TUBULAR GAS HEATERS FOR FREE VOLUME WATER HEATING AS AN ALTERNATIVE TO HOT WATER BOILERS

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Abstract

The mathematical model of a tubular gas heater in an open volume has the form of a hydraulic circuit with adjustable parameters in the form of ordinary nonlinear differential equations. Two criteria - the criterion of thermal efficiency and the criterion of material intensity of the heater - are allocated for setting the problemю. For the solution of the problem of optimal design of tubular heater the binary relation of selection of the most preferable solutions is constructed, and the search of the solution is carried out by means of the algorithm of evolutionary search with several branches of evolutionary search of the concept. The convergence of the design optimization algorithm to the desired solution with probability 1 on all branches of solution evolution is shown. Numerical solutions of the optimization problem have shown that it is possible to achieve sufficiently high thermal efficiency of the heater at moderate material intensity. It is shown that wood pellets can be effectively used as fuel for tubular gas heaters when heating water in free volume. An example of practical use of tubular gas heaters for heating water with a thermal power of 400 kW in a bath with a free surface is given.

Introduction:-

Infrared tube gas heaters (ITGO) are used for autonomous heating and heating, they consist of a gas burner and a tube heater, inside of which the combustion products of gas and air move, as well as a fan (supply or exhaust), thanks to which the coolant moves inside the tube and is removed outside after its cooling. The tube heater is equipped with radiant flux reflectors. Considerable experience in the development and application of ITGOs has been accumulated [1-3] . Tubular gas heaters are used, as a rule, as an industrial product, e.g. [4] including partial recirculation of the gas-air mixture [5]. As an extension of the ITGO concept, the concept of tubular gas heaters (TGH) should be considered. TGHs also consist of a gas burner and a tubular heater, the surface of which is heated by a mixture of gas and air combustion products. THNs are used not only for infrared heating of surfaces, but also for heating air, water, and obtaining water vapor [6]. As a rule, TGH are used as a result of individual design of heating and gas supply systems, which requires appropriate methodological support and calculations for decision-making. Relatively recently in tubular gas heaters began to use instead of combustible gas - wood pellets

[7], as a result of combustion processes of which a gas-air mixture is formed, which is the heat transfer medium of TGN. Mathematical models of tubular gas heaters with pellets and solution of the problem of optimal design of tubular gas heaters are known, for example, [8]. The paper [9] outlines the developed air-water heat supply system for greenhouses with tubular gas heaters. The scheme of greenhouse heat supply is shown in Fig.1.

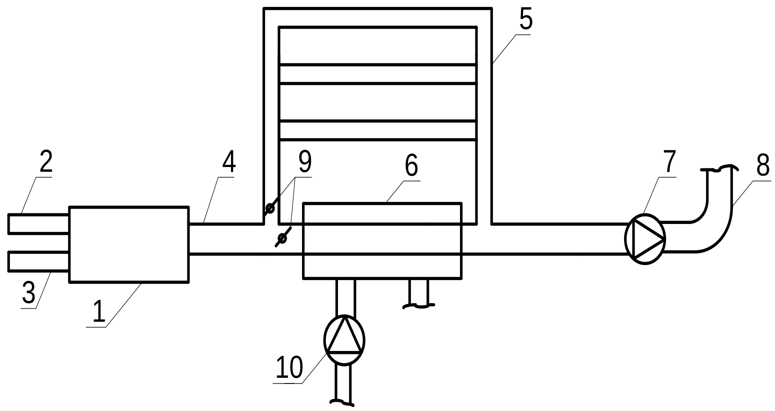


Fig.1. Principal scheme of air-water heat supply system

1 - gas burner; 2,3 - combustible gas and air supply pipes; 4 - initial section of the tubular heater, where the combustion process is completed; 5 - air tubular heater with several circuits; 6 - section of heater of 'gas-air mixture-water' type; 7 - exhaust fan for circulation of heat carrier; 8 - section for removal of exhaust combustion products from outside; 9 - regulating gate valves; 10 - circulation pump of the water part of the heat supply system.

