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EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER IN A RECUPERATOR OF A CONVECTIVE DRYER

ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ ТЕПЛОПЕРЕДАЧІ В РЕКУПЕРАТОРІ КОНВЕКТИВНОЇ СУШАРКИ

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Abstract. *The issue of increasing the energy efficiency of condensing heat pumps, which are used in convective drying devices with the closed circulation of the drying agent, was considered. In these devices, moisture from the volume of the drying chamber was removed in liquid form by cooling the humidified drying agent to the dew point temperature and condensing the water vapor contained in it. At the same time, the productivity of the drying device for the removed moisture was limited by the value of the refrigerating capacity of the heat pump device. It was shown that the increase in moisture removal and the increase in the energy efficiency of the process can be achieved by "cold" recuperating. A recuperative heat exchanger based on thermosiphon heat pipes was developed and investigated, and its performance characteristics were obtained. In the recuperator, the moistened drying agent was partially cooled before being fed into the heat pump evaporator due to heat exchange with the already cooled dry heat carrier, which, depending on the efficiency of the recuperator and the temperature regime of the heat pump operation, made it possible to reduce the energy consumption for the drying process by 1.5-2 times.*

Key words: *drying; heat pump; heat recuperation.*

Introduction. Convective drying processes are widely used in various industries and belong to the most energy-intensive technological processes. Along with the undoubted advantages, expressed in the simplicity of design and operation, convective drying devices have a number of significant disadvantages, the main ones of which are: significant heat loss with the exhaust drying agent, the dependence of the intensity of the drying process on the moisture content of atmospheric air, as well as insufficient protection of products from possible damage microorganisms found in the environment. The consumption of thermal energy during convective drying reaches 6000 kJ per kilogram of removed moisture, therefore, solving the issue of reducing energy consumption and intensifying the drying process is an urgent scientific and technical problem.

One of the promising directions in solving this problem is the use of heat pumps. The use of heat pumps in convective drying processes provides a significant reduction in the value of specific energy consumption in comparison with traditional systems [1, 2]. In addition, the heat pump allows, regardless of environmental conditions, to maintain the required heat and humidity parameters of the drying agent and create well-controlled drying conditions. In case of heat pump drying, the moisture removed from the product was not carried out by the drying agent into the environment, but was condensed on the cold surface of the evaporator and was removed in liquid form. The physical heat of the exhaust air perceived by the evaporator and the latent heat of condensation of the water vapor contained in it at a higher temperature level were returned to the drying process, which made it possible to reduce the consumption of primary energy.

Materials and methods. Heat pumps used in convection dryers are divided into two types - recuperative and condensing. Recuperative heat pumps are used in direct-flow drying devices, in which there is a one-time passage of the heat carrier through the material which must be dried. The circulation of the heat carrier is organized in such a way that moist air ejected from the dryer is fed into the evaporator of the heat pump, and atmospheric air entering the dryer is fed into the condenser. The energy efficiency of a recuperative heat pump was estimated by the conversion factor and depended on the temperature difference between the input and output air flows. The smaller this difference, the higher the conversion factor.

Condensing heat pumps are used in dryers with closed circulation of the drying agent. Removal of moisture from the volume of the drying chamber was carried out by dehumidification of the heat carrier. In this case, the spent humidified heat carrier was cooled in the heat pump evaporator to the dew point temperature, at which the moisture, assimilated by it, condensed. The energy efficiency of a condensing heat pump was characterized by the amount of condensed water in kilograms per kilowatt-hour of energy consumed.

Condensing heat pumps are able to controllably reduce the moisture content of the drying agent, which made them indispensable in solving the problem of intensifying moisture removal during low-temperature drying of thermolabile materials. So, at drying temperatures below 50°C, the moisture content of the drying agent decreased from 15 to 10 g / kg d.m. intensified heat and mass transfer by 25%, and a further decrease in moisture content to 8 g / kg d.m. provided an increase in intensity by 35% [3].

