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The Results of Experimental Studies of the Jet Thermal Module

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Abstract. An improved design and technological scheme of a jet thermal module for efficient water heating for use in autonomous heat supply and technological processes at agricultural facilities with a brief description of its device and technological process is presented. Positive results of experimental studies and laboratory tests of the jet thermal module are given, the main parameters of which were: productivity - 1120-2145 kCal/h, water heating temperature – 34–61.5 °C (maximum - 72.7 °C), duration of water heating to operating mode – 1 - 1.5 h, water supply – 18 – 25 m^3/h, the pressure of the supplied water is 25-37 m, the power consumed is 2.1 kW, the efficiency of the heat generator and the heat generating device is 0.85 – 0.95, the efficiency of the jet thermal module is 0.6 - 0.7.

Keywords: improved design, technological scheme, jet thermal module, experimental study, laboratory test, heat supply, positive result.

Introduction

The article is aimed at improving the efficiency of alternative, energy-saving and environmentally friendly water heating technology for autonomous heat supply and technological processes at agricultural facilities using a jet thermal module, which, compared with analogues - electrode water heaters (boilers), reduces energy consumption by 30-50% and improves ambient air quality [1-3, 10].

In modern heat engineering systems it is important to increase the efficiency of heat exchange, reduce energy costs and increase the reliability of equipment operation. Jet heat modules represent a promising direction in the field of heat and mass transfer, as they provide high intensity of heat transfer due to the directional effect of gas or liquid jets. Their application is possible in aviation and space technology, power engineering, metallurgy, mechanical engineering and other industries where precise control of thermal processes is required [1, 2].

Despite significant progress in the development of jet thermal systems, the issues of optimisation of module design, regulation of jet flow parameters and increase of heat transfer coefficient remain relevant. Experimental studies provide accurate data on the characteristics of such modules, which contributes to the improvement of heat transfer technologies and the development of energy-efficient solutions [2].

The issues of heat transfer using jet technologies are widely studied in domestic and foreign scientific literature. Classical studies of heat transfer under the influence of gas and liquid jets are presented in the works [2, 3]. These studies consider the mechanisms of turbulent transport and heat transfer peculiarities at different modes of jet flow.

The works [2, 5] analyse the influence of flow parameters (velocity, pressure, temperature) on heat transfer efficiency. The authors note that the use of jet systems allows to significantly increase the heat transfer coefficient compared to traditional cooling and heating methods.

Current research [3, 7] focuses on numerical modelling and experimental methods for the study of jet thermal modules. They show that the choice of nozzle geometry and characteristics of the supplied flow plays a decisive role in the heat transfer efficiency. However, despite the considerable amount of theoretical and experimental work, there is still a need for a detailed study of the performance of jet heat modules under varying external conditions and different operating modes.

The present work is aimed at expanding the existing knowledge on the operation of jet thermal modules by conducting comprehensive experimental studies. In contrast to earlier works, the study considers [4]:

The influence of geometrical parameters of the nozzle system on the uniformity of heat flux distribution.

Optimal operating modes of the jet thermal module depending on the pressure and temperature of the working body.

Stability analysis of thermal characteristics under different operating conditions.

The obtained experimental data allow more accurately assess the efficiency of the jet thermal module and form recommendations for its application in various technical systems. The results of the study can be useful in the development of new energy-efficient heat exchange technologies.

The object of research is the technology of hydroheating water using a jet thermal module, technological and hydrodynamic processes occurring in a jet thermal module.

The research method. The work uses analytical and experimental studies and laboratory tests of a prototype development.

1. Materials and methods

A jet termal module is a device in which a directed flow acts on a heated surface, providing intensive heat exchange. This study investigated the operation of the module using compressed air as a working body [5, 8].

The module design included the following elements[6]:

Nozzle system, providing the formation of gas flow with certain characteristics (velocity, directionality, turbulence). Nozzles of different geometry (cylindrical, conical, Laval nozzles) were used during the experiment.

A gas supply chamber stabilising the pressure and ensuring uniformity of the flow.

Fixing and guiding elements allowing to change the position of the module relative to the examined surface.

The material of the module construction is stainless steel with high temperature and corrosion resistance.

Experimental studies of the jet thermal module were carried out in several stages, including preparation of the setup, measurements, data processing and analyses of the results. This section details the methods applied in each stage of the experiment [6, 9].

