Heat exchange model in adsorbers of sorption refrigeration units

ANDRZEJ GRZEBIELEC

INSTYTUT TECHNIKI CIEPLNEJ, WYDZIAŁ MECHANICZNY ENERGETYKI I LOTNICTWA, POLITECHNIKA WARSZAWSKA

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ABSTRACT:

One of the specific components of the construction of refrigeration equipment are adsorbers whose main task is to replace the compressors located in typical refrigeration plants. In contrast to adsorbers used in other industries for the purification of gases or liquids, in the case of refrigeration applications, also the process of heat exchange is very important in addition to the sorption/desorption process. This paper proposes a heat exchange model in the adsorbers used in refrigeration equipment. The model has been verified experimentally. As a result of experimental research, the average discrepancy of results at the level of 7.4 K was obtained.

Model wymiany ciepła w adsorberach sorpcyjnych urządzeń chłodniczych

Słowa kluczowe: energetyka, chłodnictwo, adsorpcyjne urządzenia chłodnicze

STRESZCZENIE:

Jednym ze specyficznych elementów budowy urządzeń chłodniczych są adsorbery, których głównym zadaniem jest zastąpienie sprężarek znajdujących się w typowych instalacjach chłodniczych. W przeciwieństwie do adsorberów stosowanych w innych gałęziach przemysłu do oczyszczania gazów lub cieczy, w przypadku zastosowań chłodniczych oprócz procesu sorpcji/desorpcji bardzo istotny jest proces wymiany ciepła. W niniejszej pracy zaproponowano model wymiany ciepła w adsorberach urządzeń chłodniczych oraz zweryfikowano go eksperymentalnie. W wyniku badań eksperymentalnych udało się uzyskać średnią rozbieżność wyników na poziomie 7,4 K.

1. INTRODUCTION

As a result of withdrawing further refrigerants, research has been carried out on the use of waste heat for the propulsion of power equipment, including refrigeration equipment, for several decades [7, 9, 11, 14, 17]. As a result of this research, a lot of refrigeration installations were created using the phenomenon of adsorption, for which the energy source is waste heat or solar energy [3, 13]. The number of commercial installations is growing from year to year. The main problem of the adsorption systems is the temperature in the condenser – after exceeding a certain value, the device simply stops working [2, 10]. This temperature depends on the temperature of the outside air. To broaden the range of adsorption devices, it is important to reduce the temperature difference of the bed and the medium that provides heat or cold production by other methods [4, 6, 8]. In contrast to absorption, adsorption consists in absorbing gas or liquid components through a solid. The fact that the sorbent is present in the system as a solid causes that the adsorption systems are significantly differ in the construction from the absorption systems [13].

There are two types of adsorption in the technique: physical and chemical adsorption. Physical adsorption, also called van der Waals adsorption, is caused by intermolecular interaction forces. In contrast, chemical adsorption is associated with chemical reactions that occur on the surface of the adsorbent. In adsorptive cooling devices, it is very important that the adsorbent can be restored to its original state by heating. Therefore, it is very important to select the adsorbent-refrigerant working pair as some types of chemical adsorption are irreversible. Table 1 presents the most frequently used adsorbent-refrigerant with the scope of their application.

1.1 Principle of the adsorption refrigeration device

Figure 1 shows a diagram of a refrigeration system using two adsorbers [1]. The system consists of two adsorbers that are either cooled or heated, from a condenser, an expansion valve and an evaporator. In order to regulate the flow of the refrigerant, there are also shut-off valves 1, 2, 3, 4 in the system.

The system works cyclically, the whole cycle consists of two half-cycles. At the beginning of the first half cycle, all four valves are closed, Adsorber I is saturated with refrigerant and has low pressure and low temperature, in Adsorber II there is low amount of refrigerant, it has high pressure and high temperature. Adsorber I begins to be heated by heat Q_{HS}, so the temperature begins to rise, the pressure begins to increase. The Adsorber II, on the other hand, starts to be cooled by what the temperature starts to drop and the pressure starts to decrease. When the temperature, and thus the pressure in Adsorber I, increases to the desorption temperature, and in Adsorber II the

Table 1 Working pairs used in adsorption refrigeration units [1, 15, 18]

