Представлено опис розробленого і виготовленого багатофункціонального теплового пункту, що дозволяє забезпечувати споживача тепловою та холодильною енергією. Для ефективної роботи тепловий пункт містить систему автоматизованого управління, що дозволяє направляти теплові потоки оптимальним чином. Розробка такого теплового пункту обумовлена тим, що в Росії в даний час немає комплексних досліджень по створенню систем електропостачання на базі теплових насосів. Існує ряд робіт, які фактично копіюють західні технології. При цьому не враховуються особливості кліматичних зон, що вкрай важливо для розвитку подібних електростанцій. Тобто, раніше ніхто не створював продукт, який однаково добре працює в умовах Південних регіонів і Крайньої Півночі. Тепловий та гідравлічний розрахунки теплового пункту, результатами яких були відповідно коефіцієнти перетворення і опору контурів теплонасосної установки, показали, що коефіцієнт перетворення по всіх контурах лежить в діапазоні від 3,352 до 4,884. В даний час проведені пускові випробування теплового пункту, які показали правильність обраних конструктивних рішень і працездатність установки.

Отримані результати будуть корисні при проектуванні аналогічних систем, так як основні характеристики каскадних теплових насосів обчислені розрахунковим шляхом.

Конкретні результати дослідження полягають у наступному:

– розроблена багатоцільова теплова точка, що дозволяє здійснювати опалення потужністю 25 кВт, гаряче водопостачання – 5 кВт, кондиціювання – 16 кВт, вентиляція 25 кВт;

– визначені ключові показники теплової ефективності електростанції, такі як коефіцієнт трансформації, термічна оцінка і т. і.;

– визначена ємність компактних акумуляторів тепла. Для нагріву при температурі в 35 °C протягом 12 годин у нічний час потрібен резервуар для котла на 2500 л, а колектор для зміни фази – 300–500 л;

– на основі аналізу наявних відновлюваних і вторинних джерел енергії, розроблена структура теплових потоків стандартного споживача з джерелами надлишкового тепла і точками його споживання

Ключові слова: тепловий насос, тепловий пункт, система кондиціонування, система опалення, поновлювані джерела енергії, сонячна енергія

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DEVELOPMENT OF THERMAL INSTALLATION ON THE BASIS OF THE CASCADE HEAT PUMP FOR ENSURING ALL THERMAL AND REFRIGERATING NEEDS OF THE CONSUMER

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1. Introduction

At present, there is widespread wear and tear on heating equipment and heating networks. There is also a constant increase in prices for all types of energy carriers and a steady trend of increasing tariffs for thermal energy. Therefore, there is a great need for a radical change in energy consumption and large-scale use of energy-saving technologies.

Today, of all technologies on renewable energy sources, the most stable on receipt of heat energy is the technology of heat pumps. Solar and wind energy is characterized by inconstancy of energy input – solar “works” only in the daytime in sunny weather, wind – with the wind speed of 5 m/s and more.

The main purpose of the appearance of heat pumps is to combat the acceleration of global warming. The multifunctional heat point under consideration corresponds to the best Western technologies and is relevant for solving modern environmental problems.

2. Literature review and problem statement

The article [1] describes the system of utilization of excess energy in subtropical regions. The model of assessment of excess heat energy was developed, at the same time in this system ventilating losses which we consider in wiring design of the multifunction thermal point were not considered. In the publication [2], the installation capable to utilize geothermal power of high potential (more than 150 °C) is described. It is quite easy to transform similar working medium to the heat carrier suitable for heating and hot water supply of the consumer. Our installation is capable to utilize the heat carrier of low potential up to 20 °C. Then the thermal point increases the heat carrier potential in the corresponding cascade and gives it to the necessary line. As the analysis of sources shows [1, 2], the consumer often throws out thermal energy outside. Generally, these emissions are: the exhaust ventilating air deleted from the room during the winter period (in the absence of a recuperation), warmth of the deleted sewage.

