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PECULIARITIES OF HEAT EXCHANGE PROCESSES UNDER THE CONDITION OF HIGH AIR PRESSURE IN THE GAS TURBINE PLANT RECUPERATORS

There had been analyzed heat transfer relationships to air of hire pressure in recuperative tube heat-transfer devices.

Key words: *gas turbine, compressor, recuperator, criteria of similarity, criteria equations.*

Introduction

The use of gas and turbine plants (GTP) in electric-power industry, as well as combined units which include GTP is typical for the second half of past millennium. Today the gas turbine cycles overcame the border of thermodynamic efficiency of 40%. Under conditions, when the price for natural gas increases, the GTP, which operated using the products of coal gasification are perspective. GTP are widely used in gas industry, on gas pumping plants as drives of gas compressors. Unlike the electric power plants of other types, GTP have more possibilities for further improvement.

The main task today is the improvement of fuel economy and reliability of GTP. The importance of GTP efficiency improvement may be shown on the example of gas pumping plants. Transport requirements of stations use approximately 8% of total consumption of gas which is pumped. Under such conditions the improvement of efficiency factor (EF) of GTP by 1 % during 15 years of gas transmission pipelines operation, may ensure the economic effect of almost 1 billion USA dollars.

There are two main ways for EF improvement of gas and turbine plants[1 – 3]. The first one is connected with the improvement of initial parameters (pressure and temperature) of working substance (products of fuel combustion) on the input of the gas turbine. When the pressure in compressor as well as the temperature of gases before the turbine increase, the specific capacity increases also, and for the set capacity of the GTP the discharge of combustion products, as well as fuel decrease. Therefore the basic parameters increase is carried out mainly in GTP for which their sizes and steel intensity are the most vital. It should be mentioned that gases temperature increase complicates cooling of the turbine circulating part at its input. At present gases temperature in front of the turbine is limited (1600 – 1700 K).

The second way is connected with complication of thermodynamic cycle by providing provisional air cooling in the squeezing process in the compressor and provisional flame products heating in the barrelling process in the turbine. Heat energy regeneration of the exhausted in the turbine gases for heating the air, which enters the combustion chamber of the GTP from the compress is the most popular. As a result, the excessive heat with air enters the combustion chamber, which stipulates for the decrease in fuel consumption. Air heating takes place in heaters (regenerators). This method does not require high pressures. It is necessary to note that the decrease in air pressure behind the compressor (on the generator input) sharply decreases the factor of heat dissipation to the air flow. The latter causes the increase in the heating surface and the increase in metal capacity of the unit itself. On the other hand, the decrease in the level of pressure increase in the compressor decreases the level of working substance expansion in the turbine which causes the decrease in the specific capacity as well as the increase in temperature of the exhausted in the turbine gases and the decrease in the efficiency of the gas and turbine plant [3, 4].

In stationary GTP the problem of sizes and mass increase isn't the main and the measure of the pressure increase in the compressor exceeds 23. That's why it should be anticipated that heat recycling of the exhausted gases in GTP should have been applied in all stationary gas-turbine plants.

It would help to reduce fuel expenditures by 20 – 25 % [4, 5].However, GTP with heat regeneration did not find application, including GTP of gas pumping plants. Regenerator constructions for air heating are developed and shown in [5] where it is also pointed out that their efficiency comparison can be carried out by the coefficient of efficiency of gas-turbine plants. Selection of air regenerators of a particular construction in a defined interval of air and gases temperatures is carried out on the basis of heat calculations that help to determine the necessary heating surface area. Heat-exchange intensity from heating gases to the wall and from the wall to the air flow shall be determined by the appropriate criteria formulas of convection heat-exchange that contain thermo physical properties of heat bearers. Heating smoke gases with a specific speed Wг move with the pressure close to the atmospheric. Their thermophysical properties for the average temperature shall be easily determined according to the reference data which are presented in many textbooks, for example, in [6]. As for the thermophysical properties of the air, they are presented for atmospheric pressure only. For higher pressures they are presented in [7], which complicates the heat exchange calculations.

Considering the above-mentioned, the task was to research the relationships in heat exchange as for the high pressure air flows in the pipe lines or in intertubular space.