Evaporate temperature	Adsorbent	Refrigerant	SCP*
[°C]	[-]	[-]	[W/kg]
8	Activated carbon	Ammonia	1000
1	Activated carbon fiber / $CaCl_2$	Ammonia	330
3	Activated carbon	Ammonia	557
-10	$SrCl_2$	Ammonia	230
-25	$(MnCl_2-NiCl_2)$	Ammonia	140
-10	Metal hydrides	Hydrogen	50
3	Graphite / silicagel	Water	75
10	Silicagel	Water	85
5	Zeolite	Water	250
-15	$CaCl_2$ / graphite	Ammonia	1000
15	Activated carbon	Methanol	30
-5	Activated carbon	Methanol	8
10	Activated carbon	Ethanol	135

*SCP – specific cooling capacity

temperature drops to the adsorption temperature, valves 1 and 2 open. The opening of these valves causes the refrigerant to flow from Adsorber I to Adsorber II. The refrigerant desorbed in Adsorber I flows into the condenser where it condenses by giving off heat Q_C, then flows through the expansion valve and flows into the evaporator where it evaporates by taking heat from the environment Q_E. Then the refrigerant is adsorbed in Adsorber II and the heat of adsorption Q_{CS} is discharged to the outside of the system.

When whole refrigerant desorbs from the Adsorber I, all valves are closed again and the adsorbers are stopped to be heated and cooled. At this point, the situation is analogous to that at the beginning of half cycle I, except that now in the Adsorber I there is no refrigerant and there is high pressure and high temperature in it, Adsorber II is saturated and there is low pressure and low temperature. Now the second half cycle begins, Adsorber I begins to be cooled, and the adsorber II starts to be heated. After reaching the appropriate pressures and temperatures in the adsorbers, this time the valves 3 and 4 open, thanks to which the factor starts to flow from Adsorber II to Adsorber I.
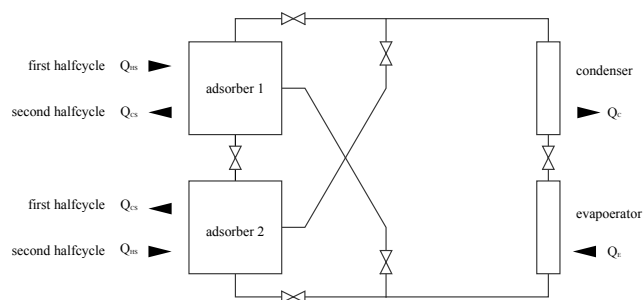

Figure 1 Two beds adsorption refrigeration unit

The adsorption refrigeration device can also be represented by thermodynamic cycles of adsorbers on the p-T graph [6]. These processes are shown in Figure 2. At the beginning of the first half cycle Adsorber I is in state A, while adsorber II is in state C. Adsorber I is supplied with Q_{HS} heat, thereby the adsorber I state changes along the isosteres[1] A-B. Heat is absorbed from the adsorber II, thus its state changes along the C-D isosteres. When the appropriate pressures are applied to both adsorbers, the valves are opened and the adsorber states change from this time along the B-C and D-A isobars.

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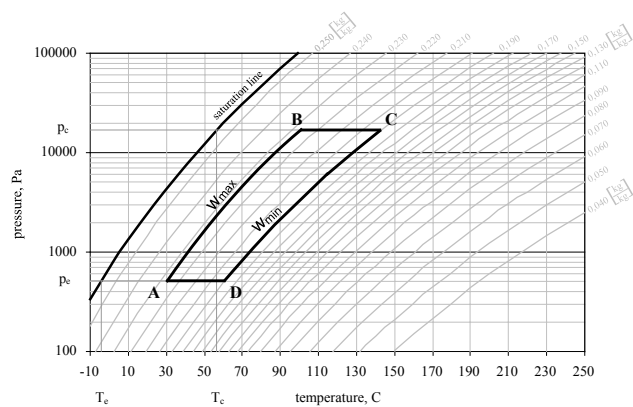[1] Isoster – constant uptake.

Figure 2 Thermodynamic states of adsorbers in the methanol-activated carbon refrigeration system

1.2 Thermal wave adsorption refrigeration units

In commercial solutions, devices are built with a temperature gradient of the medium supplying and receiving heat from adsorbers along the bed and it is called thermal wave. The construction of such a device makes it relatively easy to use the heat and mass recovery process between the adsorbers [12].