In the work [3], possibilities of optimization of conditioning system for office buildings of four main cities of the Iberian Peninsula are investigated. The reverse heat pumps working as traditional split systems are used. The thermal point developed by us can use passive conditioning. Passive conditioning works even with the switched-off heat pump and provides big economy of electrical energy.

There is a set of the maintaining systems of microclimate rooms which use various fuels in the world. At present, heat pump systems for heating buildings are very common [4]. Also, the use of heat pumps for air conditioning of domestic and industrial premises [5]. Also, the systems working at the expense of difference of average and seasonal temperatures. Such energy complexes are designed for power supply of autonomous consumers with thermal energy, cold energy and electric energy, and also provide the consumer with hot water with the temperature of 60 °C from a solar radiation [6]. The systems working for ventilation are less widespread [7]. As a rule, these systems are aimed at one of the tasks: heating, hot water supply, conditioning or ventilation. The complex solution of an objective decides the use of several systems at once. This approach limits a possibility of the secondary energy sources received is collateral during the work of any of the systems [8]. The deficiency of organic fuel increasing in the world dictates the need for an increase in power effectiveness of installations by the use as renewables, and the secondary energy resources [9]. It is possible to provide high only with the heat and cold energy combined with development on the general power platform [10].

Thus, a clear niche of the research is revealed – the creation of an installation in a single unit that solves the problem of heating, air conditioning, hot water supply and ventilation.

We change thermal loads of the evaporator and condenser in our research. This is done using the settings of the multifunction heat point. The principle of operation is described below. From the tank-receiver of a multifunctional heat point, heat is cascaded to the receiver tank. At the same time, the parameters are measured: the amount of heat extracted from the source, the amount of heat transferred to the receiver, the amount of electricity supplied to the compressor drive of the cascade. The temperature level between the tanks maintains a circulation circuit that transfers heat from the receptacle to the source tank. The regulation of this temperature level is carried out by changing the frequency of circulation in the circuit by affecting the flow rate of the heating medium by the control valve and the position of the speed of the circulation pump. Excess heat that will be accumulated in the system by supplying energy to the compressor is diverted to the external environment by replacing part of the circulating water with make-up water.

For an increase in economic efficiency of heat pumping technologies, it is necessary to increase, on the one hand, their power efficiency, and on the other hand, to reduce the cost of a single installation. For heating, conditioning and hot water supply of the consumer with the maximum power efficiency, we suggest to develop the multifunction thermal point, in which the heat pumping cycle is assumed as a basis. Reduction in the cost of a single installation can be reached by domestic production of units. The import parts and nodes are involved less, the cost will be lower.

Generally, all sources on the studied subject consider particular parts of the problem. However, nobody works on the common increase in the effectiveness of a heat pumping cycle and multifunctionality of the installation [3–10].

3. The aim and objectives of the study

The aim of the work is to create a highly efficient and economical multifunctional thermal point based on the Russian cascade heat pump. It provides thermal energy and cold energy by transforming the heat of renewable energy sources and household heat for autonomous and decentralized energy supply systems to consumers.

To accomplish the aim, the following tasks have been set:

– development of a scheme for the utilization of heat and cold by various cascades of a heat pump in one common multilevel scheme;

– development of methods for increasing the economic efficiency of heat pump plants;

– description and definition of internal and external energy sources of the building;

– identification of consumers of thermal and refrigeration energy.

4. Material and methods of research

The following measures are taken for ensuring an increase in the utilization coefficient of primary energy and according to power efficiency:

1) losses in the "low-potential source/consumer" system are reduced;

2) secondary power sources are used;

3) the additional power sources having the higher thermal potential, than the most widespread soil, water and air are introduced;

4) discrepancies of schedules of consumption of warmth and schedules of secondary energy resources intake and additional external sources of warmth are eliminated;

5) heat pumping cycles are optimized.

The scheme provides driving of thermal energy from sources to receivers in and out of the consumer due to the graduated structure of vapor-compression heat pumping plants. This scheme allows to provide the simultaneous production of the necessary amount of thermal energy with various required temperature and power of the heat carrier. Energy is used for heating, for hot water and also receiving cold for the functioning of the ventilation and air conditioning system up to food freezing.