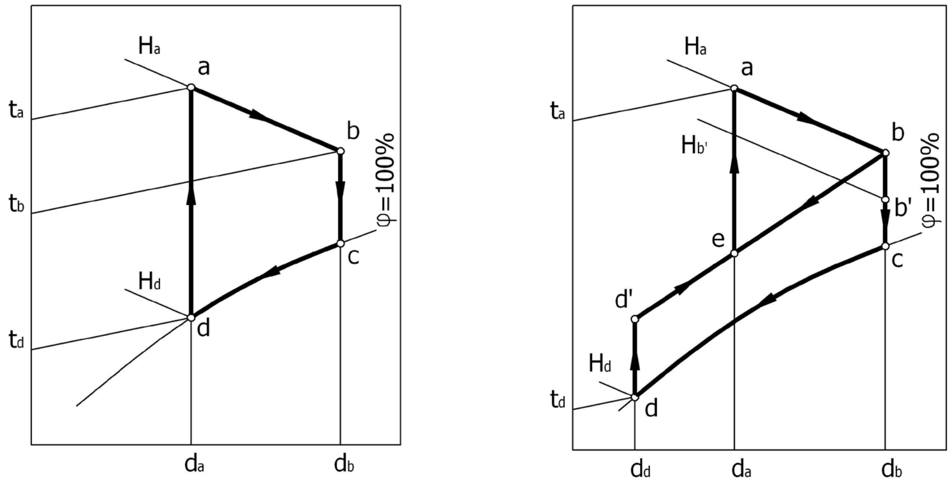
When the coolant was dehumidified by condensation, the capacity of the device for the removed moisture was limited by the value of the cooling capacity of the heat pump device. Under these conditions, the increase in moisture removal and the increase in the energy efficiency of the process can be achieved by "cold" recuperating.

Recuperating of "cold" in the cycle of heat pump condensation drying can be carried out in the following ways:

1. After passing over the product which must be dried (Fig. 1a, process a–b), the humidified heat carrier was partially cooled in the «air-to-air» recuperator due to heat exchange with the cold heat carrier leaving the evaporator (process b–b') and was further cooled in the heat pump evaporator (process b'–c–d) to the specified dew point temperature (state d). The dried cold heat carrier was heated in the «air-to-air» recuperator due to heat exchange with the flow entering for cooling (process d–d'), was warmed up in the condenser of the heat pump (process d–a) and was returned to the drying chamber.

2. The heat carrier passing over the product which must be dried (Fig.1b, process a–b) was divided into two streams, one of which was cooled and dehumidified similarly to the previous version (process b–b'–c–d), after which it was mixed with the rest of the damp heat carrier (processes d–e and b–e) and in state e entered the heat pump condenser for heating (process e–a).

Thus, in both cases, the use of a recuperator made it possible to reduce the load on the heat pump evaporator by the value Hb - Hb'.



a) **b)**

Fig. 1 – H-d diagram of the process of condensation heat pump drying: a) with "cold" recuperation and cooling of the entire heat carrier flow; b) with "cold" recuperation and cooling of the part of heat carrier flow

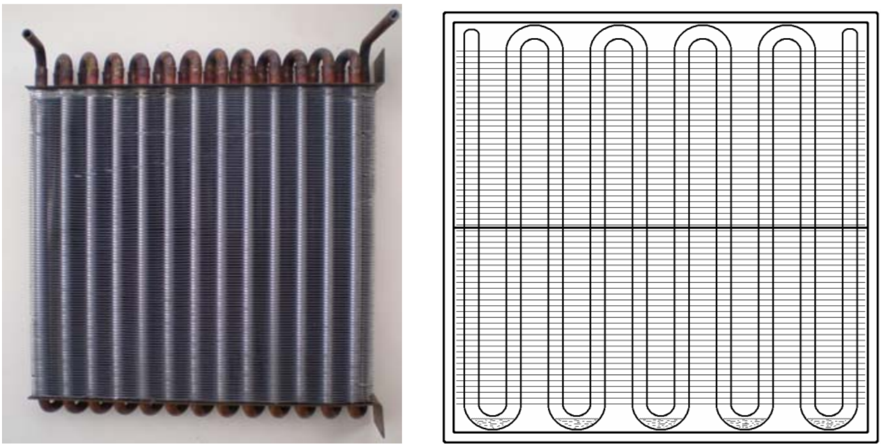
Earlier, there was developed an «air-to-air» recuperator operating on the principle of a vapor-liquid thermosiphon and the efficiency of its use for heat recuperation of the spent heat carrier in a spray dryer was studied [4].

