



Application of Various Computer Tools for the Optimization of the Heat Pump Heating Systems with Extraction of Low-Grade Heat from Surface Watercourses

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Abstract. A number of computer tools have been applied to solve optimization issues of the heat pump heating systems with extraction of low grade heat from surface watercourses are described. Among them: 3D modeling in CAD KOMPAS-3D, calculations using numerical methods and programming elements in MathCAD, measurements using a specially designed computer monitoring system. The example of a novel design of the submersible water-brine heat exchanger is presented.

Keywords: Water-source heat pump · Low-grade heat · Watercourse Monitoring system

1 Introduction

In many countries heat pump installations (HPI) implemented and actively used in the heating sector for a long time. Especially they are suitable for heating of private houses with no connection to the main gas pipeline where the electric grid or deliverable fuel can be the only power sources. The main obstacles for a more widespread adoption of such plants are the high cost and, consequently, long payback period of installations using heat of soil or aquatic environments. On the other hand, more affordable air source heat pumps are characterized by low efficiency at low temperatures of outdoor air. The last type is suitable mostly only for regions with relatively mild climates.

A significant share of the total capital expenditure in the construction of HPI is the cost of the heat-transfer system for the selection of low-grade heat. If you use ground or groundwater as a heat source significantly reduce installation costs in most cases not possible due to the need for a huge excavation. However, in the case of the existence of the open water heat source suitable in parameters there is an opportunity to reduce installation costs.

Particularly promising in this respect is the use of the heat of the watercourse. Analysis of the situation with the practice of creating such HPI shows that, due to the low experience and lack of research in this area, in many cases not optimal solutions are used. That leads to increased costs, and sometimes to situations where the characteristics of the installation are much worse than expected. In some cases when you try to design HPI with the use of classical methods of selection of heat from the water mass the results of preliminary calculations make this project unattractive to the customer, and this idea was rejected. In the same time more in-depth approach to the issue and the use of other technical solutions could make installation much more cost-effective.

It should also be noted that in addition to natural aquatic environments, there are many relatively warm water bodies and watercourses, bearing the bargain anthropogenic or geothermal heat, which are at HPI is possible to significantly reduce the cost of heating.

There are several possible methods of selection of heat from a reservoir or watercourse [1]. The most simple, inexpensive and effective at first glance seems to be open loop without intermediate heat carrier, that is, with the extraction and subsequent discharge of water. But this scheme is not possible in all cases and due to significant drawbacks usually not recommended for use. Thus, in practice mostly applied passive methods for the selection of heat with circuit of an intermediate heat carrier. The most widely used method is based on the laying on the bottom of the so-called mats made of polyethylene pipes. That can be called an analog of the horizontal ground collectors at HPI, which use the heat of the soil. However, despite the simplicity of design and low cost of polyethylene pipes, such a scheme of selection of heat from the aquatic environment is not always the most rational.

We reviewed ways of enhancing technical and economic characteristics of heat pump systems using the heat of the water environment, especially the watercourse.

A water stream in full can be called a medium with high heat transfer, and to achieve the best technical-economic performance of heat pumps, which use the heat of the watercourse, it is advisable to use this feature. In Fig. 1 is a block-diagram showing the principal steps to be taken in the design of the heat exchanger and the overall contour of the selection of low-grade heat from the watercourse to achieve estimated goals.

As can be seen from the diagram, this way requires a more careful approach to the calculation and optimization of parameters, but designed according to this manner HPI with metal immersion heat exchangers in many cases should be more profitable than HPI with bottom mats, and in some cases this is the only acceptable solution.

2 Practical Solutions

One can offer several different designs of water-brine heat exchangers, designed for selection heat from the stream corresponding to the above criteria of maximum efficiency. A variant of such heat exchanger basing on use of a flat coil of metal tubing of circular cross-section is modeled in CAD KOMPAS-3D and shown in Fig. 2 [2].