Main results

To solve the set task, we determine and calculate the air thermophysical properties within the pressure range of 0,1 – 5 MPa and within the temperature range of 250 – 1200 K. the value of the selected thermal capacity C_p, caloric conductibility factor λ and dynamic coefficient of viscosity μ shall be determined from the tables [7]. Air density ρ shall be calculated from the equation of the state [3] with the sufficient accuracy. Prandtl number, which occurs in the criterial equations of heat exchange and takes into account main thermophysical properties of the heat transfer medium, shall be calculated according to the formula [6, 8]

$$\mathrm{Pr} = \frac{\mu / \rho}{\lambda / (C_p \cdot \rho)} = \frac{\mu \cdot C_p}{\lambda}. \tag{1}$$

The values of the thermophysical properties of the air within the set intervals of pressure and temperature change are reduced in the Table 1, where ρ, kg/m^3; C_p, kJ /(kcal); $\lambda \cdot 10^3$, W/(m·K); $\mu \cdot 10^7$, Pa./s.

Table 1

The thermophysical properties of the air

Temperature, K	Factors	Presure *P*, bar					
		1	10	20	30	40	50
1	2	3	4	5	6	7	8
250	ρ	1,394	14,045	27,874	42,880	57,636	72,5
	C_p	1,012	1,028	1,055	1,081	1,097	1,11
	λ	22,10	22,9	23,5	24,2	24,9	25,6
	μ	159,6	161,2	163,1	165,2	167,7	169,8
	Pr	0,722	0,723	0,732	0,738	0,738	0,736
300	ρ	1,161	11,650	23,342	35,075	46,838	58,616
	C_p	1,008	1,021	1,037	1,053	1,068	1,081
	λ	26,2	26,8	27,3	27,9	28,4	28,9
	μ	181,6	185,9	187,4	189,1	191	192,8
	P_r	0,698	0,708	0,712	0,7137	0,7182	0,721
400	ρ	0,871	8,688	17,340	25,947	34,482	42,992
	C_p	1,014	1,021	1,029	1,037	1,044	1,05
	λ	33,8	34,2	34,6	34,9	35,2	35,5
	μ	230,1	231,1	232,1	233,3	234,5	235,4
	P_r	0,690	0,690	0,690	0,693	0,695	0,696

Continuation of the table 1

Temperature, K	Factors	Presure P, bar					
		1	10	20	30	40	50
1	2	3	4	5	6	7	8
500	ρ	0,696	6,944	13,833	20,674	27,457	34,176
	C_p	1,03	1,034	1,039	1,043	1,049	1,051
	λ	40,7	41,3	41,6	41,8	42,1	42,45
	μ	270,1	270,9	271,7	272,6	273,5	274,6
	P_r	0,683	0,680	0,6785	0,680	0,681	0,680
600	ρ	0,580	5,784	11,51	17,208	22,852	28,449
	C_p	1,051	1,055	1,057	1,06	1,063	1,066
	λ	46,9	47,4	47,8	48,2	48,5	48,8
	μ	305,8	306,4	307,1	307,8	308,6	309,3
	P_r	0,685	0,682	0,677	0,677	0,676	0,675
700	ρ	0,4975	4,968	9,871	14,751	19,588	24,384
	C_p	1,075	1,077	1,079	1,081	1,083	1,085
	λ	52,4	52,9	53,3	53,7	54,1	54,56
	μ	338,8	339,4	339,9	340,5	341,2	341,7
	P_r	0,695	0,691	0,688	0,685	0,683	0,679
800	ρ	0,435	4,347	8,692	12,913	17,151	21,349
	C_p	1,099	1,101	1,103	1,104	1,105	1,106
	λ	57,3	57,8	58,2	58,6	58,9	59,2
	μ	369,8	370,3	370,8	371,3	371,7	372,2
	P_r	0,709	0,705	0,702	0,700	0,697	0,695
1000	ρ	0,348	3,481	6,922	10,342	13,740	17,114
	C_p	1,140	1,142	1,143	1,144	1,145	1,146
	λ	66,7	67,1	67,5	67,8	68,1	68,4
	μ	424,4	424,8	425,2	425,6	426	426,4
	P_r	0,725	0,723	0,701	0,718	0,716	0,714
1200	ρ	0,290	2,316	4,316	8,628	10,050	14,287
	C_p	1,175	1,176	1,176	1,176	1,177	1,177
	λ	76,3	76,6	76,9	77,2	77,4	77,6
	μ	473	473,2	473,6	473,9	474,3	474,7
	P_r	0,728	0,726	0,724	0,722	0,721	0,720

Table 1 shows that the selected thermal capacity of the air increases a little (by 3 – 9 %) together with the pressure increase and by the same value with increase in temperature. Air density increases directly-proportional with the increase in pressure (on condition T = const) and decreases with temperature increase (on condition P = const). As an example Fig. 1 presents the character of density variation depending on temperature for $P = 20$ bar, with designations: $T^* = T/T_1$; $T_1 = 250$ K; $\rho^* = \rho / \rho_1$, ρ_1 – density at temperature T_1. Within the selected temperature intervals the density of the air decreases by 6,5 times, and within the selected pressure intervals– increases by 50 times.

