







Possibility of Using Liquid-Metals for Gas Turbine Cooling System

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Abstract. The possibility of using heat pipes to cool elements of a gas turbine is considered. The temperature of the parts gas turbine should be approximately equal to 850–950 °C to ensure its safe operation. This temperature range is suitable for a special type of heat pipes with a liquid metal coolant. It is proposed to reduce the temperature gradients on the turbine blade by mounting porous reservoirs with a liquid metal coolant on the inner surface of the blade body. In a closed porous reservoir, a two-phase state of the coolant is maintained, and heat is transferred by the mutually opposite movement of steam and liquid due to diffusion. The solution to the problem of modeling the processes of motion and phase transition in a porous medium filled with coolant is presented. The problem of thermal conductivity of a multilayer system consisting of a heated shell of a blade and a porous reservoir filled with a liquid metal coolant is formulated, and a numerical solution is proposed. As a practical example of the use of high-temperature heat pipes, a new type of aircraft engine nozzle cooling system has been developed. The example consists of two parts. The first part showed a decreasing temperature gradient in the leading edge of the gas turbine nozzle. The second part concerns the development of the cooling system of the nozzle as the whole.

Keywords: Gas turbine · Cooling system · Two-phase model · Porous reservoir · Liquid-metal heat carrier · Nozzle vane · Gas turbine blade

1 Introduction

Currently, an important direction in the development of energy gas turbine engineering is the creation of large unit capacity installations and their inclusion in combined-cycle plants. The tasks of improving stationary and transport gas turbine installations and gas turbine engines of all types are solved by mastering ever higher gas temperatures (T_g). Since the rates of increasing the heat resistance of alloys for gas turbines are significantly behind the growth of T_g , the only real way to increase T_g shortly is to use cooling of the most heated and most loaded parts of gas turbines, primarily nozzle and rotor blades. Therefore, the study and development of the problems of mastering high gas temperatures in gas turbine installations through the use of highly efficient cooling of

turbine parts are one of the most relevant directions in the development of modern gas turbine engineering [1].

2 Literature Review

Despite the fact that there is a lot of experience of design organizations and firms in the development of various methods of cooling gas turbine parts, in particular, convective, film, porous and combined cooling systems, the creation of new, more efficient cooling methods remains relevant [2–6].

Porous heat pipes are characterized by a high value of the conditional coefficient of thermal conductivity, which makes them suitable for heat transfer of high power in almost isothermal conditions. This property is very attractive for using heat pipes to cool gas turbine elements. A set of R&D papers dedicated to the implementation of heat pipes or their elements in a process of high-temperature gas turbines components cooling is known. Some of them propose double-circuit cooling using thermo-siphon systems. The thermo-siphon is a special case of the heat pipe with gravitational reversing of condensate to an evaporation zone. It doesn't use a porous structure and, consequently, the capillary effect is not observed. The authors of [7] proposed a mixed version of a high-temperature cooling system for gas turbine engine blades, in which a thermo-siphon with Na or K as a cooling medium is inserted into the deflector and used together with air cooling. In this case, the blade is the evaporation zone for the thermo-siphon, and the condensation zone is discharged into the second circuit, where the heat carrier is cooled by the air coming from the fan.

The authors of [8] analyze the advantages and disadvantages of thermo-siphon cooling systems developed on the concepts of closed and open thermo-siphon and thermo-siphon with mixed convection. The same source describes liquid metals as a heat carrier and the essential blades of gas turbines cooled by liquid metal over the turbines with air cooling concerning the greater specific capacity.

Cooling elements made from porous materials are one of the perspectives and effective ways for heat exchange intensification. The physical basis of this method is an extremely high intensity of heat exchange between a porous body and flowing through its heat carrier due to a very extensive surface of contact. The analysis showed that the use of heat pipes for cooling elements of gas turbines is limited due to the variety of positions in the space of the cooling elements and, consequently, the different effects of gravitational forces on them. However, it is promising to use heat pipes to equalize the temperature field of bodies in those places where the boundary conditions change quite sharply. An example of such highly loaded elements is the leading edge of the nozzle and blades, the zone of the laminar-turbulent transition. In these cases, the heat transfer coefficient on the outer surface of the blade at a short distance varies from two to three times. Note that the starting and ending points of the transitional regime of the boundary layer are not determined reliably and may fluctuate depending on the engine mode. As it follows, the position of the maximum heat transfer coefficient in the transition zone cannot be accurately fixed. The specified uncertainty of the heat transfer coefficient from gas does not allow organizing reliable adequate heat removal from the inside of the blade to the air. In this regard, it is of interest to study the possibility of

reducing temperature gradients along the shell of the blade by installing a porous reservoir with a liquid metal coolant on the inner surface of the blade.

