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PHYSICS

CHAMBER DRYER WITH A STIRLING HEAT PUMP

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Abstract
We describe the operation principle of the closed type chamber dryer with a Stirling heat pump.
Keywords: active ventilation, agricultural material, humidity, temperature, Stirling heat pump.

Introduction. The vast majority of drying units operate on an open thermodynamic cycle principle. In such drying units, the coolant removes moisture outside the drying chamber, it is accompanied by air pollution, irreversible heat loss and reduced efficiency. Some dryers have waste heat recovery units or regenerators that partially return the waste heat to the drying chamber. For wood drying, a dryer with a heat pump and full heat recirculation has been proposed [1, 2]. Modern development of refrigeration and microprocessor technology makes it possible to significantly improve the energy performance of dryers and fundamentally change the drying process, namely to separate moisture from the coolant and remove it from the drying chamber without losing high-energy coolant.

Open type dryers have low energy efficiency, so the study of the ways to improve dryers and the development of the new ones in order to increase the efficiency of energy resources is an urgent task.

The purpose of this work is to substantiate the feasibility of using Stirling heat pumps in chamber dryers.

Presentation of the main research material. Let's consider a small chamber dryer with a heat pump, which operates in a closed thermodynamic cycle with complete heat recirculation. The main element of the dryer is a heat pump. For moderate temperatures, heat pumps by the type of working fluid are divided into absorbtion (working fluid ammonia-water, lithium bromide-water), vapor compression (working fluid – freon) and gas pumps (working fluid – hydrogen, helium, neon, nitrogen, methane, air) [3, 4, 5, 6, 7, 8]. Absorbtion heat pumps are quite sensitive to temperature changes, so they are most often used in air conditioning systems. Steam-pressure heat pumps are environmentally dangerous and have a high cost, so their use in drying plants is impractical. Gas is environmentally friendly and has a fairly high thermodynamic characteristics. The operation of gas heat pumps is based on the reverse Stirling cycle (fig. 1), which consists of two isotherms and two isochores [3]. The real thermodynamic cycle of the Stirling heat pump (fig. 1b) is far from ideal (fig. 1a).

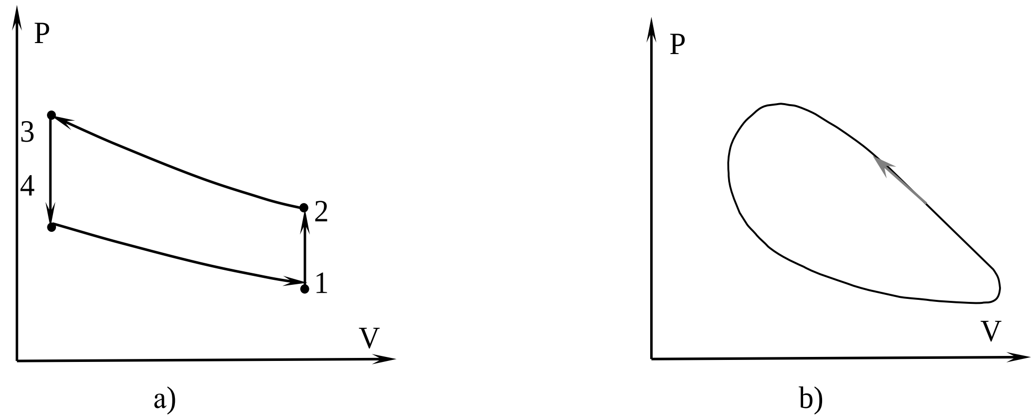

Fig.1. Stirling cycle

In real operating conditions, energy performance is affected by «dead volumes», viscous friction forces during the flow of the working fluid through the regenerator, hydraulic resistance when moving in cavities, the size of the thermal boundary layer, heat transfer in the regenerator, heat loss in thermodynamic processes and their imperfection. All these factors reduce the energy performance of the heat pump.