The schematic diagram of the tubular gas free volume water heater is shown in Fig.2.

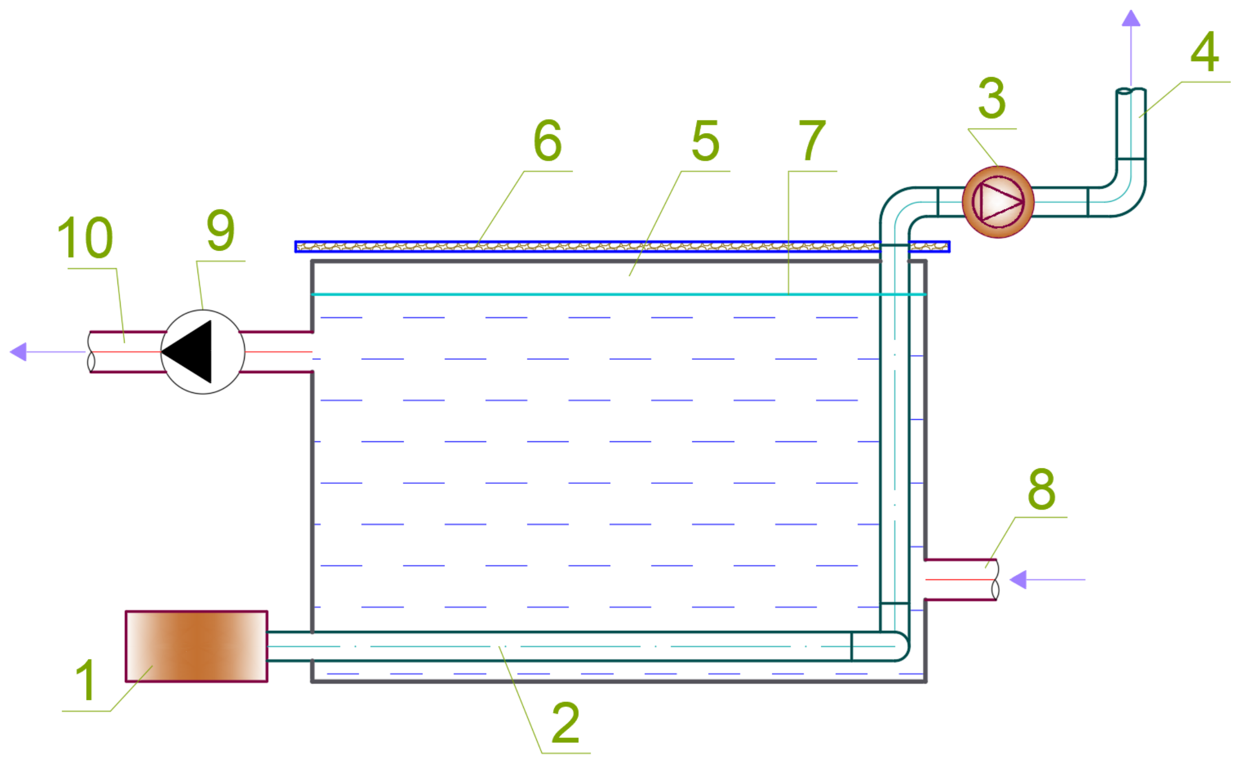
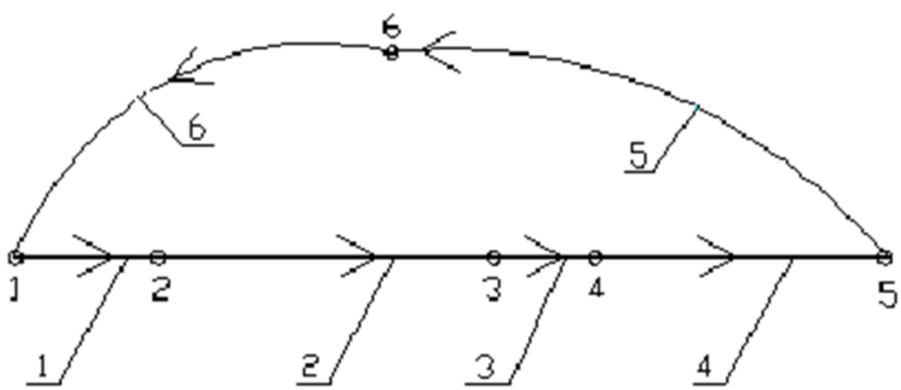


