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THERMAL HYDRAULIC ACTUATOR

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ТЕПЛОВОЙ ГИДРАВЛИЧЕСКИЙ ПРИВОД

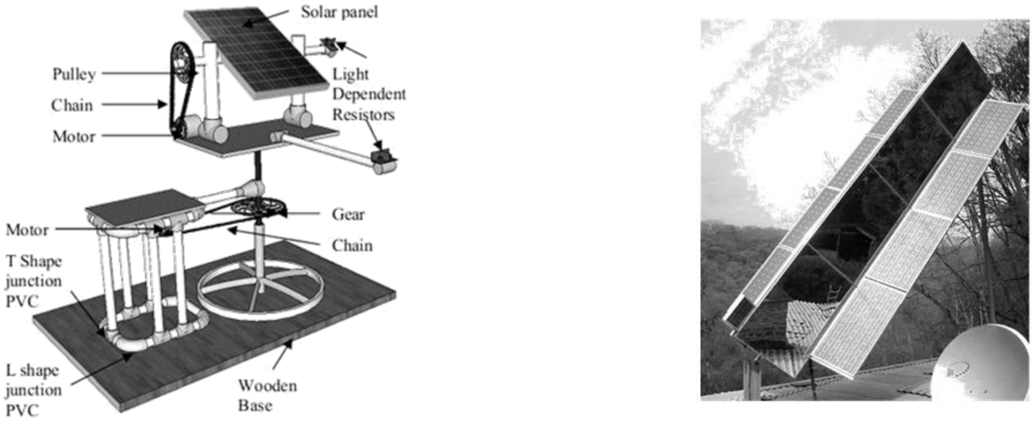
Purpose. Justification of the possibility of using the thermal hydraulic actuator as tracker in solar power systems, design of the rational construction of actuator and development of mathematical tools for prediction its characteristics.
Design/methodology/approach. The design and principle of known trackers of solar power systems were considered. The overview of design and principle of thermal actuators carried out. Ability of fluids to expand by influence of temperatures was chosen as principle for the thermal hydraulic actuator. The working fluid of the module of the thermal hydraulic actuator to produce necessary pusher's displacement was selected. The expansion of the working fluid depends of its temperature was investigated by experimental research. There is theoretical calculation based on experimental data for prediction parameters of idling of the module of the thermal hydraulic actuator were performed.
Findings. It is found that there are possibilities of using the thermal hydraulic actuator that based on the thermal volumetric expansion of the working fluid as tracker for the solar power systems.
Originality/value. Using of the thermal hydraulic actuator in the solar power system makes possible positioning of receiver without consuming of electrical energy. It leads to more efficiency work of the solar power system.
Keywords: hydraulic actuator, thermal actuator, tracker

Introduction. For efficiency increasing of solar power system from 18…22% to 30…40% electromechanical actuators - trackers are used [1]. But such systems require constant current source with sophisticated control algorithms. That's lead to increasing of cost of the whole structure. Power consumption does not allow to implement all energy potential of photovoltaic (PV) panels.

There is solution for efficiency increasing by using thermal actuator as tracker. The principle of thermal actuators is based on extension of working substance. It means that extension of working substance is thermal extension of gases, or increase of amount of working substance by phase transformation "liquid - gas" [2]. Gases are very compressible and their use for the work, which requires moving of large masses on low speed, is ineffective. Employment of the fluid as working substance puts the problem of obtaining of necessary displacement with some force.

Goals and Objectives. The main objective of the work is research of possibilities of using the thermal hydraulic actuator, which uses thermal volumetric expansion of the liquid for positioning of receiver of solar power system. One of the objectives of the research is rational layout of the actuator and design analytic system for forecasting of characteristics of the thermal hydraulic actuator.

