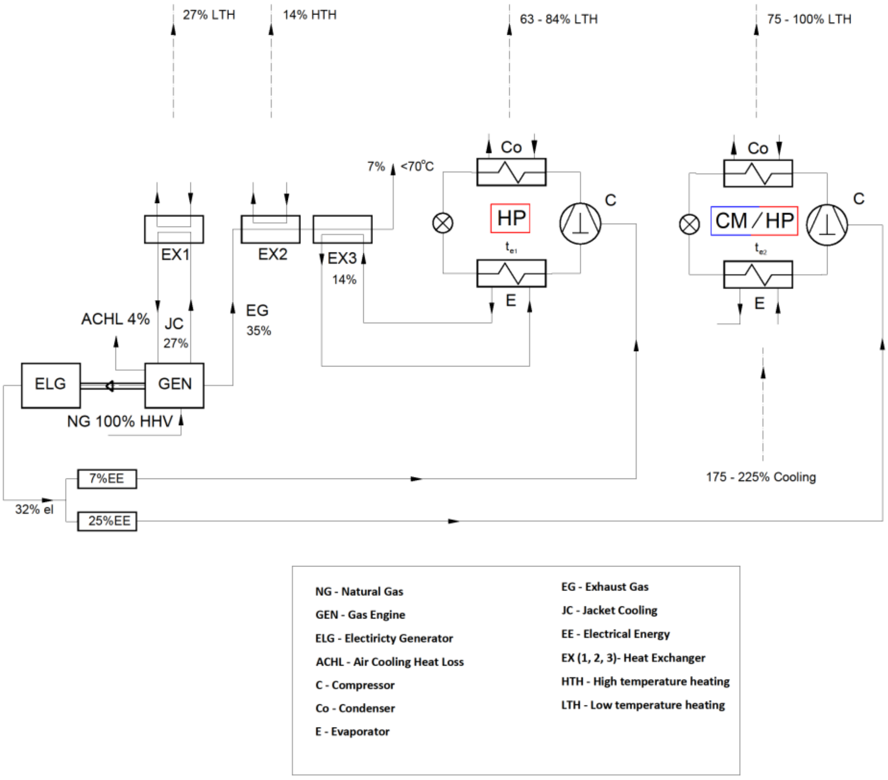

Figure 4 Poly-generation system with cascade compressor heat pumps / cooling machines

4 Conclusions

Analysis of the thermal characteristics of energy efficient buildings is given. Combined compressor and ejector poly-generation systems for production of electricity, chilling water and heating hot water for application in HVAC systems and production of sanitary hot water are presented. Procedure for determination of the optimal capacity of the proposed original thermal systems following techno–economic criteria is defined. Calculated demands for thermal energy for heating, cooling and sanitary hot water production are utilized as basic information for optimal techno-economic concept of the combined thermal poly-generation compressor and ejector systems. The proposed concept of poly-generation enables maximal utilization of the waste heat from the combustion process in the gas engine thus exploiting the higher heating value of the natural gas used as fuel.

High coefficient of thermal transformation are reached in the poly-generation system with combined compressor – ejector refrigeration / heat pump system: cooling mode (COP_{th} = 0.8 – 0.9; COP_{mech} = 15 – 17) and heating mode (COP_{th} = 1.9 – 2.1; COP_{mech} = 16 – 19). The produced electrical energy is 27 – 33% of the HHV of the natural gas.

The poly-generation system with compressor refrigeration machines / heat pumps, in which the generated electrical energy is used as motive energy in refrigerating compressors, can produce 179–225 % heating energy from 100 % HHV of the natural gas. In comparison with conventional heating systems with natural gas boilers, in which 85–90 % heating energy can be obtained from 100 % HHV of the natural gas, it means that the proposed poly-generation system can provide over two times higher energy efficiency.

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