Approach development to the pipeline networks design an integrated heat and cold supply system on the example of Yakutsk city

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Abstract. The pipeline networks design approach for integrated heat and cold supply systems based on absorption chillers has been developed. Within the framework of the approach, following tasks are solved: modeling consumers demand for cooling; hydraulic calculations of district cooling pipeline systems; technical and economic calculations to choose the optimal layout of pipeline systems; heat supply and cold supply systems repair and commissioning works compatibility assessment, and modeling of thermal interaction between permafrost massif and cold supply pipeline. The study of integrated heat and cold supply systems was carried out on the example of a Yakutsk city quarter using the developed approach to determine optimal variant of the system. The simulation results showed that district cooling pipelines can be laid underground with the implementation of measures to ensure preservation of permafrost soil temperature regime.

Keywords: *integrated energy systems; district cooling; absorption chiller; fancoil; pipeline systems design; hydraulic calculations; permafrost soils.*

Problem statement

Currently, studies on integrated energy systems are increasing worldwide aimed at optimizing the production, distribution and consumption of energy in several forms (electricity, heat, cold, gas supply, etc.), considering them as interconnected subsystems of a single system. The introduction of integrated energy systems can improve energy efficiency, reduce energy losses, and enhance the overall reliability of energy systems [1, 7]. For example, waste heat from a power plant can be used to supply consumers with cold [2-4]. Overall, research and development on integrated energy systems are an important step towards an efficient and sustainable energy future.

The introduction of integrated systems in the Russian Far East requires re-evaluation of existing methods and models due to specific climates. For example, the climate in the Republic of Sakha (Yakutia) has cold winters and hot summers in the permafrost zone, and

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higher standards of reliability and performance are imposed on engineering systems. Climatological data analysis shows that the republic has low calculated outdoor air temperatures for heating systems design (up to -60°C in the Oymyakon village), and there are summer temperature peaks, which often reach plus 35 - 38°C in some parts of the republic [6]. Furhtermore, permafrost thickness in the republic central zone reaches several hundred meters in some places.

The objective of this study is the development of integrated heating and cooling systems pipeline networks in regions with cold winters and hot summers in Russia, located in the permafrost zone. An approach to the design of pipeline systems has been developed with additional consideration of interaction processes with permafrost. The purpose of the district cooling (DC) pipeline networks design approach is to select the most appropriate technical solution: pipeline laying method, consumers connecting scheme, and pipeline material. The end result is a complete list of DC pipeline system elements and equipment, their technical parameters, connection schemes, hydraulic modes, and pipeline temperature regime. Figure 1 shows a schematic diagram of the approach.

District cooling pipeline networks design approach

Stage 1. The design methodology begins with calculations of cooling demand. The potential consumers of the district cooling system (DCS) are city buildings located near the chiller station, which can be situated next to central heating points (CHP). Consumers are divided into 5 archetypes: residential, administrative, hospital, retail space, and hotel. Cooling demand is calculated using BEM methods of energy consumption mathematical modeling in buildings (Building Energy Modeling). The modeling is performed using the eQuest program based on the DOE-2 program.

Cold consumption hourly modeling is performed depending on the ambient temperature, solar insolation, number of floors, area, internal heat inflows, walls thermal conductivity, etc. Yakutsk city energy system modeling was performed using the average statistical meteorological data of EnergyPlus [8]. The cold load hourly simulation maximum values are taken as the DCS operating parameters.