For the implementation of the first two points, the scheme of the heat fluxes movement in the building is formed. Proceeding from the principles of energy saving and comfort for the consumer, flows are redirected so that by the production of heat/cold, cold/heat received at the same time it was useful. Also, this scheme joins flows of secondary sources of warmth to minimize energy loss with waste warmth. This scheme is presented in Fig. 1. For the implementation of the third point as the high-potential source of warmth, solar energy is used. The existing schemes of solar energy are not rather effective as they use accumulation in one accumulator (boiler). But we separate the potential of solar energy into 3 levels for accumulation in different devices and use in different cascades of the scheme. The innovation approach was applied to the elimination of discrepancy of receipt of solar energy and secondary energy resources and the schedule of heat and cold consumption. The approach consists in the use of multi-level accumulation of warmth at different thermal potentials with reduction of dimensions of accumulators due to the use of the effect of change of substance phase.

For the optimization of heat pumping cycles of different cascades, the following two factors are used.

1. On the basis of research of the types of existing compressors and operating conditions of the cascade, the optimum compressor for each of cascades is defined. During the research, the main criteria of definition of the type of the compressor were: cascade power, operating mode – the frequency of inclusions, operating time for life cycle, temperature of the source in the cascade, receiver temperature in the cascade.

2. On the basis of research of the types of Freon and operating conditions of the cascade, the optimum working medium for each of cascades is defined. During the researches, the main criteria of definition of the type of freon were the operating mode – the frequency of inclusions, operating time supports life cycle, temperature of the source in the cascade, receiver temperature in the cascade.

For checking the physical aspects of thermal point advantages, the experimental stand on the basis of the cascade thermal pump was assembled (Fig. 1).

During preliminary technical and economic calculations of the multifunction thermal point on the basis of the cascade heat pump, traditional systems of heating including heat pumping single-stage systems were analyzed. It is known that under different entry conditions, such as the cost of energy carriers, availability of connection of gas, the electric power, geographical arrangement of the building, geology, depth of occurrence of subsoil waters, orientation of the building concerning parts of the world, capital and operational expenditure is different. In one case the main gas, in another – bituminous coal, in the third the heat pump and so on will be an optimum system of heating. The option which reflects the most probable situation for the Midland of Russia is studied. One of the tasks of the multifunction thermal point is the creation of a system of heating, conditioning and hot water supply more favorable and energetically effective, than traditional systems. For continuation of further research, the maximum threshold capital expenditure and these values designate the lower bound of the economic feasibility of the developed installation.

Fig. 1. Experimental stand of multifunction thermal point

The above ways of increase in power efficiency at a certain value of capital expenditure allow developing the domestic thermal point providing the consumer with heat, cold and hot water. Besides, this thermal point is more economically attractive, than the existing systems for average Russian conditions.

5. Results of the multifunction thermal point block diagram development

For effective operation of the heat pump, it is necessary to use not only external sources of low-potential energy, but also internal overflows of energy in the building. Sewer drains, ventilating emissions, warmth of rooms in which air cooling is carried out (conditioning, or refrigeration chambers) belong to internal sources. External sources include: low-potential energy of soil, air, energy received from solar collectors. The structure of heat fluxes of the standard consumer with sources of excess heat and points of its consumption is presented in Fig. 2.

The flows shown on the scheme were used in cascades of the heat pump of different functions. Apparently from the drawing, the scheme contains low – average and high-potential sources of heat energy. These sources can be utilized, transforming to heat energy for heating, conditioning, hot water supply and ventilation.

