Chapter 7
Innovative Instruments for Extraction of Low-Grade Heat from Surface Watercourses for Heating Systems with Heat Pump

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7.1 Introduction

In many countries heat pump installations (HPI) are implemented and actively used in the heating sector for a long time, especially for heating of private houses, where they are a good alternative to gas, oil, or solid fuel boilers as well as devices with direct electrical heating in cases when there is no connection to the main gas pipeline and the electric grid or deliverable fuel can be the only power sources. The main obstacles for a more widespread adoption of such plants are, on the one hand, the high cost and, consequently, long payback period of installations using heat of soil or aquatic environments and, on the other hand, low efficiency at low temperatures of more affordable heat pumps using warmth 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 heat pumps that use heat soil or aquatic environments is the cost of the circuit arrangement for the selection of low-grade heat. If you use ground or groundwater as a heat source to significantly reduce installation costs, in most cases it is 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—a water body or watercourse—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, this practice is not

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the optimal solution since it may lead 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, although more in-depth approach to the issue and the use of other technical solutions could make such an 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 possible to significantly reduce the cost of heating.

7.2 Possible Ways to Improve Indicators

There are several possible methods of selection of heat from a reservoir or watercourse. 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 is not possible in all cases and, in analyzing significant drawbacks, usually not recommended for use. Thus, in practice the applied passive methods for the selection of heat with circuit of an intermediate heat carrier are the most widely used methods for laying the bottom of the so-called mats made of polyethylene pipes that can be called by analogy 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.

Fig. 7.1 shows a block diagram which describes the rationale for choosing key technical solutions in the case of selection of heat from the environment with low heat output (emission), such as ground [1]. The scheme allows understanding the reasons why the collectors made of polyethylene pipes are the best solution in such conditions.

In the case of selection of heat from the water environment, the picture changes [2]. A fixed water mass in stagnant water, especially in the bottom region, cannot be considered as a source with high heat transfer, but the arising convective flows allow to use schemes with a higher density of the heat flux and less heat transfer surface. Thus, in some situations, large-scale bottom collectors of polyethylene pipe can become more compact, submersible heat exchangers, and in some cases they are already used in practice in creating such heat pump installations. However, today there is a lack of available data and an absence of any comparative studies that would accurately determine the optimal solution in each specific case—the selection of heat from the water.

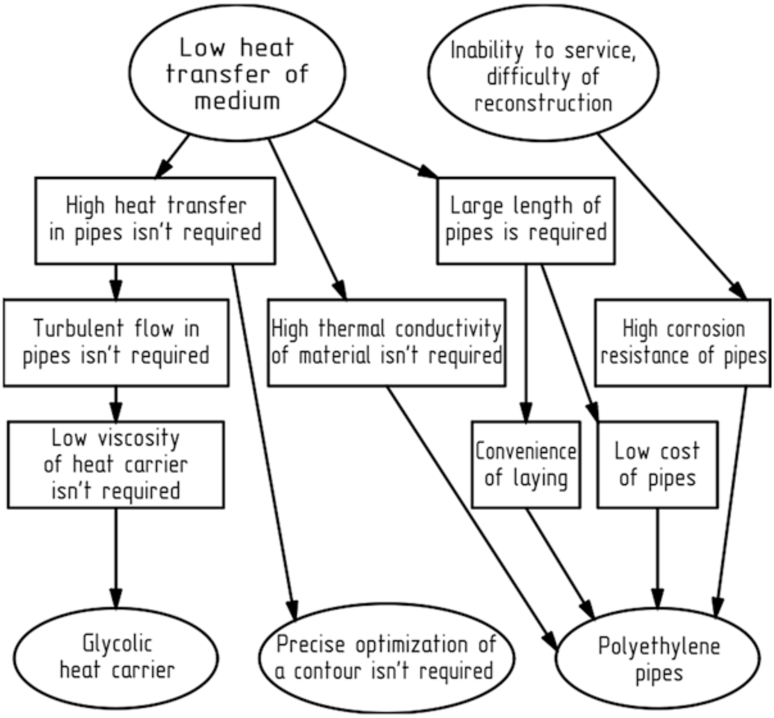

Fig. 7.1 Logic of a choice of optimum technical solutions for warmth selection from medium with a low heat output

In turn, 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. 7.2 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 the estimated goals.

