Journal of Engineering and Applied Sciences 13 (1): 119-129, 2018
ISSN: 1816-949X

Energy Efficiency of Combined Autunomous Energy Supply Systems Based on Ground Source Polygeneration Plants in the Conditions of the Extreme Continental Climate of Kazakhstan

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Abstract: In recent years, an interest in autonomous energy generation among consumers in rural, remote and difficult to access areas has been growing in Kazakhstan. One of the ways to provide modern energy services is the creation of energy efficient and reliable local energy systems based on combined generation of energy. In this study, we propose a new structure of energy-generating equipment adapted to the extreme continental climate a ground source polygeneration plant. The proposed structure makes it possible to exclude the direct combustion of fuel and provides a high energy efficiency of heat, cold and electric energy generation in conditions of significant load irregularities throughout the year. A mathematical model for calculation of the energy performance of ground source polygeneration plant in real conditions is presented and specialized software as a tool for designing autonomous systems of energy supply on the basis of GSPP was developed. For configuring and calibrating of the mathematical model, the results of experimental studies of the experimental plant created by the researcher in Almaty University of Power Engineering and Telecommunications were used.

Key words: Ground source polygeneration plant, decentralized combined energy supply system, polygeneration, cogeneration, dynamic simulation, electric energy

INTRODUCTION

Nowadays, one of the urgent tasks for Kazakhstan is energy supply of remote rural areas that are difficult of access and objects that lack electric and heat energy. The solution for this problem in a number of key mid-term and long-term government programs is mentioned (Anonymous, 2013a).

According to the US Energy Information Administration report 2012 (Anonymous, 2017b), the Republic of Kazakhstan is at one of the last places (18 3rd) in the world in terms of GDP power consumption indexes. This is closely related to the vast territory of the country, which requires low power transmission over long distances, thus causing considerable losses in power networks. The Republic of Kazakhstan is the 9th biggest country in the world (Anonymous, 2017a). At the same time, its population density is 19 times smaller than in the countries of the European Union (Anonymous, 2017c). The great distance from oceans and the vast territory are the reasons behind the dominating sharply continental climate of the country and its zoning. The average temperature in January ranges from -19 to -2°C while the average temperature in July ranges from +19 to 26°C. In winter, the temperature drops to -50°C while in summer, it rises to +45°C. The abovementioned conditions have a significant impact on the quality and reliability of energy supply system.

Today, the Republic of Kazakhstan has 35 settlements and 6982 villages. More than 8 million people live in these settlements and villages (Anonymous, 2017b). Energy consumption does not exceed 2.5% of the total energy generated in the country (Anonymous, 2013b).

At present, the agricultural productivity in the Republic of Kazakhstan is lower than in developed European states (Anonymous, 2015). This agricultural productivity loss is related to the lack of energy efficiency of production: the power supply shortage hinders the implementation of cutting-edge technologies in agriculture and has an adverse effect on the development of small business in regions. As a direct

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result thereof, the share of agriculture in the GDP dropped (4.8% according to the results of 2015) (Anonymous, 2017a).

In recent years, the percentage of centralized heat supply systems for the end user in Kazakhstan is 15-17%. If centralized energy supply is unavailable, the power supply is usually provided by generating stations based on diesel (or gas piston) engines that produce monogeneration of electricity. The energy efficiency of such systems usually does not exceed 30%. At the same time, other fuel energy dissipates in the environment. Heat supply is mainly provided by using furnace heating or shallow boiler rooms that run on solid fuel. In general, the power efficiency of such systems is 50-70%.

Serious problems in the energy supply of housing and communal services, along with the depletion of traditional resources and environmental protection, the impact on global warming and climate change, require radical changes in energy generation, distribution and consumption. Using of renewable energy sources, in combination with the already existing energy efficient technologies is a key factor in the achievement of efficient and reliable power supply. Combined energy generation is one of the most promising technologies for the achievement of strategic objectives such as energy safety and efficiency. The achievement of these objectives will have a positive effect on economy and simultaneously reduce the environmental threat.

Studies on combined complex energy supply systems (based on cogeneration, trigeneration and polygeneration processes and plants) that were conducted by various researchers over the last decade show that such systems are very energy efficient and reliable. Cogeneration (Moradi *et al*., 2013) and trigeneration (Angrisani *et al*., 2016) systems allow to save fuel and reduce air pollution and emissions of greenhouse gases. Such advantages will lead to the development of autonomous combined energy generation systems in the near future.

Asaee *et al*. (2015) gives a technical and economic assessment of cogeneration systems based on the Internal Combustion Engine (ICE) for Canada housing and utilities. The study was conducted by using the CHREM Software (Canadian Hybrid Residential End-use Energy and Greenhouse Gas Emissions Model) which database includes about 17,000 unique houses. The hypothesis of the study was the idea that an autonomous cogeneration system based on ICE was suitable for all houses that use a centralized heating system and had suitable space inside a building or in a basement. The results of this study show that cogeneration systems enable saving up to 13% of energy in Canada housing and utilities and reducing the emission of greenhouse gases by up to 35%.