Before starting the tests, the equipment was set up and calibrated [10]:

- air supply system leak check.
- calibration of the thermocouples and thermal imaging camera.
- adjustment of air supply parameters (pressure, flow rate, temperature).
- setting the heated plate in a fixed position.
- determination of reference points for temperature measurement.

Experimental studies included variation of the main parameters of the module operation and registration of thermal and aerodynamic characteristics.

The applied methods allowed to obtain accurate data on heat transfer in the jet heat module, to reveal dependences between flow parameters and heat transfer efficiency. The data can be used to optimise the design and operating modes of such systems.

Verification and refinement of the calculated parameters of the thermal module was carried out in accordance with the program, the purpose of which is to clarify the calculated limit and accept their rational values.

The inner diameter of the active ejector nozzle. The maximum vacuum created and the maximum flow rate of the sucked air by the ejector are accepted as the criterion of verification and refinement.

According to the calculation, the diameter of the active nozzle was assumed to be 8.5-21 mm, a value of 19 mm was experimentally obtained, at which a maximum vacuum of 8.4 m is created and the intake air flow rate (supply) is 210 m^3/h, which is accepted as a refined parameter [4, 13].

The required flow of the centrifugal pump. According to the calculation, the pump supply is 0.00102-0.0044 m3/s, experimentally 0.003-0.0039 m^3/s (11-14 m^3/h), which corresponds to the calculated values and satisfies the performance of the technological process of heating water with a thermal module [8, 11].

The useful, expended power and efficiency of the jet thermal module. According to calculations, the useful power is 403.4 - 868.8 kW, the consumed power is 718.2 - 541.6 Watts and the efficiency is 0.56. Experimentally, 573 - 1479 watts, 2100 W efficiency of 0.60-0.70, which in terms of useful and expended power satisfy the calculated values, in terms of efficiency, higher values can be obtained experimentally with specified useful power for heating the room.

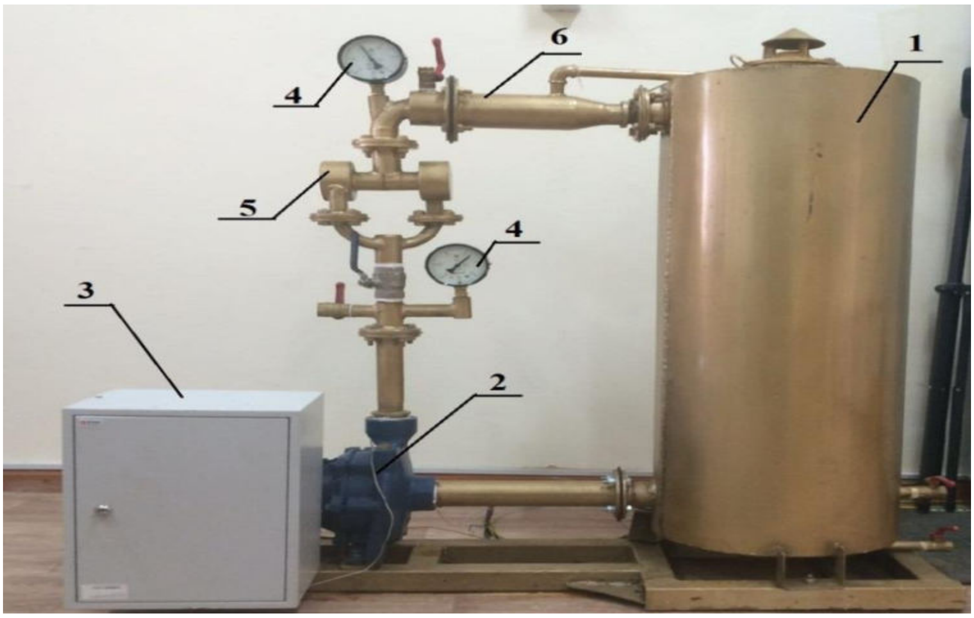
The tests of the prototype of the jet thermal module were carried out in laboratory conditions with the following initial parameters: the room is not heated with a volume of 170 m^3; the volume of heated water is 70 dm^3; the capacity of heated water is not insulated; the initial temperature of heated water is 18 -19.6 °C and indoor air is 15 °C; ejector parameters: the inner diameter of the active nozzle is 25mm and the mixing chamber – 34 mm; the diameter of the L-shaped passive nozzle of the heat generating device is 15 mm; the diameter of the heat generator twist chamber is 86 mm; parameters of the centrifugal pump: supply 18...25 m^3/h, nominal head Hp = 25 -35 m, power consumption – 1.8 – 2.1 kW [10, 12].