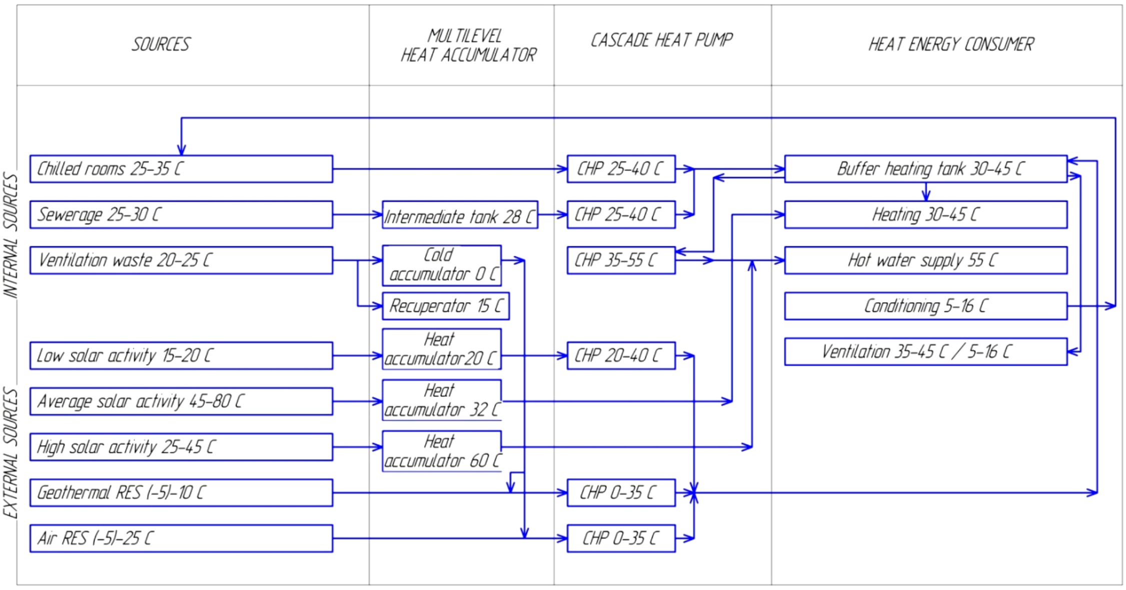

Fig. 2. The structure of heat fluxes of the standard consumer with sources of excess warmth and points of its consumption

6. Internal power sources – chilled rooms, sewerage, ventilation waste

For conditioning, the most effective mode is passive conditioning – use of soil heat exchangers for transfer of the building air heat in a soil. This type of conditioning belongs to "soft" as soil temperature depending on the region is 8–12 °C. At such temperatures, in peak loads, it is impossible to receive the cooled air with comfortable temperature. There are modes when deeper cooling of air because of requirements of comfort, decrease in air humidity is necessary or when using refrigeration chambers. In standard cases, when cooling rooms, the received heat is taken away in circumambient via the outside block in the freon conditioner. In the scheme of the multifunction thermal point, this heat is useful. It goes to buffer tank of the heating system where it can be used directly for heating of heat-insulated floors that is urgent for bathrooms even during the warm period of the year. This warmth can be directed to hot water supply, previously having lifted the potential in the corresponding cascade of the heat pump.

Sewer drains contain the considerable warmth lost when using hot water supply and heating due to warming up of the water supply system in the pipe when passing the tie of the heat-insulated floor. As receipt of sewer drains unevenly, the intermediate tank is provided in the scheme. When the tank is filled, the corresponding cascade of the thermal pump turns on and transfers warmth from sewer tank to buffer tank of heating. In this case, there is no sense to accumulate warmth in the additional accumulator of warmth as the sewer tank acts as it. Warmth from the buffer tank, as well as in the previous case, is used for heating and hot water supply via the additional cascade of the heat pump.

In ventilation of rooms, the warmth of waste air which is taken away in circumambient is lost. In standard schemes, recuperation (heating by the leaving air of the incoming) is applied at which part of warmth of waste air returns to the building. The possibility of application of recuperation is also provided in our scheme. In addition, in the scheme the possibility of energy storage in ice is implemented that is provided with cold accumulators on the principle of change of substance phase (water or other substances). The scheme operation principle is as follows: the thermal pumps connected to the external source (air and soil) take away warmth from the cold accumulator, freezing it, then switch to the main source. The dumped ventilating air passes through the cold accumulator and melts the heat carrier, giving warmth. The cold accumulator in this case acts as the buffer, allowing heating thermal pumps to work in the design condition and to refuse the additional heat pump only for active recuperation of the leaving air. Besides the use of temperature potential (0 °C above), working substance (water) of the cold accumulator allows to provide a higher coefficient of performance, than on their main source (soil and air) which in the dynamic mode have a temperature lower than 0 °C.