As can be seen from the diagram, the possible ways require 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.

The important and difficult issue is the choice of the optimal heat carrier meeting all the requirements. In conditions of near-zero temperatures, viscosity starts to play a crucial role. High viscosity at a low temperature of most used solutions, especially based on propylene glycol, significantly affects the performance and makes inefficient metal heat exchangers. Moreover, this factor significantly affects the characteristics of the classic collectors of polyethylene pipes. Thus, the question of choosing the best heat carrier is relevant for any schemes for the selection of low-grade heat.

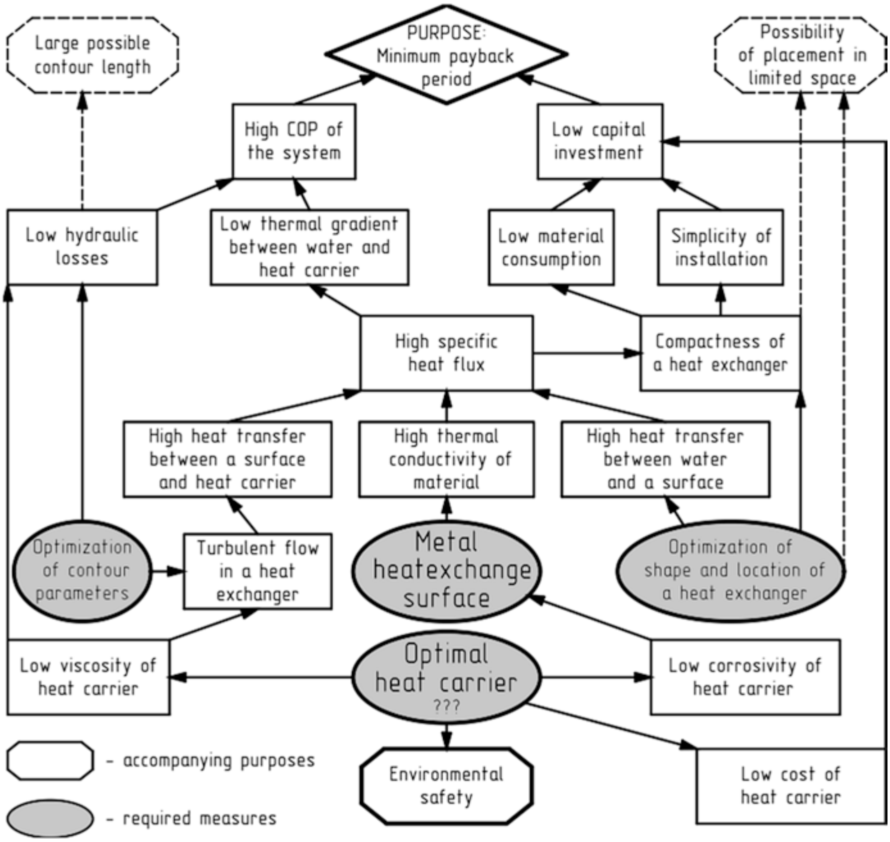

Fig. 7.2 Possible ways to improve technical and economic indicators of heat pump-based systems in case of warmth selection from a watercourse

Analysis of a large number of used in various fields low freezing compounds showed the absence of heat carrier, which would meet all the requirements, but a compromise may be the use of a solution of calcium chloride, despite its corrosiveness, which largely will be mitigated by the use of certain corrosion inhibitors. In addition to low viscosity, the fluid has low cost, which is also a significant factor affecting the overall installation cost, as well as the environmental safety.

7.3 Practical Solutions

One can offer several different designs of water-brine heat exchangers, designed for the selection of heat from the stream corresponding to the above criteria of maximum efficiency. A variant of such heat exchanger based on the use of a flat coil of metal tubing of circular cross-section is shown in Fig. 7.3 [3].

