A study of thermal devices with porous coatings

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Abstract. Thermal devices (mechanisms) with porous coatings designed for combustion chambers of gas turbine units, as well as for cutting and drilling turbo foundations of power plants, which solve the problem affiliated with the appearance of cracks from the reflected wave, have been developed and studied. The porous coating provides a powerful thermodynamic screen in the similitude of three heat sources. The studies were unleashed on five samples with different porosity and hardness values (5 ÷ 30\%). Thermal movements, deformations, and stresses were recorded on a holographic unit in real-time. A thermal device in the form of a rocket-type burner with a detonation jet has proved high efficiency for a capillary-porous and flow-through cooling system. Photographs of combustion chambers and nozzles studied depending on their geometry and thickening of the nozzle wall, an excess oxidizer (0.3 ÷ 0.8), and operating conditions until of the metal limiting condition (1106 W/m\textsuperscript{2}) are presented. The optimal geometry of the chambers and nozzles either the type of porous structure was specified. It has been found that the economic effect is 200-300 $ for 1 burner, and the consumption of coolant is reduced several times.

1. Introduction

The introduction of energy efficiency measures are among the priorities in all country's energy policy and correspond to the objectives in the new Energy Policy for Europe [1]. The paper aims to study the heat transfer during boiling of water in porous structures of thermal power units of thermal power plants (TPP) and devices for cutting natural and artificial mineral media. The experiments were carried out on a rocket-type burner. The combustion chambers and supersonic nozzles with different porous structures were cooled.

In the modern literature [2, 3] studies of heat transfer of various homogeneous and inhomogeneous porous surfaces of coatings (multilayer), as well as specially designed wicks able to increase their heat transfer abilities, are still of interest. Studies [4, 5] of the thermohydraulic parameters of boiling in porous media using thermocouple measurements and monitoring with a high frame rates camera (bubble sizes, discharge frequency, and density of nucleating seed) started to appear. According to the comparative analysis of different methods for calculating the heat transfer from boiling water with vertical subcooling is suggested [6].

The main task for the power units of TPPs is arranging a cooling system for highly heat-stressed parts and assemblies [7]. These include furnace walls of highly accelerated boiler units, combustion chambers, nozzles, and vanes of gas turbine units, thermal devices (tools) for the execution of construction and assembling works.
Created a powerful heat screen relative to the generation of deformation fields and thermal stresses is an obstacle to the propagation of the reflected blast wave, causing the appearance and growth of the cracks. The integration of mesh structures with capillary-porous coatings from natural mineral materials makes a synergistic effect of combining into the technology of their manufacture, expanding the removal of critical loads, monitoring and adjusting the coating limiting conditions.

Designed and studied combustion chambers and nozzles that can be used in gas turbines of TPPs and thermal devices for cutting natural stones and artificial mineral materials [8, 9, 10, 11, 12].

2. An experimental method for studying capillary-porous samples

The studies were conducted on five natural samples made from various rocks (figure 1). The shown investigated materials of capillary-porous samples are respectively: 1 – granite; 2 – marble; 3 – tuff; 4 – granite, 5 – tuff.

![Figure 1. The studied samples of capillary-porous mineral media.](image)

Three holes with dimensions 6·10⁻³ m in diameter and depth of 12·10⁻³ m were drilled perpendicular to the surface of the front side (samples №2 and №5), or perpendicular to the surface of the minor side (sample №1). Thus, a thermodynamic screen was created when three heat sources (electricity) were turned on. One heat source was also studied (samples №3 and №4).

On figure 2 is shown the operation of the evaporation-condensation circuit in a closed cycle. The operating principle of the installation is as follows: the electricity is supplied to the core heater from a welding transformer (TSD). The output voltage is: 2.5; 5; 7.5 and 10 V. For the current measurement of the heater was used a universal current transformer (UCT). The primary current is between 100 A and 2000 A, thus secondary - 5 A. The heater voltage drop was measured. The accuracy for the current is ±0.6%; voltage drop – ±1%; power – ±1.6%. The heater there is a backup power provided by the voltage regulator (VR).

The flow rating of the cooling and circulating liquids were measured with a rotameter. The flows of the draining liquid and condensate are stored in a measuring tank with a scale of 0.5·10⁻³ l and the time for filling is measured with a chronometer, it has reached an accuracy of 0.1 s. The errors in measurement of the rotameter no more than ±3%, and for the volumetric method < ±2%.
Figure 2. Experimental measurement of the flows on the heat-exchange surface and capillary-porous coating.

The input power $N_e$ was equal to $(7 \div 30)$ W. When the drilled diameter of the screw $d_s=(3 \div 6).10^{-3}$ m, the specific heat flux reach to following values:

$$q = \frac{N_e}{\pi d_s^2} = \frac{7+30}{\pi (3+6)^2 \times 10^{-6}} = (0.99 \div 1.06) \times 10^6, \text{ W/m}^2$$ (1)

To study porous thermodynamic screens, the method of holographic interferometry was used. The stressed and deformed state of the samples was studied. Deformations of the samples were recorded in real-time (figure 3).