A general view of the prototype of the jet thermal module is shown in Figure 1.

Laboratory tests of the jet thermal module to determine its main parameters were carried out in the following sequence:

1. the thermal module assembly was installed in an unheated room, the electrical part of the centrifugal pump was connected to a single-phase electric meter, the heated water tank was filled with tap water to the level of the lower mark of the diffuser of the mixing chamber of the ejector and using a control valve on the discharge nozzle of the centrifugal pump, the pressure was set and fixed by a pressure gauge, starting with the valve fully open, and then changing upward pressure with an interval of 1-2 m [13].

after stabilization of the technological process of the thermal module at the set pressure parameter, with a time interval of 0.5 - 1 hour, the following measurements were carried out in 3-fold repetition: the temperature of the heated water in the tank according to the readings of the thermometer, the readings of the three-phase energy meter, the volume of heated water in the tank and the pump rotation speed in rpm according to the tachometer readings. The



1– tank for heated water; 2 – centrifugal electric pump; 3 - control panel; 4 – pressure gauge; 5 – heat generator; 6 – heat generating device.

Fig. 4. - General view of the prototype of the jet thermal module

2. processing of test results based on the obtained measurements was determined using the following formulas.

The supply of the centrifugal pump was determined by the formula [14]:

$$Q_i = \frac{\sum_{i=1}^{m} V_i}{\sum_{i=1}^{m} t_i}, \quad (1)$$

The amount of heat obtained by heating water is determined from experimental data according to the formula (9), the useful power according to (12), the consumed power according to (14) and the efficiency of the thermal module according to (16).

The power consumption of the centrifugal pump was determined by the formula [14]:

$$N_p = \frac{1}{m} \cdot k \cdot \sum_{i=1}^{m} (U\text{a} + Ub + Uc), \text{ W} \quad (2)$$

The efficiency of a centrifugal pump is determined by the formula [14]:

$$\eta_p = \rho \cdot g \cdot Q_p \cdot H_p / N_p. \quad (3)$$

The efficiency of the thermal module: was determined by the formula [14]:

$$\eta = \frac{P_u}{P_s} = \frac{W_u}{W_c}. \quad (4)$$

The tests carried out on the prototype of the jet thermal module according to the developed methodology showed positive results – the thermal module is operational and meets the requirements of the technical specification for the prototype according to the main indicators obtained [15].

Laboratory tests were carried out with positive results, the main parameters of which were: productivity - 1120 - 2145 kCal/h, water heating temperature – 34 – 61.5 °C (maximum -72.7 °C), duration of water heating to operating mode – 1 - 1.5 hours, water supply – 18 – 25 m3/h, pressure of supplied water – 25-37 m, power consumption – 2.1 kW, efficiency of the heat generator and heat generating device – 0.85 – 0.95, efficiency of the jet thermal module – 0.6 - 0.7.