Rey *et al*. (2015) offered a design of a microtrigeneration plant with heat regeneration based on the Honda gas engine. The system includes a heat pump for air conditioning. A completely functional prototype was constructed and tested in various operation modes in a laboratory. The goal was to conduct an operational analysis of the trigeneration system and its capacities. The model of the system was designed using TRNSYS Software components and was verified by comparing it to the data obtained during various tests.

Santo (2012) assumed that the trigeneration system is the reasonable choice for energy supply of objects with different energy needs. He has researched the efficiency of energy and exergy polygeneration systems in different operating modes. The results of the study showe that heat utilization efficiency ranged from 65-81% while exergy efficiency ranged from 35-38.4%. Therefore, the proposed trigeneration system could compete with the high-performance heat generation boilers.

Santo (2014) estimated how the demand for energy changes over 1 year using Mixed Integer Linear Programming (MILP). He also considered using a cogeneration system to satisfy this demand. In their study, Moussawi *et al*. (2016) presented a method for assessing the efficiency of a trigeneration system for typical summer and winter energy consumption profiles.

In order to ensure the maximum efficiency of a complex energy supply system, it is necessary to consider the dynamics of the short-term and long-term energy consumption by the object. Asmar *et al*. (2015) offered a new control algorithm of power generation. This algorithm takes into account the electric and heat loads and uneven production of renewables. It also reduces the cost of the system and environmental pollution by integrating renewables and cogeneration systems.

Wang *et al*. (2010) investigated the capacity and efficiency of a polygeneration system that was based on ICE and included absorptive coolers. ECLIPSE Software was used to model the operating process of the offered polygeneration system. It should be noted that high-quality models of such rigs are a reliable tool in the design of co/polygeneration systems (Unal *et al*., 2016). During the model analysis of heating and conditioning system's load profiles, the researcher (Bracco and Delfino, 2017) pay close attention to the dynamic nature of heat exchange processes in buildings and constructions as a factor that reveals the possibilities for reducing the energy consumption of buildings.

The objective of current paper is to calculate the dynamic profiles of daily and annual loads with regard to the external and internal climatic parameters of power supply facilities with a view to improve the efficiency and optimal operating mode of combined energy supply systems.

Power supply efficiency can reach 80-90% if cogeneration plants are used under favorable combinations of electric and heat loads. Cogeneration plants reach maximum power efficiency at approximately 40/60 electricity generation to heat generation ratio using piston gas or diesel engines as the drive. For housing, utilities and social facilities in the conditions of a sharply continental climate this ratio will be achieved only within short time periods in spring and autumn. In Summer when the heat load reduces significantly, most of the generated heat has to be vented into the environment while in winter it is necessary to generate most of the heat energy in boilers. As a result, the average annual efficiency of cogeneration systems in the conditions of the sharply continental climate does not exceed 60-70% (Braun *et al*., 2016).

Nowadays, one of the promising ways to improve the power efficiency and cost-effectiveness of cogeneration plants is to use cogeneration plants in combination with low-potential heat converters, heat pumps, in particular (Papadopoulos and Azar, 2016). One could call this system as an integrated system in power supply. It draws interest to studying the energy efficiency of different types of power generators combined with low-potential heat converters. When heat pumps are combined with devices that collect low-potential heat (geothermal heat) from the upper ground levels they have very high power performance. The conducted experiments and numerical studies showed that this method allows to increase the efficiency of fuel that is used to generate heat energy (Stoyak *et al*., 2016). The purpose of this study is to design and build power-generating equipment for a complex energy supply of decentralized objects. The following main requirements for the designed equipment were set:

- To abandon direct fossil fuel (fluid or gaseous) combustion for heat supply needs
- To ensure a high power performance of the energy supply systems during the entire year (within a wide range of changes in the ratios of need for different energy types electricity, heat and cold caused by climatic conditions)
- To involve available renewable energy sources that are not exposed to a significant effect of climatic conditions

The hypothesis is that in order to solve the abovementioned problem, it is possible to use Ground Source Polygeneration Plants (GSPP) which include an electric generator based on ICE (gas or diesel) with a heat recovery system and compressor heat pumps with a direct engine drive. The renewable energy source used in this study was low-potential ground heat, obtained from ground sources heat exchangers system. In order to create such equipment, it is necessary to solve a series of problems related to its design and the assurance of optimal operating conditions in real conditions.

The goal of this study requires predicting the power efficiency of autonomous energy supply systems. This prediction can be used to create energy load profiles for all the generated energy types that are highly irregular both during one day and during the entire year.

The solution of this problem requires the creation of adequate mathematical models and corresponding specialized software products and subsequent numerical studies. In turn, experimental studies using real physical prototypes are needed, in order to adjust and calibrate mathematical models.

MATERIALS AND METHODS

The generic technical structure of the decentralized combined energy supply system based on ground source polygeneration plant. This study offers a concept of energy system dynamic modelling which includes a polygeneration plant, a ground sources heat exchangers system and a complex energy supply micro-grid (which includes a heat and electric energy storage system and a energy consumer). Figure 1 shows the general technical structure of the Decentralized Combined Energy Supply System based on Ground Source Polygeneration Plant (DCESS-GSPP) that was used during the development of the model and the construction of the experimental plant. The complex simulation model includes: the model of internal combustion engine's power characteristics, the model of an electric generator's power characteristics, the model of the compressor heat pump's power characteristics, the static and dynamic models of the ground sources heat exchangers system's power characteristics, the dynamic simulation model of the energy consumer, including the energy balance model of the supply object (for example, housing). Based on the developed complex simulation models, specialized software has been created which allows carrying out numerical studies to solve the following theoretical and practical objectives: to determine the energy performance of GSPP and combined energy supply system, for given profiles of the electric, thermal and cooling loads to choose an optimum capacity of the backbone elements to select and configure the optimal structure of the real DCESS-GSPP in real time, to determine the optimal operation modes of basic elements with regard to their interaction between them.