The interferogram photographing frequency is 0.5 frames per second; 30 shots were taken from each sample. Photo prints were placed in two frames reflecting the surface state of the samples every 6 seconds.

The decoding of holographic interferograms was made according to the accepted technique. The displacement vector was determined $\overrightarrow{d}$, according to:

$$|\overrightarrow{d}| = \frac{N \lambda}{1 + \cos \varphi},$$ (2)

where $N$ – is the measured number of bands between the studied point and the zero-order band; $\lambda$ – is the wavelength; $\varphi$ – is the angle between the illumination of the studied $\overrightarrow{r}_i$ and the observation $\overrightarrow{r}_s$ point on the hologram, i.e. $\overrightarrow{r}_s \Lambda \overrightarrow{r}_i$.

The deformation for one heat source can be determined by the displacement gradient which has the greatest value in the filled with the heater with a radius < $10$ mm and increased with the extension of the heat exposure period.

Furthermore, three simultaneously acting heat sources with independent displacement field led to a simple superposition on the sample surface. This phenomenon took place both for displacement fields along a plane passing through the centers of sources and for planes spaced 6 mm apart from them.
Figure 3. Experimental stand for measurement of main processes of steam generation and stressing and deformation coatings by optical methods: 1 - laser; 2 - film camera SKS-1M; 3 - porous cooling element.

A holographic unit with samples from mesh structures and porous rock coatings allows to obtain real-time interferograms and to interpret them according to internal (thermohydraulic) boiling characteristics, thermal stresses, and deformations appearing in thermodynamic screens.

3. Results and discussion
The tested combustion chambers and nozzles having different lengths and wall thickenings are shown on figure 4, and some of the chambers were cooled with a capillary-porous system. The excess oxidizer coefficient $\alpha$ varied within $0.3 \div 0.8$ [8].

Figure 4. Samples of combustion chambers and nozzles.
The structures were made of mesh with a hydraulic diameter of \( b_h = 0.4 \times 10 \text{ mm} \). We investigated some of the operational and technological capabilities of combustion chambers and nozzles up to their destruction. The following notation is accepted for figure 4:

a) samples of combustion chambers having different lengths and design on the nozzle exit: I – IV – oxidizer excess coefficient \( \alpha = 0.3 \); V – VII – \( \alpha = 0.65 \) – 0.7; VIII – \( \alpha = 0.8 \); I – IV – porous cooling is used at \( q_{\text{cr.c-s.}} = 5 \times 10^6 \text{ W/m}^2 \); V – VIII – a water cooling system is used at \( q_{\text{cr.c-s.}} = 1 \times 10^6 \text{ W/m}^2 \); 

\( \overline{w_c} = 10 \text{ m/s} \);

b) the nozzles are made with a wall thickening: I - VIII – excess oxidizer coefficient \( \alpha = 0.6 \) – 0.65; the destruction occurred as a result of gases breakthrough into the water cooling system during seals depressurization; V – is an experimental sample of a combustion chamber with a melted swirl nozzle. The cooling system used is a capillary-porous cooling system at \( q_{\text{cr.c-s.}} = 1 \times 10^6 \text{ W/m}^2 \);

c) nozzles are made without wall thickening: I - IV – before operation; V - VI – after 40 hours of operation (deflector rings are destroyed and nozzle cross-sections are widened); I - VI – \( \alpha = 0.8 \); III - VI – \( \alpha = 0.6 \); IV – a sample of the combustion chamber made with a shortened nozzle (provided the detonation mode of combustion). The cooling system used is a water cooling system at \( q_{\text{cr.c-s.}} = 1 \times 10^6 \text{ W/m}^2 \).

d) destroyed combustion chambers, nozzles, and “skirts” as a result of the penetration of bubbles due to poor brazing of the chamber afterbody (I - II); \( \alpha = 0.65 \); nozzles are made with a cylindrical outer surface [8]; III - IV – sample chamber with a shortened nozzle with wall thickening; destruction began to occur at the beginning of the operation on the external surface ahead of the critical section; the excess oxidizer coefficient \( \alpha \) was equal to \( = 0.65 \); I - II – water flow cooling at \( q_{\text{cr.c-s.}} = 1 \times 10^6 \text{ W/m}^2 \), \( \overline{w_c} = 10 \text{ m/s} \), III - IV – capillary-porous cooling at \( q_{\text{cr.c-s.}} = 1 \times 10^6 \text{ W/m}^2 \), \( \overline{w_c} = 10 \text{ m/s} \).

4. Conclusion

The proposed investigated capillary-porous system has a better advantage than the pool boiling. Thus it’s possible to regulate the heat flow of the processes. The main advantages of the proposed system are the unification of capillary forces and mass transfer. Thus resulting in an improvement of the thermal and strength characteristics of the system.

The conducted results confirmed the high efficiency of the proposed capillary-porous and flow-through burner cooling systems. The results obtained can be applied to the cooling towers in relation to the environment by a tenfold reduction in coolant consumption.

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