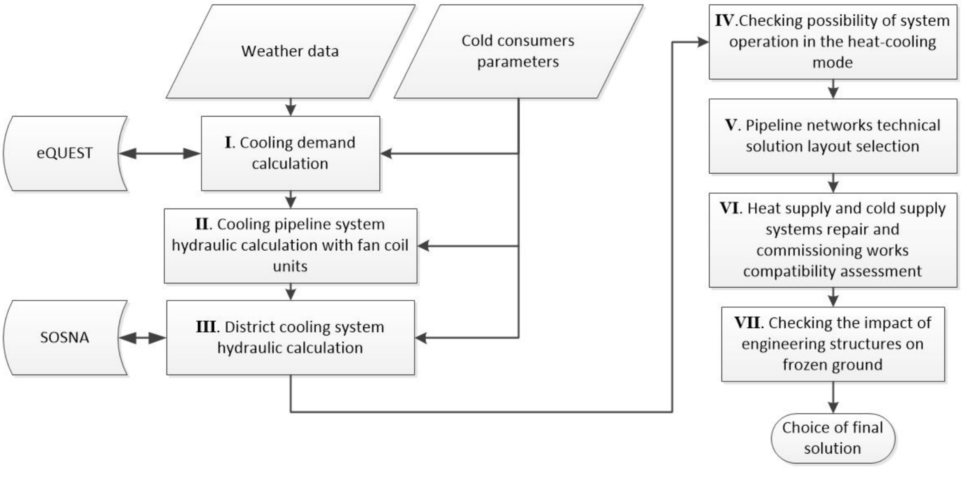

Fig. 1. Approach scheme.

Stage 2. The hydraulic calculation of cooling supply pipeline system with fan coil units inside buildings is made on the basis of the calculated cold loads. The purpose of the second stage is to calculate the required building entrance pressure. Pipeline diameters are calculated based on the recommended flow rate of fluid in pipelines and available pressure drop [9-13]. The temperature difference in cooling system pipelines is very small and the change in water density is insignificant, so the natural circulation pressure (negative) can be neglected [14].

The consumers available head $H_{\text{available head}}$ must take into account buildings pile foundations height h_{pile} built on permafrost soils, lower technical floor height $h_{\text{technical floor}}$, building height h_{building} and pressure losses sum in the building's cold supply system ΔP.

$$H_{\text{available head}} = h_{\text{pile}} + h_{\text{technical floor}} + h_{\text{building}} + \Delta P \quad (1)$$

Stage 3. The district cooling system quarterly pipeline networks optimal parameters are determined. The district cooling system pipeline networks design task is to minimize the discounted payback period, taking into account the fulfillment of technological restrictions and conditions. This task includes the calculation of hydraulic pressure losses due to friction, the calculation of local energy losses during the water flow in pipeline various elements, as well as other elements of the hydraulic system, the calculation of heat exchanger parameters, thermal calculations of insulating structures, the calculation of pumping equipment parameters, the calculation of technical and economic system parameters [11-13]. Given are: time period; pipeline lengths; number of pipelines; air conditioning demand; operating water temperatures; water dynamic viscosity; outdoor air temperature; pipes thermal conductivity; insulation thermal conductivity; heat transfer coefficient from outer layer insulation to air.

As a result of the tasks solving, for each variant of DCS, pipeline networks optimal parameters are calculated: pipelines optimal internal diameters; pipeline wall thickness; insulation thickness; average flow rates, liquid mass flow.

In further work, it is planned to use new generation algorithms to determine optimal parameters of heat supply systems, implemented in the SOSNA software package [15]. The program uses the method of multi-loop optimization with solution successive improvement, based on dynamic programming. It will be necessary to upgrade the program to determine the DCS hydraulic system optimal parameters: change in operating temperatures of direct 5 °C and return pipelines 15 °C; increase liquid values of dynamic and kinetic viscosity; adding hydraulic resistance chiller and fan coil units.

Stage 4. The possibility of existing quarterly heat supply systems (HSS) operating in heat and cold supply mode is checked. The main technical restrictions on use of existing HSS in the cold supply mode in summer are compliance water average flow rate and condensate formation prevention on the aboveground pipelines surface.

$$\omega_{\min} \leq \omega \leq \omega_{\max},\ m \in M \quad (2)$$

Stage 5. The optimal variant choice for the district cooling pipeline system layout is carried out in accordance with a standard integrated methodology for assessing investment project effectiveness. The options differences are the method of laying pipelines (underground, aboveground), consumer connection scheme (dependent, independent), and pipeline material (high-density polyethylene (HDPE), steel).