The construction of an adsorption thermal wave device is not significantly different from other constructions. The differences are only in the method of providing heat to adsorbers [5].

According to Figure 3, the adsorption refrigeration unit has two circuits in this case. One circuit is well known from the previously presented system, the refrigerant circuit. The second circuit, which is a novelty here, is the circulation of the medium supplying and receiving heat from adsorbers. This working medium is usually thermal oil or water (when the device works at low parameters of the driving heat) [5, 16]. At this point, pay attention to the fact that the oil flow rate must be small. This is due to the fact that the goal is quite a large temperature difference between the inflow and outflow of oil from the adsorber.

The principle of the thermal wave adsorption refrigeration device is as follows. The oil flows through the cooling system and flows out of it at low temperatures. Then it flows into the adsorber, where the adsorption process takes place – that is, the heat is released. The oil absorbs this heat, which results in its temperature increasing. Leaving the adsorber the oil already has a fairly high temperature. Then the oil flows into the heating system, where its temperature is additionally raised, above the desorption temperature. Then the oil flows into the second adsorber where the

desorption process takes place. The desorption process requires heat – so it receives heat from the oil. The oil leaving the second adsorber has a relatively low temperature. Then the oil flows into the cooling system, where its temperature is lowered again. And thus begins the next cycle of oil flow.
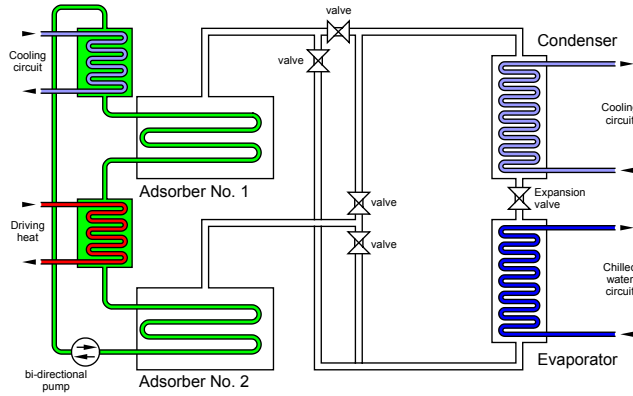

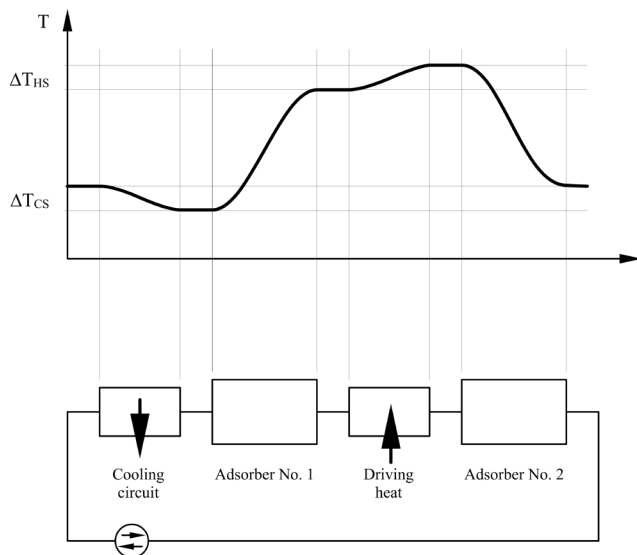**Figure 3** Thermal wave adsorption refrigeration device

Figure 4 The oil temperature change throughout the cycle

Figure 4 shows the temperature distribution of oil along its entire circulation. The advantage of this solution is to reduce the energy consumption needed for heating and cooling adsorbers. As shown in Figure 4, the heating system and the cooling system must change the temperature of the oil by only ΔT_H , and ΔT_S .

Another advantage of this solution is a quick and uncomplicated change in the heating and cooling of adsorbers. All what is needed to do is to switch the reverse pump so that it pumps the oil in the opposite direction. This causes the adsorber that was heated is cooled, and the adsorber that was cooled is heated.

