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Resource Saving in the Area of Decentralized Geothermal Energy Supply

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ABSTRACT

The heating system as an economic structure for providing life support of any country deserves attention in terms of consumption of primary energy resources, its capital intensity and environmental safety. The goal of the study is to analyze the operation modes of the combined heating systems on the basis of boiler plants and vapor-compression heat pumps with low-boiling substance R134a, working on low-temperature geothermal heat sources at t= 10÷35°C. The studies showed that the use of the vapor-compression heat pump equipment together with the boiler system in the areas of decentralized heating can significantly reduce the consumption of fossil fuels under various operating modes of the system components (separate, bivalent) compared with autonomous conventional heating boiler systems and improve eco-efficiency of the heating system. Two independent heat sources increases reliability of heat supply. At that, the heating power of a boiler plant as a peak heat source can be significantly reduced based on the total heat balance of the combined heating system and technical capabilities of selected compressor. The Freon (R134a) power station with the installed capacity of 4000 kW is considered. The number of hours of installed capacity use per year is 7000. The location is Kamchatka region (the Upper-Mutnovsky geothermal field). According to results of system studies, at combined electricity and heat production the Freon units with the considered capacities provide a return on investment for less than a year for the entire set of primary fuel-energy resources. This effect is provided by resource saving of the used organic fuels and environmental component of environmental protection in the Kamchatka region.

1. INTRODUCTION

Among the promising directions of development of heat pump systems are the combined heating systems. At that, heat pump setups (HPS) can operate in monovalent mode, covering heat demands (for example, in autumn and spring), and in bivalent mode in conjunction with a boiler system (abroad it is the so-called «PERCHE» system [1]). One or another heat source is turned on depending on the outdoor temperature. At that, HPS are switched on only during the period of discount rates. Russia has the uniform electricity rate for population. However, the foreign experience is attractive and allows the analysis of combined technology of heat supply for the vapor-compression heat pump and boiler setups.

While generating electricity on low-boiling working fluids, the Freon power plants consume low-grade heat with the temperatures of 70÷130°C. These coolants, ready to use, are available in geothermal sources, discharges of industrial enterprises and so on; they cannot be used in the existing engineering cycles for various reasons (inefficiency, technical limitations, etc.). The pilot projects on construction of binary power plants in our country and abroad have shown that this technology is resource saving, it demonstrates high performance at low temperatures, it is environmentally responsible and reliable in operation. According to the first foreign estimates of the impact of fuel and energy complex (FEC) on environmental pollution, when using the «dirty» fuels (sulfur coal and heavy oil), the damage to environment is comparable with their price for the consumer. It is shown in [2] that damage from burning fossil fuels is on average $125 / t e.f., while for the «dirty» fuels this damage reaches $165 and more, and for natural gas (NG) it is about 40 USD / t e.f.

2. ENERGY SAVING IN THE ZONE OF DECENTRALIZED HEAT SUPPLY

Consumption of organic fuel is taken as an efficiency criterion for the combined heating system. The task of research is to analyze the modes of operation of combined heating systems on the basis of boiler plants and vapor-compression heat pumps with low boiling R134a in order to further improvement of heating systems efficiency. Different modes of boiler plant and heat pump operation are examined, including separate operation (monovalent mode) of each of the system elements and their combined operation (bivalent mode).

The installed heat capacity is taken Q_{heat}= 1 Gcal/h with heating season h= 5450 h/year. Depending on the outdoor temperature, direct heating-system water in the supplying pipeline corresponds to the diagram 95/70°C and its temperature is regulated qualitatively. Consumption of equivalent fuel per a boiler is determined by the heat load and boiler efficiency η, taken equal to 0.8. Under these conditions, when only a boiler is active, the annual consumption of equivalent fuel in the heating system is

$$B_b = Q_{heat} \Big/ (Q^p \times \eta) = 973.2 \quad \text{t e.f./year} \quad . \tag{1}$$