This way, the problem is reduced to the determination of multilayer system heat balance, which comprises a heated blade shell, porous medium filled with liquid metal heat carrier and internal separated thin wall cooled by air. Compared to ordinary heat pipes schemes, this variant assumes the system without steam catch channels, i.e. completely closed porous reservoir, in which the two-phase state of heat carrier is maintained and heat transfer is carried out by concurrent diffusion-induced motion of steam and liquid.

3 Research Methodology

The two-phase model [9, 10] has been used to describe the processes. The model allows reducing the number of governing energy conservation equations. It is quite completely described in referenced literature, therefore only the main idea and practical implementation are presented here.

The model was adapted to gas turbine conditions and numerically solved with the finite element method. The mixed two-phase model was presented as a multiphase mixture of diffusing components (phases) where the interfacial zone between components is not a negligible magnitude but occupies a whole volume of the reservoir.

The model comprises conservation equations of mass, impulse, and energy as well as boundary and initial conditions based on a suggestion of independent phase motion. Thus, the target parameters are the parameters of two-phase media (density – ρ , velocity – u , enthalpy – h , relative enthalpy – H) connected by algebraic correlations to corresponding parameters of separate phases taking into account saturation and mobility of separate phases (λ_l, λ_v):

$$\begin{aligned}\rho &= s\rho_l + (1 - s)\rho_v, \\ \rho u &= \lambda_l u_l + \lambda_v u_v, \\ \rho h &= s\rho_l h_l + (1 - s)\rho_v h_v, \\ H &= \rho h - \rho_v h_v,\end{aligned}\tag{1}$$

where, index l refers to the liquid phase, v to steam phase. Liquid and steam densities and enthalpies in these equations correspond with saturation curves for the taken value of pressure.

Phases' mobility (λ_l, λ_v) depends on steam and liquid kinematical viscosity and value of saturation. The completely closed system is under consideration, in which two-phase media remains immobile while steam and liquid mass velocities equal in absolute value and have opposite directions.

$$\lambda_l u_l + \lambda_v u_v = 0.\tag{2}$$

A driving force of separate phases is capillary pressure:

$$p_c = p_v - p_l, \tag{3}$$

that can be defined by expression as follows

$$p_c = \left(\frac{\varepsilon}{K}\right)^{1/2} \sigma J(s), \tag{4}$$

where Leverett’s J -function is formed by the saturation only.

The energy conservation equation, with the exception of the gravity element, can be represented with respect to the conditional enthalpy of the mixture H as

$$\Omega \frac{\partial H}{\partial t} + \nabla \cdot (\gamma_h u H) = \nabla \cdot \left(\frac{\Gamma_h}{\rho} \nabla H\right). \tag{5}$$

Entered in (5) factors, i.e. heat capacities ratio Ω , advection correction coefficient γ_h , and diffusion coefficient Γ_h are determined respectively:

$$\Omega = \varepsilon + \rho_s c_s (1 - \varepsilon) \frac{dT}{dH}, \tag{6}$$

$$\gamma_h = \left[s + \frac{\rho_v}{\rho_l} (1 - s) \right] \frac{\lambda_l(s)}{s}, \tag{7}$$

$$\frac{\Gamma_h}{\rho} = D + k_{eff} \frac{dT}{dH}, \tag{8}$$

where dT/dH is a mixture enthalpy derivative of temperature; $\lambda_l(s)$ – is relative mobility of the liquid phase; k_{eff} – is an effective heat conductivity of porous material; D – is a coefficient of capillary diffusion.

The diffusion coefficient reflects cross-motion phases and varies within the region of computation dependently on the saturation value

$$D(s) = \frac{\sqrt{\varepsilon K} \sigma}{\mu_l} \frac{s(1-s)}{\frac{v_v}{v_l} s + (1-s)} \frac{dJ(s)}{ds} \tag{9}$$

Equations (5–9) are correct as for the two-phase zone as for steam and liquid zones are taken separately. As far as the two-phase zone is considered, it is assumed that energy transfer is carried out exclusively at the account of diffusion and there is no heat exchange between porous solid and heat carrier. As practice shows, this assumption is quite valid for liquid-metal heat carriers.