2. MODEL

Adsorber will be built of tubes inside which the intermediate medium will flow. There is an adsorbent outside the tube. Figure 5 shows a cross-section through one of these tube. Adsorber in this case is also a heat exchanger.
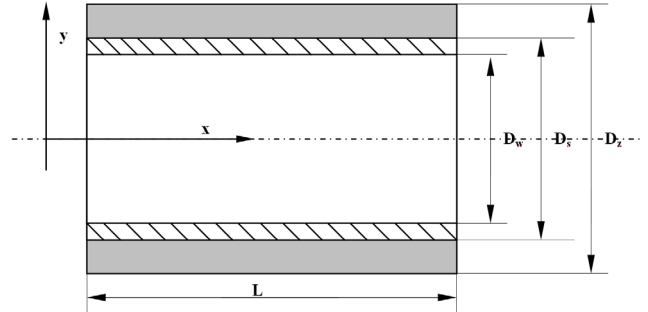

Figure 5 Adsorber construction for modeling purposes

2.1 Energy conservation

Assuming that:
• the pressure in the adsorber from the side of the refrigerant along its entire length is the same
• thermodynamic properties of the materials used are constant (thermal conductivity coefficient, specific heat)
• the adsorbed refrigerant phase is treated as a liquid
it is possible to write the following equations:
on the side of the supplying heat fluid:

$$m_f \cdot c_f \frac{\partial T_f}{\partial t} = -\overset{\bullet}{m}_f \cdot c_f \cdot L \cdot \frac{\partial T_f}{\partial x} + \lambda_f \cdot A_f \cdot L\left(\frac{\partial^2 T_f}{\partial x^2} + \frac{\partial^2 T_f}{\partial y^2}\right) \quad (1)$$

where:

m_f – secondary fluid mass;

$\overset{\bullet}{m}_f$ – mass flow of secondary fluid;
c_f – specific heat of secondary fluid;
T_f – secondary fluid temperature;
λ_f – secondary fluid thermal conductivity;
A_f – heat exchange area (inside the small tube);
L – heat exchanger length;

From the adsorber side:

$$m_{ads}\left(c_{pa} + c_{pg} \cdot w + \frac{m_m \cdot c_m}{m_{ads}}\right)\frac{\partial T_{ads}}{\partial t} - \rho_{ads} \cdot A_{ads} \cdot L \cdot \Delta H \frac{\partial w}{\partial t} =$$
$$= -k_z \cdot A_{ads} \cdot L\left(\frac{\partial^2 T_{ads}}{\partial x^2} + \frac{\partial^2 T_{ads}}{\partial y^2}\right) \quad (2)$$

where:
m_{ads} – adsorbent mass;
c_{pa} – adsorbent specific heat;

c_{pg} – adsorbent refrigerant specific heat;
w – uptake;
m_m – tube mass;
c_m – tube specific heat;
T_{ads} – adsorbent temperature;
ρ_{ads} – adsorbent density;
A_{ads} – outside area of adsorbent;
ΔH – specific heat of adsorption;
k_z – heat transfer coefficient between the bed and the surrounding gas.

2.2 Mass conservation

From the point of view of the principle of mass conservation in the absorber, we note that the change in the degree of adsorption depends on the difference of equilibrium uptake and current uptake.

$$m_{ads}\frac{\partial w}{\partial t} = D \cdot (w_R - w) \qquad (3)$$

where:
D – diffusion coefficient;
w_R – equilibrium uptake;
w – current uptake.

2.3. Desorption process

Figure 6 shows the changes of the temperature of the secondary fluid along the length of the adsorber. During desorption, the task of the medium is to provide the right amount of heat for this process to take place. As we can see from Figure 4, energy is supplied to the adsorber, as a result of which the temperature of the refrigerant decreases.
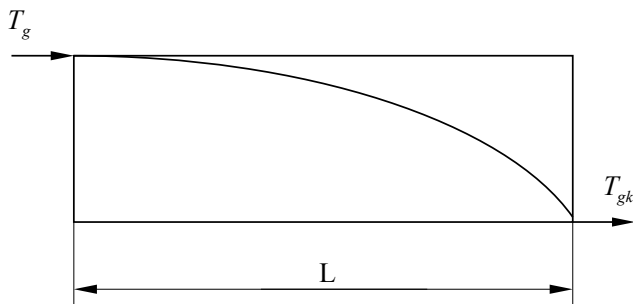