The principle of tracker. Trackers are divided into one- and two-axle (Fig. 1) [1, 3]. One-axial trackers adjust



а б

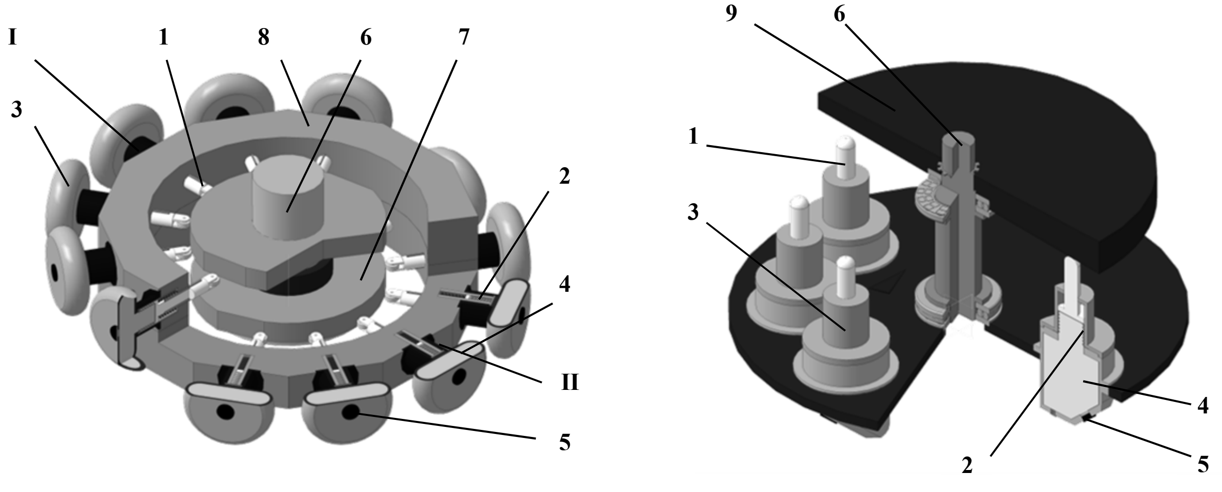
Fig. 1. Schematic design of biaxial tracker (*a*) and an example of solar power system with one-axial tracker (*b*)

the receiver displacement for efficient absorb of solar energy in horizontal or vertical tracking plane and biaxial monitor both directions.

Vertical adjustment of the receiver ranges from 10º to 85º and horizontal angle of tracking is in the range of angles from 180 º to 360º. It depends on the design and type of tracker's actuators [3, 4].

There are rotary or linear actuators in tracking systems. System is managed by controller. There are optical sensors of solar insolation used for detecting the sun position [5]. Weight of rotary structure with installed solar panels can be up to 1000 kg and above. Maximum speed of electromechanical rotary actuators is 10 rpm, linear to 1 m/s. Speed control is performed by the controller and control system.

Justification of tracker design. There is tracker is based on design of thermal hydraulic radial motor (Fig. 2.a). Individual modules (pusher - bellows - expansion chamber) placed over in the radial direction around the shaft. Heat conductive surface of expansion chambers installed in position, which sun will take at the appropriate time. Heat flow of the sun is concentrated on the perceiving surface of the expansion chamber and energy is transferred through the conductive element to the working fluid. The increasing of the temperature leads to thermal expansion of fluid. Bellows convert volume expansion of the fluid into linear displacement of the pusher. Pusher acts on cam and rotates the shaft to the relevant angle.



a *b*

Fig. 2. Construction scheme of radial-designed tracker *a*): I - first row of pushers, II - second row of pushers, and axial-designed tracker *b*): 1 – pusher; 2 – bellows;3 – expansion chamber; 4 – working fluid; 5 – heat-conducting element; 6 – the output shaft; 7 - cam; 8 - corps; 9 – sloping disc

Receiver is set to the position, what relatively corresponds to the position of sun at the beginning of tracking. Solar energy is concentrated on the first module; it transforms value of thermal expansion of fluid to linear displacement of pusher. Pusher acts on cam and rotate receiver at required angle with certain speed. The second module will start working, when the solar energy concentrates on its heat-conducting element. Every next module works by the same principle - sequential algorithm of thermal hydraulic radial actuator.

Tracking range for thermal hydraulic tracker is near 180°. It is enough for efficient work of solar power system. This range corresponds to the time of the most efficient work of PV-panels [6].

The main drawback of such construction is the algorithm of functioning between the modules. But this is provisioned by the design. If one of modules did not work for some reason, the further positioning of the receiver will not occur. To restart the work of tracker it is necessary to ensure the establishment of the receiver to its initial position. This operation requires an additional actuator, which will return the parts of mechanism on the starting position.

