Calculation methodology of the heat pump in the process of oscillating vacuum-conductive drying of lumber

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Abstract. The oscillating technologies consisting in alternating of the stage of heating of the material and vacuumization are the most advanced in the process of wood drying. In this regard, the article examines the energy-saving technology of the oscillating vacuum-conductive drying of lumber, during which the thermal energy of the moisture evaporated from the material under vacuum in one chamber by using the heat pump is transferred to the heating of the material in the other chamber. The authors develop the method of calculating the rate of removal of moisture from the heated material at the stage of vacuumization depending on the depth of vacuum, temperature, humidity and thickness of the material, which is the initial condition for calculating the heat pump.

1. Introduction
Drying the materials carried out under reduced pressure allows obtaining a high quality of dried wood and shortening of the process duration. Thus, despite the undeniable advantages, vacuum drying has a problem with the supply of thermal energy to the dried material [1]. The familiar drying technologies existing in various industries, such as microwave, convection, radiation methods do not always allow obtaining a material with the required quality and little energy consumption. Therefore the development of the technologies for accelerated drying with the lowest energy consumption is an important issue [2].

Thus in terms of reducing the energy costs for drying processes most attention is paid to the use of alternative energy sources, particularly waste wood in recent years [3].

At the same time the energy saving techniques well known in other industries, applied to woodworking industry are still not widely used or are of a single character. So, for example, heat pumps used in convective dryers have not received further development and application in other methods of drying, in particular in vacuum technologies [4, 5]. Conducting the process in a sealed condition allows the most effectively catching of heat energy of moisture evaporating from the material. However, the difficulty lies in the fact that the smallest duration of the process of vacuum wood drying is provided by the cyclic modes, consisting of the stages of heating and vacuuming. At the stage of heating, there is the accumulation of heat energy by the material, and at the stage of vacuumization there is the removal of moisture from the material only at the expense of energy previously accumulated by the material, that is, heating the material at this stage is not performed. Such management of the drying process ensures the positive effect of gradients of temperature, pressure and humidity inside of the material, providing accelerated drying without the significant
internal stresses. Thus, the energy captured by the heat pump at the stage of vacuumization cannot be directed to the heating of the material at that moment [6].

2. Materials and methods
A programmable vacuum drying oven Memmert 400 was used for experimental studies of the drying rate of lumber heated under vacuum. The input data at the experiment planning were such factors as the residual pressure at the stage of vacuumization, temperature, thickness, average moisture content and basic density of the material. In order to improve the accuracy of calculation output value (the speed of drying), depending on various factors, the process of moisture removal is considered in two intervals: sample drying with moisture, which is above the saturation limit of the cell walls (80-40%) and sample drying with the moisture content, which is below the saturation limit of the cell walls (30-10%).

With the aim of reducing the energy consumption in the processes of vacuum lumber drying the technology of oscillating vacuum-conductive drying with the use of a heat pump was developed. The feature of the proposed technology is the transfer of thermal energy of the moisture evaporated from the material under vacuum in one chamber for heating the material in the other chamber [7, 8].

On the basis of this technology, which allows rational using of energy resources, the technological complex was developed, in which the waste wood, accumulating in large volumes in woodworking industry, can be used as fuel [9]. The process of this complex consists of the following operations: gasification of wood waste to produce synthesis gas, followed by cooling; combustion of synthesis gas in the internal combustion engine to produce mechanical energy to carry out the operation of the compressor of the heat pump [10].

For experimental studies of the drying process according to the developed technology the installation was created (Figure 1).

**Figure 1.** Experimental setup for the study of oscillating vacuum-conductive drying of lumber: 1 - top chamber; 2 - lower chamber; 3 - plate with liquid heating; 4 - heat pump system; 5 - condenser; 6 - evaporator; 7 - pipeline; 8 - circulating pump; 9 - three-way valve; 10 - vacuum pump; 11 - electromechanical valve; 12 - vacuum gauge; 13 - flow meter; 14 - valve; 15 - additional electric heater; 16 - internal combustion engine; 17 - cooling of the synthesis gas; 18 - gasifier

Recently studied cut wood samples are placed in the chambers on the heated plates. Thus the flanks of the wood are painted over with the last quick-drying paint to prevent the intensive removal of moisture from it. The rest of the chambers are sealed with flaps, and after turning on an additional heater and coolant circulation in a small circle, heating of the sample in the first chamber starts. Wood heating continues until the temperature inside of the sample reaches a predetermined value. After heating the first chamber is vacuumized and lumber is kept until it is cooled [11]. Thus the moisture evaporated from the dried material condenses on the evaporator of the heat pump, transfers the thermal energy to the refrigerant, due to what the stage of material heating in the second chamber is realized.
The duration of the vacuumization stage in one chamber is determined by the duration of material heating in the second one. Furthermore, there is a simultaneous change of stages in the chambers. Drying is carried out until the moisture content of lumber reaches the finite value [12].

3. Results
As the result of the experimental studies of drying rate of lumber heated at vacuum the following regression equations were obtained:

– for the moisture content above the saturation limit of the cell walls:

\[ N_1 = -0.06416W - 0.08354T - 0.0000415TP - 0.000076PW + 0.00142TW + 3.7666, \]  

where:
- \( W \) – humidity, (%);
- \( T \) - temperature; (°C);
- \( P \) – pressure, (kPa);
- \( \rho \) – reference density, (kg/m³);
- \( S \) – thickness of lumber, (mm).