Figure 6 Secondary fluid temperature change along the desorption process

Initial and boundary conditions:

$$T_{ads}(x,y,t) = T_k \ \text{dla} \ t = 0 \qquad (4)$$

At the initial moment, the adsorber temperature is T_k, the temperature it reached after the adsorption process;

$$T_f(x,y,t) = T_g \ \text{for} \ x = 0 \qquad (5)$$

The temperature of secondary fluid that provides heat to the adsorber for $x = 0$ is equal to T_g;

$$\frac{\partial T_f}{\partial x} = 0 \ \text{for} \ x = 0 \qquad (6)$$

Temperature change of the secondary fluid that provides heat to the adsorber for $x = 0$ is equal to 0;

$$\frac{\partial T_f}{\partial y} = 0 \ \text{for} \ y = 0 \qquad (7)$$

Temperature change of the secondary fluid that provides heat to the adsorber for $y = 0$ is equal to 0;

$$\lambda_f \frac{\partial T_f}{\partial y} = k_{zast}\left(T_{ads} - T_f\right) \ \text{for} \ y = \frac{D_w}{2} \qquad (8)$$

Temperature change of secondary fluid that provides heat to the adsorber for $y = \frac{D_w}{2}$ for whole process;

$$\lambda_f \frac{\partial T_{ads}}{\partial y} = k_{zast}\left(T_{ads} - T_f\right) \ \text{for} \ y = \frac{D_s}{2} \qquad (9)$$

Temperature change of adsorber for $y = \frac{D_s}{2}$ for whole process;

$$\frac{\partial T_{ads}}{\partial y} = 0 \ \text{for} \ y = \frac{D_z}{2} \qquad (10)$$

For $y = \frac{D_z}{2}$ there is no adsorber temperature change;

$$w(t) = w_{max} \ \text{for} \ t = 0 \qquad (11)$$

at the instant the adsorber is maximally saturated with refrigerant.

2.4 Adsorption process

Figure 7 presents the temperature distribution of the secondary fluid during the adsorption process. The heat that has been released before the adsorbed gas is picked up by the secondary fluid, thereby increasing the temperature of the fluid. As the diagram shows in this case, the secondary fluid flows in the opposite direction than it was during the desorption process.
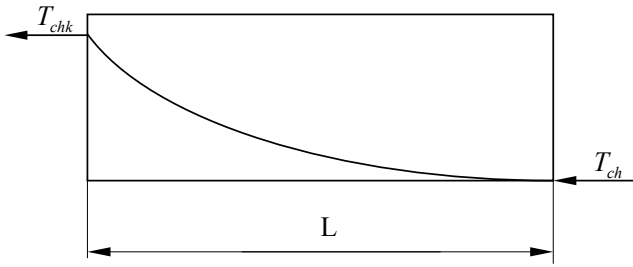
Figure 7. Secondary fluid temperature change along the adsorption process

Initial and boundary conditions:

$$T_{ads}(x,y,t) = T_k \text{ for } t = 0 \qquad (12)$$

At the initial moment, the temperature of the adsorbent is equal to T_k the temperature reached by the adsorber with the desorption process;

$$T_f(x,y,t) = T_{ch} \text{ for } x = L \qquad (13)$$

The temperature of the secondary fluid for $x = L$ is equal to T_{ch}, the temperature of the cooling system;

$$\frac{\partial T_f}{\partial x} = 0 \text{ for } x = L \qquad (14)$$

The temperature change of the secondary fluid for $x = L$ is equal to 0;

$$\frac{\partial T_f}{\partial y} = 0 \text{ for } y = 0 \qquad (15)$$

The temperature change of the secondary fluid for $y = 0$ for whole process is equal to 0;

$$\lambda_f \frac{\partial T_f}{\partial y} = k_{zast}\left(T_{ads} - T_f\right) \text{ for } y = \frac{D_w}{2} \qquad (16)$$

The temperature change of the secondary fluid for $y = \frac{D_w}{2}$ for whole process;

$$\lambda_f \frac{\partial T_{ads}}{\partial y} = k_{zast}\left(T_{ads} - T_f\right) \text{ for } y = \frac{D_s}{2} \qquad (17)$$

The temperature change for the adsorbent for $y = \frac{D_s}{2}$ for whole process;

$$\frac{\partial T_{ads}}{\partial y} = 0 \text{ for } y = \frac{D_z}{2} \qquad (18)$$