Efficiency of heat pump technology assumes the presence of a source of low-potential heat. Since the scope of sources and their temperature ranges are very wide, in the studies the temperature of Freon evaporation t_{eva} varied from 5 to 30°C. The temperature of water in the supplying pipeline t_{dir}, which is the function of the ambient temperature with consideration of temperature difference, allows us to determine the temperature of Freon condensation t_{cond}. Coefficient of energy transformation φ_i (of the low-potential source and work of Freon compression) in the heat pump is determined by dependence:

$$\varphi_i = (0.65 \div 0.75) \times T_{eva} / (T_{cond} - T_{eva}). \quad (2)$$

The mode of separate operation of the heat pump and boiler was analyzed. There are some restriction to operation of heat pump compressor; they relate to a compression degree of the vapors of low-boiling substance $\pi \leq 7$ and the value of absolute Freon pressure behind the compressor $p_c = 21 \div 25$ (30) bar. The versions of heat pump application at the temperatures close to the outdoor temperatures $t_{o.t.}$= -25°C were considered in the studies (Table 1). With a decrease in the outdoor temperature and a corresponding increase in the temperature of direct heating-system water at the fixed temperature of the low-potential heat source, the ratio of pressure behind the compressor to the Freon pressure at compressor inlet increases, and this leads to the out-of-limit boundary conditions.

Table 1

Initial characteristics

$t_{o.t.}$, °C	+ 8	0	- 5	- 10	-15	- 20	- 25	-30	-35	-40
t_{dir}, °C	32.9	47.2	53.7	60.1	66.2	72.2	78.0	83.8	89.4	95.0
t_{rev}, °C	29.5	39.4	43.8	48.0	52.0	55.8	59.5	63.1	66.6	70.0
h_{st}, h	5450	4270	3290	2430	1550	910	488	205	89	15

To achieve the mentioned parameters, the compressors of new generation of type 6FE-50YBitzer, 19XRCarrier with stage compression, sectional condensers and coolers of overheated vapor are required. Development of new compressors is caused by the fact that their operation should guarantee qualitative regulation of temperature of heating-system water, supplied into the heating system during the whole period of their operation depending on the outdoor temperature.

To calculate the average annual coefficient of energy transformation in the heat pump during the period of its operation h_{hp}, the following expression was used:

$$\varphi_{ave} = \Sigma(\varphi_i \times h_i) / h_{hp}. \quad (3)$$

Effective capacity of compressor was calculated:

$$Ne = Q_{heat} / \varphi_{ave} \quad (4)$$

and amount of heat involved in the system of heat supply from the low-potential source

$$Q_{lph} = Q_{heat} - Ne. \quad (5)$$

Consumption of organic fuel at operation of the heat pump setup was determined by the amount of consumed electricity obtained from JSC Energo at the terms of consumption for electricity production of 340.5 t e.f./kWh.

Table 2

Consumption of equivalent fuel in the combined heating system at separate operation of heat pump and boiler

$t_{o.t.}$, °C	-10	-15	-20
t_{eva}, °C	5/10/15/20/30	5/10/15/20/30	5/10/15/20/30
B_{hp}	355.8/306.4/259.5 /212.1/115.8	435/376.1/319.9 /263.6/145.8	488.8/424.4/363.2 300/168.7
B_b	276.8	162.5	87.1
$B_{hp} + B_b$	632.6/583.2/536.3 /488.9/392.6	597.5/538.6/482.4 426.1/308.3	575.9/511.5/450.3 /387.1/255.8

Consumption of equivalent fuel at separate operation of heat pump and boiler is shown in Table 2 for different evaporation temperatures of Freon R134a at different outdoor temperatures (the number of hours of installed thermal power use). The boundary outdoor temperatures, separating operation of heat sources are considered (before – heat pump operation, after – boiler operation).

According to comparative analysis (Fig.1), for all modes of separate operation of vapor-compression heat pump and boiler setup, the high temperature of low-potential source allows a decrease in the work of compression in the heat pump and electricity consumption as well as an increase in the coefficient of energy transformation and a decrease in equivalent fuel consumption. This is the general law for all ambient temperatures.

With a decrease in the outdoor temperature, the heat load on the vapor-compression heat pump increases, the coefficient of energy transformation decreases, the compression work increases and, as a sequence, the consumption of equivalent fuel increases.

