Heat transfer for the boiling crisis in porous systems

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Abstract. In this paper we analyzed and investigated the heat exchange crisis of boiling in porous structures, applicable in thermal power plants. Then we describe the heat exchange processes mechanism and determined the ideal sizes and thicknesses of porous structures. The designed porous structures can be implemented in gas turbine’s nozzles and combustion chambers. From an environmental point of view, the consumption coolant liquid is reduced by ten times in comparison the standard flow system. It’s effectively to develop mesh structures to allow the extension of the critical loads and manage the surface border.

1. Introduction

The advanced technologies play a significant part in the mechanical engineering – nanotech and plasma processing allows of creation the porous coatings on the product’s surfaces. They can serve as a tank and a micro-channels for lubricants, ensuring operational efficiency of rubbing body parts [1-8].

One of the promising and effective methods of intensification of heat exchange is the use of highly conductive capillary-porous and mesh materials (PSM). Such materials have long been used in liquid-propellant rocket engine (LPRE), as filters, capillary intake devices, in the manufacture of permeable firing bottoms of mixing heads and other devices [9-10].

In the production of porous materials one of the main characteristics of processing and application is stated by the structure of the pores of the material. The porous materials are robust and resistant to corrosion, with wide operating temperature range, don’t clog the filtered liquid, machinability, allow multiple regeneration, have high electrical and thermal conductivity [11-15].

2. Experimental setup

In our research we used a rocket-type flame-jet burner (marked with 1 on figure 1) with a porous cooling system 2 and with 3 is denoted the casing. With such rocket – type jet burner can be produced different heat transfer intensifiers for cooling of nozzles and combustion chambers [13, 15].
Figure 1. Rocket-type flame-jet burner.

Burner (figure 2) Combustion chamber 1, a Laval nozzle 2 with confusor 3 and diffuser 4 parts and critical section 5 between them, swirl 6, atomizer 7 and distribution head 11 with branch pipes 12, 13, 14 for supply of oxidizer 19 and fuel 20 to combustion chamber 1 and coolant 18 to the cooling cavity 10 formed between shell 8 and the outer walls of combustion chamber 1 and Laval nozzle 2, installed in the housing 8. The casing 8 has holes 9, 21 for outlet of the coolant 18. The diffuser part 4 of the Laval nozzle 2 is provided with an insert 15 having a capillary-porous coating 16 on the side facing the cooling cavity 10.

Figure 2. Burner cooling system for high pressure detonation combustion mode.

Number 16 (capillary-porous coating) is produced by a multilayer grid, the layers cells size increases with 0.08; 0.14 and 1.0 mm in the way of the outer surface of the coating. The radius of curvature of groove 17 is 2.5-5 times greater than its depth. Combustion products 22 are drained from the diffuser part 4 of nozzle 2.

The coolant lubricants 18 is passed through the branch pipe 14, in this way the coolant lubricants moving toward the cavity cooling 10. The coolant lubricants cools the combustion chamber 1 and the nozzle 2, then is discharged outside via the holes 9 and 21. Oxidizer 19 is mixed with the fuel 20, ignited by an ignition source and the resulting mixture is burned.

In the combustion chamber 1 a flow is formed with a temperature above (2000÷2500) °C and a speed of about 1600÷2000 m/s (in Laval nozzle 2) thus processing combustion products 22 [9].

Making the radius of curvature of groove 17 2.5÷5 times bigger than its depth redound to the elimination of thermal stress concentration and indemnification of thermal distention in the thermal
groove. High capillary pressure is created if the capillary-porous coating is isotropic, i.e. the size of the cell increases towards the outer surface. [14]

The listed advantages are realized both at nominal load and at alternating and emergency operation modes (no blockage of the cooling cavity by steam bubbles). Coolant liquid consumption is significantly reduced four times.