For $y = \frac{D_z}{2}$ there is no temperature change for the adsorber;

$$w(t) = w_{min} \text{ for } t = 0 \qquad (18)$$

at the instant the adsorber is at w_{min} uptake level of the with refrigerant;

2.5 Regeneration efficiency

The model presented above can also be looked at as a process of heat regeneration [1]. The heat recovered during the adsorption process in one of the adsorbers is used for the desorption process in the second one. Thus, an important parameter determining the adsorption refrigeration unit work with a temperature gradient along the bed is the degree of regeneration. This parameter tells what percentage of heat is obtained from regeneration and what percentage of heat should be adequately supplied to the adsorber in which the desorption process takes place.

$$\eta_{reg} = \frac{T_{chk} - T_{ch}}{T_g - T_{ch}} \qquad (20)$$

The above equation is true of course for the case in which the specific heat of the supplying and receiving heat from adsorbers is constant in the range of its operation. Since T_{chk} is dependent on the temperature to the above formula, its average value should be used throughout the entire process.

$$T_{chk} = \frac{1}{\tau}\int_0^\tau T_{chk}(t)dt \qquad (21)$$

where:
τ – process time.

3. EXPERIMENTAL APPARATUS

The test stand was constructed in accordance with Figure 3 and the adsorbers in accordance with scheme 8, with additional layers such as the outer tube and the foam insulation used. The main role of the outer tube is to maintain the correct adsorbent layer around the inner tube. Foam insulation is supposed to prevent heat loss during adsorber heating. As a factor, thermal oil was used due to the fact that it can operate at atmospheric pressure up to 220°C.
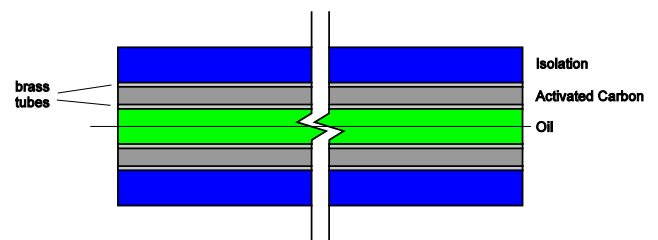

Figure 8 The view of experimental adsorber

Two adsorbers were built for testing – one was used as the adsorber, the second as desorber. The length of the active carbon bed in the pipe was 1250 mm. Outer diameter of the oil tube was 12 mm. The diameter of the outer tube in which the bed was stored was 28 mm. The thickness of both tubes was 1 mm. The insulation thickness was 10 mm.

4. RESULTS

Energy and mass equations have been solved by the finite difference method. To compare the results of modeling with the results of experiments, the oil temperature after the bed was determined. The results of the comparison are shown in Figure 9.
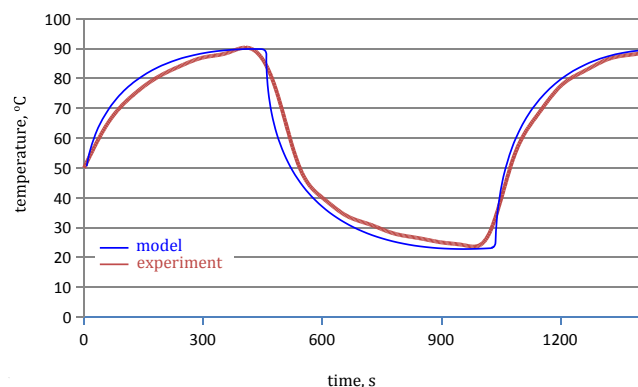

Figure 9 Model and experiment results

According to Figure 9, it should be concluded that the calculations are fairly consistent with the measurements. The average discrepancy of results was calculated at 7.4 K, although in some cases it reached even several degrees.

5. CONCLUSIONS

The proposed model with sufficient accuracy allows modeling the work of adsorbers with the proposed structure in a sorption cooling device. The obtained accuracy of calculations allows for the design of devices with sufficient accuracy from an engineering point of view. The largest temperature differences were obtained for the rapid temperature change processes. This is most likely the fault of the thermal inertia of the temperature sensors, and the fact that the measurement was on the outside of the tubes – not directly on the oil side.

Both in the calculations and in the experiment, it was noticed that it is quite difficult in the porous bed to obtain a slight temperature difference between the temperature of the oil and the temperature of the bed. The proposed model can be easily transformed for the needs of other construction solutions.

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