In this design, enhancing the heat transfer is primarily achieved through the use of the natural movement of water in the direction of flow in the flow core for heat transfer

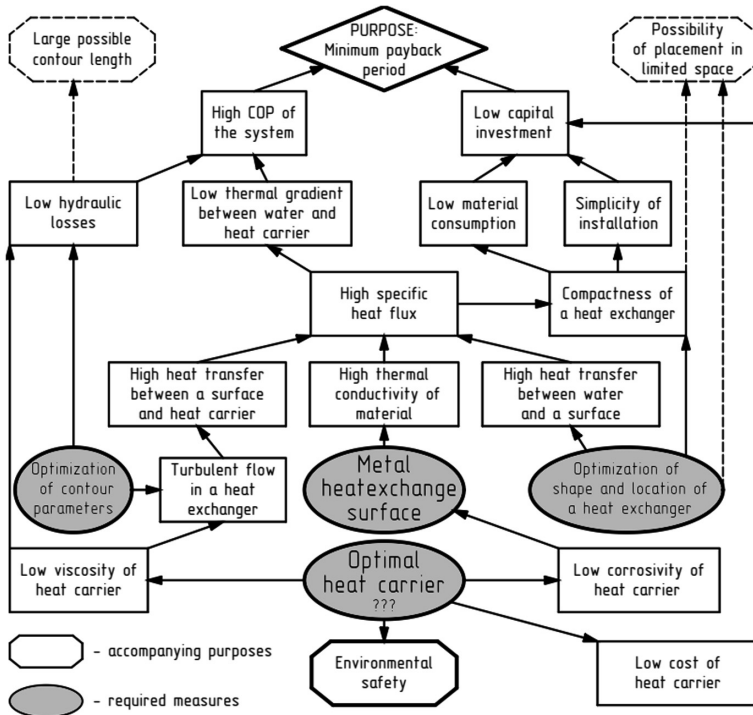


Fig. 1. Possible ways to improve technical and economic indicators of heat pump based systems in case of warmth selection from a watercourse.

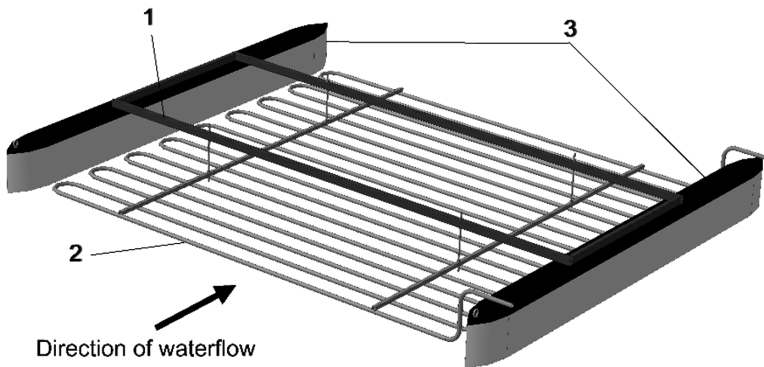


Fig. 2. Submersible floating water-brine heat exchanger: 1 – frame, 2 – coil-pipe, 3 – floats.

processes intensification. It is known that the rate of flow of water in an open channel takes the highest values near the surface, and in the case of the ice-cover area of greatest flow velocity is shifted inland, closer to the middle of the stream. For installing the heat exchanger in the zone of greatest velocity it is equipped with floats, which

gives it buoyancy and ropes and anchors so that the heat exchanger can be positioned and retained in the area of best heat transfer (Figs. 3 and 4).

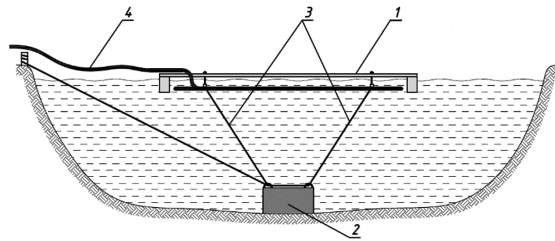


Fig. 3. Arrangement of the heat exchanger in a watercourse: 1 – floating heat exchanger, 2 – anchors, 3 – ropes, 4 – flexible hose.

