A STUDY CONCERNING THE EFFICIENCY OF FILM COOLING UNDER REAL CONDITIONS IN VARIOUS MOVING SYSTEMS

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The results are analyzed of an experimental study concerning the efficiency of film cooling under conditions of a zero-gradient and an accelerated flow of the main and the injected stream.

Film cooling is recently used more and more in various branches of industry for protecting the structural components of systems which are exposed to high temperatures and to chemical attack.

Many experimental and theoretical studies [1-3] have been concerned with the efficiency of film cooling under ideal conditions, i.e., under a uniform distribution of parameters in the main and in the injected stream at the entrance section without any external forces present. The basic performance parameter to be determined in these studies was the efficiency of film cooling, defined by the ratio

$$\eta = \frac{T_{\text{a.st}} - T_0}{T_s - T_0}. \quad (1)$$

The results of these studies, as well as those derived from dimensional theory, show that the efficiency of film cooling depends on such basic dimensionless parameters as: $\mathrm{Re_s}$, m, Θ, x/s, etc.

A very valuable method of calculating the film cooling in natural moving systems would be one based on using the curve of efficiency plotted for ideal conditions as a function of these basic dimensionless parameters and then adding corrections which account for the departure of real conditions from the ideal ones [3, 4]. There are not yet sufficient experimental data available, however, for implementing this method. First of all, the range of parameter values for which the relation $\eta = f(\mathrm{Re_s}, m, \Theta, x/s)$ has been

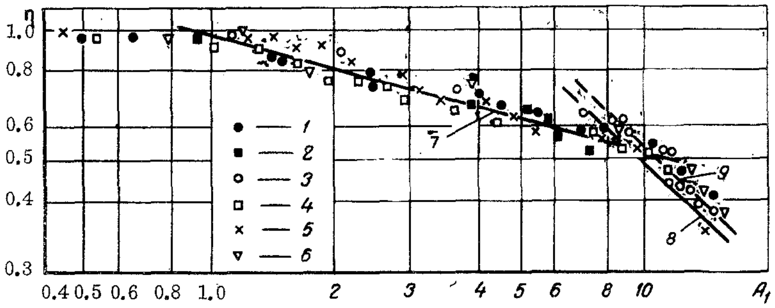

Fig. 1. Efficiency η as a function of the parameter $A_1 = \mathrm{Re_s^{-0.25}} \cdot m^{-1.25}\Theta^{-1.25}x/s$: 1) m = 1.335; 2) 0.98; 3) 0.713; 4) 0.949; 5) 0.887; 6) 0.795; 1) $\mathrm{Re_s}$ = 16,000; 2) 20,400; 3) 20,100; 4) 21,000; 5) 20,000; 6) 22,100; 1) Θ = 1.22; 2) 1.217; 3) 1.217; 4) 1.193; 5) 1.20; 6) 1.195; 7) $\eta = 0.98(A_1)^{-0.27}$; 8) $\eta = 3.09\ [(x/ms)(\mathrm{Re_s^*}(\mu_s\ \mu_0))^{-0.25}]^{-0.8}$; 9) $\eta = 3.47\ (A_1)^{-0.8}$.

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established is rather narrow; secondly, there are no corrections given which would account for any interaction between the main and the injected stream in natural moving systems, where such an interaction almost always occurs within the zone of influence of external force fields.

The purpose of this experimental study concerning the efficiency of film cooling was to obtain some data necessary for making this method of calculation feasible.

An analysis of the conditions in real turbomachines has shown that, at an initial pressure from 0.5 to 2.0 MN/m^2 and an initial temperature from 973 to 1173°K, at velocities of 100-500 m/sec and an orifice height $s = 1 \cdot 10^{-3}$ m, the value of the Re_s number varies from 5,000 to 30,000. All these studies concerning the efficiency of film cooling were made in aerodynamic tunnels at low velocities and Re_s numbers up to 2,500. In order to determine how the efficiency of film cooling under ideal conditions depends on those basic parameters, a series of experiments was performed on a static test stand with the Re_s number varied from 16,000 to 25,000. The other parameters were varied within the following ranges: m from 0.5 to 1.5 and Θ from 1.185 to 1.265. The results of these tests have been evaluated in terms of the efficiency of film cooling as a function of the parameter $A_1 = Re_s^{0.25} m^{-1.25} \Theta^{-1.25} x/s$, which, except for the factor $\Delta^{1.5}$, is the same as the generalized parameter A in [3]. The parameter Δ, which accounts for the initial dynamic boundary layer on the main stream, has in our experiment had a value close to unity with insignificant variations.