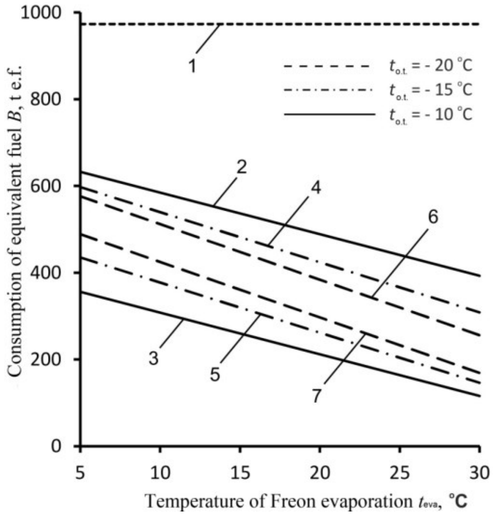

Figure 1: Consumption of equivalent fuel in the combined heating system depending on the temperature of Freon evaporation at different outdoor temperatures (1– at boiler operation; 2, 4, 6 – total fuel consumption at separate operation of heat pump and boiler; 3, 5, 7 – at operation of heat pump on R134a).

At that, redistribution of heat loads occurs, and fuel consumption by the boiler setup decreases. This effect becomes stronger with an increase in the temperature of Freon evaporationa (the temperature of low-potential heat source). In general, with a decrease in the ambient temperature the total fuel consumption in the combined heat supply system decreases (Fig.2). With fuel economy, ecological damage associated with environmental pollution decreases.

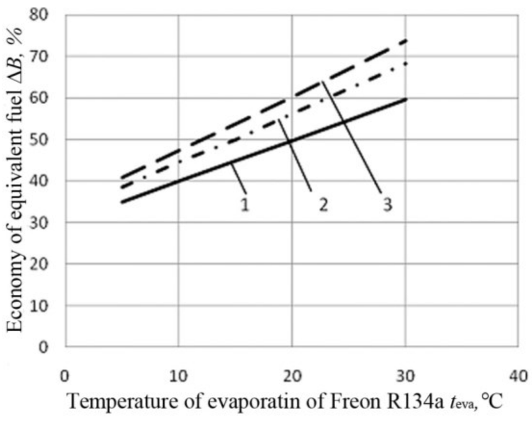

Figure 2: Fuel saving in the combined system of heat supply depending on the outdoor temperatures at different evaporation temperatures of Freon R134a (1, 2, 3 – at $t_{o.t.}$= -10, -15, -20°C, respectively).

Under the bivalent conditions of heat pump and boiler operation, return heating-system water (Table 1) is sent to the compressor inlet, and the temperature of Freon vapor is registered at the outlet of this compressor (e.g., at $t_{o.t.}$= -15°C, t_{dir}= 66.2°C= *const*). Following water heating, related to a decrease in the outdoor temperature, occurs in the boiler setup.

At that, under the condition of $t_{ret} < t_{dir}$ the return water from the heating system is sent for heating to the heat pump condenser. Under these conditions at $t_{o.t.}$< -25°C, the absolutely boiler operation occurs. The heat load between heat pump and boiler under the bivalent operation is distributed by the temperatures of water heating in every element of the combined heating system. The similar procedure is implemented for the lower ambient temperatures. Consumption of fuel in the boiler setup is shown in Fig.3 for the mentioned range of outdoor temperatures without consideration of heat pump operationa (1) and in the bivalent mode (2).

Consumptions of equivalent fuel at bivalent operation of the combined heating system are shown in Table 3 for the outdoor temperatures $t_{o.t.}$= -15°C; -20°C; -25°C.

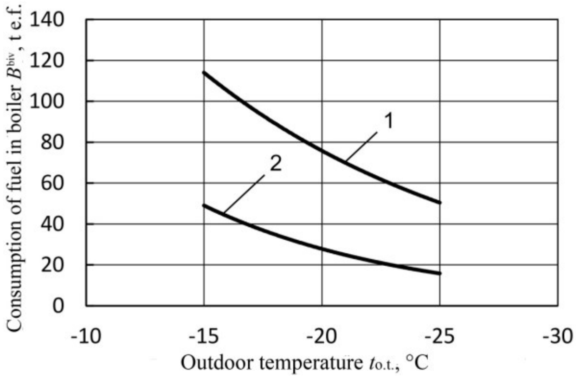

Figure 3: Consumption of equivalent fuel in boiler (1 – autonomous boiler operation, 2 – bivalent boiler operation).