Table 1. Test results of a prototype jet thermal module

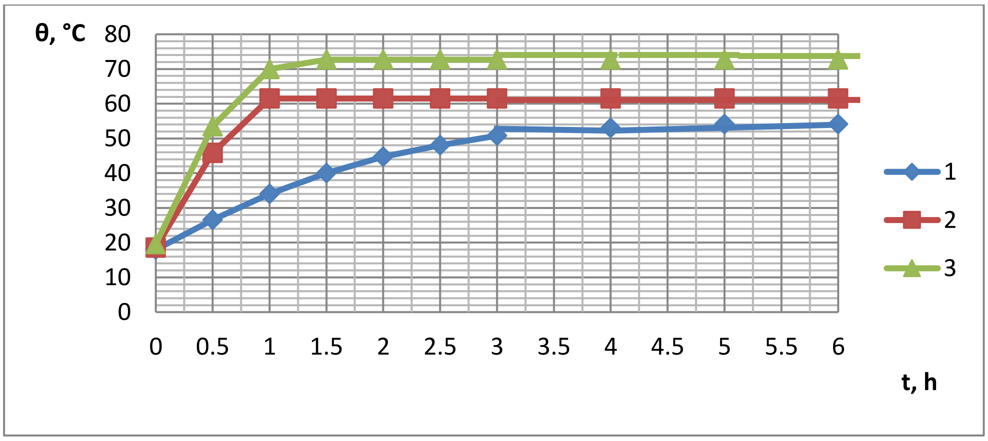
Name of indicators	Designation	Unit of measurement	The value of the indicators
Initial parameters for water heating			
The initial temperature of the heated water	Θ	°C	14-15
Initial indoor air temperature	Θ_a	°C	15-16
The volume of heated water	V	dm^3	70
The main indicators of the jet thermal module			
The final temperature of the heated water	Θ_f	°C	54-72.7
The heat generated by heating the water	Q_h	kCal	602-2527
Useful thermal power	P_u	kW	1.47 – 1.276
Useful thermal energy	W_u	kWh	0.7 – 2.95
Spent thermal power	P_s	kW	2.1
Spent thermal energy	W_s	kWh	1.05 – 4.2
The vacuum created by the ejector	H_{vac}	m	2.8 – 8.4
Intake air flow rate (supply) by the ejector	Q_a	m^3/h	100 – 210
Water pressure in the ejector	H_e	m	7 – 17.5
Efficiency of the thermal module	η_{tm}		0.7 – 0.6

2. Results and discussion

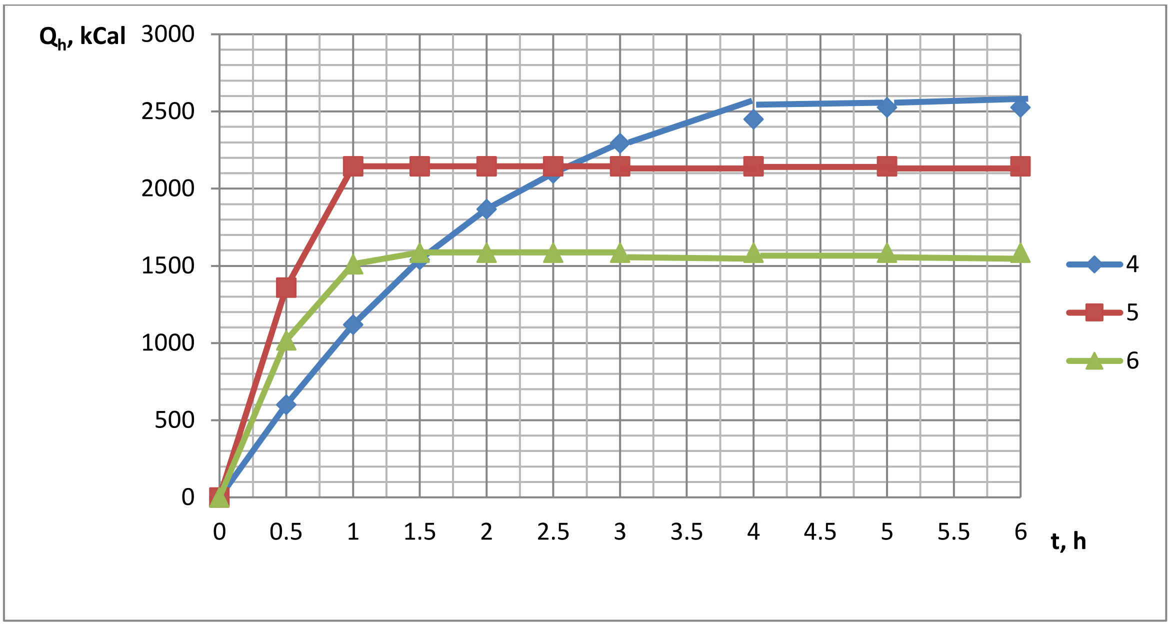
The main research of the jet thermal module was aimed at studying the technological process of the proposed jet–vacuum method of water heating, determining the essential factors affecting water heating: ejector parameters – the internal diameters of the active and passive nozzles, the amount of vacuum created in the chambers of the active and passive nozzles, air flow (gas-air mixture); parameters of the pump used – feed, pressure and efficiency; changes in technological parameters: water heating temperature, heat received, useful and expended power and useful and expended energy from the duration of water heating (operation of the thermal module) [3, 6].