Traditional thermosiphon heat exchangers-recuperators are structurally a package of vertically arranged heat pipes placed in a single body. The lower half of the heat pipes is in the zone of the heating medium, and the upper half is in the zone of the heated one. In such heat exchangers, each heat pipe is an independent element of the system and is a sealed edged tube filled with a working agent. The main advantage of the traditional design of recuperators with heat pipes is their high operational reliability, since depressurization of several heat pipes does not lead to a loss of efficiency of the entire system. The disadvantages include low maintainability due to the complexity of diagnosing the failure of individual heat pipes, as well as the high labor intensity of manufacture and the relatively high cost of these devices.

In order to reduce the labor intensity of manufacturing recuperators on heat pipes and to make them cheaper, there was investigated the possibility of creating the recuperator based on industrial air heaters, as well as air condensers and evaporators used in refrigeration technology.

To determine the heat transfer capacity of the recuperators of this design and to identify their operational features, laboratory tests of experimental samples of devices made on the basis of edged heat-exchange sections produced by the "Conditioner" plant (Kramatorsk) were carried out.

The heat exchange section (Fig. 1a) had 2 rows of copper pipes with aluminum edges fitted on them. The pipes were connected in series with each other by rolls and formed a continuous coil with input and output on the extreme tubes. The manufacture of a thermosiphon heat exchanger included evacuation of the tube bundle, filling it with the required amount of working agent, and sealing. In the recuperator body (Fig. 1b), the heat exchanger tubes were located vertically, and the heat exchange section was divided by a horizontal partition into two cavities, isolated from air flows. The upper part of the heat exchanger was the condensation zone of the thermosiphon and served to heat the cold air flow, and the lower part was the evaporative zone of the thermosiphon and served to extract heat from the hot air flow.



a) b)

Fig. 2. Experimental recuperative heat exchanger:
a) – edged heat exchanger section; b) – scheme of the heat exchanger in the recuperator body

In contrast to recuperators of traditional design, in which each tube was a separately charged heat pipe, in this unit all pipes were interconnected by rolls and the recuperator had only one branch pipe for filling the agent and sealing the system. After filling into the system, the liquid agent was initially located in the tubes closest to the filling nozzle, and its redistribution along the heat exchanger occured already during the operation of the apparatus: when hot and cold air flows were supplied to the recuperator, the working agent was uniformly distributed through the system by successive evaporation and condensation in the communicating tubes. The amount of agent charged into the system was calculated based on the condition of filling all the lower heats of the heat exchanger to about a third of the height.

In comparison with a traditional heat pipe recuperator scheme, a heat exchanger with a similar circuit organization can have a number of thermal engineering advantages:

- by providing the possibility of mass and heat transfer not only along individual pipes, but also between adjacent pipes, conditions were created for smoothing possible temperature irregularities in the heat carrierflow;

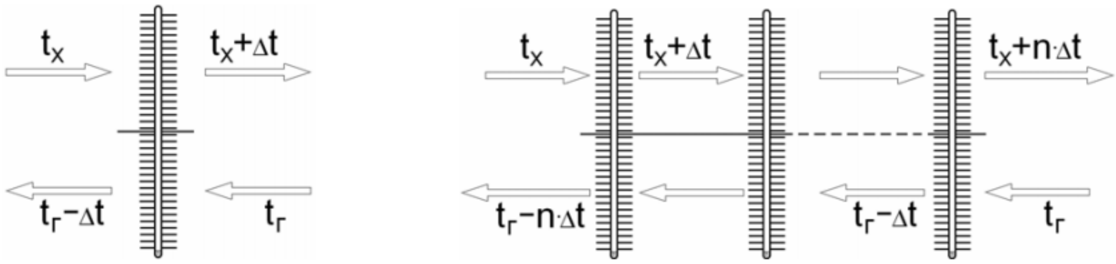
- the procedure for diagnosing and refueling the system was simplified in the event of a leaking working agent (it was almost impossible to find a separate heat pipe that failed in a conventional apparatus).