The improving heat transfer characteristics also occur due to the fact that this construction and arrangement of the heat exchanger permit to direct the flow of water in the direction of straight segments of pipe of the coil that intensify the process of heat transfer.

When using the heat exchanger in the freezing conditions of the watercourse for the period the ice-cover it is advisable to pull the cables closer to the bottom (Fig. 4b, d), and the rest of the time to keep the surface of the watercourse (Fig. 4a, b), thus the coil will be in the areas of highest velocity and will not be frozen in the ice. In the same time, even a significant decrease in the level of water in the canal will not result in drying up pipes of the coil, as the heat exchanger will start to drop after the water level.

To test the described method of extraction of heat from the watercourse, as well as for testing other technical solutions aimed at improving technical and economic indicators of HPI, there was collected the experimental setup, which was a heat pump heating and air conditioning system of residential house water-to-air type with capacity up to 7 kW (Fig. 5). The system of selection of low-potential heat based on the floating heat exchanger was mounted on a specially selected ice-free watercourse (Fig. 6).

3 Calculation Program

For this scheme, the efficiency of the entire system depends on parameters such as the size and configuration of the submersible heat exchanger, the composition and specific consumption of heat carrier and others. The total coefficient of performance (COP) of the whole installation is also affected by the power required for circulation. To determine the best configuration and optimization of all parameters for the specific initial conditions previously a special calculation program in MathCAD was compiled [3].

The process of heat carrier heating in a coil-pipe, not covered by ice, is described by the differential equation as below:

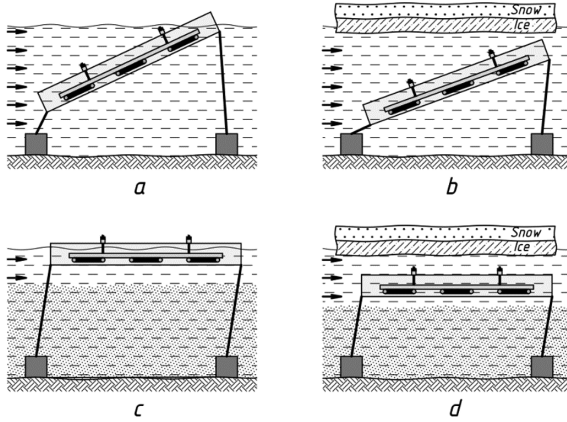


Fig. 4. Examples of arrangement of the heat exchanger in a watercourse depending on conditions: a – clear channel; b – existence of an ice cover; c – silted channel; d – the presence of bottom sludge and ice cover.

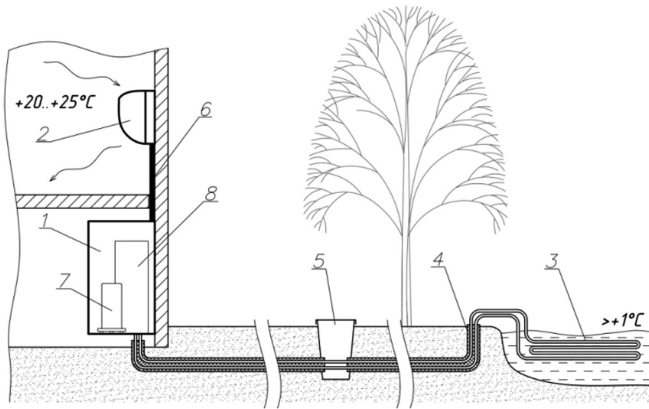


Fig. 5. Schematic diagram of the experimental installation 1 – outdoor unit; 2 – indoor unit; 3 – water-brine heat exchanger; 4 – heat-insulated underground pipeline; 5 – caisson; 6 – freon line; 7 – compressor; 8 – brine-freon heat exchanger.

$$\frac{dT(x)}{dx} = \frac{\pi \cdot d \cdot K \cdot (T_R - T(x))}{G \cdot C}, \tag{1}$$

where $T(x)$ – temperature of heat carrier along the path through the heat exchanger; d – average pipe diameter; K – coefficient of heat transfer from water to heat carrier; T_R – temperature of river water; G – flow rate of heat carrier; C – specific heat of heat carrier.