We present the results obtained from experimental studies of the jet-vacuum heating method: the dependence of the temperature of the heated water, the heat received, useful and expended power, useful and expended energy on the duration of water heating, that is θ_f, Q_h, P_u, P_s, W_u, $W_e = f(t)$, which are represented by graphs (Figures 2 and 3) with an optimal value of the diameter of the active nozzle of the ejector = 25 mm.

The graph (Figure 1) shows the dependences of the temperature of the heated water and the heat received on the duration of heating the water at a volume of heated water of 70 dm^3 (1), 50 dm^3 (2) and 30 (3) dm^3 [7].



a) 1, 2 and 3 are curves of dependence of the water heating temperature at the diameter of the active ejector nozzle of 25 mm on the heating time at the volume of heated water of 70 dm^3 (1), 50 dm^3 (2) and 30 (3) dm^3;



b) 4, 5 and 6 are curves of dependence of the heat obtained when heating water at an ejector of 25 mm on the heating time at a volume of heated water of 70 dm^3 (4), 50 dm^3 (5) and 30 (6) dm^3

Fig. 2. - Dependences of the temperature of the heated water and the heat received on the duration of water heating (operation of the thermal module) with a volume of heated water of 70 dm3 , 50 dm^3 and 30 dm^3.

During the experiments, the initial water temperature was – 18 - 19.6 °C and the final at V = 70 dm^3 (1) – 54.1 °C, at V = 50 dm^3 (2) – 61.5 °C and at V= 30 dm^3 (3) – 72.7 °C, with a decrease in the volume of heated water, the temperature of its heating The operating time of the laboratory unit increased from 5 hours to 1.5 hours at lower costs. The total duration of the thermal module is 0.5...6 hours, depending on the installed technological and technical parameters and external influences. The thermal module was tested in an unheated room with a volume of 170 m^3, the capacity of the heated water was not insulated, and therefore, simultaneously with the heating of the water, the air in the room was heated from 18 ... 19.5 °C to 23 °C [4, 8].

Curves 1, 2 and 3 (Figure 2 a) in the graph are based on experimental data, and 4, 5 and 6 (Figure 2 b) were determined using a formula using experimental data [9]:

$$Q_h = C \cdot m \cdot \Delta\theta = C \cdot V \cdot \rho \cdot \Delta\theta, \text{kCal} \quad (5)$$

where C – specific heat capacity, kCal/kg·deg (for water C=1 kCal/kg·deg);

m – mass of heated water, kg:

$$m = V \cdot \rho, \quad (6)$$

where V – volume of heated water, m^3;

ρ = 1000 kg/m^3 – the density of the heated water;

$\Delta\theta$ – increasing the water heating temperature, °C:

$$\Delta\theta = \theta_f - \theta_i , \quad (7)$$

where θ_i, θ_f – the temperature of the heated water is initial and final, °C.

The nature of the curve changes can be clearly seen on the graphs.

It follows from the graph (Figure 1) that with increasing heating time, the temperature of the heated water and the heat received increase, the intensity of the increase is higher for the variant of the thermal module with a smaller volume of heated water, for example, during the first 0.5 hours of heating, the temperature of the heated water increases for the first variant at V=70 dm^3 - by 8.6 °C, for the second at V = 50 dm^3 - at 27.2 °C and for the third option at V = 30 dm^3 - at 33.9^{0}C, and in 1.5 hours of operation, the water of the corresponding volume is heated by 40.0^{0}C , 61.5 °C and 72.7 °C, reaching its maximum value, except for the option at V = 70 dm^3, which is achieved with 5 hours of operation of the thermal module [5, 7].

At the same time, the heat obtained from the water heating is: at the volume of heated water V=70 dm^3 Q_h =2527 kCal (at a capacity of 1120 kCal/h), at V=50 dm^3 Q_h =2145 kCal (at a capacity of 2145 kCal/h) and at V=30 dm^3 Q_h = 1587 kCal (at capacity 11512 kCal/h), i.e. the efficiency of the technological process of water heating by the jet-vacuum method depends on the optimization of the technological and technical parameters of the jet thermal module.

Numerical parameter data for constructing dependency curves P_u and $W_u=f(t)$ were determined by the formula (4) and (5) using experimental data on Q_T or from the graph (Figure 3) [10]:

$$P_u = \frac{Q_h \cdot A}{t}, \text{W} \tag{8}$$

where A – the mechanical equivalent of heat (A=4.2 j/kCal);

t – duration of water heating (operation of the thermal module), s.

