DISINTEGRATION OF MOISTURE FILMS RUNNING OFF THE EDGES OF STEAM TURBINE NOZZLE BLADES

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The dimensions of the droplets and moisture "tongues" running off the edges of the nozzle blades of wet-steam stages have been determined experimentally and as a result of calculations based on the formulas of various authors. A physical picture of runoff and disintegration in the edge wake has been obtained for subsonic, near-sonic, and supersonic wet-steam flows.

In studying the erosion of the blades of wet-steam stages and determining the components of the mechanical losses due to moisture it is necessary to consider the formation, magnitude, and motion of the moisture droplets in the axial gaps. There have been extensive experimental and theoretical studies of the breakup of liquids flowing from orifices and jets [1]. This material is suitable for use in studying the formation of droplets from the moisture films that run off the edges of fixed blades. This leads to the problem of comparing the experimental data obtained for jets and fixed turbine blading.

The breakup of moisture films running off nozzle edges has been studied at the Leningrad Polytechnic Institute. The working section of the experimental rig contained a row of nozzle profiles with a pitch of 69 mm and a flow outlet angle of 19°. The same cascade had previously been thoroughly tested on wet steam [2].

In order to study the formation and motion of the droplets we installed an optical system that enabled us to carry out high-speed motion-picture photography (Fig. 1). The SKS-1M camera operated at film speeds of 3700–4500 frames per second. Various moisture levels ahead of the cascade were investigated in subsonic, sonic, and supersonic flow regimes. The moisture content at the cascade inlet varied from 0 (saturated steam) to 10%. The intervals of variation of the M and Re numbers were 0.5–1.67 and $(1.65-3.5)\cdot 10^5$, respectively. The back pressure beyond the cascade varied from 0.06 to 0.1 bar depending on the regime.

By studying the films obtained we were able to reconstruct the process of film runoff from the blade edge and breakup of the moisture in the edge wake. The runoff picture changed substantially on transition from subsonic (M = 0.5) to near-sonic or supersonic flow velocities beyond the nozzle channel.

For the near-sonic and supersonic regimes the runoff picture remained almost the same. Moisture accumulated gradually at the edge. Separation took place only after the condensate film had reached a sufficient thickness. At a small initial moisture content ($y_0 \cong 3\%$) the moisture film was alternately dragged 0.2–0.3 mm into the wake and returned to the blade in a pulsating motion. A tongue of moisture separated from the swollen film (Fig. 2). In 10^{-3} sec this tongue was dragged 2–3 mm into the wake, after which a droplet of radius 0.1–0.2 mm detached itself from the tip. Sometimes several fine droplets 0.02–0.05 mm in radius were formed from the neck associated with the formation of the terminal droplet. Droplets were also observed to form from several tongues originating in the same bulge of the film. At near-sonic and supersonic velocities the maximum length of the tongues was 3–4 mm. Sometimes their length reached only 0.5–1 mm. To a considerable extent the frequency of film runoff from the nozzle edge was determined by the initial moisture content ahead of the cascade. At small moisture contents at the cascade inlet (less than 2–3%) runoff was observed only twice per second in the camera field (approximately 6 mm along the length of the blade edge). As the initial moisture content increased, so did the runoff frequency. However, the nature of the runoff remained the same at small and large moisture contents for near-sonic and supersonic regimes. The following stages of droplet formation was observed: accumulation of a film, development of a tongue, disintegration of the tip of the tongue, contraction of the remainder of the tongue toward the edge, acceleration of the droplet in the wake, and breakup of the droplet in the flow.

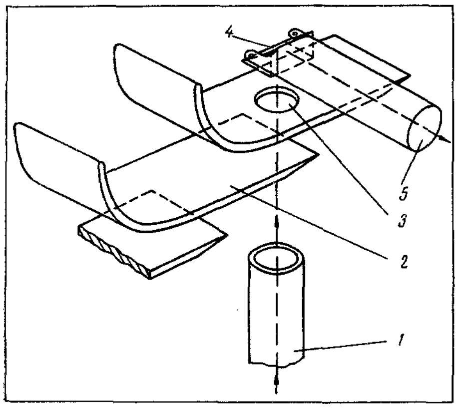

Fig. 1. Arrangement for photographing the runoff of moisture films and droplets from the edge of a nozzle blade: 1) illuminating tube; 2) nozzle blade; 3) window glazed flush with convex surface of blade; 4) prism; 5) output tube.

Another picture was observed at small subsonic velocities (M = 0.5). At an initial mositure content of

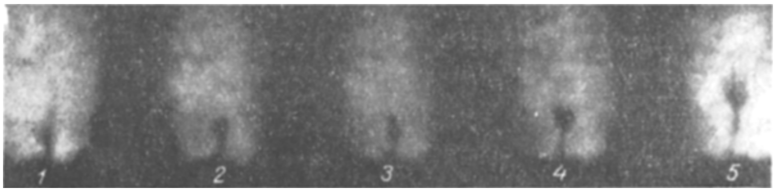

Fig. 2. Formation and breakup of moisture droplet at trailing edge (five successive frames). $p_1 = 0.23$ bar, $y_1 = 6.7\%$; $M = 0.567$; film speed 4000 frames per second.