The working fluid of high-efficiency Stirling heat pumps is helium or hydrogen, which has high thermal conductivity and low viscosity [4, 5, 6]. In [10, 11, 12] it is proved that for moderate temperatures and frequencies up to 10 s^{-1} the use of alternative to helium working fluids (nitrogen and methane) in Stirling heat pumps can allow to create machines that are not inferior in efficiency to helium and hydrogen refrigeration machines. Heat pumps for cryogenic temperatures are high-tech, their cost is quite high. For operating temperatures of 5… 60 ^{0}C, the design of heat pumps is significantly simplified, and accordingly their cost is reduced.

The main difference between Stirling heat pumps and other types of heat pumps is that the working fluid of the Stirling heat pump does not change its phase state during the whole cycle, which allows the use of low-potential ambient heat at temperatures below 0 ^{0}C. They are widely used in cryocoolers, refrigerators, heating systems and air conditioning of residential buildings [5, 6, 7, 8]. The use of Stirling heat pumps in closed type dryers with complete heat recovery is promising [9] (fig. 2).

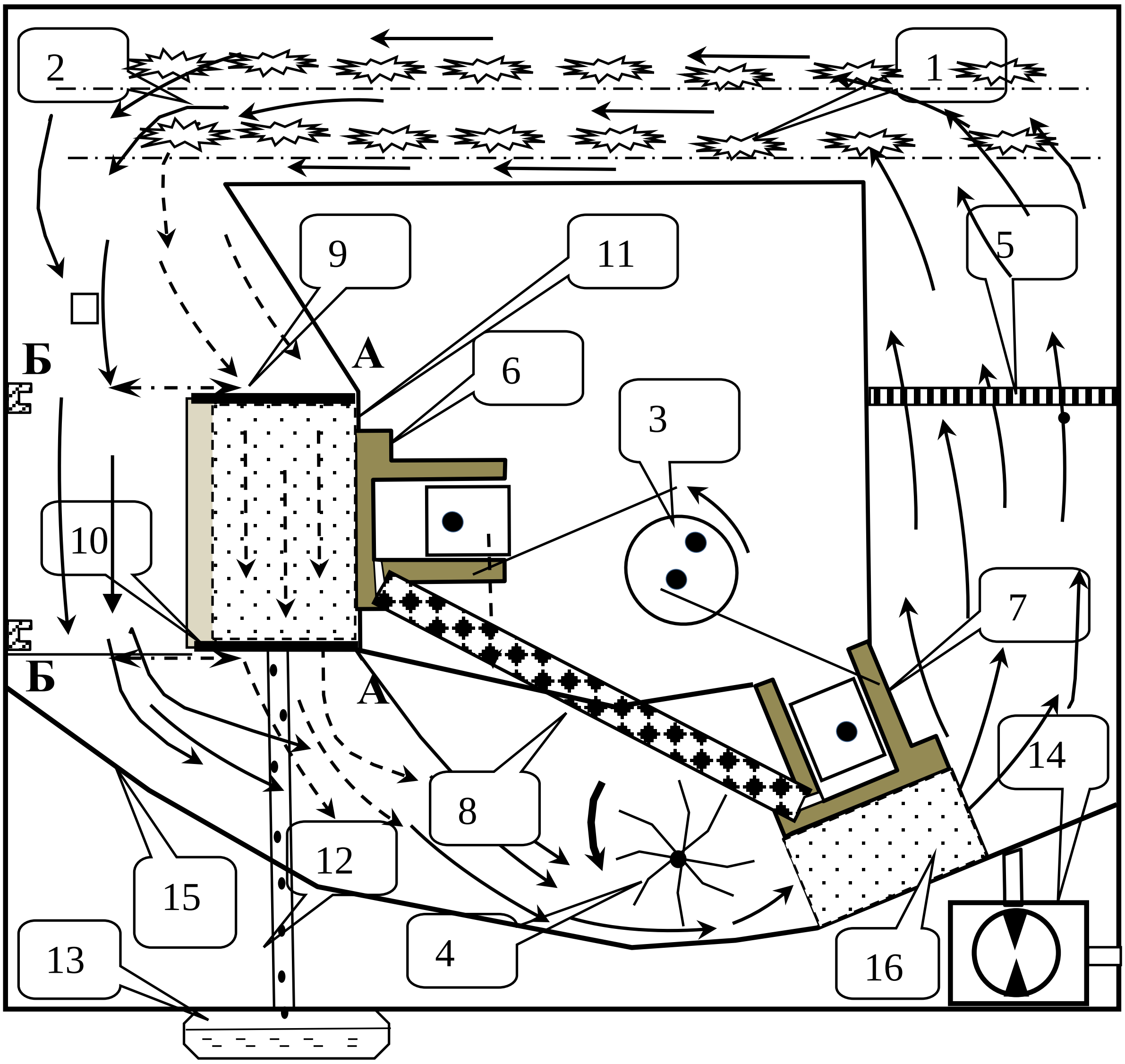

Fig. 2. Drying installation. 1 – material for drying, 2 – drying chamber, 3 – heat pump drive motor, 4 – fan, 5 – auxiliary heater, 6 – cold part of heat pump, 7 – hot part of heat pump, 8 – regenerator of heat pump, 9, 10 – dampers, 11 – refrigeration chamber with cold accumulator, 12 – condensate drain outside the installation, 13 – condensate collection tank, 14 – reverse air pump, 15 – drying agent chamber.

At room temperature T_K, materials 1 for drying (fruits, berries, vegetables, mushrooms, seeds, grains, oilseeds) are loaded into the drying chamber 2. The electric motor 3 of the installation drives the heat pump mechanism. The fan 4 creates a circular directed air flow in the drying unit, which provides active ventilation in the drying chamber 2. At the initial stage of the drying process by the electric heater 5, the dryer is driven to a given operating temperature. When the required drying temperature is reached, the electric heater is switched off and no longer switched on during the drying process. The Stirling heat pump pumps heat from the refrigeration chamber 11 of the drying unit to the hot part 7 of the heat pump. Upon contact with the surface of the heat exchanger 16 of the hot part of the heat pump the air (coolant, drying agent) is heated, then enters the drying chamber of the installation. When passing through the working chamber, the air heats the loaded raw