This model was adapted to the operating conditions of gas turbines and numerically solved by the finite element method (FEM).

The energy equation for a solid is usually represented relative to temperature

$$c \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T), \quad (10)$$

where c – is the volumetric heat capacity, k – is the thermal conductivity.

The solution to this equation was carried out in the framework of a single code using the FEM. The joint problem of the thermal conductivity of a porous body with a liquid metal coolant and a solid was solved by two methods: joint and separate. The first method involved solving a complete system of equations for the entire object as a whole, together with conjugation equations at similar points. The second method was based on the sequential solution of the problem for solids and porous bodies, after which boundary conditions were imposed at the mating boundaries based on the solution obtained at this iteration.

A comparison of the two methods showed greater stability of the joint method, although in most cases a separate method allows you to get a solution more quickly.

To solve the problem of the thermal state of a multilayer system, the conjugation conditions at the interface between a solid and a porous body were formulated, and a number of model problems were solved [11, 12].

4 Results

The choice of the working fluid should be carried out first of all based on the range of the operating temperatures and capability with the material of casing to provide high thermal stability. The working fluid must be able to wet a wick and the material of the casing. The edge angle must be zero-order or very little. For the providing of the high heat-transfer capability of the pipe at the lowest flow rate of working fluid and hence at the minimal drop of pressure along the pipe it is desirable to use liquid with a high value of latent heat of vaporization. Hydraulic resistance of the flow will be low if the working medium has little viscosity of the steam and liquid phases. The temperature range of the gas-turbine at which it is necessary to cool the vanes is 900–1100 °C. The high-temperature heat pipes with liquid-metal heat-carrying agents run in such a range of temperatures. The liquid-metals have the best property for this case. Among them, there is potassium, natrium, lithium. Especially satisfactory properties are found to have natrium and lithium. Lithium owns the most favorable properties regarding heat transfer among all heat-carrying agents. Natrium has slightly worse thermophysical properties. However, at the running of lithium, the casing of pipe must be manufactured from expensive chemically stable to lithium alloy while natrium can run in a pipe made from stainless steel. That is why natrium is widely used in high-temperature heat pipe [13, 14]. We also chose Na as a heat-carrying agent for the current study. Natrium at operating temperature 900 °C has thermophysical properties that are equal: $h_{fg} = 3913$ kJ/kg – the latent heat of vaporization, $\rho = 745,4$ kg/m³ – density, $\mu = 0,17 \cdot 10^{-3}$ Pa·s – dynamic viscosity, $\sigma = 0,113$ N/m – surface tension [13, 14].

The usage of the heat pipe for the cooling of the turbine blades has some difficulties. The main one among them is the gravitation action which forces differently on

the heat pipes capacity depending on the arrangement of vanes in a guide vane assembly. That is why the choice of the porous structure is predetermined by the maximum height of the liquid lifting. In the simplest case, the design of the heat pipe maybe is presented as a vane with two times enlarged height. The vane should be made as a shell with the arranged porous structure on its interface. The boiler of such a heat pipe will be located on the working part of a vane that flowed around by hot gas. The condenser must be out of the flow-through part of the turbine and cooled for example by air.

It is known that the most effective porous material is the homogeneous low-trans wick in case of the acting of gravity. This condition is contented by copper caked powder with the radius of pores $r = 9 \cdot 10^{-6}$ m, by permeability $K = 1.74 \cdot 10^{-12}$ and by porosity $\varepsilon = 0.27$ [12]. Specific heat flux from the hot gas to the vane surface can be estimated by value $q > 106 \text{ W/m}^2$. The vane height usually approximately can be ranged as 0.04–0.1 m. Hence, the height of the liquid phase lifting in the capillary structure must be $l = 0.08\text{--}0.2$ m. The maximum value of lifting liquid Na for given wick is $l = \frac{2r}{\rho g \sigma} = 3,4$ m. Therefore, this wick covers all probable requirements of lifting liquid.