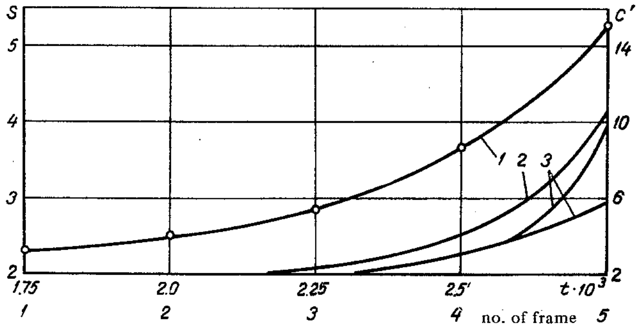

Fig. 3. Path (mm) and velocity (m/sec) of droplet after separation from tongue: 1) experimental path of droplet; 2) experimental velocity of droplet; 3) velocity of droplet according to (1).

about 5% runoff took the form of separation from the edge of individual parts of the film entrained by the flow. At a distance of about 10 mm along the wake from the edge large pieces of film were broken up by the flow. Sometimes at subsonic velocities continuous ribbons of moisture 7–8 mm long separated from the edge.

In no regime was the runoff point constant along the length of the blade. The only exception was the tongues from secondary flows. Their position on the blade was at approximately one fourth the height of the channel from the end walls.

The velocities of the droplets and films in the wake immediately after separation from the continuous part of the condensate film were 0.3–0.5 m/sec. At a distance of 3.7 mm from the blade edge along the wake at $M = 1$, $y_1 = 5\%$ the droplet was accelerated to 4 m/sec. After this the droplet became deformed and broke up. Figure 3 shows the path of a droplet on the interval from 2.3 to 5.3 mm along the wake from the blade edge taken from five successive frames. In the last two frames the droplet began to deform and break up. The deformation was particularly great in the last frame. In the subsequent frames the droplet could not be distinguished.

The velocity of the droplet on the above-mentioned interval was calculated from the formula

$$c_l' = \sqrt{2ASc''^{3/2}_{\mathrm{av}}}, \qquad (1)$$

where

$$A = \frac{9.38}{\rho'}\sqrt{\frac{\mu''\rho''}{d_{\mathrm{d}}^3}}.$$

The velocity of the steam in the wake was estimated from the results of [6].

On the length in question the edge wake had a width of about 1.2 mm, i.e., commensurable with the dimensions of the droplets formed, which were about 0.5 mm in diameter. When a droplet is accelerated, its surface is acted upon by a variable dynamic head corresponding to the steam velocity, which varies over the width of the wake. Good agreement between formula (1) and the experimental results (Fig. 3) was obtained for

$$c''_{\mathrm{av}} = \frac{c''_{\mathrm{w}_0} + c''_{\mathrm{w}_{0.5}}}{2},$$

where c''_{w_0} is the minimum steam velocity in the wake (core of wake), and $c''_{\mathrm{w}_{0.5}}$ is the steam velocity at a point in the wake where the deviation of the steam velocity in the wake from the velocity in the flow core is half that in the core of the wake [6].

In deriving formula (1) it was assumed that $C_x = 12.5\mathrm{Re}^{-0.5}$.

The criterion used to test the stability of the droplet was

$$\mathrm{We} = \frac{2\rho''(c''_{\mathrm{w}} - c')^2 r_{\mathrm{d}}}{\sigma},$$

where σ is the surface tension.

Calculation of We for frames 4 and 5 (Fig. 3) gave a value close to 14, which is usually [7] regarded as the upper limit of disintegration. For theoretical curves 3 (Fig. 3) we assumed disintegration of the droplet in accordance with frame 4. Calculation of the velocity for the largest droplet determined for We = 14 gave the lower curve. The upper branch of curve 3 characterizes the velocity of the average droplet, whose radius was taken equal to half the radius of the maximum droplet [8].

When the droplet enters the flow, it is defomed by aerodynamic forces. At the same time the droplet is accelerated by the flow. In this case the relative velocity and the value of the We number decrease. If the time required to reach the critical phase of deformation is less than the acceleration time to We ≅ 14, the droplet will disintegrate. Otherwise deformation, having reached a certain maximum, begins to decrease. As the relative velocity decreases, the shape of the droplet begins to approach that of a sphere.

The time required to reach the critical phase can be estimated from the formula [7]

$$t = 1.65\, d_{\mathrm{d}} (c'' - c')^{-1} \rho'^{0.5} \rho''^{-0.5},$$

for the regime of Fig. 2, $t = 0.5 \cdot 10^{-3}$ sec. The time required for acceleration of the droplet to the position shown in the fourth frame is $2.5 \cdot 10^{-3}$ sec. Consequently, the correctness of the calculation is confirmed by the breakup of the droplet observed in frames 4 and 5.