Fig.2. The scheme of tubular gas water heater in free volume. 1 - gas burner; 2 - section of heater of 'gas-air mixture-water' type; 3 - exhaust fan for circulation of heat carrier; 4 - section for removal of exhaust combustion products from outside; 5 - free space above water; 6 - insulating surface; 7 - water level in the heated volume; 8 - cold water inlet; 9 - water circulation pump; 10 - heated water outlet.

The gas-air-water tube heater can be represented by the flat graph shown below.



where the sections are: 1 - (between nodes 1,2) - the initial section of the tube heater, where the combustion of gas begins and ends; 2 - (between nodes 2,3) - the main section of the tube heater, where the transfer of heat from the combustion products with air to the surrounding water space is carried out; 3 - the section of the fan model, where the transition from the parameters at the fan inlet (node 3) to the parameters at the fan outlet (node 4) 4, - (between nodes 4,5) - the section of combustion products removal to the atmosphere; 5 - (between nodes 5,6) - conditional section that connects the final node 5 of the tube heater with conditional node 6 (conditional node 6 - node with parameters that correspond to the parameters of the surrounding space); 6 - (between nodes 6,1) - section of transition from the parameters of the surrounding space to the parameters at the inlet of the tube heater, taking into account the hydraulic resistance in the gas burner.

Among all the graph sections of the tubular gas heater in Figure 3.8, three sections can be distinguished. These are the initial section, the main section and the combustion product removal section. The basic processes of motion and heat exchange at these sections are largely identical. Therefore, a mathematical model of the processes at these sections can be presented in a general form.

For sections 1, 2 and 3, the mathematical model of the section can be written as follows.

Equations of Motion:

$$dp = -\Lambda\ dx/D\ \rho\ w^2/2 + dh\ (\rho_a - \rho)g$$

$$d\rho = (dp - \rho R dT)/RT$$

$$dw = (-\rho w dF - wF d\rho)/(\rho F)$$

Heat transfer equations:

$$dQ_{1K} = \pi D\, dx\, \alpha_1 \left(T - T_{wi}\right)$$

$$dQ_{1Л} = \pi D\, dx\, c_0\ \varepsilon\ (T^4 - T_{wi}^4)\, 10^{(-8)}$$

$$dQ_2 = \pi D\, dx \frac{\lambda}{\delta}\left(T_{wi} - T_{wo}\right)$$

$$dQ_3 = \pi D\, dx\, c_o\ \varepsilon_w \left(T_{wo}^4 - T_o^4\right) 10^{(-8)}\ \acute{\eta}(i)$$

$$dQ_4 = \pi D\, dx\, \alpha_2 \left(T_{wo} - T_o\right)$$

$$dQ_1 = dQ_{1K} + dQ_{1Л}$$

$$d(\rho\ w\ F c_p\ T) = -dQ_1 + \xi(i) \cdot dQ_0$$

$$dQ_1 = dQ_2$$

$$dQ_2 = dQ_3 + dQ_4$$

$$dQ_0/dx = \xi(i)\ Q_0/S_f \cdot 2\pi \cdot y_f(x) \text{ if } 0 < x \le L_f$$

where $\xi(i)$- section indicator:

$\xi(i)$= 1 for section number 1 (initial secton)

$\xi(i)$= 0 for sections numbered 2 and 4 (main section and combustion product removal section).