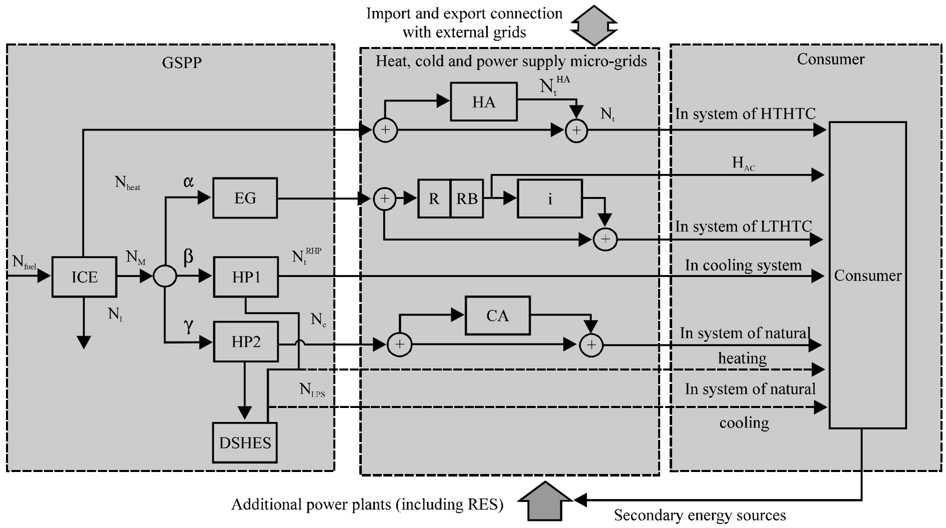

Fig. 1: The DCESS-GSPP technical structure: ICE) Internal Combustion Engine; HA) Heat Accumulator tank; CA) Cold Accumulator tank; EG) Electric Generator; HP1 and 2) Heat Pumps 1 and 2; DSHES) The ground sources heat exchangers system; RB) Rechargeable Battery; R) Rectifier; I DC-AC) Converter (inverter); $N_{fue}l$) Power of fuel (energy equivalent) (W); N_{heat}) Mechanical output of internal combustion engine (W); N_L) Irretrievable losses (W); N_{heat}) Heating capacity utilized from the ICE cooling jacket and a waste heat recovery unit (W); N_t^{HA}) Output heating capacity of the heat accumulator tank (W); H^t) Heating capacity that is released in the High-Temperature Heat-Transfer Circuit (HTHTC) (W); N_t^{HP}) Heating capacity developed by a heat pump, released in the Low-Temperature Heat-Transfer Circuit (LTHTC) (W); N_C) Heating capacity generated by a heat pump, released in air conditioning system (W); N_{LPS}) Cooling capacity of a low-potential source (W); N_{DC}) DC power transferred to the consumer (W); N_{AC}) AC power transferred to the consumer (W) and α, ß, γ) Distribution coefficients of ICE mechanical power output on the generator drive and heat pumps compressors

A software product has been developed in graphical programming environment LabVIEW 2014 and in a high-level language for technical calculations Matlab. The model of internal combustion engine's power characteristics.

The model establishes the relationship between the power of used fuel, the mechanical power of the engine, the cooling jacket heating capacity, the waste heat exchanger and mechanical efficiency of internal combustion engine. Figure 2 shows the corresponding dependences which typical for internal combustion engines used as drives of small power generators (Perkins, Caterpillar, Mitsubishi L3E SD, etc.) (Anonymous, 2007).

To form a model of ICE's power characteristics mechanical power; the heat utilized from the ICE cooling jacket, the heat of exhaust gases and the dependence of the ICE efficiency from the load was proposed where approximation of the polynomial trends corresponding dependencies of the n-th order in accordance with Eq. 1:

$$Y = Ax^4+Bx^3+Cx^2+Dx+E \quad (1)$$

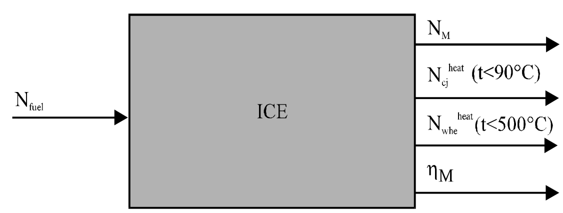

Fig. 2: The model of ICE's power characteristics; the model establishes the relationship between the power of used fuel, N_{fuel} the mechanical power of the engine, $_{NM}$ the cooling jacket heating capacity, N_{cj}^{heat} the waste heat exchanger, N_{wha}^{heat} and mechanical efficiency of internal combustion engine η_M

where, A-E are constant coefficients which depend on the characteristics of a specific engine are found during the calibration of the model based on experimental data. For Perkins engine 403D-15G, researcher identified the coefficients presented in Table 1.