The main indicator characterizing the degree of perfection of recuperative heat exchangers is the efficiency (E) of the apparatus. The value E shows the share of useful heat used and is numerically equal to the ratio of the actually transferred heat to the maximum possible.

With the same mass flow rates of the heated and cooled heat carrier flows, the efficiency of the recuperator is expressed by the formula

$$E = \frac{T_c^{output} - T_c^{input}}{T_h^{input} - T_c^{input}}$$

In recuperators with heat pipes, the efficiency depended on the number of rows of heat pipes. The limiting efficiency of a recuperator with one row of heat pipes was estimated (Fig. 3a).



a) b)

Fig. 3. Scheme of recuperator on heat pipes:
a) – with one row of heat pipes; b) – with n rows of heat pipes

During the operation of the recuperator, the transfer of heat from the hot air flow to the cold one was carried out due to the evaporation and condensation of the working agent in the heat pipe. The working agent evaporated in the hot lower zone of the heat pipe and condensed in the cold upper zone, after which it returned downward by gravity. As a result, the cold air stream was heated up and took on the temperature tc+Δt, and the hot stream was cooled down to the temperature th–Δt. When the temperature tc+Δt = th-Δt was reached, the heat transfer stopped, because the temperatures in the condensing and evaporating zones of the heat pipe equalized.

Hence it followed that the maximum heating of the heat carrier in a single-row recuperator on heat pipes cannot exceed the value Δt = (th–tc)/2 and the limiting (theoretical) efficiency of such a heat exchanger was E = 0.5.

The recuperator with n rows of heat pipes (Fig. 3b) was considered. Similarly to the previous variant, with the same mass flow rates of the heated and cooled flows, the heat transfer stopped when the temperature in the evaporating and condensing zones of the heat pipe was equalized, i.e. upon reaching the temperature at the output of the recuperator tc+n Δt = th - Δt. From which it follows:

$$\Delta t = \frac{t_h - t_c}{n+1} \text{ and } E = \frac{n \cdot \Delta t}{t_h - t_c} = \frac{n}{n+1}$$

The curve of the dependence of the maximum efficiency of the recuperator on the number of rows of heat pipes (Fig. 4) showed that with 4 or more rows, the efficiency of these devices approached that of rotary recuperators.

An experimental sample of a recuperator based on thermosiphon heat pipes was investigated as part of a heat pump device of a laboratory condensation dryer (Fig. 5).