$\acute{\eta}(i)$ = 1 for section 4

$\acute{\eta}(i)$ = 0 for sections 1 and 2.

α_2 is the heat transfer coefficient from the outer surface of the pipe to the surrounding medium, for sections 1 and 2 it is the water space and for section 4 it is the air space.

For section 3 of the fan model we can write the following relationship

$$\Delta p_i = \Psi(v_i),\ i=3$$

Where Ψ is a known function for a particular fan between head and airflow.

In mathematical form, Kirchhoff's second law can be represented as

$$\int dp_i(x_i) + \Delta p_5 + \Delta p_6 - \Delta p_3 = 0$$

where under the integral is the sum of algebraic pressure losses along the sections of the tubular heater, x_i is the coordinate of the length of the i-th section, i= 1,2,4; $p_i(x_i)$ is the pressure distribution along the i-th section of the tubular heater; Δp_5, Δp_6 are the pressure losses on the conditional sections of the heater 5 and 6; Δp_3 is the active pressure developed by the fan (section 3 of the heater graph).

Problem of optimal design of a tubular gas heater for heating water in an open volume

The main criterion is the heater efficiency criterion E_1 , which is the ratio of the heat flux transferred from the outer surface of the heater to the heat flux introduced to the heater inlet in the form of a chemical energy flow from the fuel and a heat energy flow from the air at the burner inlet.

An additional criterion is the criterion E_2 - characteristic of the heater material consumption

$$E_2 = (\sum_i \pi l_i \Delta_i D_i - M_{\max}) / M_{\max} ,$$

Where $M_{\max}$ is the maximum permissible value of the heater material consumption.

Загальне відношення вибору R_{SS} між двома можливими рішеннями *x* та *y* має вигляд:

The general relation R_{SS} of choosing between two possible solutions *x* and *y* is as follows:

$$xR_{SS}y = [E_2(x) \le 0 \wedge E_2(y) > 0] \vee$$
$$[E_2(x) > 0 \wedge E_2(y) > 0 \wedge E_2(x) \le E_2(y)] \vee$$
$$[E_2(x) \le 0 \wedge E_2(y) \le 0 \wedge E_1(x) \ge E_1(y)] \quad (1)$$

Apparently up to [16, 17], the evolutionary search looks like this:

$$X_{jk} = S(G(X_{jk-1})),\ j = \overline{1, N_B}, k = 1,2,... \quad (2)$$

where *S(X)* is the function of choice in the form (1).

$G(X)$ - generation function. The generation function looks like

$$G(X) = X \cup G_H(X)$$
$$G_H(X) = \{y \in \Omega | \exists x \in X, yR_G x, \mu_{R_G}(x, y) > 0\}, \quad (3)$$

Where relation R_G – fuzzy generation relation with the dependency function:

$$\mu_{R_G}(x, y) : \Omega \times \Omega \to [0,1] .$$

It is significant that $R^+_S(x)$- is the upper strut of the relationship R_{SS} on the set Ω.

$$R^+_S(x) = \{y \in \Omega \mid y\ R_{SS}\ x\} \quad (4)$$

The following statement holds.

Statement 1. If $R_S^+(x)$ – the upper intersection with respect to relation R_{SS} has the property:

$$\forall x \ne x_0, mesR_S^+(x) > 0, \quad (5)$$

where x_0 - is the R_{SS} - optimal solution on the set Ω,

and the generating function satisfies the fact that if $x_H \in G_H(X)$, then

$$\forall x \neq x_0,\ P\{x_H \in R_S^+(x)\} \geq \delta > 0, \tag{6}$$

then in this case, for any $x \in \Omega$, $x \neq x_0$, there will be a number K, such that for any $k \geq K$ and for all search branches $j = \overline{1, N_B}$ with probability 1 the requirement will be fulfilled $x_{jk} \subset R_S^+(x)$, which proves the convergence of the iterative process for choice (1) with probability 1 to R_{SS}-optimal solution for all branches of evolutionary search.