materials and removes some moisture from it. In the heating mode, the valves 9, 10 of the refrigeration chamber 11 are in position A, the cold part of the heat pump is hermetically separated from the drying chamber. Humid air circulates in a large circuit outside the refrigerator. When cooling the cold part of the pump by 10… 15 ^{0}C below the dew point and reaching humidity up to 85…95% the dampers of the refrigerator 9 and 10 are moved to position B. At the same time the air flow rate is reduced by the fan 4. The flow of the humidified air enters the refrigerator 11 where it is cooled. Part of the moisture is condensed in the refrigeration chamber, the condensate is discharged outside the installation through the line 12. The heat taken from the wet coolant is pumped by a heat pump from its cold part to the hot one. When the cold part of the pump reaches a temperature close to the dew point, the valves 9, 10 are moved to the position A, the cold part of the pump is hermetically separated from the drying chamber and the process is repeated periodically until the desired residual humidity of the loaded raw material is attained. If necessary, the pressure of the drying agent can be increased or decreased by means of a reverse air pump 14. The working agent can be pumped into a sealed chamber 15 or discharged directly into the atmosphere. It is also possible to replace the drying agent, for example to replace the air with nitrogen or other gas. The temperature of the drying chamber, drying raw materials, coolant, cold and hot parts of the heat pump are controlled by temperature sensors, the humidity in the drying chamber is controlled with an electronic hygrometer, the operation of the dryer valves and the drying process are directed and controlled by a microprocessor.

We will carry out a theoretical analysis of the drying unit with a Stirling heat pump and evaluate the efficiency of its operation. Heat pumps are characterized by an efficiency factor equal to the ratio of the heat dissipated in the hot part to the spent work of extraneous force in one cycle [3]:

$$\mu = \frac{Q_h}{A} = \frac{T_h}{T_h - T_c} = \frac{\tau}{1-\tau} \qquad (1)$$

where $\tau = \frac{T_h}{T_c}$ – is the ratio of the absolute temperatures of the working fluid of the hot and cold parts.

Heat transfer in the cylinders of Stirling heat engines is quite complex. There are various mathematical models and algorithms for calculating Stirling refrigeration machines [3]. Most of them are based on systems of differential equations, which are solved by numerical methods on a computer [12, 13].