7. External renewable energy resources

In standard schemes, effective use of solar energy is difficult. Solar energy is used effectively only for hot water supply on the traditional algorithm: the boiler is warmed up from solar energy from 5–10 °C (water supply system temperature) up to the temperature which is provided by solar energy. If solar energy is not enough, then the tank is warmed up by the boiler to the established value. When heating, in which the temperature of the return water is 20–30 °C, we cannot use the bulk of low solar activity which is characteristic of the heating period. Therefore, relative division of operating modes of the system according to solar activity is provided in our scheme: low-potential, average and high-potential solar activity.

During off-season when solar activity small, and the need for heating and hot water supply nevertheless is available, in standard schemes it is difficult to use solar energy effectively because of the low reheat temperature of the coolant (15–25 °C). The solar collector works in such mode for a considerable part of the heating period, therefore there is a sense to use it. It is possible to accumulate energy at the low potential for the implementation of it. It is possible to use this energy as needed, transforming it up to the necessary temperature in the corresponding contour of the cascade thermal pump. Accumulation in the boiler of explicit warmth in this case is inefficient as at a low temperature of the coolant (water) and the big needs for heating dimensions of the accumulator will be too big. Therefore, in this case accumulation is most reasonable in compact heat accumulators. For example, when heating the house of 100 sq.m in the Rostov region of the Russian Federation, average heat losses make 10 kW (at outside temperature minus 22 °C), and during the transition period about 3.5 kW. Heating with such power and with the temperature of 35 °C, within 12 hours of night-time requires the boiler tank of 2,500 l, whereas the accumulator on change of phase of 300–500 l.

The energy which is saved up in the warmth accumulator is used by the corresponding cascade of the heat pump and goes to the buffer tank for heating. From this tank via the corresponding cascade of the thermal pump, warmth can go for hot water supply in addition.

On clear days of the transition period, high solar activity and heating of the coolant to 80 °C and more is possible. In this case, the use of high-potential heat energy; is the most effective for storage in the boiler and the subsequent use (for hot water supply). The density of energy is higher and in total with a low share of heat consumption on hot water supply in the overall balance of the building, the boiler sizes are small. The use of the high-potential energy from the solar collector for heating is inexpedient as for this purpose it is necessary to reduce its potential. Its share in the overall balance of the scheme is small and will be most effectively used for hot water supply.

The solar energy of average potential sufficient for heating, optimum to direct to heating, passing cascades of the heat pump and buffer tank of the heating system as irregularity of its receipt and consumption will cause too big size of the buffer tank. The warmth accumulator with a heat-retaining material having a change of phase corresponding to the temperature of the coolant heated in the temperature condition by solar energy of average potential acts as the buffering zone.

8. Low-potential sources – geothermal, air, solar

Geothermal renewable power doesn't need accumulation as soil itself acts as the accumulator of warmth of the off-season. Among all above-mentioned sources, it has the lowest temperature potential and therefore it needs to be substituted with sources with higher temperature potential for an increase in the coefficient of performance to the maximum. Low-potential warmth is transformed in the corresponding cascade of the heat pump and goes to the buffer tank. For this cascade, a priority source is the cold accumulator which is used in ventilation as has a temperature above 0 °C, at air temperature during the heating period lower than 0 °C there is lower than 0 °C and temperature of the heat carrier of a ground contour in the dynamic mode. When the entire heat-retaining material (water) of the cold accumulator turns into solidity, the cascade switches to the main source (soil/air), on a priority at what temperature potential is higher.

External air, as a renewable source of low-potential energy, is used in a completely analogous manner to a geothermal source. These sources work not in parallel, and replace each other. In the dynamic mode, warmth of a geothermal source will be in the range from minus 5 °C to minus 8 °C. It means the temperature of external air more setpoint value so far, it is more effective to use air for a high coefficient of performance of a heat pump.