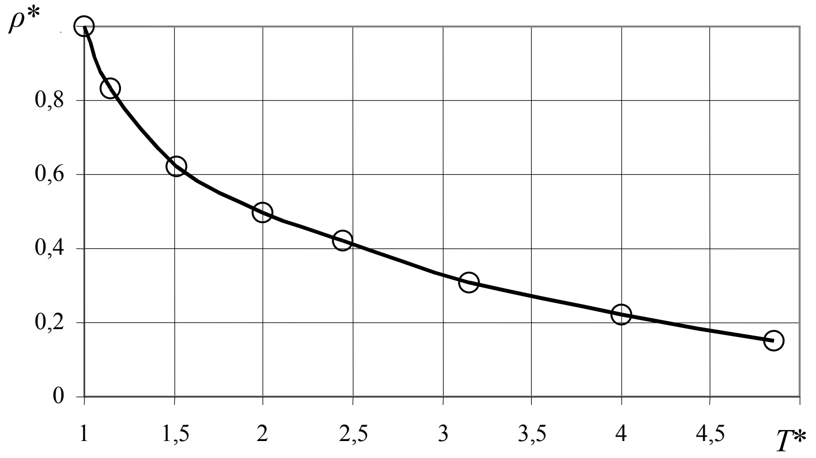

Fig. 1. Dependence of density on temperature for $P = 20$ bar

The factor of the dynamic density alike the thermal capacity slightly depends on pressure, but increases with the increase of the temperature. Nature of μ behavior on temperature for $P = 20$ bar is presented in Fig. 2, where $\mu^* = \mu/\mu_1$; μ_1 – dynamic coefficient of viscosity for $T_1 = 250$ K.

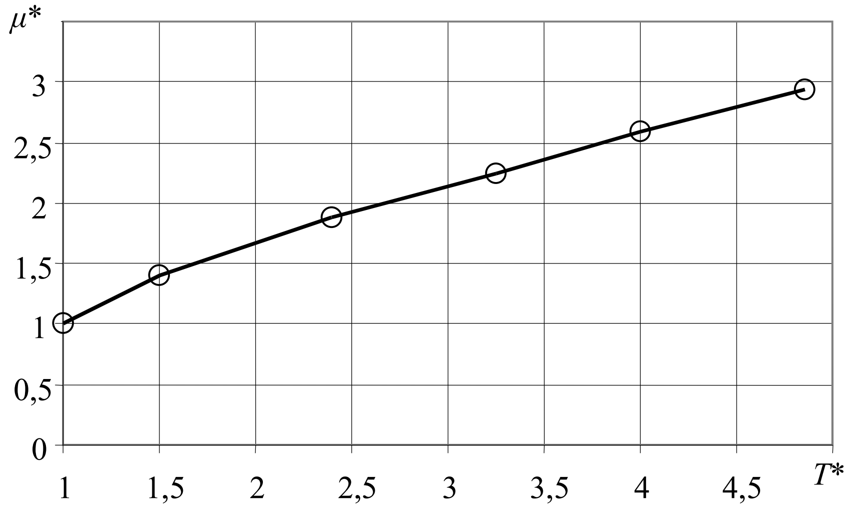

Fig. 2. Dependence of dynamic coefficient of viscosity density on temperature for $P = 20$ bar

Fig. 2 shows that in the set range of temperatures μ increases by 2.9 times.

So, the increase in pressure (on condition $T = \text{const}$) causes the significant increase in air density, insignificant increase in thermal capacity and the dynamic coefficient of viscosity. The rate of density increase greatly exceeds the rate of viscosity increase. It follows that the pressure increase (density) should favor the intensification of convective heat transfer processes, which are described by the criterion equation [5, 6, 8]

$$Nu = \frac{\alpha \cdot \ell^*}{\lambda} = C \cdot \mathrm{Re}^n \cdot \mathrm{Pr}^m, \tag{2}$$

where $Re = w \cdot \ell^* \cdot \rho / \mu$ – Reynolds criterion; w – average discharge speed of the stream; ℓ^* – typical linear heat exchange surface size (for pipes $\ell^* = d$, where d – diameter); α – factor of heat transfer which characterizes heat exchange intensively; C – constant; n i m – index of the degree.

