TEMPERATURE FIELD AT AN ACTIVE BLADE OF A GAS TURBINE COOLED EXTERNALLY WITH AN AIR–LIQUID MIXTURE

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A design method which will ensure a uniform temperature field at the active blades of a gas turbine with external air–liquid cooling has been developed and also proved out experimentally, as the results shown here indicate.

In developing any method of cooling the active blades of a gas turbine, one must aim to ensure not only a high efficiency but also a uniform temperature field at the blade.

The gist of our method of designing the cooling is as follows. From one of the few nozzle blades (Fig. 1) the air–liquid mixture is ejected through the clearance between the exit edges. Liquid droplets fall on the surface of active blades. A film produced as a result of dynamic interaction between a liquid droplet and the blade surface heats up and boils for a length of time which depends on the initial droplet size, on the kind of liquid, on the pressure, and on the gas as well as the blade temperature. Under conditions typical of modern power station and aircraft gas turbines, the "lifetime" of liquid films on hot active blade surfaces is so short that the heat transfer during external cooling becomes a periodic process governed by the differences between heat transfer coefficients as well as by differences between the gas and the coolant temperature. The coefficient of heat transfer between gas and blade is assumed here to be the same as it would be if the gas stream were dry. The coefficient of heat transfer between liquid and blade is defined in an analogous manner. Such an approach to the problem has made it possible to construct a physical and a mathematical model of the external-cooling process [4].

Some results of theoretical and experimental studies concerning the effectiveness of external cooling applied to active blades of gas turbines have already been shown in [1, 2, 4, 5].

In this article we describe a design method which will ensure a uniform temperature field at a cooled active blade. The problem has been reduced to determining the size spectrum of particles at the atomizer

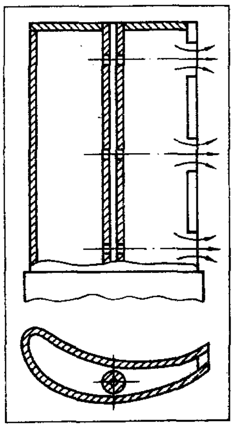

Fig. 1. Nozzle blade which ensures the proper supply of air–liquid mixture.

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outlet which will produce the required distribution of liquid over the blade profile.*

The initial size spectrum of droplets, referred to the pitch of the profiles mesh, determines the initial distribution density of particles of each size. As the liquid droplets move through the axial clearance and the passage between blades in the running wheel, the distribution density of particles changes continually. At the end of the flow process, when the droplets separate at the blade surface or leave the running wheel altogether, it is very different than it was initially.

Many attempts were made to solve the problem concerning the variable spectrum of particles in various physicochemical processes, but they have been successful only in the simplest case. With merely ten particle sizes selected for control, tracking the changes in their distribution density during the flow through a running turbine wheel would require so many iterations that the problem could not be solved numerically even with the aid of a digital computer. Moreover, the initial spectrum of particle sizes will, obviously, not be the optimum.

The solution process can be optimized, with a much reduced number of iterations, by the simplex method of linear programing: a single solution is selected from a multitude of possible solutions, namely the one with which the unknown function attains its extremum under specified constraints.

The problem is formulated as follows. We are seeking the minimum of the target function

$$M = \sum_{j=1}^{k} m_j x_j \tag{1}$$

under constraints

$$\begin{gathered} \sum_{j=1}^{k} a_{ji} m_j x_j \geqslant M_i \quad (i = 1,\ 2,\ \ldots,\ n), \\ x_j \geqslant 0;\ a_{ji} \geqslant 0;\ m_j \geqslant 0. \end{gathered} \tag{2}$$

Our linear programing problem can be solved on a digital computer, if the parameters a_{ji} and M_i are determined first. We will consider this in more detail.

If the perimeter of a blade profile at a given section is subdivided into approximately equal small segments, then it will be accurate enough for all practical purposes to consider all parameters constant within each such segment.

In accordance with the adopted physical model of the process, we have for the i-th segment of a profile:

$$M_i (i_V - i_L) = \alpha_G h \Delta l_i (t_G - t_L) \left(1 - \frac{\tau_1}{T} \right). \tag{3}$$

This relation yields the distribution of necessary liquid flow rates M_i around the profile perimeter, provided that the α_G field and the relative time of coolant action on an active blade are known. The other quantities in (3) may be considered known.

The coefficient α_G of heat transfer from gas to blade across a given profile can be calculated by the method developed in [6, 7] or by other methods.

The relative time of coolant action on an active blade cooled externally can be found according to [4]. An evaluation of test results on the cooling of ÉGTU-1 blades, obtained at the S. M. Kirov Turbogenerator Works in Khar'kov, has shown that $\tau_1/T = 0.1\text{-}0.3$ and may be considered the same for all profile segments.

Finally, in order to determine the separation coefficients, one must construct the trajectories of liquid droplets in the passages between blades. First, on the basis of actual turbine parameters, one determines the velocity field in the gaseous phase in the axial clearance and in the passages between blades of a running wheel. With the radial components of the gas velocity neglected here, the problem reduces to the two-dimensional hydrodynamic problem of a vortex-free flow of an inviscid gas through a mesh. Such a problem has been solved approximately by Stepanov and his solution was then used in [3] for analyzing the flow of a two-phase stream through a turbine stage.