The design of axial thermal hydraulic tracker (Fig. 2.b) is based on independent functioning of modules. There is no sequential algorithm of work. In this scheme the orientation angle of the most heated module determinate angle of receiver direction. Actual angle of orientation of the receiver is determined by the power balance if to take into account the interaction of neighboring modules. Receiver's rotation velocity depends on the speed of the thermodynamic processes of heating and cooling and kinematic of the modules.

Selection of the working fluid was fulfilled with taking into account the coefficient of temperature expansion (Table 1), critical temperatures and allowable pressures. The coefficient of temperature expansion of the working fluid should be as high as possible. This allows to get higher value of the working fluid expansion at the same initial volume.

Methyl alcohol was chosen as working fluid for thermal hydraulic tracker because it has higher coefficient of expansion than the other examined fluids on the temperature range up to 100 °C.

Table 1

Coefficients of temperature expansion of working fluids.

Fluid	β 10^{-3} by the temperature (˚C)							
	–20	0	20	40	60	80	100	120
Water	–	–0,06	0,21	0,39	0,53	0,63	0,75	0,86
Isopropyl alcohol	0,98	1,01	1,05	1,08	1,12	1,16	1,2	1,27
Methyl alcohol	1,09	1,14	1,19	1,27	1,3	1,42	1,61	1,81
Ethyl alcohol	1,18	1,05	1,08	1,13	1,22	1,33	1,44	1,87

Calculation of kinematic parameters. Accuracy of the receiver orientation relative to the sun position depends on the number of pushers. Maximal deviation between orientation angle of receiver and current azimuth of the sun is in the range of step between modules' placement, if both modules are heated. It depends on the speed of the thermodynamic and hydrodynamic processes in modules and its maximal value equal to working angle of one module. Step between modules' placement determined as:

$$\Delta\alpha = 2k\arcsin\left(\frac{D}{2R}\right), k > 1,$$

$$k = \frac{\Pi R \cdot \alpha_{повн}}{D \cdot n \cdot 180^{o}},$$

where *n – the number of pushers; R - placement radius of the pushers;* $\alpha_{повн}$ *– tracking range; D – pusher's size.*

Current deviation between orientation angle of the receiver and angle of the sun position, without taking into account force interaction between modules, for functioning of two modules can be determined by equation:

where φ_S *– angle of the sun position;* φ_R *– orientation angle of receiver (take* $\varphi_S \approx \alpha_i$*;* α_i *– orientation angle of previous module (last orientation angle of receiver);* x_{i+1} *– pusher's displacement of the next module;* $[x]_{i+1}$ *– idling of pusher;*

$$\begin{cases} \Delta\phi = \phi_S - \left(\phi_R + \arcsin\left(\dfrac{x_{i+1} - [x]_{i+1}}{[x]_{\max}}\right)\right) & \left| \begin{array}{l} if\; 0 \le x \le [x], \\ then\; x = [x]. \end{array} \right. ; \\ [x]_i = R \cdot tg\gamma \cdot \cos(\phi_R - \alpha_i), \end{cases}$$

[x]max – maximal idling.

As tracker consists of modules, the additional challenge is to build their rational design. Design of module with direct connection of bellows with extension chamber – monoblock (Fig. 3.a), leads to increase of size and material capacity of actuator. Connection of the bellows and chamber by pipeline (Fig. 3.b) facilitates placement of modules in the drive.

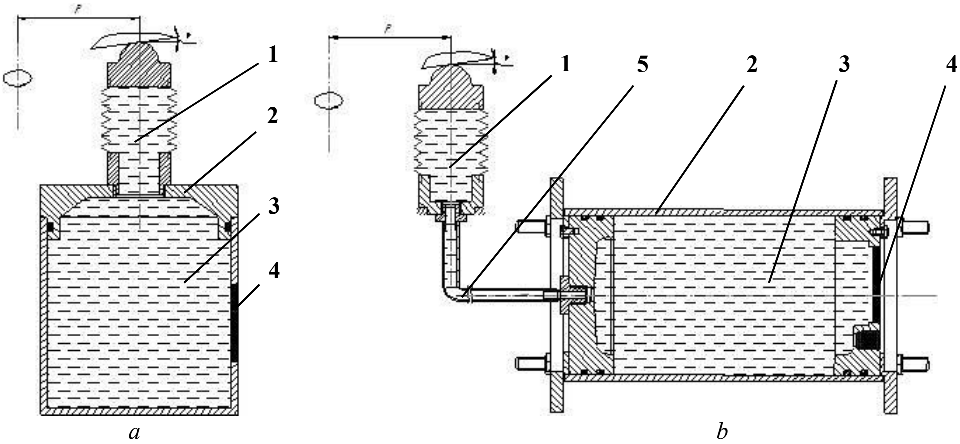


Fig. 3. The design of the module of thermal hydraulic actuator with direct connection of pusher and expansion chamber (*a*) and with pipeline connection (*b*): 1 - bellows, 2 – expansion chamber, 3 - working fluid, 4 – heat-conducting element; 5 - pipeline