Solving the problem of optimal design of tubular gas heater for heating water in free volume

As an example, we give a solution to the problem of optimal design of a tubular gas heater for heating water in a free volume under the following conditions. There are 6 required quantities in the problem: x^1 - thermal power of the heater, kW; x^2 - air flow rate, m3/hour; x^3 - diameter of the tubular heater, m; x^4 - wall thickness of the heater pipe, m; x^5 - length of the heater pipe, m; x^6 - water temperature in the heated volume, deg. Celsius. Ranges of variation of the values sought:

$$60 \leq x^1 \geq 73;\ 207.3 \leq x^2 \geq 300;\ 0.10 \leq x^3 \geq 0.15;\ 0.003 \leq x^4 \geq 0.005;\ 9 \leq x^5 \geq 12;\ 70 \leq x^6 \geq 85.$$

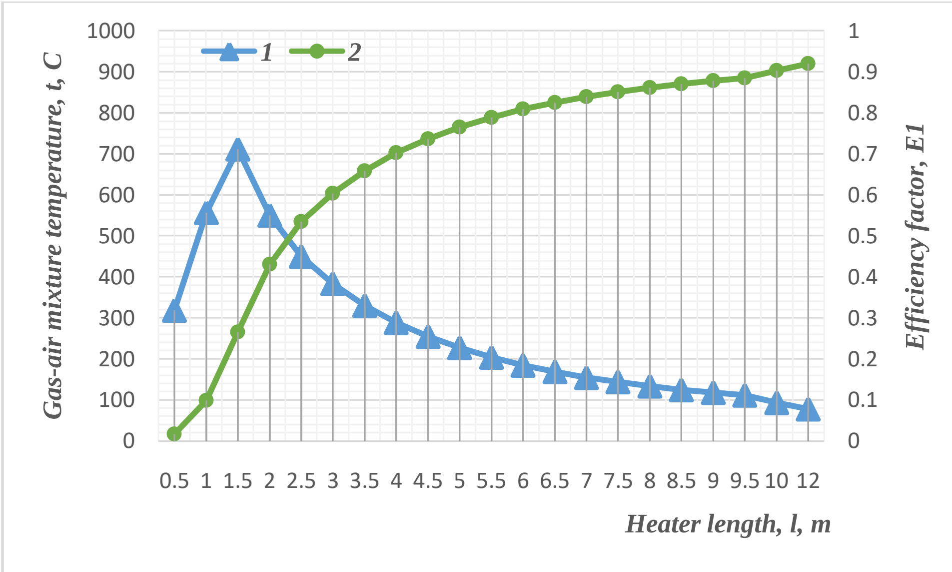
The table below summarizes the process of finding the optimal solution in the design problem of a tubular gas heater in a free water volume.

Evolutionary search for the selection of the most preferable solution of a tubular gas heater in a free volume of water

Iteration stet	x^1, kW	x^2, m^3/h	x^3, m	x^4, m	x^5, m	x^6, C	E_1	E_2
1	67.99617	255.916	0.1417433	0.00485	11.28	75.01	0.8476743	0.003157
	63.34189	289.58	0.15	0.005	12	76.55	0.8108368	0
	62.5341	235.24	0.15	0.00376	12	76.55	0.8681758	0
2	69.06225	207.3	0.148484	0.005	12	79.89	0.891323	0.000285
	61.82673	273.51	0.15	0.003	12	83.22	0.8145416	0
	66.57325	207.3	0.15	0.005	12	70	0.8983043	0
3	69.12177	207.3	0.15	0.005	12	74.86	0.896919	0
	70.36949	207.3	0.15	0.00316	12	85	0.8889592	0
	66.57325	207.3	0.15	0.005	12	70	0.8983043	0
4	73.0	207.3	0.15	0.005	12	70	0.9063782	0
	71.02945	207.3	0.15	0.00468	12	70	0.9040395	0
	67.76108	207.3	0.15	0.00393	12	70	0.8999071	0
5	73.0	207.3	0.15	0.00467	12	70	0.9063782	0
	73.0	207.3	0.15	0.00468	12	70	0.9063782	0
	73.0	207.2	0.15	0.00305	12	70	0.9063782	0