The model of an electric generator's power characteristics: The model is based on the dependence

Table 1: The polynomial trends coefficients of the ICE Model

Y	A	B	C	D	E
The mechanical power of the ICE (N_M)	-	-	-0.0059	0.8601	1.4231
The heat utilized from the ICE cooling jacket (N_{cj}^{heat})	-	-8E-05	0.0162	-1.1601	67.8070
The heat of exhaust gases (N_{whe}^{heat})	-	-	0.0008	0.1269	26.8290
The mechanical efficiency coefficient of ICE (η_M)	4.00E-05	-0.009	0.7970	0.2130	-

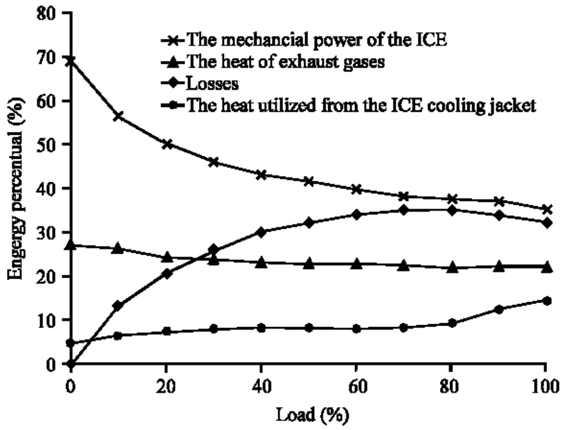

Fig. 3: Energy balance of the cogenerator based on the ICE

Fig. 4: The model of an electric generator's power characteristics

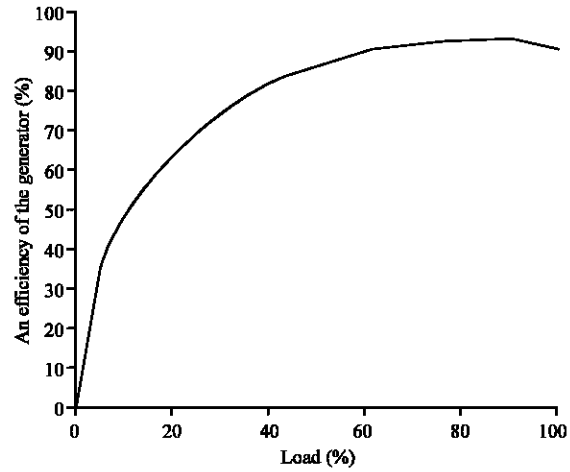

Fig. 5: Dependency of the efficiency of a STAMFORD LL3014F electric two-point generator

of the efficiency on the changes in electrical load. The input parameters of the model are the load of the electricity supply system (Fig. 3-5). The electrical power which produced by the generator is defined by the Eq. 2:

$$N_e = \alpha \times N_M \times \eta_e = \alpha \times N_{fuel} \times \eta_M \times \eta_e \quad (2)$$

Where:

- N_M = The Mechanical power of the ICE
- η_M = The Mechanical efficiency coefficient of the ICE
- η_e = An efficiency of the generator
- α = The mechanical power fraction consumed to drive the electric generator
- N_{fuel} = Fuel power

In this study, the dependency of the electric machine's efficiency on the load was approximated by a fourth order polynomial trend, according to Eq. 3:

$$\eta_e = Rx^4 + Sx^3 + Tx^2 + Vx + W \quad (3)$$

where, R, S, T, V, W are constant coefficients of a specific electric generator which are found during the calibration of the model. Based on experimental data for the electric generator STAMFORD obtained coefficients of R = -961.02, S = 2249.3, T = -1860.1, V = 643.82, W = 10.583.

The static and dynamic models of the ground sources heat exchangers system's power characteristics: Static and dynamic models of the ground sources heat exchangers system is required to determine the actual temperature of the heat transfer agent at the outlet of the Ground Sources Heat Exchangers System (GHES) in the process of operation. The static properties of GHES characterize the seasonal temperature variation. During calculations, the researcher assumed that this temperature dropped over the course of the heating period from its initial level (15°C was taken in the calculations) to a certain minimum (0°C was taken in the calculations) in proportion to the amount of extracted heat with subsequent regenerations to the initial level over the course of the warm period.

Figure 6 shows the calculated changing curve of the heat transfer agent temperature in the ground sources heat exchangers system, heat removal in an amount proportional to the heat load of the supply object.

The dynamic properties reflect changes of the heat transfer agent temperature in a short period of inclusions within days (modulation capacity control of the heat pump. Figure 7a shows the graph of the heat transfer agent changing temperature in the ground sources heat exchangers system at short-term removal of heat from the GHES. Figure 7b shows a graph of switching on/off heat pumps. During calculations, the dynamic properties of the ground sources heat exchangers system were approximated by a transfer function in accordance with Eq. 4:

$$W(s)=\frac{k}{Ts+1}\times e^{-s\tau} \tag{4}$$

The values of coefficients k, T, τ were found during the experimental studies of pilot single U-tube ground sources heat exchangers system, at 13.3 kW input stepped action. Ground sources heat exchangers were placed in wells with a total length of 360 m (6 wells, each 60 m deep). For this system, the empirical coefficients $k = 2.837$, $T = 7.329\times10^3$ c, $t = 1.188\times10^3$ c were obtained.