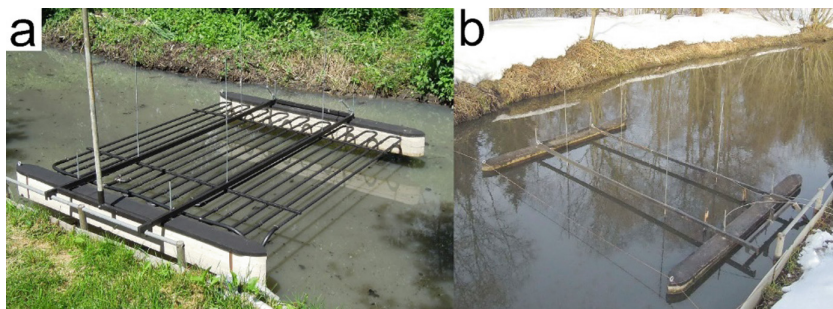


Fig. 6. Experimental sample of the floating heat exchanger: a – lifted over water in the summer; b – in working position in the winter

In cold countries such as Russia, Finland, Sweden, etc. the operation of the designed system can be associated with a possibility of icing, that is with a formation of ice layer of different thicknesses on walls of the heat exchanger, which is located in water [4].

To design heat exchangers taking into account the possibility of forming an ice layer on the coil-pipe surface, another differential equation was derived:

$$\frac{dT(x)}{dx} = \frac{\pi \cdot (d_O + 2 \cdot \Delta_I(T(x))) \cdot \alpha_I(\Delta_I(T(x))) \cdot (T_R - 273.15)}{G \cdot C}, \quad (2)$$

where $T(x)$ – temperature of heat carrier depending on the path traveled through the heat exchanger; d_O – outside pipe diameter; $\Delta_I(T(x))$ – steady-state thickness of the ice layer on the surface of the pipe, depending on the temperature of heat carrier at a given point of the coil-pipe; $\alpha_I(\Delta_I(T(x)))$ – coefficient of heat transfer from water to the ice-covered pipe, depending on the thickness of the ice layer; Δ_I at a given point of the coil-pipe; T_R – temperature of river water; G – flow rate of heat carrier; C – specific heat of heat carrier.

This equation is obtained at the condition that the temperature of the outer surface of the ice layer is 0°C (273.15 K), which means a constant temperature gradient between river water and the ice surface at a variable coefficient of heat transfer, which depends on the outer diameter of the ice covered pipe:

$$\alpha_I(\Delta_I) = \frac{1}{2} \cdot \lambda_W \cdot \frac{\text{Pr}_W^{0.38}}{\text{Pr}_W} \cdot \sqrt{\frac{V_W}{v_W \cdot (d_O + 2 \cdot \Delta_I)}}, \quad (3)$$

where λ_W , Pr_W , v_W – thermal conductivity, Prandtl number and kinematical viscosity of river water, V_W – the speed of water in the river, d_O – outside pipe diameter.

The dependence of ice layer thickness on heat carrier temperature at a given point of the coil-pipe $\Delta_I(T(x))$ is in turn calculated out of the constancy of the linear density of the heat flux through the pipe wall in this section:

$$\begin{aligned} & \left(\frac{d_I + d_O + 2 \cdot \Delta_I(T(x))}{2} \right) \cdot K \cdot (T_R - T(x)) = \\ & = (d_O + 2 \cdot \Delta_I(T(x))) \cdot \alpha_I(\Delta_I(T(x))) \cdot (T_R - 273.15), \end{aligned} \quad (4)$$

where d_I, d_O – inside and outside pipe diameter, K – coefficient of heat transfer from water to heat carrier, $\alpha_I(\Delta_I(T(x)))$ – coefficient of heat transfer from water to ice-covered pipe, depending on the thickness of the ice layer at a given point of the coil-pipe.

The differential equation (1) has an analytic solution, which simplifies the calculations:

$$T(x) = T_R - \exp\left(\ln(T_R - T_0) - \frac{\pi \cdot d \cdot K \cdot x}{G \cdot C}\right), \quad (5)$$

where T_0 – temperature of heat carrier at the inlet to the coil-pipe.