– for the moisture content below the saturation limit of the cell walls:

\[ N_2 = -0.001473W - 0.000341\rho - 0.001152S - 0.0000097TP - 0.00001875TW - 0.0000282P^2 + 0.00000067\rho^2 - 0.0000368S^2 + 0.303571. \]

Based on the experimental data, kinetic curves of temperature, pressure in the chamber and the humidity of the wood in the process of vacuum-oscillating drying were constructed (Figure 2).

\[ \text{Figure 2. Graphs of the process of oscillating vacuum-conductive drying: a} - \text{temperature curve; b} - \text{kinematic dependence of the pressure in the chamber; c} - \text{drying curve} \]
The studies have shown that the transfer of heat from one chamber to another occurs with partial loss of heat, due to which the optimal parameters of the drying process are retained and the loss of thermal energy must be compensated by the additional heat. The amount of thermal energy for compensating the heat loss is presented in Figure 3.

![Figure 3. Indicators of additional thermal energy for offsetting heat losses](image)

It was found that a slight reduction of the required additional energy with the decreasing moisture content of the material happens because of the duration reduction of the heating stage due to the increase in the thermal diffusivity of the material.

As a result of the series of experiments it was found that the duration of the vacuumization stage in the drying process increases, while the duration of the heating stage, on the contrary, decreases (Figure 4).

![Figure 4. Dependence of duration of heating and vacuumization stages on moisture](image)

The stages change in the chambers should be realized simultaneously and the current moisture content of the material at the vacuumization stage has been studied. Moreover, the potential for further material drying at the vacuumization stage, at the moment the material under heating achieves a predetermined temperature, has been analyzed. It has been established that at this point in time dehumidification of material under vacuum reaches 87 % of the maximum possible value. For this reason it was decided to hold the change of stages when the material reaches the set temperature at the heating stage, which, in turn, reduces the total duration of the drying process of wood material with a slight increase in the number of cycles of ‘heating-vacuumization’.

To confirm the conducted research the curves of the dependence of the amount of dehumidification on the duration of the vacuumization stage were built (Figure 5).

![Figure 5. Dependence of amount of dehumidification on duration of vacuumization stage](image)

With the aim of obtaining data on the energy efficiency of the use of heat pump in the process of vacuum-oscillating drying of wood materials, a comparison of the energy consumption of the established installation for various types of wood with electric and heat pump heating (Figure 6) was conducted. From the graphs we can see that the drying with an electric supply of heat takes place with a significantly higher power consumption (about 3 times). Thus, it has been found that the use of the
heat pump in the process of oscillating vacuum-contact drying of wood-based materials is a promising direction of efficient use of heat and electricity.

![Figure 5. The dependence of the amount of dehumidification on the duration of the vacuumization stage](image)

![Figure 6. The energy consumption of the installation of the oscillating vacuum-conductive drying for different species of lumber](image)

Taking into account the experimental data of the oscillating vacuum-conductive drying an engineering calculation methodology of the pilot plant using a heat pump was developed.

The data for calculation are as follows:

- heat load $Q_{hp}$ is determined by the rate of lumber drying in the vacuum process:
  \[ Q_{hp} = N \cdot V_m \cdot \rho_m \cdot r, \]  \( (3) \)

- low-grade temperature of the coolant at the evaporator inlet is equal to the temperature of the water vapour evaporated from the material, which is located in free space of the drying chamber:
  \[ T_{l-g1} = T_v = \frac{B}{(A-\lg P)} - C, \]  \( (4) \)

where: $N$ – speed of drying, (%/min); $V_m$ – volume material of timber, (m$^3$); $r$ – latent heat of vaporization, (j/kg); $A$, $B$, $C$ – coefficients of the Antoine equation.

- the temperature of a high-potential heat carrier (hot water) at the inlet of heat pump $T_{h-pl}$ and after heat pump $T_{h-pl2}$ is set not less than 15 °C and 5 °C respectively above the temperature of lumber after the heating stage, which was used earlier when calculating the speed of material drying:
  \[ T_{h-pl2} = T_m + (15 \div 20), \]  \( (5) \)
  \[ T_{h-pl1} = T_m + (5 \div 10), \]  \( (6) \)
The pilot plant with application of the heat pump, the energy efficiency indicators of which are presented in table, is designed according to the developed engineering methodology.

**Table 1.** The index of the energy efficiency of the estimated heat pump

| Indicator                                      | Value |
|------------------------------------------------|-------|
| Heat load density of the heat pump $q_{hp}$, (kJ/kg) | 146   |
| Specific energy consumed by the motor $W$, (kJ/kg)     | 27,63 |
| The degree of compression in the compressor $\varepsilon$ | 7,10  |
| The conversion factor of heat $\mu$                   | 6,95  |
| The conversion factor of electricity $\mu_e$          | 5,28  |
| Specific consumption of primary energy                | 0,49  |

The efficiency of a heat pump with electric drive is determined by the ratio of heat transferred to the hot coolant, to the electric power supplied, to the drive motor of the compressor (the conversion factor of electricity $\mu_e$) and condition $\mu_e > 1$.

4. Conclusions
The complex, based on the consumption of wood waste by gasification to produce synthesis gas for the operation of the internal combustion engine, bringing heat pump of vacuum drying equipment to action has been developed.

According to recent experimental studies it has been determined that the changes in stages should be carried out at the heating stage when the material achieves the set temperature. The result duration of the drying process reduces with a slight increase in the number of cycles of ‘heating-vacuumization’. The proposed technology allows almost three-times reduction in the consumption of energy resources and an increase in the efficiency of the process of lumber drying.

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