The model of the compressor heat pump's power characteristics: This study used a static model of the COP which was suggested in research of Chepurnoy and Resident (2015). Summarizing the available experimental data from Vasilyev and Shilkin (2016), Dai *et al.* (2016) and Klimenko (2011), in study of Chepurnoy and Resident (2015) proposed Eq. 5 to calculate valid values of COP:

$$COP = \exp(a-b\times T_k)\times C \tag{5}$$

Where:

a = $0.08.\ T_e$-14,54
b = $2.T_e\ 10^{-4}$-0.0366
C = $0.4+0.678\ \eta_{km}$ an efficiency coefficient of the compressor (Tk, °C)

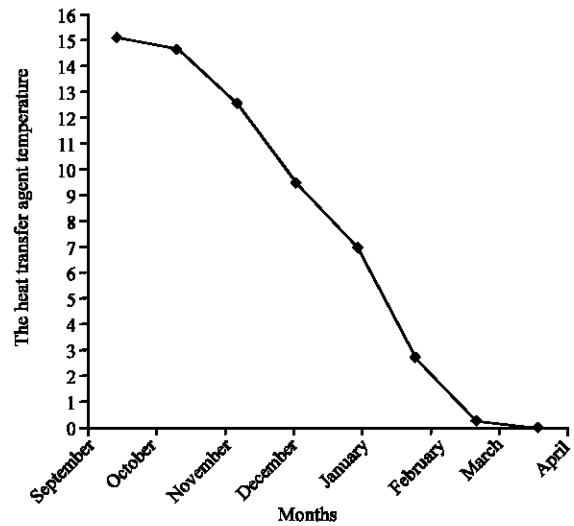

Fig. 6: Dependency of the heat transfer agent temperature in the ground sources heat exchanger system from the heating period month

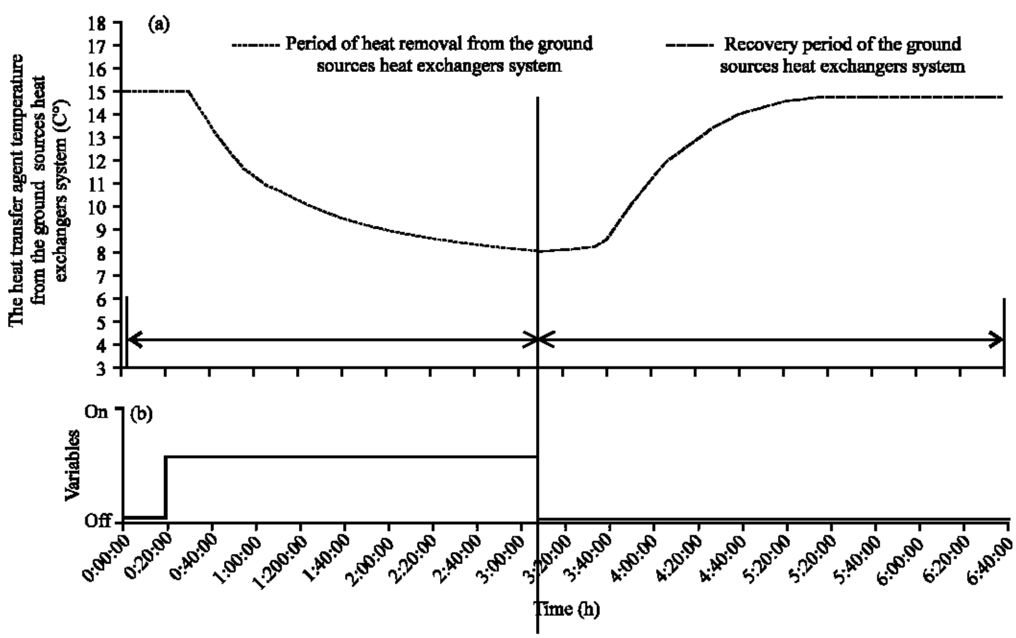

Fig. 7: Changes in heat transfer agent temperature from the ground sources heat exchangers system with short-term heat removal

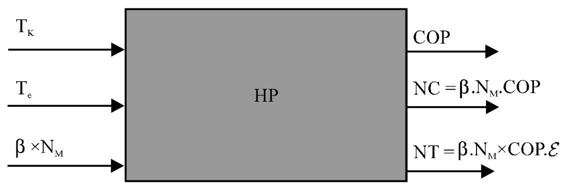

Fig. 8: The power characteristics model for the compressor heat pump: T_e, T_k absolute temperatures in the evaporator and the HPU condenser. ß: distribution coefficient of mechanical power output from engine to the heat pumps compressors