3. Experiment conditions
The main heater was made of nichrome foil, with thickness 0.05; 0.1; 0.3; 0.5; 0.7·10⁻³ m, or stainless-steel plate – 1 and 2·10⁻³ m. The heater size was from 0.05 m to 0.3 m with height 0.15 m to 0.7 m. The different structures were prepared of woven brass, copper and stainless steel woven meshes, composed of several layers (max 3). For the cooling surface we used 12X18H9T or 18H10T stainless steel type, copper M2, brass L8O, bronze, alundum, nickel and glass. The minimum thickness of the wall was 0.05 and the maximum 2·10⁻³ m. Before the experiments, the cooled wall and structure were cleaned and degreased.

The SKS-1M high speed camera was used for observations of the evaporation processes. Experimental installations, conditions and experimental data processing methods are described in [9-12, 14].

In the experiments we used both water with a pressure of 0.001 to 1 MPa and an aqueous solution of the foaming agent type PO-1. The fluid velocity varies from 1.1·10⁻³ to 0.1 m/s, underheating 0 to 20 K, fluid excess was from 1 to 14 from the overall steam consumption. The heat load 1÷60·10⁴ W/m², thermal pressure 1÷60 K, orientation of the system was relative to the verticals ±0°÷±90°.

4. Data analysis
For the experimental data analysis we used transitional boiling mode with heat transfer flows \( q = (1÷8)·10⁴ \) W/m². We found a significant effect of coolant-flow rate and type of structure for this type of boiling mode. This applies to grids with a large mesh size. The incensement of the value \( q \) is associated with a decrease of the amount of the heat-transfer coefficient and the appearance of vapor bubbles and also with an incensement of the thermal resistance of the boundary layer.

No restriction in the heat capacity rate of the system for different sizes of the cells. Hence in the case of heat pipes, the increased hydraulic resistance of the structure or the decrease in capillary absorption does not restrict the fluid flow.

A one-layer 0.14 structure or a two-layer 0.14 structure may be an acceptable option 0.4 and 0.55. Large cell sizes reduce fluid cleaning requirements and hydrogasdynamic resistance.

Increasing the coolant flow leads to redistribution of the flushing and boiling streams. For this reason, it is necessary to create a uniform temperature field along the height and length of the heat exchange surface through the concept of optimal excess liquid.

The ideal flow rate is defined as follows: up to \( q \leq 100 \) kW/m², the fluid flow rate is kept close to the heat pipes operation mode at the hydraulic diameter 0.28·10⁻³ m and 30%, for values > 0.28·10⁻³ m; at \( q > 100 \) kW/m² exceeding the flow rate 1.3÷2 times for values \( \leq 0.28·10⁻³ \) m allows to increase the range of removal of the value of \( q \) in 2÷3 times in contrast with heat pipes.

On another hand the heat flow intensity is decreased with 40% for \( q > 100 \) kW/m², or the heat pipes are non-operational. The high intensity of the heat pipes can be obtained at \( q \leq 20 \) kW/m².

5. Conclusions
From the conducted research it’s evident that with the used of capillary-porous material and value of the dimensionless temperature in the range from 1.0 ÷ 1.3 the cooling system can be in normal operation mode. For the proposed burner device the optimum working area is accepted to be in the range of dimensionless temperature 1.25÷1.30 (working range). In the operating range \( \Delta q = 8.5 – 10.2 \) MW/m² and operating interval \( \Theta = 1.25÷1.30 \), the following capillary-porous materials are possible: combined with a ratio of width of cells of a parietal layer and the subsequent 0.7…(0.7x1.0·10⁻⁷ m);
single-layer, with cell width $1.0 \times 10^{-3}$ m; two-layer (with a layer thickness in width of a wire) with width of a cell $0.02 \times 10^{-3}$ m. From the technical point of view a two-layer capillary-porous structure with a cell width $0.02 \times 10^{-3}$ m is hard to achieve. To define the best capillary-porous material with the determination of the ideal combination of the cooling system, an analysis by the dimensionless criterion $St$ is required. Determination of the characteristics and the kind of capillary-porous material must be done, in the general case, by at least two criteria: dimensionless temperature and $St$.

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