The values for the efficiency obtained in this test series are shown in Fig. 1. The relative error in determining η varies from 1.5 to 5% as the efficiency decreases from 1.0 to 0.2. The $\eta = f(A_1)$ curve consists distinctly of three characteristic ranges, with the test points in each of them easily approximated by power functions. The power exponent is zero for the initial range, because here the protected surface is in contact with the coolant only and, therefore, the temperature at all points is the same and equal to the temperature of the injected air. In the transition range $(1 \leq A_1 \leq 10)$ there develops a thermal boundary layer and the streams mix gradually, while the efficiency begins to decrease. The power function which closely approximates the test data here is

$$\eta = 0.98\,(A_1)^{-0.27}, \tag{2}$$

which agrees rather well with the results in [3].

In the main range $(A_1 > 10)$ the test data conform closely to the theoretical relation

$$\eta = 3.09 \left[\left(\frac{x}{ms} \right) \left(Re_s^* \frac{\mu_s}{\mu_0} \right)^{-0.25} \right]^{-0.8}, \tag{3}$$

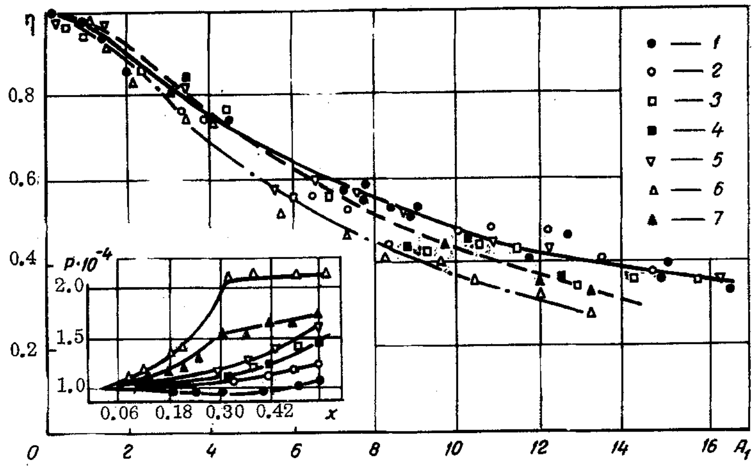

Fig. 2. Efficiency η as a function of the parameter $A_1 = Re_m^{-0.25} \cdot m^{-1.25} \Theta^{-1.25} x/s$ at an acceleration of the streams corresponding to a drop in static pressure along the x-coordinate (in meters): 1) m = 0.793; $Re_s = 2.27 \cdot 10^4$; $\Theta = 1.226$; 2) 0.785; $2.34 \cdot 10^4$; 1.234; 3) 0.75; $2.33 \cdot 10^4$; 1.23; 4) 0.766; $2.39 \cdot 10^4$; 1.22; 5) 0.733; $2.34 \cdot 10^4$; 1.225; 6) 0.795; $2.29 \cdot 10^4$; 1.185; 7) 0.804; $2.32 \cdot 10^4$; 1.205.

which has been derived in [1]. The test data can be generalized even better by the relation

$$\eta = 3.47 (A_1)^{-0.8}. \tag{4}$$

It was in this operating range where we studied the efficiency of film cooling during acceleration of the main and the injected stream. The basic parameters were varied in the tests within the following ranges: m from 0.5 to 0.8, Θ from 1.2 to 1.25, and Re_s from 23,000 to 25,000. A major part of the tests was performed with the pressure along the protective sheath varying by not more than $2.5 \cdot 10^4$ N/m² per length. Acceleration was produced by means of straight deflectors of various lengths above the test plate. Typical curves of (static) pressure variation along the plate are shown in the lower left-hand corner of Fig. 2. On this diagram we also show the essential results of our tests. An analysis of the data on the efficiency of film cooling under a low pressure gradient, corresponding to an increase in the velocity of the streams from 100 to 150 m/sec, has shown that η decrease slightly. Almost all test points obtained in this series can be confined between two curves: one of them is the efficiency curve for a zero-gradient flow, the other is shown in Fig. 2 by a dashed line. The efficiency values read on these curves at corresponding points do not differ by more than 5%. From this we may conclude that a slight acceleration of the streams during film cooling causes an insignificant reduction of the efficiency.

It is to be noted that the data which have been obtained with a change in the velocity from 100 to 200 m/sec at the surface show a somewhat greater reduction of the efficiency (the dashed-dotted curve in Fig. 2).

NOTATION

T	is the temperature, °K;
$m = \rho_s u_s / \rho_0 u_0$	is the ratio of mass flow rates in the injected and in the main stream per unit area;
ρ	is the density, kg/m³;
u	is the stream velocity, m/sec;
s	is the orifice height, m;
$Re_s = \rho_0 u_0 s / \mu_0$	is the Reynolds number based on the parameters of the main stream and on the orifice height;
Θ	is the temperature factor;
x	is the distance from the injection orifice, m;
$Re_s^* = \rho_s u_s s / \mu_s$	is the Reynolds number based on the parameters of the injected stream and on the orifice height;
μ	is the dynamic viscosity of a stream, N·sec/m².

Subscripts

0	refers to the main stream;
s	refers to the injected stream;
a.st.	denotes the sheath parameter under adiabatic conditions.

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