By calculation of monoblock construction the size of expansion chamber is need to take into account, whereas calculation of construction with pipeline takes into account sizes of pushers and extension chambers singly.

Number of pushers, their size and construction of the module affects the size of the actuator. Placement radius of pushers and slope of disk determined pusher's displacement reserve (Table 2)

$$x = R \cdot \mathrm{tg}\gamma \cdot \sin\alpha,$$

where γ – slope of disk; α – angle of slope disk rotation relative to the placement of the pusher.

Table 2

Dependence between pusher's displacement and rotation of slope disk (slope of the disk γ = 5°)

φ_R	Pusher's displacement				
	R = 100 mm	R = 150 mm	R = 200 mm	R = 250 mm	R = 300 mm
0°	0	0	0	0	0
15°	2,3	3,4	4,5	5,7	6,8
30°	4,4	6,6	8,8	10,9	13,1
40°	5,6	8,4	11,3	14,1	16,9
50°	6,7	10,1	13,4	16,8	20,1
60°	7,6	11,4	15,2	18,9	22,7
70°	8,2	12,3	16,4	20,6	24,7
80°	8,6	12,9	17,2	21,5	25,9
90°	8,8	13,1	17,5	21,9	26,3

There are relation between pusher's displacement and angle of the shaft rotation. It's necessary to ensure the pusher's displacement which corresponds to rotation of the shaft on 90°.

Experimental research of the working fluid expansion. The main factor that affects on displacement of the pusher is the value of the working fluid expansion. For determination of factors which affect on the value of the working fluid expansion series of experiments were done.

The experimental equipment (Fig. 4) includes a metal container filled with water, heater, bulb filled with studying fluid (methyl alcohol) and measuring tube. Water was heating in a metal container, the heat transferred from the water through the walls of the bulb to the fluid. There is a wood pad to prevent heat transfer from the bottom of container to the bulb. A small heating rate of water provided a more uniform temperature distribution on the outer surface of the bulb.

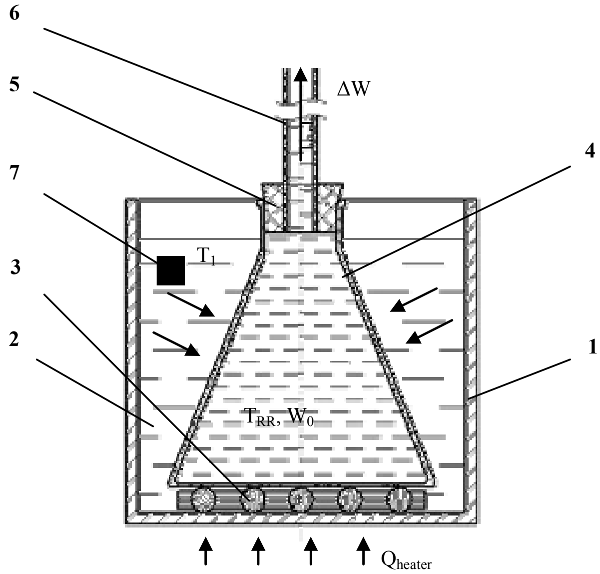


Fig. 4. The experimental equipment: 1 - metal container, 2 - water 3 – wood pad; 4 - bulb filled with investigated fluid, 5 - cork, 6 - measuring tube; 7 – temperature sensor

Bulb was filled with the investigated fluid (methyl alcohol) up to zero mark of measuring tube. Initial volume of methyl alcohol in the bulb is 375ml at temperature 18°C. As the bulb was completely immersed into the water, its walls can be taken as conductive element through which the heat flow transmitted to the working fluid. Initial temperature of water was lower than that of alcohol, what caused reducing of alcohol level in measuring tube below zero mark. During heating the level of alcohol in the tube reached zero mark at water temperature 19-20°C. This indicates on equilibration time of temperatures inside and outside the bulb. But water was continuously heated and its temperature is increased by a specific law. Measurement of fluid expansion in the bulb was carried out for process of heating and free-cooling of fluid.