Despite a decrease in the coefficient of energy transformation with an increase in the temperature of return water, connected with a decrease in the outdoor temperature, the total fuel consumption at bivalent operation of the combined heating system decreases. With a decrease in the ambient temperature, the period of average daily temperature equal or below the given one decreases. Therefore, fuel consumption in the boiler decreases. These results argue the economic character of this mode in comparison with the traditional boiler mode of heat supply (Table 3, Fig.4).

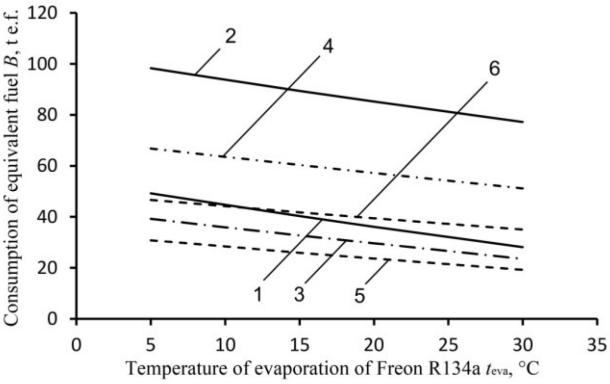

Figure 4: Consumption of equivalent fuel at bivalent operation of heat pump and boiler at outdoor temperatures $t_{o.t.}$ = -15, -20, -25°C (1, 3, 5 – heat pump operation; 2, 4, 6 – at heat pump and boiler operation). The strokes correspond to the legend in Fig.1.

Table 3

Consumption of equivalent fuel B^{biv} (t e.f.) at bivalent operation of heat pump and boiler

$t_{o.t.}$, °C	-15	-20	-15 ÷ -20	-25	-20 ÷ -25
t_{eva}, °C	5/10/15 /20/30	5/10/15 /20/30	5/10/15 /20/30	5/10/15 /20/30	5/10/15 /20/30
B_{hp}^{biv}	49.2/44.7 /40.3/36.1 /28.1	39.2/35.9/ 32.7/29.6 /23.5	38.8/34.5/ 34.0/30.7 /24.5	30.8/28.4/ 25.9/23.6 /19.2	38.6/35.4/ 32.3/29.2 /23.5
B_b^{biv}	49.1	27.6	139.9	15.8	80.3
$B_{hp}^{biv} + B_b^{biv}$	98.3/93.8 /89.4/85.2 /77.2	66.8/63.5 /60.3/57.2 /51.1	178.7/174.4 /173.9/170.6 /164.4	46.6/44.2/ 41.7/39.4 /35.0	118.9/115.7/ 112.6/109.5 /103.8
B_b	114.3	75.3	189.6	50.5	125.9

3. SYSTEM FEASIBILITY STUDY OF FREON GEOTHERMAL POWER PLANTS

Since the binary power plants are used in the fuel and energy complex of Russia, the amount of saved fuel can be a criterion for the estimate of the mentioned energy-saving technical avenue from the point of system approach. The Freon power plane with the installed capacity of 4000 kW is considered as an object of study. The power of water-Freon energy unit of 4000 kW is taken on the basis of pre-project studies carried out by JSC «Geoterm» (Moscow department), Moscow Energy Institute and Institute of Thermophysics SB RAS at Verkhne-Mutnovsk geo-power plant, which were used for the development of binary power plant. The project of a binary power plant is a combination of two thermodynamic cycles: water-vapor one, which produces geothermal separated saturated steam, and Freon steam-power circuit, where a separate with the initial temperature of geothermal water-vapor mixture of 148-165°C serves as a heating medium.

Hours of installed capacity use per year is 7000. Location is Kamchatka region (Verkhne-Mutnovsk geothermal deposit). The following consumptions of specific fuel were assumed for the power plant of JSC Energo: for electricity production – 340.5 t e.f./kWh, for heat production – 146.2 t e.f./Gcal.