9. Consumers of thermal energy

Heating by the multifunctional thermal point on the basis of the cascade heat pump is provided through a buffer tank to which all sources of warmth are connected. Heating devices – modern systems operating in the temperature range of 30–45 °C. For heating sources which use is followed by the least expenses of primary energy at the moment are a priority. Here the priority of sources in decreasing order is listed: solar energy, sewer drains, ventilating dumpings, air and geothermal renewables (depending on environment temperature). The criterion of priority are costs of transfer of energy from a source to the receiver. The least expensive is solar energy. The priority is built from the temperature potential of a source – it is higher than a coefficient of performance of a heat pump.

Hot water supply is provided by means of the boiler of indirect heating of the multifunctional thermal point where water with the temperature of 55 °C is collected. In the scheme, there are 2 sources for heating of hot water. The first – high-potential solar energy. The second – increase in the potential of the heat carrier of buffer capacity to level 55 °C due to the operation of the cascade of a vapor-compression heat pump.

10. Experimental research of the multifunctional thermal point

During the research, the massifs of the equations reflecting the processes happening in it were developed for receiving the main principal specifications of the thermal point. Specifically, processes of a heat mass transfer of freon and water contours of the thermal point were worked out. The boundary conditions of the mathematical model allowing to apply it in the conditions of moderate and continental climate were established. By scaling the developed mathematical model on everything a contour and clusters of the multipurpose thermal point on the basis of a cascade heat pump, it is possible to obtain reliable data and output principal specifications of the entire installation.

The calculated indexes of power effectiveness of contours of a cascade heat pump are presented in Table 1.

On the basis of Table 1, the chart of dependence of the coefficient of transformation on the difference of an evaporator and the condenser temperatures is constructed. The chart of COP dependence on the difference of temperatures of an evaporator and the condenser is submitted in Fig. 3.

During tests, first of all, the main characteristics of the heat pumping installation – coefficient of performance for all cascades were obtained. The coefficient of performance is in the range from 3.352 to 4.884. The difference of temperatures on all cascades – from 13 to 35.5 °C is also received.

Table 1

Indexes of power effectiveness of contours of the cascade heat pump

Purpose of a contour	Conditioning	Warmth of a kanalation	Hot water supply	Warmth of ventilation	Heating by the ground and air probe	
Unit thermal load of a heat pump, kJ/kg	174.35	174.35	148.035	144.116	127.929	127.929
The specific energy consumed by the electric motor, kJ/kg	35.698	35.698	36.743	35.916	36.222	36.222
Degree of compression	2.392	2.392	3.337	4.063	4.695	4.695
Intensity of compression in the compressor	6.426	6.426	5.301	5.28	4.647	4.647
Average temperature of the evaporator (source), °C	23	24.5	23	17.5	2	2.5
Average temperature of the condenser (receiver), °C	37.5	37.5	50	37.5	37.5	37.5
Evaporator and the condenser difference of temperature, °C	14.5	13	27	20	35.5	35
Coefficient of performance (electric power), COP	4.884	4.884	4.029	4.013	3.532	3.532
Specific consumption of primary energy	0.539	0.539	0.653	0.656	0.745	0.745
Exergy Energy efficiency	0.196	0.77	0.383	0.053	0.017	0.017

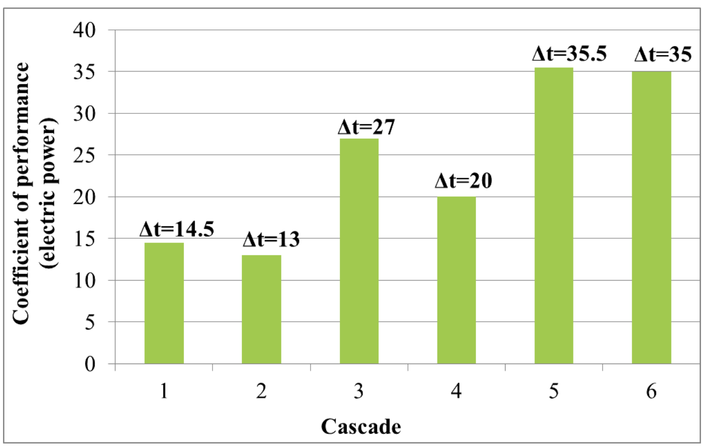

Fig. 3. Dependence of COP on the difference of temperatures of an evaporator and the condenser

11. Discussion of results of research of the multifunctional thermal point

In the article, the development of the multifunctional thermal point on the basis of the cascade heat pump providing the development of thermal energy and cold for heating, hot water supply, conditioning and ventilation is described.