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*It is rather simple to attain the required temperature distribution along a blade, inasmuch as a blade zone 25-30 mm high can be cooled by liquid coming out of a single orifice [1].

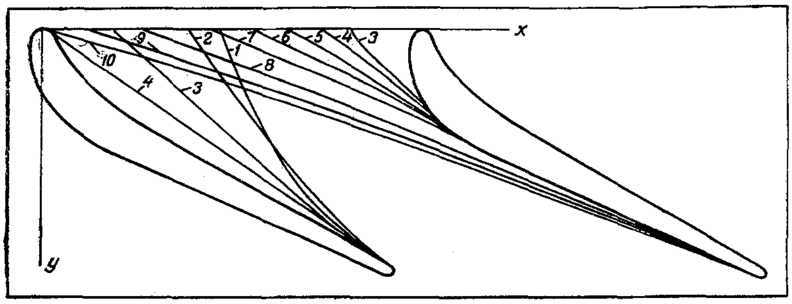

Fig. 2. Limiting trajectories (viewed from the profile tip) of liquid droplets with diameters in the 0.01-0.10 mm range.

Generally, the differential equation of motion for a liquid droplet in an irregular gas stream signifies that the force which accelerates the droplet (together with the adjoining gas mass) is equal to the vector sum of: gravity, the aerodynamic resistance force, the reaction force due to an irregular drain of vapor from various portions of the droplet surface, the Archimedes force, the Coriolis force, the centrifugal forces, the forces produced by a pressure gradient, and also forces which propel the droplet along with the medium. A thorough evaluation of all these forces under conditions of a two-phase flow through a stage of a gas turbine has shown that most of them have either very little effect on the trajectory of a droplet or they cancel one another.

According to [3, 9], for example, the radial displacement of moisture droplets within a turbine runner is small. For this reason, the centrifugal forces may be neglected, and the problem of determining a droplet trajectory may be treated as a two-dimensional one. Therefore, it suffices to consider the equation of motion for a droplet as one which represents a balance between the force necessary to accelerate the center of mass of the droplet and the force of aerodynamic resistance to the relative motion of the droplet. A typical calculation of the trajectory is shown in Fig. 2 for a droplet moving through a passage between blades.

In order to solve system of equations (1)-(2), it is necessary first to determine with the aid of a digital computer:

the velocities around the perimeter of a given profile of an active blade;

the field of gas velocity in a passage between blades;

the velocities of droplets of selected sizes (typically 10 sizes, depending on the gas parameters for a given turbine) at the entrance to the running wheel;

the trajectories of these droplets;

the local separation coefficients at 10-15 segments into which a given profile has been subdivided;

the distribution of heat transfer coefficients over a given profile of an active blade;

the distribution of necessary liquid flow rates around the perimeter of a given profile.

Such calculations were made on a Ural-4 digital computer. As a result, we established the optimum selection of droplet diameters and the corresponding distribution of liquid flow rates. In other words, we found the initial spectrum of droplet sizes yielding the optimum utilization of coolant liquid.

An analysis of the size spectra produced by various types of atomizers – one of them shown in Fig. 1 – indicates that the test results fit closely into the universal relation derived in [8]:

$$\frac{M_j}{M_m} = \exp\left[-\pi \left(\frac{r_j}{r_m} - 1 \right)^2 \right]. \tag{4}$$

For determining the modal dimension of droplets, the following ratio was given in [8]:

$$\frac{r_m}{L} = D\mathrm{We}^{-1}. \tag{5}$$

It was found in our tests that

$$D = B/\omega. \tag{6}$$

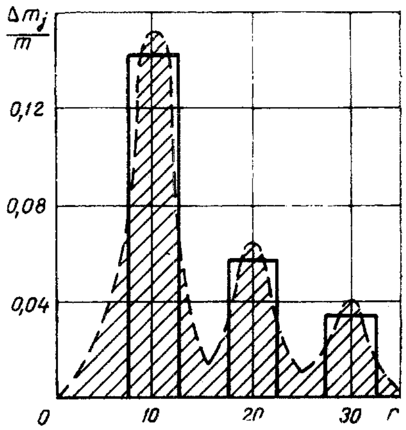

Fig. 3

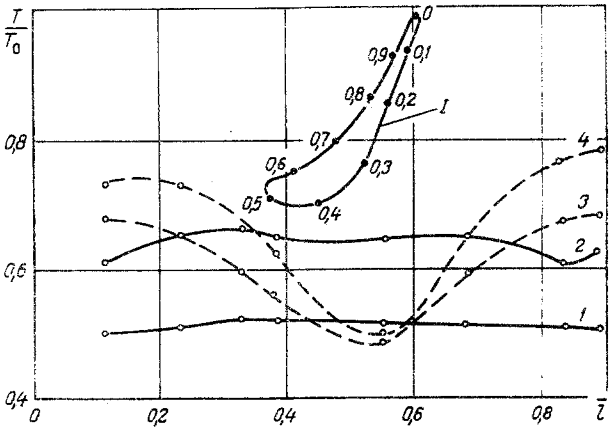

Fig. 4

Fig. 3. Calculated (solid lines) and actual (dashed lines) spectra of particle sizes.