According to Schmidt's model (the model is quite simple, the real efficiency of the heat engine is ~ 0,3 of the calculated) [3] the amount of heat taken away from the hot part per cycle is:

$$Q_h = \mathrm{p}_{max} V_T \frac{\pi\tau}{k+1} \left(\frac{1-\delta}{1+\delta}\right)^{1/2} \frac{\delta \sin\theta}{1+(1-\delta^2)^{1/2}}, \qquad (2)$$

where $\delta = \frac{(\tau^2 + k^2 + 2\tau k \cos\alpha)^{1/2}}{(\tau + k + 2S)}$; $\theta = arctg \frac{k \sin\alpha}{\tau + k \cos\alpha}$;

$k = V_h / V_c$ – the ratio of displaced volumes of hot and cold parts;

$V_T = V_h + V_c$ – total displaced volume;

$S = \frac{2X\tau}{\tau+1}$ – reduced «dead volume»; $X = V_d / V_c$- «relative dead volume»;

V_d – «dead volume» (total internal volume of heat exchangers, regenerator, connecting channels and holes).

The amount of heat extracted from the cold part:

$$Q_c = \frac{Q_h}{\tau} \qquad (3)$$

Heat pump drive power at shaft speed ν:

$$N = \frac{Q_h (1-\tau)\, \nu}{\tau} \qquad (4)$$

Lot's evaluate the energy and thermodynamic characteristics of the drying unit according to the model (1-5). Let the working fluid of the heat pump is nitrogen, pressure is $3 \cdot 10^6$ Pa, the volume of each cylinder is 400 cm^3, the «dead volume» of the heat pump is 200 cm^3, the phase shift between the movements of the pistons of the heat pump is 75 .. .140^0, maximum drying temperature is 50 ^{0}C, engine speed of the heat pump drive is 600 rpm. With the real efficiency of the Schmidt model $\mu_P \sim 0{,}3\mu_T$, we have (fig. 3, fig. 4).

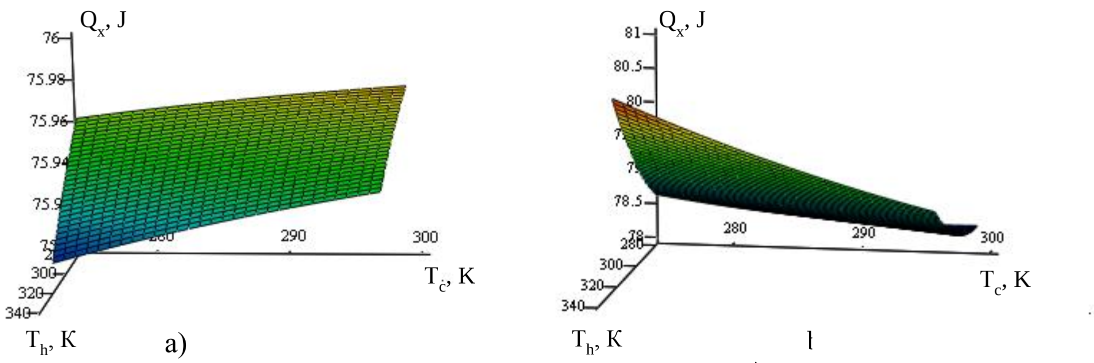

Fig. 3. Dependence of $Q_c = F(T_c, T_h)$ at the angle of shift of the phases of change of volumes of movements of the compressor and expansion cavities: a) 75^o, b) 140^o

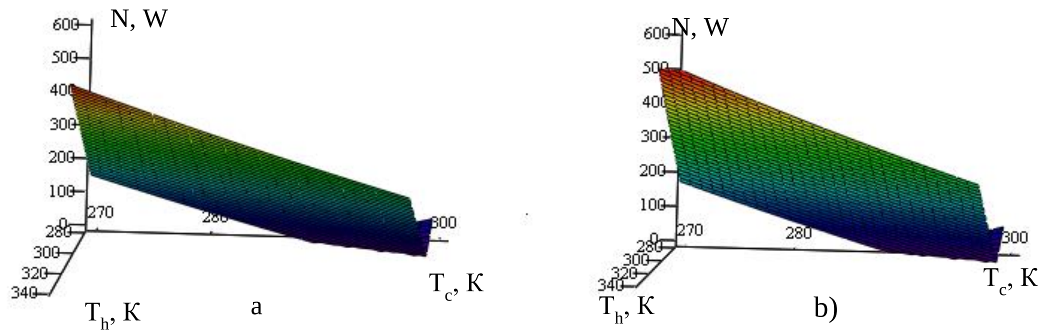

Fig. 4. Dependence of $N = F(T_c, T_h)$ at the angle of displacement of the phases of change of the volumes of movements of the compressor and expansion cavities: a) 75°, b) 140°