Q_h – the amount of heat obtained by heating water, kCal;

$$W_u = P_u \cdot \text{T} \ , \text{kW·h} \tag{9}$$

where P_u – useful power, kW;

T – operating time of the thermal module, h.

The numerical values of the consumed power and energy are determined from experimental data using the formulas [10]:

$$P_s = \frac{\rho \cdot g \cdot Q_p \cdot H_p}{\eta_p}, \text{W} \tag{10}$$

where ρ = 1000 kg/m^3 is the density of the heated water;

g = 9.81 m/s^2 – acceleration of free fall;

Q_p – heat module pump supply at operating pressure H_p, m^3/s;

H_p – working pressure of the pump, m;

η_p – the efficiency of the pump used in the thermal module;

$$W_c = P_s \cdot T, \text{kWh} \tag{11}$$

where P_s– power consumption, kW;

T – operating time of the thermal module, h

Curves P_u and P_c (Figure 2) $P = f(t)$ and curves W_u, W_c $W = f(t)$ the graph is based on experimental data using formulas (6), (7) or obtained from the readings of a three-phase active energy meter, the heat module installed on the electric drive of the centrifugal pump, in terms of full capacity, taking into account $cos\varphi$ = 0.8 according to the formula [10]:

$$W_c = W_a / cos\varphi, \tag{12}$$

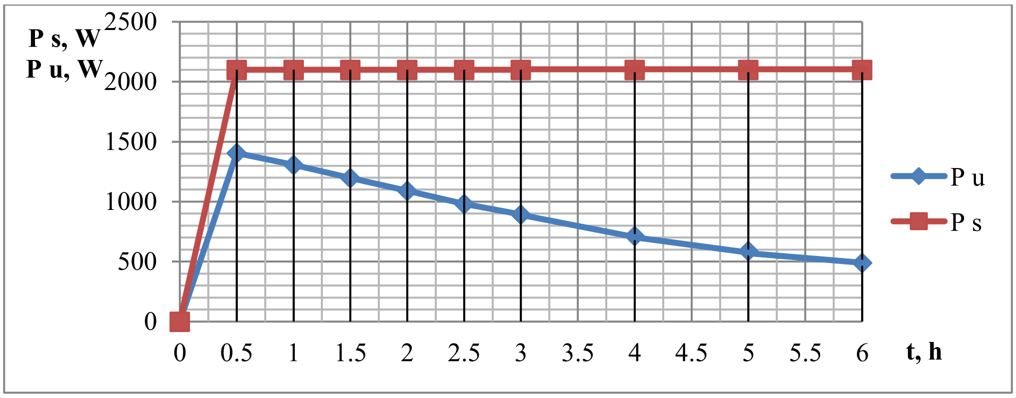
where W_a – useful active energy according to the readings of a three-phase active energy meter, kW·h.

It can be seen from the graph (Figure 3) that the curves of useful thermal power and energy P_u, $W_u = f(t)$ they have a curvilinear dependence with a maximum in the first hour of heating, and the remaining curves P_s and $W_c = f(t)$ they have straightforward dependencies.