A technical solution with the shortest discounted payback period is selected, subject to the following technical restrictions:

average flow rate, similarly according to formula (2),

consumer water pressure:

$$H_{\min} \leq H_i \leq H_{\max},\ i \in I \quad (3)$$

balance between total load and consumers cooling demand:

$$Q_{ch} = \sum Q_i,\ i \in I \tag{4}$$

liquid flow balance between main section and branching consumer's sections:

$$q_{main} = \sum q_i,\ i \in I \tag{5}$$

Stage 6. The compatibility assessment of heat supply and cold supply systems repair and commissioning works is carried out, along with the verification of the possibility of carrying out additional work during summer for maintaining cold networks. In further work, it is planned to take into account the operation impact assessment in the heat and cold supply mode on depreciation costs and premature wear of heat supply networks.

Stage 7. Permafrost soils in Yakutsk city create technical restrictions for DCS underground pipelines that must be taken into account when designing. A thermotechnical calculation of cold losses during transportation through DCS underground pipelines networks must be carried out. It is necessary to perform a numerical calculation of dangerous geocryological processes that affect the stability and reliability of the system permafrost - pipeline, resulting from their thermal interaction. It is required to assess the thermal interaction of DC pipelines with the frozen soil array and to check the technical feasibility of underground laying, to assess the impact on the thermal regime of frozen soils.

The heat transfer process in soil mass is described by a quasilinear parabolic equation with discontinuous coefficients, taking into account the "water-ice" phase transition [16]. Thermal interaction modeling of the soil mass with the pipeline is carried out in COMSOL Multiphysics 6.0 software package, taking into account pore moisture phase transitions. The computational domain is a transverse section of a soil mass 10 m wide and 6 m deep with pipelines laid at a depth of 1 m parallel to each other [4]. The pipelines laying method is underground, non-channel.

The approach practical application example

The developed approach is applied to the study of Yakutsk quarter 167. This quarter includes 8 buildings, including 7 five-story residential buildings and 1 hospital. All consumers are connected to district heating through central heating station No. 400. The pipeline heat networks are made in above-ground laying on concrete supports. The total length of heating networks in a single-pipe design is 445.1 meters.

District cooling system layout options considered in the study differ in pipe laying method, consumer connection scheme, and pipelines material. Technical and economic parameters calculations were carried out according to a standard integrated methodology for assessing investment projects effectiveness. As a result of applying the developed approach, the best DC pipeline networks layout option was chosen - underground laying of pipelines with direct connection of consumers, the pipeline material is HDPE.

The distance between pipes for underground laying is one meter in the developed model. Internal diameter of the pipelines is 268.6 mm and wall thickness is 23.2 mm. The pipelines are covered with a heat-insulating sheath made of polyurethane foam with a thickness of 25.4 mm. The cooling source is chilled water, water temperature in forward direction is 5°C, in reverse direction 15°C. The water flow rate in pipelines is 1.059 m/s. The thermal interaction modeling results showed that the engineering system operation has a strong impact on the soil upper layers temperature regime, and below a depth of 2.5 m, the change in soil temperature is not significant [4]. In turn, the support-concrete piles bearing capacity with a length of 6–12 meters depends on the strength of the soil much below a depth of 2.5 m.

Conclusion

An approach has been developed for designing district cooling pipeline networks with chiller-fancoil building cooling technology. The stages of the approach application are described. The approach was practically applied to the Yakutsk city quarter 167 example. Calculations results of hydraulic regimes were obtained, the pipelines diameters, pumping equipment parameters, laying pipelines methods, consumers connection schemes, pipeline material were determined. Economic indicators were assessed for the system. The calculation result in the determination of the optimal DCS variant – underground pipeline laying with direct connection of consumers, pipeline material - HDPE. The simulation results showed that underground laying of the district cooling pipelines is possible while ensuring measures to preserve the permafrost soils temperature regime. According to the initial assessment, the cooling cost can be 1.9-2.4 rubles/kWh, and the discounted payback period is 17-27 years.

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