The thermodynamics and physico-mathematical models of the process are evaluative in nature, in the first approximation, the dynamics of temperature change of the warm and cold parts of the heat pump of the drying unit has such a form:

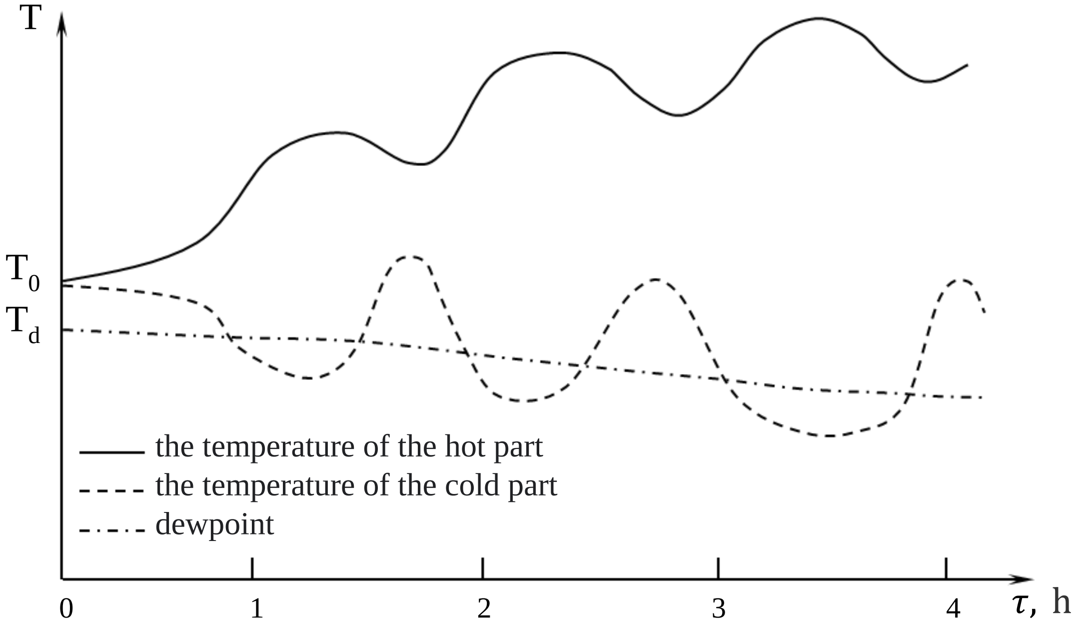

Fig.5. Temperature change of the hot and cold parts of the heat pump of the dryer

Let's assume that the average value of $Q_x \sim 70$ J, the average power of the heat pump N ~ 200 W. The drying installation, in the steady-state mode of operation gives the chance to take away from the dried material 0,1-0,2 kg of moisture for a period of time τ ~ 3 h.

Conclusions.

The chamber dryer with the Stirling heat pump works in a closed cycle. Exhaust heat in the dryer is not released into the environment, but only «pumped» from the cold part of the heat pump to the hot one so its work from an energy point of view is much more efficient than of conventional dryer where moisture is taken away simultaneously with the coolant outside the dryer.

Due to the fact that the cycle of the dryer is closed, it eliminates the possibility of environmental pollution and the possibility of working with environmentally hazardous materials, as well as the use of other drying agents, such as nitrogen [14], which has better thermophysical properties than moist air.

The drying process can be carried out at different absolute pressures in the drying chamber, which allows you to choose the optimal operating modes of the installation

The dryer makes it possible to take away the separated droplet moisture from the dried raw material outside the drying chamber and collect it in its condensate container.

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