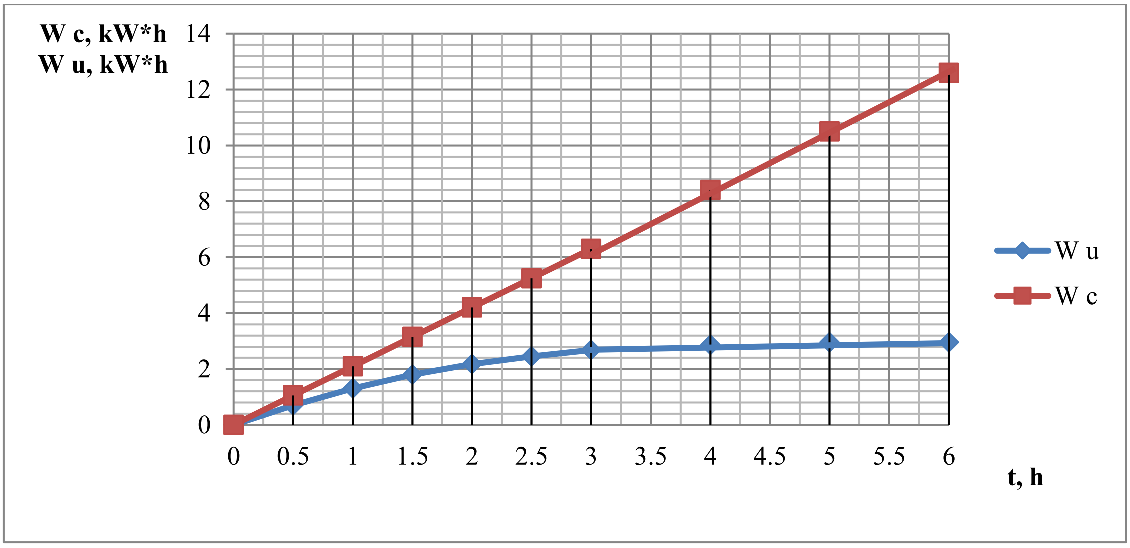
On the graph (Figure 3) dependencies $P_s = f(t)$ and $W_c = f(t)$ they show the total energy costs of the entire jet thermal module, which amount to 2100 W of power or 1.05- 12.6 kW·h of energy, and dependencies $P_u = f(t)$ and $W_u = f(t)$ they show the useful thermal power - 0.49 – 1.4 kW and useful thermal energy – 0.70 – 2.95 kW·h only for heating water without taking into account the useful costs of heating a room in the volume of 170 m^3, which was heated due to an unheated water heating tank [1, 6].

It follows from the graph (Figure 4) that the indoor air heating temperature increases in a straight–line relationship with an increase interval of 1 °C per hour of operation of the heating module with a small useful power in the range of 61 - 82 Watts, and the total useful power when heating water and indoor air varies according to curvilinear dependence with a maximum in the first 1 - 1.5 hours of operation of the thermal module with an efficiency of 0.7 – 0.6.

The pressure losses in the discharge pipeline were experimentally determined: for the variant of the thermal module with an internal diameter of the active nozzle of 25 m, the losses were 2.3-3.1 m; at 15 mm, 4.7-5.1 mm, which correspond to the calculated data.



a) – curves of the dependence of the useful thermal power and the expended one with a diameter of the active nozzle of the ejector of 25 mm on the heating time with a volume of heated water of 70 dm^3



b) – curves of the dependence of the useful thermal energy and the spent at the ejector of 25 mm on the heating time at a volume of heated water of 70 dm^3.

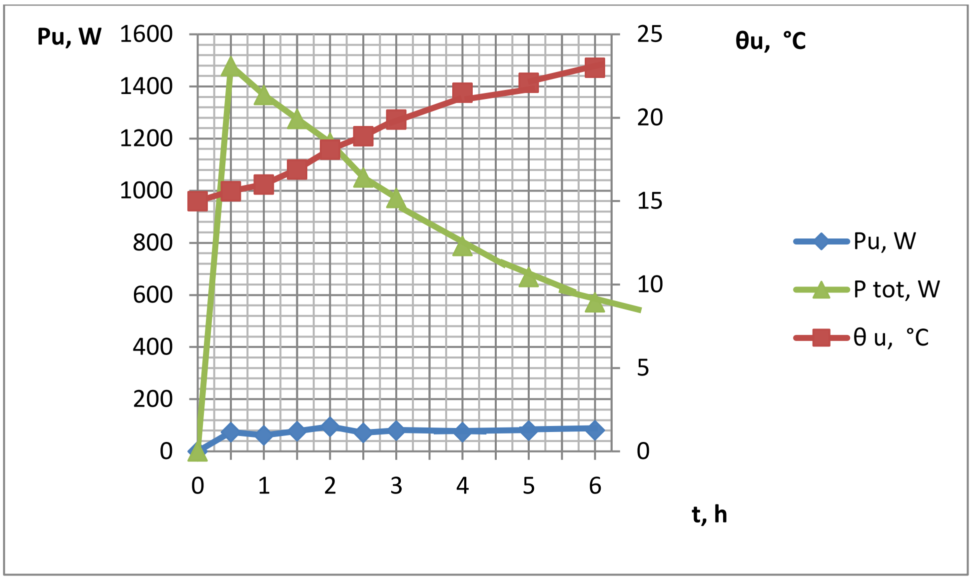
Fig. 3. - Dependences of useful thermal power and spent and useful and spent energy on the duration of water heating (operation of the thermal module)

The graph (Figure 4) shows the dependences of the temperature of the heated indoor air, the useful thermal power when heating the air and the total useful power when heating water and indoor air on the duration of heating the indoor air (operation of the thermal module) with a volume of heated water of 70 dm^3 and a volume of 170 m^3 [11].