The differential equation (2) does not have a simple analytical solution, therefore, to calculate heat carrier temperature in this case numerical methods for solving differential equations available in the MathCAD environment, such as the “rkadapt” and “rkfixed” commands, are used.

The algorithm of calculation and optimization of the river heat exchanger includes a lot of subroutines, conditional operators, cycles and iterations, and the performed works, thus, demonstrates the wide possibilities of the MathCAD package, which proved to be indispensable for the solution of the task.

4 Monitoring System

When conducting research of the experimental heat pump system operation, it is necessary to monitor simultaneously a multitude of operating parameters. One of the main tasks is to optimize the installation characteristics. Therefore, it is necessary to monitor in real time the result parameters such as performance and COP of the installation that can't be measured directly, but can only be calculated from other data.

In this regard the special system for monitoring the operating parameters of the installation with the possibility of receiving in nearly real-time mode (with an insignificant delay compared to the characteristic reaction time of the installation) the values of performance and efficiency indicators has been developed.

The monitoring system is based on a simple 8-channel analog-to-digital converter (ADC), however, due to the non-standardity of the task, it is performed according to the developed novel scheme and assumes a special algorithm for data processing by means of a specially written plugin for a personal computer. Besides, a method has been developed that allows one ADC channel to feed a signal from two or more sensors, which greatly expands the capabilities of ADC.

In system it is used the following sensors: many temperature sensors based on NTC thermal resistors, electric power meter, heat carrier flow meter, compressor and fan motor speed sensors. Other indicators are calculated on the basis of data from these sensors.

Another feature of the system (to be exact the feature of the plugin) is the function of automatic detection the steady-state operating modes of the installation with the calculation and output of their duration and averages for the steady-state indicators. Heat pump system with a long contour of the intermediate heat carrier and large volume of liquid in it has significant inertia and any purposeful change during the experiment of any initial parameter or essential change of conditions, independent of the operator (for example, changes in air or watercourse temperature) is accompanied by a prolonged (from several minutes to tens of minutes) transition process which in most cases isn't of interest for analysis. To study the influence of various parameters on the efficiency of the installation, it is required to determine the average performance and efficiency indicators over long periods of steady operation, accompanied by only a small fluctuation in values. Due to these it was important to provide that the monitoring system automatically according to defined criteria detects such established operating modes and collects data on them in the separate table (file).

The Fig. 7 shows the program window while the system is running, which displays the current system parameters and the graphs of their changes over time.