Two important examples of the use of porous reservoirs in the design of a gas turbine blade cooling system are presented in this part of the paper. The first example has shown decreasing the temperature gradient in the leading edge of gas turbine nozzle vane. The second example concerns the development of the cooling system of the nozzle vane on the whole. Let us consider the design of blade leading edge (LE) to prove the effectiveness of porous element with liquid metal.

It is known that boundary conditions at the LE can be changing in a wide range. For example, the heat transfer coefficient can be about 5–6 kW/(m²·K) at the stagnation point and then it decreases to a value of 2–3 kW/(m²·K) at the short distance in 2–5 mm along blade surface. You can imagine a situation where the stagnation point moved along the profile of the blade relative to its initial position due to changes in working conditions. At the same time, the air cools the inner surface with the same efficiency. These conditions should cause thermal unevenness, which can be weakened by the porous element. We considered only part of LE of 2 mm in width and with a porous element of 1.5 mm in width that was fixed inside of blade. The thin of 0.2 mm cover was touched at the porous element to protect liquid metal leakage. The average pore diameter was about 0.009 mm that corresponded to the porosity of 0.6. The air of 450 °C cooled the internal surface of the system with heat transfer intensity 1250 W/m² K. Gas temperature was 1100 °C and its intensity was changed at the LE surface in a range of 2–6 kW/(m²·K). Thermal analysis of the LE showed the appropriate temperature irregularity: the maximum temperature was about 930 °C and minimum –880 °C at the external surface (Fig. 1). So the drop in temperature was 50 °C. The temperature distribution was much more irregular when the porous element was replaced by the metal: maximum and minimum of the temperature was 1010 °C and 940 °C.

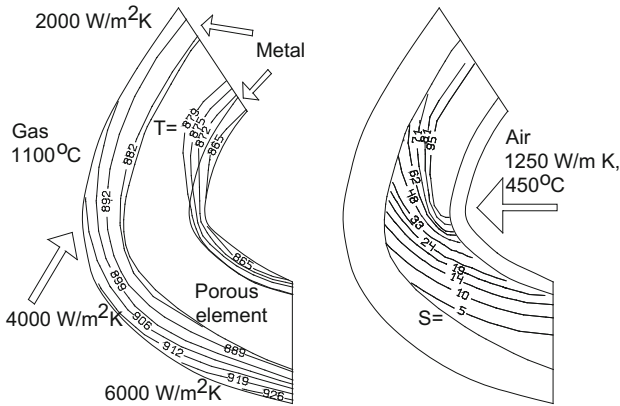


Fig. 1. Temperature (left), a saturation of porous element (right) of the LE part.

The following example concerns the efficiency of the nozzle blade cooling system of a high-temperature gas turbine as a whole (Fig. 2). The boundary conditions on the surface of the blade on the gas side were obtained using the integral method of calculating the boundary layer. The boundary conditions between the inner surface of the shell and the air were determined using hydraulic and thermal calculations of the cooling system [15].

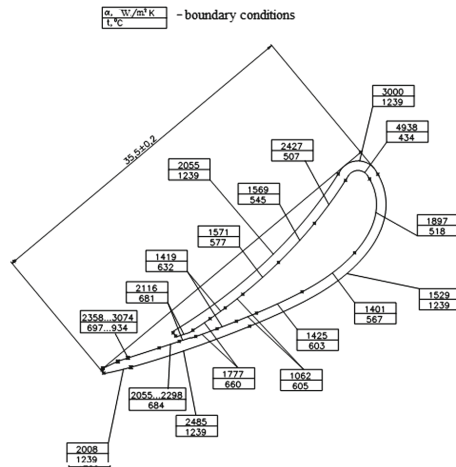


Fig. 2. Boundary conditions from gas and air.

The temperature field of the initial blade design was calculated using the developed here method and the ANSYS (Fig. 3). The calculations were performed under the same boundary conditions. A comparison of the results showed their complete identity, which indicates the reliability of the proposed method and software implementation.

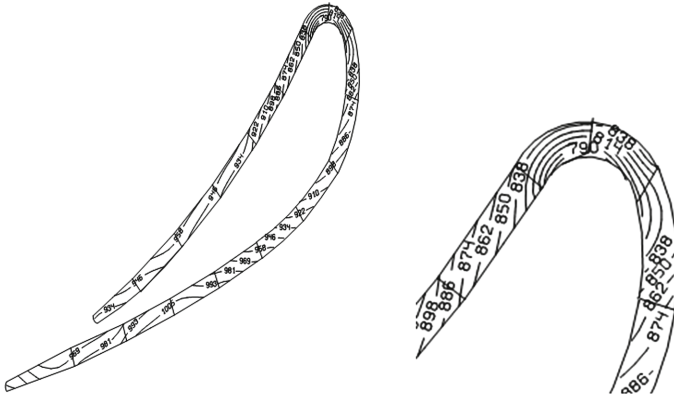


Fig. 3. The temperature field of the metal shell.