As a result of studies of the technological process of heating water with a jet thermal module, it was found that the heating process is carried out in all modes of operation of the centrifugal pump with a supply from 18 m^3/h at a nominal head of 35 m of a water column to 21.5 m^3/h at H_P = 25 m, as well as at a head of 6-8 m and the main parameters of the ejector: internal the diameter of the active nozzle is 8-25mm and the vacuum created in the chamber of the active nozzle is 0.8–2.8 m, the passive nozzle is 2.0-8.5 m and the mixing chamber is 0.2-1.2 m.

However, the heating intensity of an equal volume of water is higher with a larger pump supply and a larger amount of vacuum created, as well as the use of heat extraction from the heated air in the upper part of the tank.

Investigation of the ejector vacuuming process [10, 11] in accordance with the accepted program of experimental studies, the purpose of which is to determine the vacuum pressure created by the ejector in an additional passive nozzle, a passive nozzle of the ejector housing and mixing chamber depending on the inner diameter of the active ejector nozzle and the water pressure in the ejector; determination of the flow rate (supply) of the sucked air by the ejector through the air inlet pipes of the additional passive nozzle and the passive nozzle of the housing, depending on the water pressure in the ejector and the vacuum created by the ejector.



ΘΘ_{ha} - the curve of dependence of the temperature of the heated air in the room on the duration of heating (operation of the thermal module), °C; P_{ha} – the curve of the dependence of the useful thermal power when heating indoor air on the heating time, W;

Fig. 4. - Dependences of the temperature of the heated indoor air, the useful thermal power when heating the air and the total useful power when heating water and indoor air on the duration of heating the indoor air (operation of the thermal module) with a volume of heated water of 70 dm^3 and a volume of 170 m^3

The need for these studies is to determine the possibility of using water heating by heat extraction from air sucked in by the ejector or gas–air mixtures, as well as cleaning polluted indoor air from dust, solid particles and odors.

The research results showed that with an increase in the supplied water pressure into the ejector, the vacuum pressure created in the ejector increases for all values of the diameter of the active nozzles of the ejector, however, the greatest vacuum pressure is created with a nozzle with a diameter of 19 mm, its value reaches 8.4 m at a pressure of 14.5 m. At the same time, the maximum consumption of the sucked air by the ejector is 210 m^3/h through the air inlet of the additional passive nozzle and 160 m^3/h through the air inlet of the passive nozzle of the ejector body [12].

Thus, the obtained results of studies of the thermal module for the created vacuum and the received supply confirm the need for its use both to increase the efficiency of water heating from the use of heat extraction of sucked air or gas-air mixtures, and to expand the scope of its use for cleaning indoor air from dust, solid particles and odors.

Conclusions

In the course of experimental studies of the jet heat module, important results have been obtained, allowing to evaluate its efficiency and prospects of application in various heat engineering systems. The tests have shown that this module provides uniform distribution of heat flow, high degree of heat transfer and stability of operation in a wide range of parameters.

The analysis of thermal characteristics has shown that optimisation of nozzle element geometry and modes of working substance supply allows to significantly increase the heat transfer coefficient. Experiments have confirmed that the use of a jet thermal module contributes to the reduction of temperature gradients on the heated surface, which is especially important for precision thermal processes.

Experimental studies were carried out, experimental and experimental samples of the jet thermal module were developed and manufactured, and laboratory tests were carried out with positive results, the parameters of which were: productivity - 1120 - 2145 kCal/h, water heating temperature – 34 – 61.5 °C (maximum -72.7 °C), the duration of water heating to operating mode – 1 - 1.5 hours, water supply – 18-25 m^3/h, pressure of the supplied water – 25-37 m, power consumption – 2.1 kW, efficiency of the heat generator and heat–generating device – 0.85 - 0.95, efficiency of the jet thermal module – 0.6 – 0.7.

The results obtained can be used to improve heat exchange technologies in power systems, industry and transport. Further research will be aimed at developing new design solutions, improving energy efficiency and expanding the application areas of jet heat modules.

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