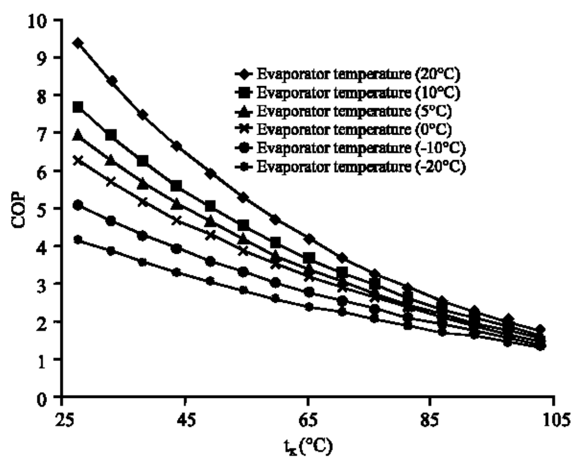

Fig. 9: Dependencies of the COP on the absolute temperatures of the evaporator and the condenser

The actual COP value is calculated in the adopted conditions: Freon R134B, the absolute temperature on the evaporator and the HPU condenser, efficiency coefficient of Bitzer compressor 4FS F 400Y. The temperature in the condenser is determined based on the adopted heating system in accordance with the temperature schedule of the heating load. The temperature of the heat transfer agent that enters the evaporator from a ground sources heat exchangers system depends on duration of the heating period. The temperature of the heat transfer agent that enters the evaporator from a ground sources heat exchangers systems depends on the calculations results of the GHES dynamic model.

Figure 8 and 9 show the dependencies of the COP on the absolute temperatures of the evaporator and the condenser that are obtained from dependency (Eq. 5).

RESULTS AND DISCUSSION

The dynamic simulation model of the energy consumer. The dynamic model of the energy consumer has been developed for an estimation of daily and annual loads profiles, caused by the influence of internal and external climatic parameters. Most of the factors affecting the thermal conditions of a building are generally determined by apriori information or by instrumental measurements, but the radiant-convective heat exchange of the building with the environment is a complex physical process and it has a significant influence, especially in such climatic conditions, when the winter and summer temperatures differ significantly from comfortable ones. For the complex accounting of radiant-convective heat transfer, it is proposed to include the following factors of the room heat balance:

- Heat gains through an opaque building envelope
- Heat gains through transparent building envelope
- Penetrating radiant heat flows, through transparent

The mathematical model of accounting for heat gains as a result of radiant-convective heat transfer through an opaque building envelope includes a linear differential heat equation which used to find solution of the heat transfer through the thickness of the building envelope with initial conditions and boundary conditions of the 3rd kind on the inner side of the wall and the complex boundary conditions of the 2nd and 3rd kind on the outside of the wall.

The parameters that were taken into account in the model: heat gains from solar radiation to the building envelope comes depending on the season, date, position of the sun, cloudiness and transparency of the atmosphere, etc., multi-layered wall; slope and arbitrary orientation of the building envelope, actual daily and seasonal variations of ambient air temperature.

To take into account the radiant heat exchange of the building, a subprogram was developed for calculating the incidence of solar radiation on the building's envelope, depending on the spatial location of the Sun. With assistance of the subprogram the flux of solar radiation is calculated on an arbitrary-oriented surface by the method proposed by Samoylov (2006) which allows calculating the instantaneous arrival of the total energy of solar radiation.

By using the developed program and meteorological data for a certain period of time, the daily and annual load profiles related to climatic parameters for an autonomous power supply system are calculated. As an example, the results of calculations for a separate room with dimensions of an outer envelope of 3×3 m, a glazing degree of 40%, an area of the room of 15 m^2 and a height of 3 m are given and also one person is in the room. So, according to the received results, in order to maintain

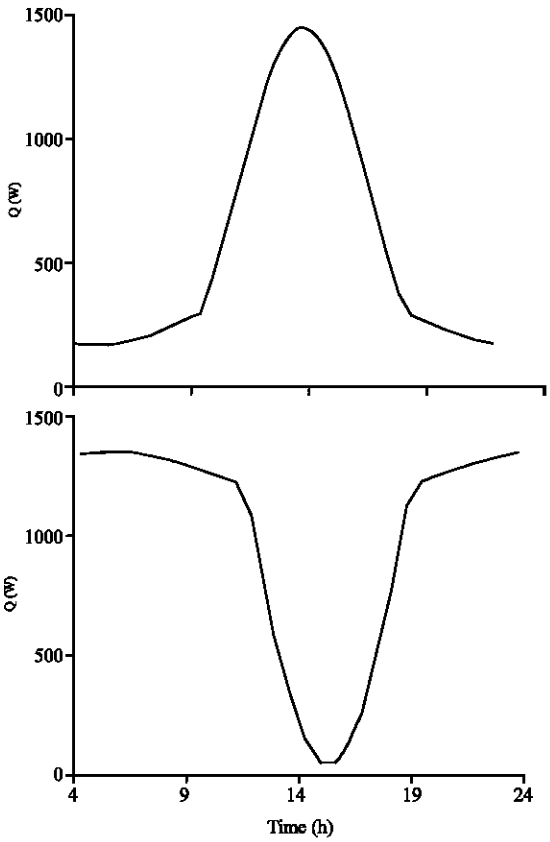

Fig. 10: a) The daily load profiles for the air conditioning system and b) Heating system

comfortable conditions in the room, it is necessary to ensure the withdrawal of heat (Fig. 10a) or heat supply (Fig. 10b) in accordance with the daily load diagrams shown in Fig. 10 (the calculations are given for conditions of Almaty City in the Summer 20.07.2016 g and Winter 20.01.2016).