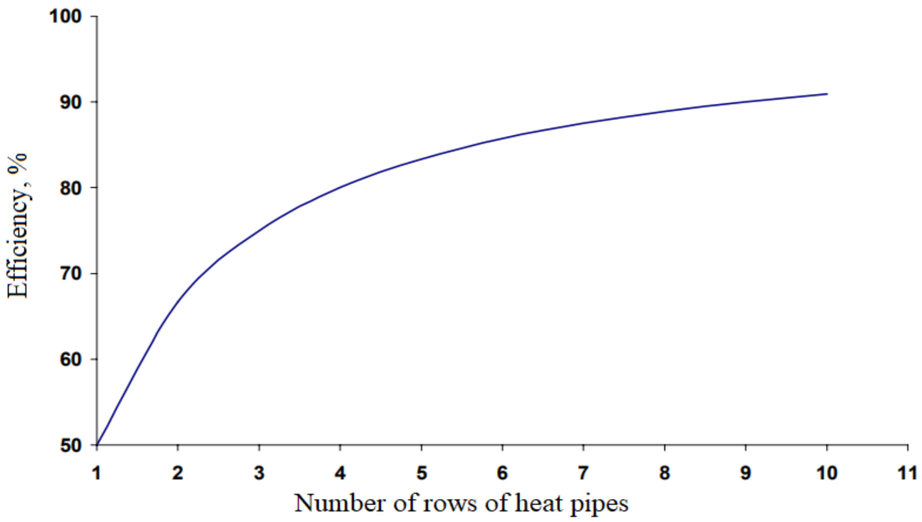


Fig. 4. Ultimate efficiency of the recuperator on heat pipes

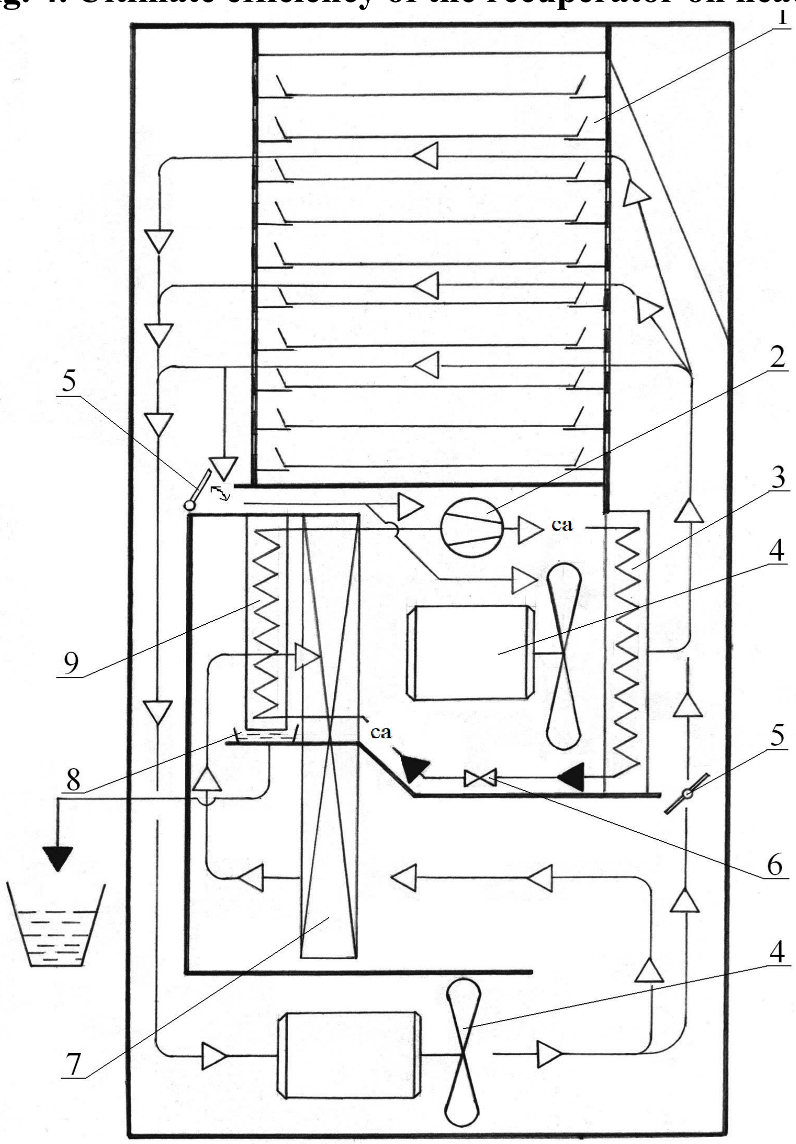


Fig. 5. Schematic diagram of the laboratory condensing heat pump dryer:

1 – drying chamber; 2 – compressor; 3 – condenser; 4 – circulating fan; 5 – rotary gate; 6 – thermoregulating valve; 7 – recuperative heat exchanger; 8 – condensate collector; 9 – evaporator

– cooling agent;

– drying agent;