Heat transfer medium can move both in pipes as well as in the tube space of the recuperative heat-transfer device. Under condition of turbulent flow in plain pipes $C = 0{,}021$; $n = 0{,}8$; $m = 0{,}43$ [8]. In case of flow by the plain pipes bank with staggered location with the same values of longitudinal and transverse pitch between pipes $C = 0{,}4$; $n = 0{,}6$; $m = 0{,}36$ on condition $10^3 < Re < 2 \cdot 10^5$ і $C = 0{,}031$; $n = 0{,}8$; $m = 0{,}4$, when $Re > 2\ 10^5$ [8]. Following the above methodic there had been made calculations of heat exchange intensity on condition of air flows with different pressures with the speed 12 m/s inside pipes with the diameters of 38/32 mm and in tube space of the recuperative heaters (with staggered location of pipes). Following the results of calculation there had been built the dependencies, presented in Fig. 3, where $Nu^* = Nu\ /\ Nu_1$; $\pi = P/P_1$, and index „1” designates values for the initial pressure $P_1 = 1$ bar.

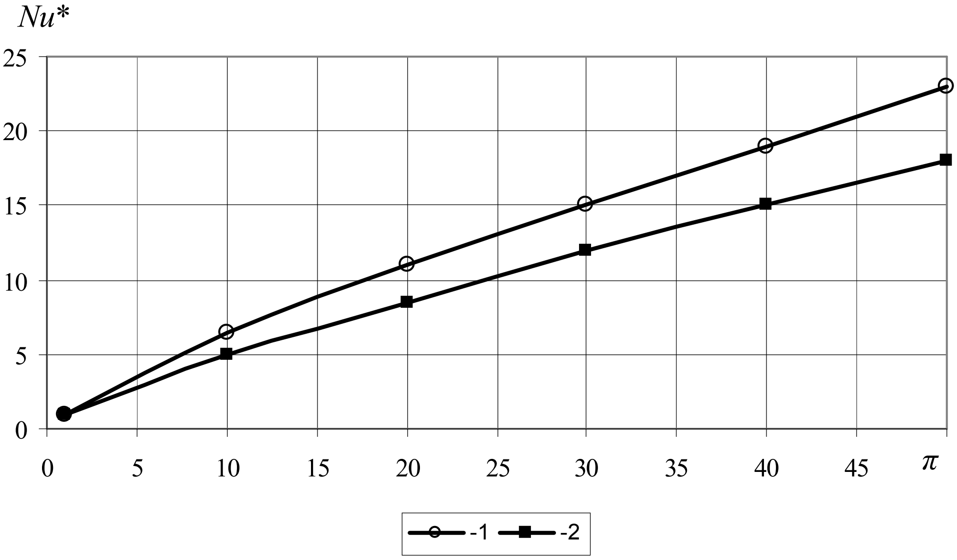

Fig. 3. Character of influence of pressure on the heat exchange intensity: in pipes (curve 1), in tube space (curve 2)

The obtained results enable to evaluate the factors of heat exchange in case of movement of air flows of higher pressure in pipes and in tube space. For the pressure of $P = 50$ bar the intensity of convective heat exchange in pipes increases by 23 times, and in tube space – by 18 times.

This is explained by the fact that the increase in density causes the increase in Reynolds and Nusselt criteria, since as it had been mentioned above, rate of increase in density exceeds the rate of increase in dynamic viscosity factor. The received dependences allow to evaluate the intensification of convective heat exchange processes. Thus, for example, for the value $\pi = 20$ which is characteristic for the temperature increase in compressors of domestic GTU, heat transfer factor increases by 11 times during the air flow in the pipes, and during the air flow in the tube space – by 8 times. The increase in factors of heat transfer stipulates for the increase in heat exchange factor which, in turn, allows to decrease the necessary area of recuperator heating surface, and specific quantity of metal of the latter. For the above example, the calculated values of heat transfer factors increased by 1.82 and 2 times. The area of heating surface will decrease correspondingly.

Conclusions

1. The increase in density causes the increase in turbulence transition of the flow and intensity of the convectional heat exchange.
2. Heat exchange intensity ensures the significant decrease in the heating surface aria of heaters as well as their specific quantity of metal .

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