In addition, experiments with timemarks were performed. They allowed to determine the characteristics of temperature on the outer surface of the bulb. This will allow to evaluate the accuracy of the theoretical calculation.

Prediction of idling parameters. The description of dependence of the output pusher's displacement from quantity of heat that transferred to the working fluid and of constructive parameters of module were done. The process of converting of thermal energy into mechanical work on the example of one of the modules was considered. Input value for the calculation is the temperature on the outer wall of the heat-conducting element. The difference between the temperatures on the outer and inner walls of the heat-conducting element leads to the heat flow that passes through it.

Quantity of heat that passes through the conductive element is determined by the relationship:

$$Q_{TE} = \lambda_{TE} \cdot \frac{T_1 - T_{RR}}{\delta} \cdot F_{TE} \cdot t,$$

where Q_{TE} – quantity of heat, that flows through area F_{TE} of heat-conducting element during the time t;T_1–temperature on the outer wall of heat-conducting element; δ – thickness of the wall of heat-conducting element; λ_{TE} – thermal conductivity of the element; T_{RR} – temperature of the working fluid.

There was made the assumption that the loss of heat by fluid has occurring only through the cylindrical wall of the expansion chamber. Their value is determined by the dependence:

$$Q_R = \frac{2 \cdot \Pi \cdot \lambda_W \cdot L \cdot (T_{RR} - T_0)}{\ln\left(D_o / D_i\right)},$$

where λ_W – thermal conductivity of wall of the chamber; D_o – outer diameter of expansion chamber; D_i – inner diameter of expansion chamber.

The quantity of heat that transferred into the fluid is the difference between heat, that transmitted by heat-conductive element, and heat, that lost through the wall of the chamber. This quantity of heat completely goes to heating of the fluid. Stabilized temperature of the fluid is determined by the dependence:

$$T_{RR} = \frac{Q_{TE} - Q_R}{c_{RR} \cdot \rho_0 \cdot W_0} + T_0,$$

where c_{RR} – thermal capacity of the fluid; ρ_0 – initial density of the fluid; W_0 – initial volume of the fluid.

Then, the value of the thermal expansion of the working fluid:

$$\Delta W = \beta(T) \cdot W_0 \cdot (T_{RR} - T_0),$$

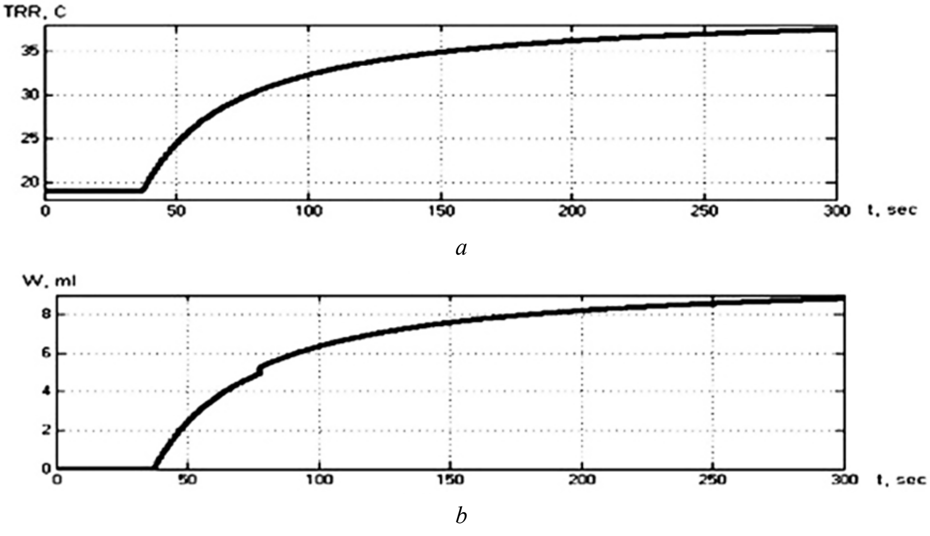
where $\beta(T)$ – coefficient of the fluid expansion.