As can be seen from the results of the presented optimal design of a tubular gas heater, it is quite realistic to achieve a sufficiently high efficiency $\eta = 0.9$ when heating water with a tubular heater in a free volume. It is possible to achieve higher efficiency by reducing the primary air flow rate and increasing the temperature of the gas-air mixture, if the wall material of the tubular part allows it. This calculation is shown graphically below, where $\eta = 0.92$.

Calculation of gas-water heater with reduced primary air flow rate



As our experimental studies have shown, tubular gas heaters can operate successfully on wood pellets. If wood pellets are used for tubular heaters in free volume water heating, we can make such an estimate of pellet heater performance as shown in the table below.

Calculation of air-to-water tube heater for pellets of 40 kW and water heating in the volume of 70 deg. Celsius

Step integration	Heater length, *l*, *m*	Gas-air mixture temperature, *t*, *C*	Efficiency factor, E_1
1	10.0	83.75042	0.8911951
2	10.5	81.40084	0.8942475
3	11.0	79.45606	0.8967741
4	11.5	77.84525	0.8988668
5	12.0	76.5104	0.9006009

As can be seen from the calculation, it is quite possible to achieve quite high efficiency $\eta = 0.9$ of the water heating process when using pellets.

There is practical experience in using tubular gas heaters to heat water in free volume.

The study was carried out in the production conditions of a pilot plant at the Dnipro Pipe Plant, which was installed in an open area for preheating pipe billets. The thermal capacity of the water heating system with four tubular gas heaters is 100 kW*4=400 kW, which is equal to the boiler room capacity. The bath was opened from the top for loading the pipe billet with a crane. The water in the bath with a volume of 17*1.5*1.2=30.6 m3 was heated to a temperature of 80-85 C with a final temperature of the gas-air mixture not exceeding 90 C, which indicates the efficient operation of tubular gas water heaters. The appearance of the water heating bath during the operation of the preheating section of the pipe billet is shown below.

The operation of the water heating unit in the open bath for heating of tube billets has shown that the use of tubular gas heaters provides good thermal efficiency of the adopted solution at low capital costs in comparison with the construction of a hot-water boiler house for these purposes.

Conclusion:

Nowadays, tubular gas heaters are developing very rapidly as an extension of the concept of "infrared tubular gas heaters" to create various autonomous heating systems. This paper indicates that one of the promising applications of tubular gas heaters is their use for free volume water heating. Mathematical model for tubular gas heaters in a free volume of water is formulated, the problem of optimization of design solutions is formulated, two criteria of optimization - the criterion of thermal efficiency and the criterion of material intensity of the heating system are allocated. The evolutionary search algorithm was used to solve the problem of optimization of design solutions. It is shown that the evolutionary algorithm with several branches of solution evolution provides convergence of the iterative process to the desired solution with probability 1 on all branches of solution evolution. The given results of numerical calculations of the solution of the problem of optimization of design solutions have shown that the use of tubular gas heaters for water heating provides a sufficiently high thermal efficiency of such application $\eta = 0.9 - 0.92$ at a very moderate material intensity of the tubular gas heater in the free volume of water. It is shown on possibility of effective application of tubular gas heaters on pellets from wood pellets $\eta = 0.9$ for water heating in the open volume. An example of practical application of tubular gas heaters for heating water in the open volume for heating a bath with a thermal capacity of 400 kW in the technological process of heating tubular blanks is given.

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