A series of experiments were conducted to calibrate the complex GSPP simulation model the power characteristics of the ground sources heat exchangers system and the power characteristics of the GSPP were studied too. Experiments were conducted on a 12 kW operating experimental ground source polygeneration plant. The experimental GSPP includes Fig. 9 and 10:

- A power-generating unit: ICE, electric generator, two opposite Freon compressors, and a heat exchanger system
- A low-potential heat source a ground sources heat exchangers system

A storage tank for the accumulation of heat during the heating season and cold during the summer: including automatic heat carrier temperature stabilization systems:

Fig. 11: Experimental polygeneration plant

- An information-control system
- An electric load switching circuit which also monitored the amount and quality of the generated electric power

Data that obtained from results of the experiments served as the basis for determination of the calibration factors of the GSPP dynamic simulation model. The results of the experimental studies of the GSPP are presented in Table 2.

Simulation results: For the purpose of comparative calculations, we took an arbitrary building with an area of 150 m^2 with the normalized specific characteristics of heat energy consumption on heating and ventilation of buildings 0.25, 0.343 and 0.455 W/($m^{3\circ}$C). Such conditions correspond to A, B and C building energy efficiency classes according to the Republic of Kazakhstan Construction Standards and Regulations CH PK 2.04-04-2011. Electric energy consumption was taken as that which ensures "comfortable living" 90 kW.h per person per month. The 5 persons live in the arbitrary building; the maximum energy consumption on DHW was taken as 230 kW.h per person per month.

This study provides a comparison of the power efficiency of two power supply systems: a bivalent system based on a cogeneration plant (including a boiler) and a geothermal polygeneration plant based on the ICE (including compressor heat pumps).

Figure 11-13 show diagrams of heat generated for Almaty in 2015 by the bivalent system based on a cogenerator and the polygeneration system.

The comparative analysis of the fuel consumption (in BOE per annum) of the bivalent system consisting of a cogeneration plant and boiler and the polygeneration system power supply for the A, B and C building energy efficiency classes (Anonymous, 2007) in buildings that

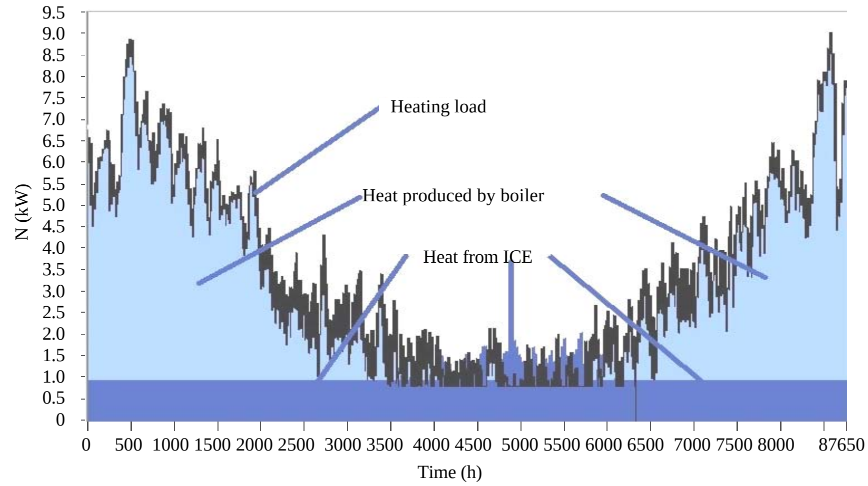

Fig. 12: Diagram of heat generated in 2015 by the bivalent system based on a cogeneration plant and boiler