Fig. 4. Temperature field at a section of a cooled active blade (solid curves indicate the rated mode, dashed curves indicate other than rated modes): 1, 3) per unit rate of liquid flow = 0.1% of gas flow rate; 2, 4) per unit rate of liquid flow = 0.5% of gas flow rate. Temperature of uncooled blade T_0 = 800°C. I) Blade contour and direction of bypass.

For our test range of the Weber number, the coefficient B is equal to 9.5-10.5 at a ratio of water rate to atomizing active air rate ω = 2.5-5. It is important to emphasize that, as can be seen in Fig. 3 for the types of atomizers considered here, droplets of modal and near-modal dimensions carry most (70-80%) of the atomized liquid mass. In this respect, the spectrum of particle sizes may be treated as one of a monodispersion, i.e., as consisting of droplets with modal dimensions only.

One example of a calculated optimum initial atomization spectrum is shown in Fig. 3, where the solid lines indicate the calculated spectra and the dashed lines indicate the possible appearance of corresponding elementary spectra. The necessary practical combinations of elementary spectra are achieved with a set of atomizers each of which produces a narrow spectrum of particles of the respective modal dimension.

A summation of M_i yields the total necessary liquid flow rate, which is then enhanced by the addition of liquid evaporated in a passage between blades and of droplets repelled from active blade surfaces after collision.

The quantity of liquid evaporating in a gas stream has been estimated on the basis of known criterial equations of heat and mass transfer for droplets in a gas stream [10]. The results of calculations indicate that, within parameter values typical of modern gas turbines, 5-15% of an injected liquid may evaporate in a single stage.

The mass fraction of droplets remaining on a profile surface after collision with it depends on many factors such as: the mode of collision between droplet and blade surface, the velocity and the angle of incidence, the time through which a droplet remains deformed, the condition of the surface, etc. If a droplet strikes a hot surface, then also its evaporation rate and the heat transfer rate increase appreciably. There are no reliable data available from which one could even roughly determine the quantity of liquid repelled after collision with a hot blade. For this reason, the respective estimate was based on the difference between the flow rate of cooling liquid actually injected in a test and the flow rate calculated by this method. According to such an estimate, approximately 10% of the moisture is repelled after collision. The method of calculation was checked on the ÉGTU-1 laboratory gas turbine at the S. M. Kirov Turbogenerator Works in Khar'kov.

The external air–liquid cooling system was tested on the first stage of this turbine, where the active blades had the following dimensions: 45 mm chord and 65 mm height.

Two atomizers designed as hollow guide vanes for the injection of atomizing air and cooling water (see Fig. 1) were selected for the test on the basis of design calculations.

The temperature distribution over the profile at the median section of an active blade is shown in Fig. 4 for two different flow rates of the cooling liquid in accordance with the calculated atomization spectrum. Also shown here are temperature distributions corresponding to other than rated atomization spectra at the same liquid flow rates.

It is evident here that, when the atomization spectrum is as rated, the temperature distribution over a profile is only slightly nonuniform ($\Delta T \approx 40°C$ at $\bar{G}_L = 0.5\%$ and $\Delta T \approx 20°$ at $\bar{G}_L = 1\%$), while with an other than rated atomization spectrum the deviations became very high ($\Delta T \approx 250°C$). Tests have verified the validity of this method of designing a uniform temperature field at active blades of gas turbines with external air–liquid cooling. It applies also to blade profiles with large twist angles and, particularly, to the root sections of the active blades in the tested turbine, for which results similar to those shown here have been obtained. Furthermore, it was possible to establish that a proper design of the air–liquid mixture supply may raise the coolant utilization factor to 75-80%.

NOTATION

x_j	is the number of droplets of the j-th diameter flowing per unit time;
m_j	is the mass of a droplet of the j-th diameter;
M	is the mass flow rate of liquid injected into a passage of a running wheel;
$M_j = m_j x_j$	is the flow rate of liquid consisting of the j-th diameter droplets at the passage entrance;
M_{ji}	is the flow rate of liquid consisting of the j-th diameter droplets at the i-th segment of a profile;
$a_{ji} = M_{ji}/M_j$	is the separation coefficient;
M_i	is the necessary flow rate of the liquid which is to separate at the i-th profile segment;
i_V	is the enthalpy of vapor at the blade temperature t_b;
i_L	is the enthalpy of liquid before separation at a blade surface;
h	is the height of a blade surface segment;
t_G	is the gas temperature;
α_G	is the coefficient of heat transfer from the gas to the blade (mean value over segment Δl_i);
T	is the period of heat transfer and temperature fluctuations in the medium;
τ_1/T	is the relative time of the coolant action on an active blade;
M_m	is the mass of droplets with the modal radius r_m;
L	is the characteristic linear dimension governed by the atomizer design and by the physical properties of atomized liquid and gaseous medium;
$\bar{l}$	is the relative profile coordinate;
We	is the Weber number.

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