The temperature field of the shell is happened to be rather uneven. The maximum temperature is observed in the region of the outlet edge and equals to about 1020 °C. The air temperature at the inlet edge is about 838 °C. The temperature gradient along the convex and concave parts of the scapula reaches 100–150 °C.

The use of a porous reservoir saturated with a two-phase coolant at a saturation temperature of 765 °C led to a leveling of the temperature field and a decrease in the temperature of the leading and trailing edges (Fig. 4). The boundary conditions on the gas side remained the same as in the original design. The porous layer had a thickness of 3 mm, which is 2 times the thickness of the shell.

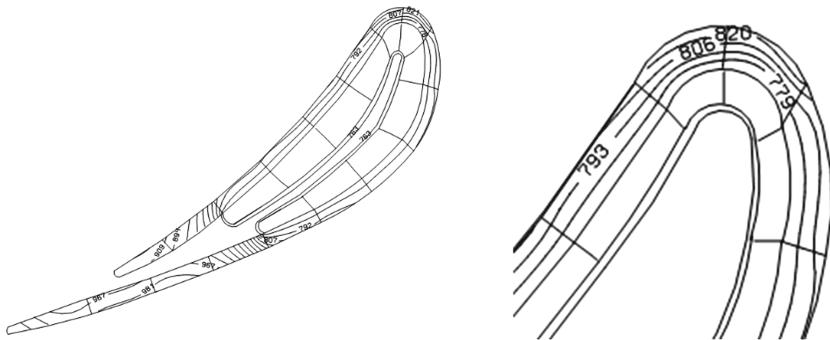


Fig. 4. The temperature field of the blade with a porous reservoir.

The temperature of the trailing edge dropped to 970 °C and the leading edge to 820 °C. The temperature gradients on the convex and concave surfaces sharply decreased at the places of installation of the porous structure and amounted to about 13 °C. However, the trailing edge cannot be cooled effectively due to the small size,

and the porous structure cannot be placed there. The average value of the saturation in the porous structure is 47% (Fig. 5).

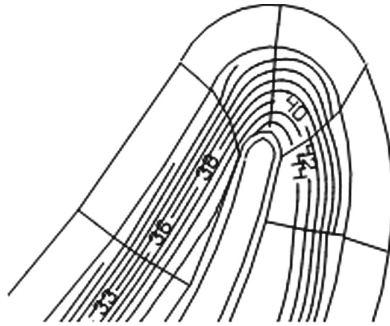


Fig. 5. Saturation lines of the blade with a porous reservoir.

In places of thinning of the porous reservoir, this value decreases. A redistribution of saturation lines is observed along the concave surface. The minimum value of saturation is 16%, where the increase in heat flux is associated with a high coefficient of heat transfer from gas ($2055 \text{ W/m}^2 \text{ K}$). Such a distribution of saturation lines indicates that in this section there is an intense, oppositely directed movement of vapor and liquid. The different intensities of the two-phase transfer also make it possible to achieve a uniform temperature field of the shell.

5 Conclusions

Based on the two-phase heat transfer model in a porous medium, a mathematical model of the boiling process and the dynamics of a liquid-metal coolant in a porous medium surrounded by an unevenly heated shell are developed.

This model allows the designing of efficient cooling systems for thermally loaded parts of gas turbines with help of the porous elements with a liquid metal coolant that even out the temperature field and increasing the degree of cooling.

It was proven that liquid natrium is a more suitable metal for cooling the blades of a gas turbine since it can work for a long time in a stainless steel tank without any changes in the properties and corrosion of the casing.

It was showed that processes in the porous reservoirs filled with a liquid metal coolant are an effective way for leveling the temperature even in areas with a sharp change in the intensity of heat transfer from gas to the surface of the blade. In particular, this applies to the leading and trailing edges of the blade, as evidenced by the distribution of saturation lines.

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