Here we consider the used set of primary fuel-energy resources: coal (Yuzhno-Sakhalinsk deposit with calorific capacity $Q^p = 6110$ kcal/kg), heavy oil (Omsk and Angarsk refineries with $Q^p = 9800$ kcal/kg), diesel fuel (with $Q^p = 10100$ kcal/kg) and natural gas (with $Q^p = 8280$ kcal/m^3). Some of technical and economical characteristics of binary power plants with combined generation of electricity and heat are shown in Table 4.

Table 4

Calculated technical and economic indicators

No.	Activities	Value of N_{ins} 4000 kW
1.	Total investments, thous. USD	5640
2.	Annual supply of electricity to the consumer, mln kWh/year	26.2
3.	Annual supply of heat to the heating system, mln $kWh_{(heat)}$/year	14436.0

Adopted initial conditions made it possible to determine the amount of replaced natural fuel at binary power plants on geothermal heat carriers with the temperature of 80°C, taking into account the efficiencies in fuel-burn devices. Results obtained are shown in Table 5.

Table 5

Economy of energy resources at cogeneration plant at combined production of electric (E) and heat (Q) energy

No.	Type of fuel	$N_{ins} = 4000$ kW $E = 26.2 \cdot 10^6$ kWh/year $Q = 115.15 \cdot 10^6$ Gcal/year	
		Total	Including electricity production
1.	Coal, t n.f./year	36899.0	12790.0
2.	Heavy oil, t n.f./year	21654.0	7507.0
3.	Diesel oil, t n.f./year	19843.0	6879.0
4.	Natural gas, 1000 m^3/year	23679.0	8209.0

The strategic guidelines of long-term state energy policy are energy and environmental security as well as energy and budget efficiency.

The purchasing prices of energy resources for the Kamchatka region adopted by the Government of Kamchatka Territory are as follows [3]: coal of 3600 rub/t n.f., heavy oil of 8800 rub/t n.f. (CIF cost is 13346 rub/t n.f.), diesel fuel of 22700 rub/t n.f. (CIF cost is 33046 rub/t n.t.).

On August 13, 2010, the Federal Tariff Service of the Russian Federation has approved the wholesale price of gas produced by JSC «Kamchatgazpromom» in the amount of 10.2 thousand rub per 1000 m^3.

Valuation of replacement of organic fuels by geothermal sources at combined production of electricity and heat on geothermal sources is presented below in Table 6. Comparative analysis of the cost of electricity generated by thermal and power plants using the renewable energy sources, performed by the Government of Kamchatka region, shows that the cost of electricity production on the renewable energy sources (Verkhne-Mutnovsk Geothermal and Mutnovsk Geothermal power plants) is 2.1 times lower than the cost of electricity generated by cogeneration power plants of the central power unit (CP-1, CP-2) [3].

According to [2] and accepted initial data in Table 7, we present ecological damage that would cause traditional power engineering at combustion of organic fuel, saved when using the renewable (conditionally) geothermal sources. The total effect of the use of a binary setup with low-boiling actuating medium is shown in Table 8 with consideration of the ecological effect.

Table 6

The cost of saved energy resources at combined production of electricity and heat at the binary power plants

No.	Type of fuel	N_{ins} = 4000 kW $E = 26.2 \cdot 10^6$ kWh/year $Q = 115.15 \cdot 10^6$ Gcal/year	
		Total	Including electricity production
1.	Coal, USD/year	4427880	1534800
2.	Heavy oil, USD/year	6351840	2202053
3.	Heavy oil CIF, USD/year	9633142.8	3339614
4.	Diesel oil, USD/year	15014537	5205110
5.	Diesel oil CIF, USD/year	21857726	7577448
6.	Natural gas, USD/year	8050860	2791060

Table 7

Damage caused by conventional power engineering at production of electric and thermal energy

No.	Type of fuel	N_{ins} = 4000 kW $E = 26.2 \cdot 10^6$ kWh/year $Q = 115.15 \cdot 10^6$ Gcal/year B^E = 8933.0 t e.f./year B^Q = 16835.0 t e.f./year	
		Total, thous. USD/year	Including electricity production, thous. USD/year
1.	Coal, heavy oil	2777.8	1473.945
2.	Natural gas	673.4	357.3