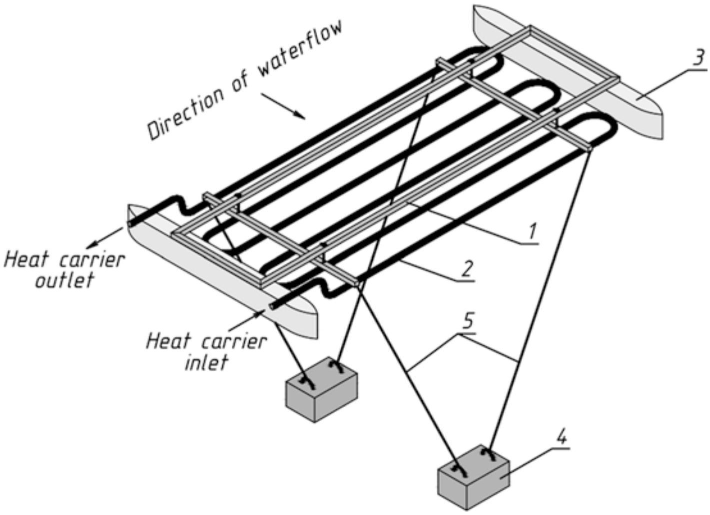

Fig. 7.3 Submersible floating water-brine heat exchanger. *1*—frame, *2*—coil-pipe, *3*—floats, *4*—anchors, *5*—ropes

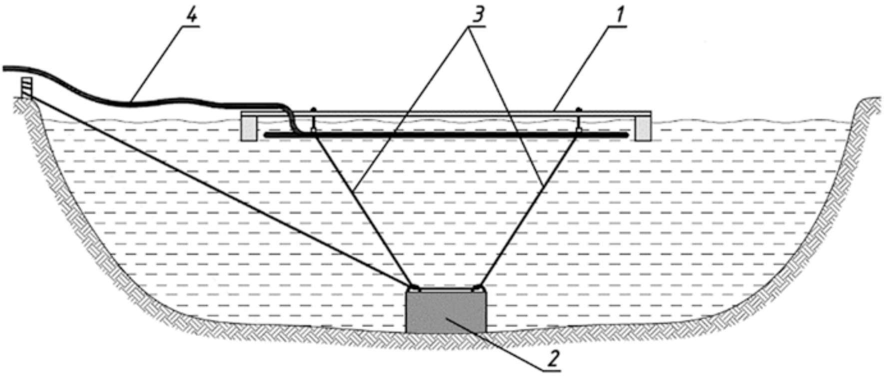

Fig. 7.4 Arrangement of the heat exchanger in a watercourse. *1*—floating heat exchanger, *2*—anchors, *3*—ropes, *4*—flexible hose

In this design, enhancing the heat transfer is primarily achieved through the use of the natural movement of water in the direction of the flow core for heat transfer 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 give it buoyancy, and ropes and anchors so that the heat exchanger can be positioned and retained in the area of best heat transfer (Figs. 7.4 and 7.5).