– The advantage of our research is its complexity. Aspects of the use of secondary and renewable energy resources are described in detail. Complexity of the research allows to evaluate authentically the possibilities of utilization of heat energy and energy of cold. The drawback of the research is that the thermal point was not tested on real object yet – in the cottage.

– The conducted research will be useful to engineers in the design of power systems for new energy efficient buildings. Such thermal points can be applied not only in southern, but also in northern climatic areas. The thermal point transforms low-potential energy and household thermal emissions and also most efficiently uses all available energy resources, including renewable and secondary energy sources

– This project is a continuation of research on the design of the heat power complex on average seasonal temperatures. These researches were begun with our collective in 2012.

The prospects of manufacture, sale and applications of the developed thermal points are found in the field of construction and power supply These opportunities reveal a larger economy of organic fuel for heating and electric energy on conditioning. Earlier we conducted researches which showed that at the transformation coefficient more than 6, the heat pumping plant will compete with gas coppers on operational expenses.

In comparison with the existing installations of heating and ventilation, our installation is capable to utilize secondary energy sources. Our system has an opportunity to carry out ventilation of the building and as shown in [7] the system with ventilation are less widespread. But the main advantage of our thermal point in multifunctionality is terminating. As a rule, the existing systems are aimed at one of the tasks: heating, hot water supply, conditioning or ventilation [8].

The drawback of the research is its applicability not to all climatic conditions. The thermal point is developed for the Midland of Russia and similar climatic conditions of the European countries (The North of Germany, Poland, Sweden, etc.). It cannot open completely the opportunities, for example, in very northern regions of Russia or in the northern countries.

Development of the project will consist in the complete assembly of the multipurpose point in various modifications. After assembly, it is necessary to make full-scale tests which can yield various results. Perhaps, there is a threat of obtaining low effectiveness of some clusters of the thermal point, for example the knot of the fissile conditioning. In this case, the consumer will need to use only passive conditioning.

12. Conclusions

1. In the article, the development of the thermal flows utilization scheme for the standard consumer with the definition of excess warmth sources and points of its consumption is described. The flows were used in cascades of a heat pump for various purposes. Low-, medium- and high-potential sources of heat were analyzed, which can be disposed of, converted into thermal energy for heating, air conditioning, hot water supply and ventilation.

Heating power in the thermal point – to 20 kW, cooling capacity of the air conditioning system – 16 kW, the power of hot water supply – 10 kW. The ventilation system can work both for heating, and for conditioning.

2. Methods of increase in power efficiency of the thermal point were given in the article. The increase in the utilization rate of primary fuel is achieved by utilizing waste heat from sewage, exhaust air from a ventilation plant, as well as the beneficial use of thermal and refrigeration energy as by-products of heating/conditioning. The coefficient of performance for all circuits is in the range from 3.352 to 4.884. The choice of pumps is carried out due to the results of the hydraulic calculation of the contours. Thus, the results of thermal and hydraulic calculations create values of the final design factor of transformation of the entire multifunction thermal point. Hydraulic calculations of thermal point cascades showed that resistance is in the range from 12 to 171 kPa.

3. Internal sources of energy are cooled rooms, sewerage, ventilation discharge. External sources are defined as solar activity (three levels), geothermal energy (–5, –10 C), energy of air heat (–5, –25 ^{o}C).

4. Consumers of heat energy – heating system (20 kW), hot water supply system (10 kW), ventilation system in winter. Consumers of cold energy – air conditioning (16 kW) and ventilation in summer.

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