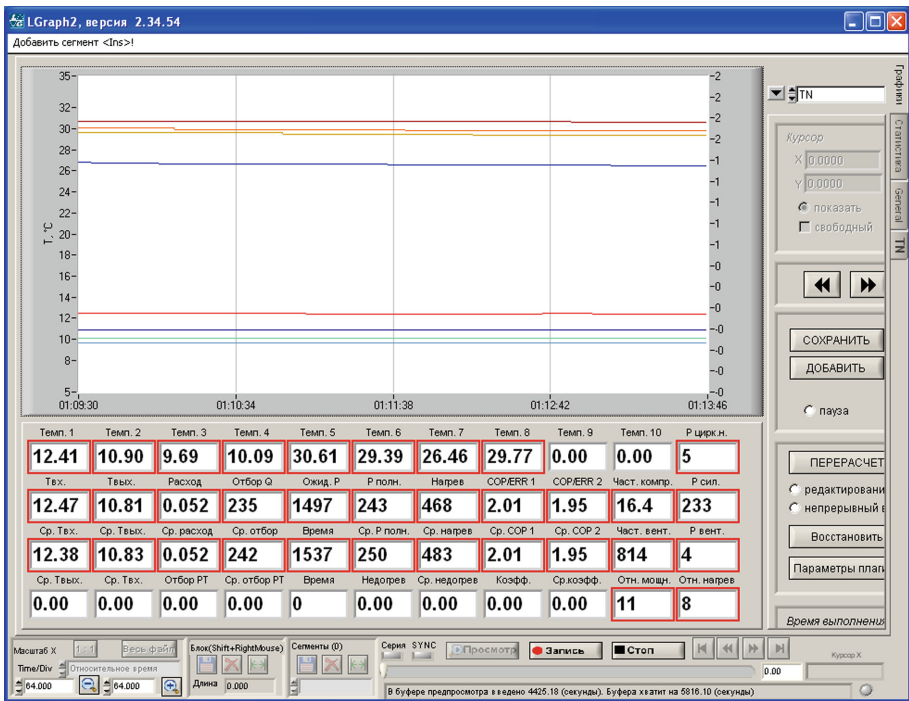


Fig. 7. The program window of the monitoring system

Thus, the monitoring system provides the receipt and processing of a large amount of data in an automatic mode, what is almost impossible to achieve by manual

measurement of individual parameters due to the large number of simultaneously changing indicators.

5 Results

Mainly, the mounted experimental setup with the monitoring system was necessary for check and specification of the calculation program, which further allows to carry out studies on the mathematical model and to calculate an optimal configuration for any case. But some visual comparative results can be obtained directly from the experimental setup. For example, Fig. 8 shows dependence between linear heat transfer coefficient of the coil-pipe and zone of the arrangement of the floating heat exchanger.

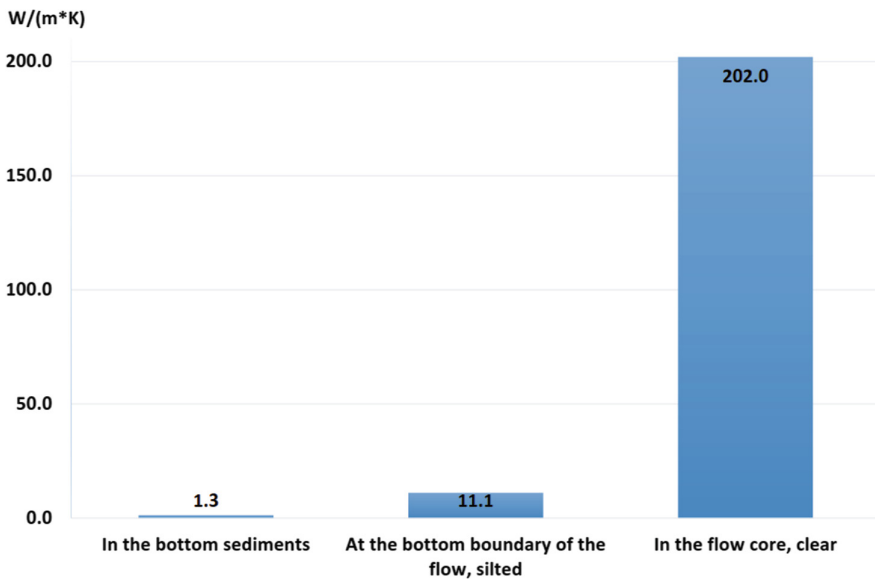


Fig. 8. Experimental results of the comparison of the linear heat transfer coefficient of the coil-pipe for various conditions of an arrangement

As can be seen, the arrangement of the coil-pipe in a flow core greatly intensifies heat exchange. That explains why it is possible to refuse huge bottom mats in favor of compact metal heat exchangers.

6 Conclusion

The use of surface water, especially channels, small rivers and other watercourses as sources of low-grade heat for heat pump systems allows reducing the cost of such systems. To achieve high technical and economic indicators such HPI new, most

optimal in each case technical solutions are required and nowadays computer tools are very useful in solving these problems.

As one of these solutions can serve the proposed submersible floating water-brine heat exchanger. Introduction to the practice of this and other solutions that can reduce the cost of heat pump installations and payback period would promote wider dissemination of such systems. A particularly promising application of systems such as described above appear to be in areas where widely used irrigation system for watering and irrigation of agricultural structures. Such areas include some territories of southern Russia, southern Kazakhstan, almost all territory of Uzbekistan, and so on.

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