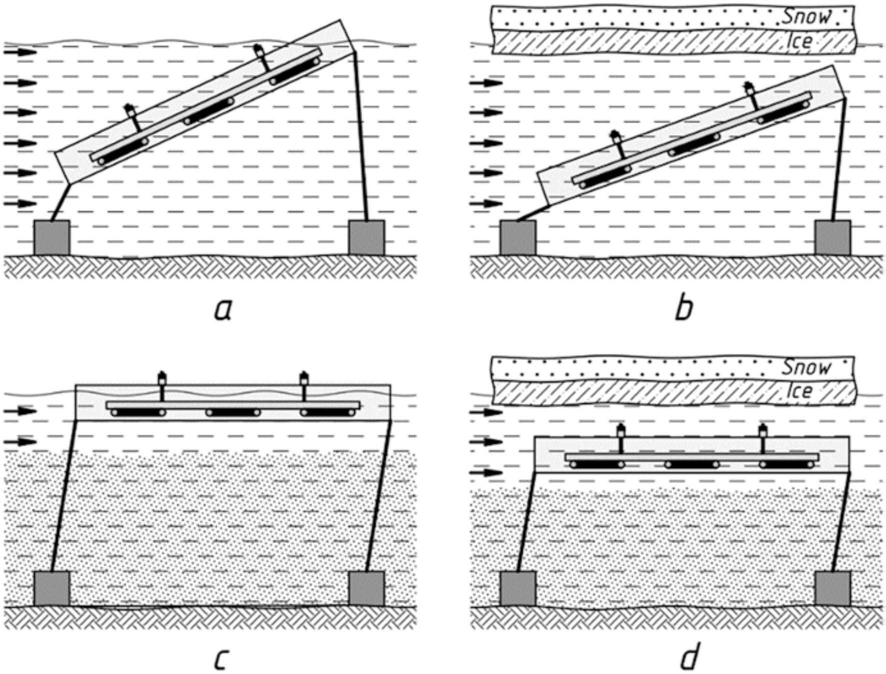

Fig. 7.5 Examples of arrangement of the heat exchanger in a watercourse depending on conditions. (**a**) clear channel; (**b**) existence of an ice cover; (**c**) silted channel; (**d**) the presence of bottom sludge and ice cover

The improving heat transfer characteristics also occur due to the fact that the 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. 7.5b, d), and the rest of the time to keep the surface of the watercourse (Fig. 7.5a, 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. 7.6). The system of selection of low-potential heat based on the floating heat exchanger was mounted on a specially selected ice-free watercourse (Fig. 7.7).

In addition to the use of special river heat exchanger, experimental setup is also distinguished by several technical solutions, which are usually not used in classical

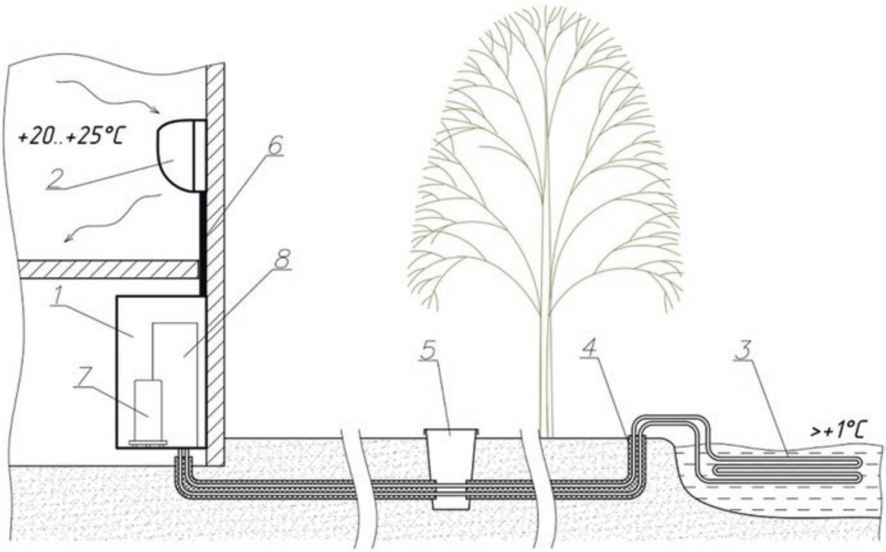

Fig. 7.6 Schematic diagram of the experimental installation. *1*—outdoor unit; *2*—indoor unit; *3*—water-brine heat exchanger; *4*—heat-insulated underground pipeline; *5*—caisson; *6*—freon line; *7*—compressor; *8*—brine-freon heat exchanger