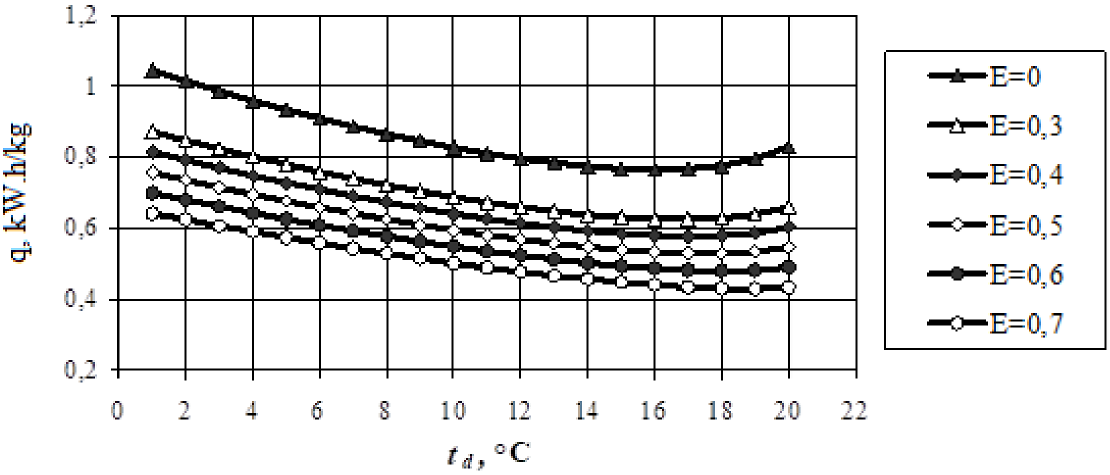


Fig. 6. Dependence of energy consumption for moisture removal on the efficiency of the recuperator E (at ta = 60 □C and da = 20 g/kg d.m.).

The drying process was as follows. The material was placed on trays and loaded into a drying chamber where a hot drying agent was circulated. Passing over the material, the drying agent heated it up and dehydrated it, while increasing its moisture content. Part of the spent wet drying agent was fed by the circulating fan 4 to the recuperative heat exchanger 7, where it was cooled by heat exchange with the drying agent leaving the evaporator 9. After precooling in the recuperator, the drying agent was cooled in the evaporator to the dew point temperature and liquefied moisture was removed from it, which was collected in the condensate collector 8 and removed from the dryer. The dehydrated drying agent was heated in the recuperative heat exchanger 7 and was fed by the fan to the condenser of the heat-carrying device 3, where it received the condensation heat of the cooling agent and was heated to the required temperature. After leaving the condenser, the hot dewatered drying agent was mixed with the spent drying agent and sent back to the drying chamber.

The results of testing the condensing heat pump with the recuperative heat exchanger showed that cold recuperation using the «air-to-air» heat exchanger was an effective technical solution that allowed to reduce the installed capacity of the heat carrier device and reduce energy consumption for the drying process by 1.5-2 times (Fig. 6).

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Анотація. *Розглядається питання підвищення енергетичної ефективності конденсаційних теплових насосів, які використовуються в конвективних сушильних установках із замкнутою циркуляцією сушильного агента. У цих установках волога з обсягу сушильної камери виводиться в рідкому вигляді, шляхом охолодження зволоженого сушильного агента до температури точки роси і конденсації міститься в ньому водяної пари. При цьому продуктивність сушильної установки по видаленій волозі лімітується величиною холодопродуктивності теплонасосного агрегату. Показано, що збільшення вологовидалення і підвищення енергетичної ефективності процесу може бути досягнуто шляхом здійснення рекуперації «холоду». Розроблено та досліджено рекуперативний теплообмінник на основі термосифонних теплових труб, отримані його робочі характеристики. У рекуператорі зволожений сушильний агент перед подачею в випарник теплового насоса частково охолоджується за рахунок теплообміну з уже охолодженим висушеним теплоносієм, що, в залежності від ефективності рекуператора і температурного режиму роботи теплового насоса, дозволяє в 1,5-2 рази зменшити енерговитрати на процес сушіння*.

Ключові слова: *сушка; тепловий насос; рекуперація тепла.*

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