The pusher's displacement, under constant pressure, is the ratio of the thermal expansion of the working fluid to the effective area of bellows:

$$x = \frac{\Delta W}{F_{ef}},$$

where F_{ef} – effective area of the bellows.

The characteristic of the thermal expansion of fluid was obtained (Fig. 5). As the effective area of the bellows is constructive parameter, and the change of the pusher's displacement depends on the thermal expansion of the fluid, the pusher's displacement wasn't considered.

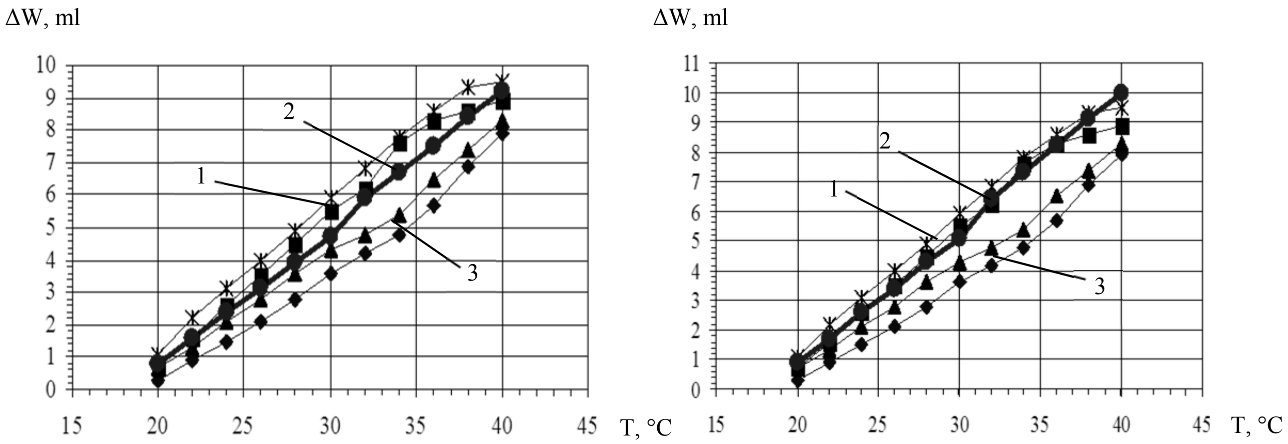


a

b

Fig. 5. Results of modeling: *a*) - change of temperature of the working fluid, *b*) - expansion of the working fluid

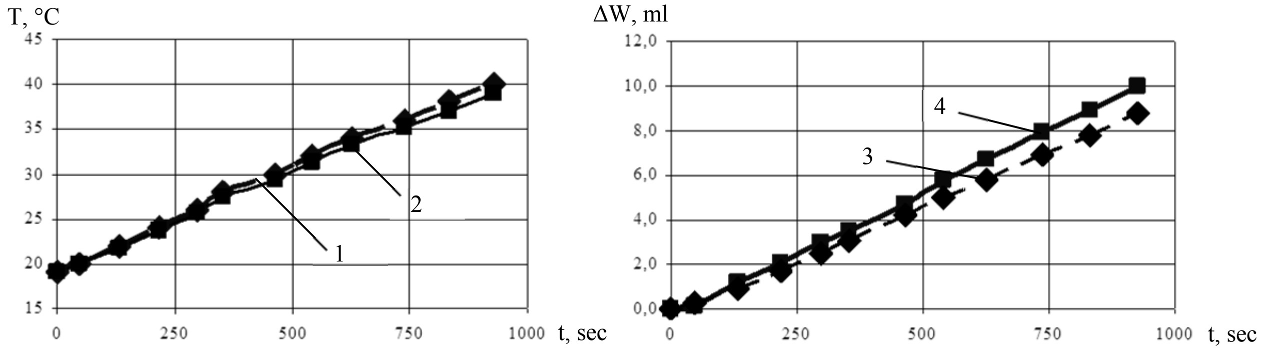
Comparative analysis of the results. At simulation without control time marks it was determined that the obtained values are in the field of experimental data (Fig. 6). With increasing of time simulation the curve of expansion obtained from the model goes closer to the experimental data that obtained from the experiment with free-chilling water (Fig.6. b). These experimental data correspond to the results of calculation during the cooling process because temperatures outside and inside the bulb were equal in the whole volume. But the calculation describes only the process of heating, but not the cooling of water. That's why this results can be used as statistic data of expansion of the fluid, not for assessing accuracy of calculation of dynamic processes during the heating fluid.