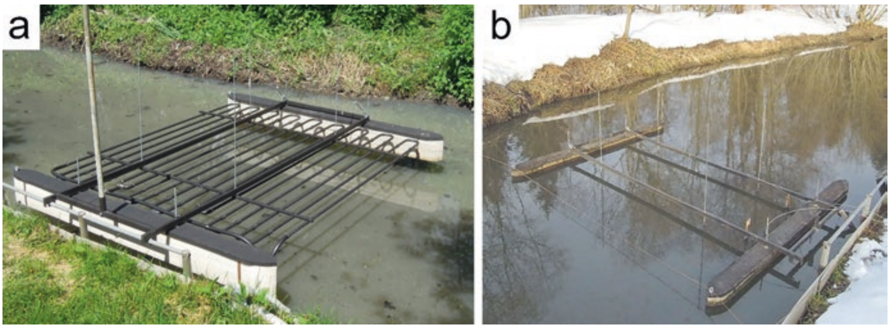

Fig. 7.7 Experimental sample of the floating heat exchanger. (**a**) Lifted over water in the summer; (**b**) in working position in the winter

heat pump systems, but which provide certain advantages and also serve as a subject of research. Such solutions are, for example, as below:

- The use of variable frequency compressor and circulating pump of a low-temperature circuit.
- Direct heating of the internal air in the heat exchanger-condenser of the heat pump without the use of intermediate contours and closed vent system to distribute warm air around the house.
- The ability to connect additional sources of low-grade heat.

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 [4].

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

$$\frac{dT(x)}{dx} = \frac{\pi \cdot d \cdot K \cdot (T_R - T(x))}{G \cdot C}, \tag{7.1}$$

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

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 [5].

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

$$\frac{dT(x)}{dx} = \frac{\pi \cdot \left(d_O + 2 \cdot \Delta_I(T(x))\right) \cdot \alpha_I\left(\Delta_I(T(x))\right) \cdot (T_R - 273.15)}{G \cdot C}, \tag{7.2}$$

where $T(x)$ is the temperature of heat carrier depending on the path traveled through the heat exchanger, d_O is the outside pipe diameter, $\Delta_I(T(x))$ is the 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, $\alpha_I(\Delta_I(T(x)))$ is the 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 is the temperature of river water, G is the flow rate of heat carrier, and C is the 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:

$$\alpha_I(\Delta_I) = \frac{1}{2} \cdot \lambda_W \cdot \mathrm{Pr}_W^{0.38} \cdot \sqrt{\frac{V_W}{\nu_W \cdot (d_O + 2 \cdot \Delta_I)}}, \tag{7.3}$$

where λ_W, Pr_W, and ν_W are the thermal conductivity, Prandtl number, and kinematical viscosity of river water, respectively, V_W is the speed of water in the river, and d_O is the 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 as follows:

$$\left(\frac{d_I + d_O + 2\cdot\Delta_I\left(T(x)\right)}{2}\right)\cdot K\cdot\left(T_R - T(x)\right) = \left(d_O + 2\cdot\Delta_I\left(T(x)\right)\right)\cdot\alpha_I\left(\Delta_I\left(T(x)\right)\right)\cdot\left(T_R - 273.15\right), \tag{7.4}$$

where d_I and d_O are the inside and outside pipe diameter, respectively, K is the coefficient of heat transfer from water to heat carrier, and $\alpha_I(\Delta_I(T(x)))$ is the 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 Eq. (7.1) has an analytic solution, which simplifies the calculations:

$$T(x) = T_R - \exp\left(\ln\left(T_R - T_0\right) - \frac{\pi\cdot d\cdot K\cdot x}{G\cdot C}\right), \tag{7.5}$$

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

The differential Eq. (7.2) 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 include a lot of subroutines, conditional operators, cycles, and iterations, and the performed works, thus, demonstrate the wide possibilities of the MathCAD package, which proved to be indispensable for the solution of the task.

7.4 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 creating such systems. To achieve high technical and economic indicators of HPI, new and most optimal technical solutions are required in each case—as one of these solutions can serve the proposed submersible floating water-brine heat exchanger. Introducing 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 appears to be in the areas where there is widely used irrigation system for watering and irrigation of agricultural structures. Such areas include some territories of southern Russia and southern Kazakhstan, almost all territories of Uzbekistan, and so on.

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