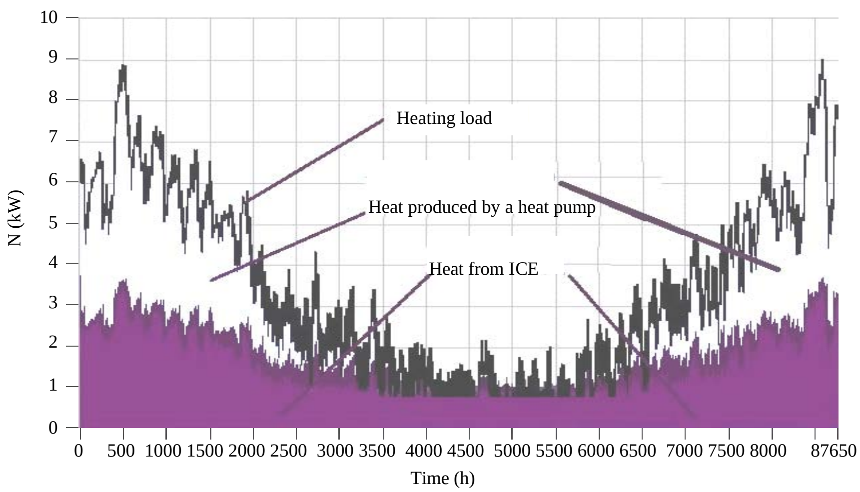

Fig. 13: Heat generated in 2015 by the geothermal polygeneration plant

Table 2: GSPP experimental study results

Engine load (%)	Electric capacity (kW)	Electrical efficiency (%)	Heating capacity (%)	Heating efficiency (%)	Total capacity (kW)	Total efficiency of GSPP (%) production	Fuel energy (kW)	Fuel rate, boe/hour×10^3 boe/kW*h×10^4	Fuel rate for electricity boe/kW*h×10^3	Fuel rate for heat production, boe/kW*h×10-4	Fuel rate for net energy production, boe/kW*h×10^3
25	3.0	19.60	9.70	63.38	12.70	82.99	15.30	6	2	0.6	0.48
50	6.0	25.93	13.30	57.49	19.30	83.42	23.14	9	15	0.7	0.48
67	7.5	26.94	15.79	56.73	23.29	83.67	27.84	11	15	0.7	0.48
75	9.0	27.87	18.15	56.20	27.15	84.07	32.29	13	14	0.7	0.47
87	10.5	27.49	21.70	56.81	32.20	84.30	38.20	15	14	0.7	0.47
100	12.0	26.07	23.65	57.77	35.65	83.84	40.95	18	2	1.0	1.00

Table 3: Annual fuel consumption for a region with 2646°C.days/year heating period (Shymkent), BOE per annum

	Cogeneration			GSPP			
Building energy efficiency class	Power supply/including conditioning	Heat supply/including through heat utilization with ICE	Total	Power supply	Heat supply/including through heat utilization with ICE	Conditioning	Total
A	9.35/0.44	14.88/6.65	24.23	8.9	10.68/8.63	0.17	19.02
B	9.5/0.600	17.51/6.77	27.01	8.9	12.2/9.33	0.24	20.60
C	9.7/0.800	18.77/6.90	28.47	8.9	12.69/9.62	0.31	21.18

Table 4: Annual fuel consumption for a region with 3629°C.days/year heating period (Almaty), BOE per annum

	Cogeneration			GSPP			
Building energy efficiency class	Power supply/including conditioning	Heat supply/including through heat utilization with ICE	Total	Power supply	Heat supply/including through heat utilization with ICE	Conditioning	Total
A	9.12/0.21	15.25/6.48	24.37	8.9	11.05/8.82	0.08	19.30
B	9.19/0.29	17.87/6.50	27.06	8.9	12.13/9.10	0.12	20.40
C	10.05/1.14	21.55/7.15	31.60	8.9	14.05/9.97	0.45	22.67

Table 5: Annual fuel consumption for a region with 6042°C.days/year heating period (Astana), BOE per annum

	Cogeneration			GSPP			
Building energy efficiency class	Power supply/including conditioning	Heat supply/including through heat utilization with ICE	Total	Power supply	Heat supply/including through heat utilization with ICE	Conditioning	Total
A	9.01/0.10	18.11/6.41	27.12	8.9	12.38/9.1	0.04	20.58
B	9.05/0.14	21.82/6.43	30.87	8.9	14.54/10.2	0.06	22.76
C	9.1/0.190	26.3/6.470	35.40	8.9	17.05/11.19	0.08	25.29

Table 6: Relative annual fuel saved for three regions of Kazakhstan with different duration of the heating period in DCESS-GSPP in comparison with a bivalent system

Building energy efficiency class	Region with 2646°C.days/year heating period (Shymkent) (%)	Region with 3629°C.days/year heating period (Almaty)	Region with 6042°C.days/year heating period (Astana)
A	27	26	32
B	31	33	36
C	34	39	42

are located in three temperature zones in Kazakhstan with different duration of heating degree days is presented in Table 3-5.

Fuel saved by using the polygeneration energy supply system, in particular, the involvement of geothermal heat pumps (replaced with low-potential heat of the earth) is shown in Table 6.

CONCLUSION

The problem of energy supply of decentralized objects continues to be valid. Significant amounts of fossil fuels are spent with unacceptably poor efficiency, while simultaneously polluting the environment. On the other hand, the requirements of final energy consumers to the quantity and quality of energy services are increasing. Power supply technologies are far behind the general level of technology development which has a number of negative consequences including gaps between the development of different regions, obstacles for the implementation of cutting-edge technologies in agriculture and local manufacturing and in-migration. These phenomena are especially obvious in countries with a cold and extreme continental climate, where living is impossible without considerable energy consumption on heat supply systems. This study proposed and created a new concept and a completely functional experimental power plant and complex energy supply system on its basis for energy supply of decentralized objects. The researcher also compared the energy efficiency of the developed system to that of the most efficient known system that is used to solve similar problems the bivalent system that includes a cogeneration plant and boiler. The comparative analysis was conducted using a complex simulation model of the system under consideration and software that was specifically developed for this purpose. The calculations confirmed that using the GSPP enabled reducing annual fossil fuel consumption by 25-40% versus bivalent systems based on a cogenerator and including a boiler. The reliability of the experiment was ensured via. model calibration based on the results of experimental studies of the power characteristics of both individual core elements and system in general.

RECOMMENDATIONS

It is worth noting that the proposed system maintains high power performance with significantly non-uniform power load profiles and ratios of the generated energy types: heat, electricity and cold which are typical for municipal power supply in regions with a sharply continental climate.

ACKNOWLEDGEMENT

The study was carried out within the framework of the grant financing project by the Ministry of Education and Science of the Republic of Kazakhstan, topic number 4818/GF4 (00117Q/1).

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