a *b*

Fig. 6. The dependence of expansion ΔW by temperature change (W_0 = 375ml; T_0 = 18°C) and experimental data: *a*) tmod = 300sec, *b*) tmod = 900sec: 1 - experimental data obtained during free-chilling of the methyl alcohol, 2 - the result of calculation, 3 - experimental data obtained during heating

There are characteristics of expansion of the fluid including timemarks obtained experimentally(Fig. 7), which were entered into the calculation model as a law of changing of temperature on the outer surface of the heat-conducting element. The deviation between experimental data and modeling results is in the range 10…25%. However, it was found experimentally that the fluid in the measuring tube reaches zero mark at 19^oC. After immersion into the water which temperature was lower than that of alcohol, the level of alcohol in the measuring tube has decreased again and reached zero mark at a temperature of 22^oC.



a *b*

Fig. 7. Characteristics of temperature change *a*: 1 - experimental data of temperature on the outer surface of the bulb; 2 - the temperature of methyl alcohol obtained by calculation; and expansion of the methyl alcohol for the given law of temperature change on the outer surface of the bulb *b*: 3 - experimental data, 4 – results of calculation.

Obtained deviation between the results of calculation and experimental data does not exceed 2ml. It can be due to the fact that there is uneven distribution of temperature in the volume of the fluid. The reason of deviation can be also the evaporation of alcohol that was observed during the experiment. This led to decrease of the initial volume of fluid, and evaporation of light fractions of alcohol could have an impact on the coefficient of thermal expansion.

Conclusions. Analysis of thermal hydraulic actuator showed that we can obtain better accuracy and reduce material consumption for axial motor type of tracker. Implementation of modules with pipeline connection between pushers and expansion chambers reduces material consumption and simplified its setting.

The pusher's displacement is equal to 0.034m by heating of working fluid from 20^o to 60^oC within the initial volume of fluid W_0 = 500 ml and the effective area of bellows Fef = 7.1 * 10-4 m^2, which corresponds to the rotation of the receiver at an angle $\alpha = 15^o$ ($\gamma = 5^o$). Increasing of the pusher's displacement can be provided by increasing of the initial volume of the working fluid and/or by decreasing of the effective area of the bellows. Positioning error of the receiver by one module is in the range 0 ... 22^o within the horizontal tracking range 160^o, placement radius of pushers R = 200mm and the number of modules n = 7. Positioning error decreases to 0 ... 14^o by increasing the number of pushers to n = 11, without consideration of the force interaction between modules. Determination of positioning errors needs to be clarified with regard to dynamic interaction between the modules.

The deviance between the modeling results and the experimental data, with known law of temperature change on the outer surface of the heat-conducting element and experimental data is in the range from 12% to 35%.

Аннотация. *Рассмотрены типовые конструктивные схемы гидравлических приводов вращения. Рассмотрены конструкции модулей теплового гидропривода. Определены основные конструктивные параметры, влияющие на выходные характеристики и работу привода. Рассмотрен ряд жидкостей, которые могут быть использованы в качестве рабочего тела для модулей теплового гидропривода. Рассмотрены процессы, которые происходят в тепловом гидроприводе на примере работы одного модуля. Проведены эксперименты по исследованию величины теплового расширения рабочей жидкости. Проведен расчет параметров холостого хода для модуля.*

Ключевые слова: гидропривод, тепловой привод, трекер

Анотація. *Розглянуто типові конструктивні схеми гідравлічних приводів обертання. Розглянуті конструкції модулів теплового гідроприводу. Визначені основні конструктивні параметри, що впливають на вихідні характеристики та роботу приводу. Розглянуто ряд рідин, які можуть бути використані в якості робочого тіла для теплового гідроприводу. Розглянуто процеси, що відбуваються в тепловому гідроприводі на прикладі одного модуля. Проведено експерименти для дослідження величини теплового розширення робочої рідини. На основі отриманих даних проведено розрахунок параметрів холостого ходу модуля.*

Ключові слова: гідропривод, тепловий привод, трекер

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