Table 8

Total effect of binary electric power plants in Kamchatka region

No.	Type of fuel	N_{ins} = 4000 kW $E = 26.2 \cdot 10^6$ kWh/year $Q = 115.15 \cdot 10^6$ Gcal/year	
		Total, thous. USD/year	Including electricity production, thous. USD/year
1.	Coal	7205.7	3008.7
2.	Heavy oil	9129.6	3676.0
3.	Heavy oil CIF	12410.9	3487.0
4.	Diesel oil	17792.3	6679.0
5.	Diesel oil CIF	24635.5	9051.4
6.	Natural gas	9724.3	3148.4

CONCLUSION

The use of vapor-compression heat pump equipment together with boilers in the zones of decentralized heat supply will allow a significant reduction in consumption of organic fuel from 35÷41% to 60÷74% (depending on the temperature of low-potential source) at different operation modes of the system elements (separate, bivalent) in comparison with autonomous conventional heating boiler systems. This will also improve environmental efficiency of the heat supply system. Results obtained demonstrate the reasonability of resource-saving bivalent operation of the combined heat supply system and possibility of its practical application. Two independent heat sources increase reliability of heat supply to the customers. At that, heat capacity of a boiler, used as a peak source, can be significantly reduced due to the total balance of the combined heat supply system and technical abilities of a chosen compressor.

Today, the most promising and economically efficient production of electricity at power plants on Freon can be achieved through their operation on geothermal energy resources. To implement this, the most favorable conditions are the presence of geothermal deposits of hot water, low and stable temperature of cooling medium during the year, and a high price of electricity in the absence of fossil fuels. This direction was tested experimentally in Russia (at Kamchatka), and it is technically real. This direction is actual, prepared in the process of developing and piloting, and deserves close attention. According to results of system studies, at combined production of electricity and heat the Freon power units of the considered capacities provide a return on investment into their creation for less than a year for the entire set of primary energy resources. This effect is achieved through resource saving of the used organic fuels and ecological component of environment protection. If only one product is generated by the Freon unit (electricity), the similar effect is achieved, when diesel fuel is removed from the energy balance. At that, for all other types of primary energy resources the positive effect of investments will be observed in two years. The studies allow us to speak about the prospects of development of binary power plants. According to performed system analysis, for the accepted initial conditions, the return of investments into the Freon power plant occurs during one or two years. This effect is achieved due to economy of primary energy resources and ecological component of environment protection in the Kamchatka region. The time factor changes the absolute costs of electricity and heat delivered to the customer. However, an increase in tariffs for electricity and heat will increase the economic efficiency of power plants, since results from the sale of products increase, and this is associated with an increase in the future price of fossil fuels. The Freon circuit with ozone-safe working substance R134a (*ODP* = 0) of the thermal power plant can be effectively used at the working geothermal power plants on vapor-water mixtures in the technology of binary vapor-water-Freon cycle. The binary thermal-power cycle provides the following opportunities: 1) an increase in electricity production at the given consumption of the vapor-gas mixture or 2) variation of consumption of vapor from the initial vapor-gas mixture aimed at achievement of the set electric power in two power generators.

NOMENCLATURE

HPS – heat pump setup,
HP – heat pump,
b – boiler,
Q – heat capacity,
E – electricity production,
h – duration of heating period,
B – consumption of equivalent fuel,
ΔB – equivalent fuel saving,
η– boiler efficiency,
Q^p – fuel calorific value,
T – temperature, K
t – temperature, °C
π – compression index
φ – coefficient of energy transformation,
Ne – effective power of compressor,
CIF – cost insurance freight,
N_{ins} – installed electric capacity,
JSC-Energo – the group of Electricity Companies Holding,
CP – cogeneration plant;
Indices:
biv – bivalent mode,
lph – low-potential heat source,
eva – evaporation,
cond – condensation,
o.t. – outdoor temperature,
dir – direct heating-system water,
ret – return heating-system water,
st – outdoor temperature equal or below the given temperature,
t e.f. – tons of equivalent fuel with Q^p = 7000 kcal/kg.

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