There have been numerous theoretical studies of the breakup of jets of liquid flowing from orifices and moving in a gas flow [1, 3, 4]. In these studies the mechanism of decay of jets as a result of the growth of unstable vibrations has been analyzed in detail. Shortwave vibrations have been found to predominate in all cases of atomization. A small section of continuous jet is almost always observed directly at the nozzle opening.

We will employ the formulas obtained for water flowing from jets and orifices for determining the size of the droplets and the length of the continuous section formed as a result of moisture runoff from the edges of nozzle blades in relation to our own experiments.

The problem of the disintegration of a liquid cylinder was first solved by Rayleigh [5]. According to Rayleigh the order of magnitude of the droplet is determined by the wavelength of the unstable vibration having the maximum growth increment. This wave is called the optimal wave. The corresponding wavelength

$$\lambda_{\mathrm{opt}} = \frac{4\pi\sigma}{\rho' c'^2}. \tag{2}$$

The instability of the jet leads to the separation of a ribbon of length λ_{opt}. As a result of its natural vibration and internal turbulence this ribbon breaks up into droplets of radius

$$r_{\mathrm{d}} = 7.56 \left[\frac{\lambda_{\mathrm{opt}} \delta_1}{2\pi} \right]^{0.5}, \tag{3}$$

where δ_1 is the thickness of the film on the concave surface of the blade.

To investigate the separation of the film from the edge of the nozzle blade, is one of the experimental regimes we maintained the parameters: pressure beyond nozzle $p_1 = 0.06$ bar, moisture content of steam beyond nozzle $y_1 = 5\%$, M = 1.5. From (2) and (3) for separation of 12% of the moisture contained in the flow at the nozzle outlet onto the concave part of the nozzle blade [2] we obtain $\lambda_{\mathrm{opt}} = 3.52 \cdot 10^{-3}$ m, $r_{\mathrm{d}} = 0.474$ mm. In our experiments for this regime we obtained $r_{\mathrm{d}} = 0.12$–0.25 mm, i. e., a result of the same order as the calculated value.

In [7], on the basis of the theory of similarity, the following relation was obtained:

$$d_{\mathrm{d}} = \delta_1 F \left(\frac{c''_{\mathrm{av}} \delta_1 \rho''}{\mu''};\ \frac{\delta_1 \rho'' \delta}{\mu''^2} \right). \tag{4}$$

By analyzing the experimental data of a number of different investigators the same authors determined the functional relationship F and obtained Eq. (4) in the form

$$d_{\mathrm{d}} = \delta_1 \left(135 + 3.67 \cdot 10^{-3} \frac{\delta_1 \rho'' \sigma}{\mu''^2} \right) \left(\frac{c''_{\mathrm{av}} \delta_1 \rho''}{\mu''^2} \right)^{0.9}. \tag{5}$$

The droplet radius was determined from (5) for $p_1 = 0.06$ bar, $y_1 = 5\%$, M = 1. The steam velocity in the wake behind the nozzle edge was estimated in accordance with [6]. As a result of the calculation we obtained a droplet radius of 0.105 mm, close to the value 0.15–0.20 mm measured under the same conditions.

The dimensions of the continuous part of the tongue were estimated in accordance with [3]. We employ the critierial relation

$$S_0 = \mathrm{B} \delta \mathrm{We}^{-0.71} \bar{\rho}^{-1.21} k^{0.308}, \tag{6}$$

where S_0 is the length of the continuous part of the jet (tongue), δ is the thickness of the nozzle edge, B = = 27 is an experimental quantity,

$$\bar{\rho} = \frac{\rho''}{\rho'}, \quad k = \frac{\mu'^2}{\rho' \delta \sigma}, \quad \mathrm{We} = \frac{c''^2 \rho' \delta}{\sigma}.$$

Equation (6) was obtained on the basis of a solution of the problem of stability and disintegration of a jet by the method of small perturbations.

According to (6) the length of the tongue is 4 mm for $p_1 = 0.06$ bar, $y_1 = 5\%$, M = 1. In the corresponding experiments the length of the tongue was equal to 2–4 mm.

As a result of these experiments and calculations we may draw the following conclusions:

1. The nature of moisture runoff from the edges of nozzle blades depends essentially on the flow velocity. For subsonic flows in the flow core (M = 0.5) the film runs off the edge in the form of a ribbon 7–8 mm long. At near-sonic, sonic, and supersonic velocities in the flow core beyond the nozzle edges (M = 0.95–1.67) the length of the runoff tongues was 2–3 mm.
2. The velocity of the droplets and films in the wake immediately after separation from the tongue was 0.3–0.5 m/sec.
3. In order to determine the length of the tongue and the size of the droplets formed it is possible to use formulas obtained for liquid jets.

NOTATION

μ'', ρ'' are the dynamic viscosity and the density of the steam; ρ' is the density of the water; S is the path of the droplet along the edge wake; c''_{av} is the mean steam velocity in the edge wake.

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