PERFORMANCE OF FILM COOLING WITH A NEGATIVE LONGITUDINAL PRESSURE GRADIENT

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Experimental evidence is presented to show that there is no effect on the performance of film cooling from a large negative longitudinal pressure gradient.

The performance of film cooling is defined by

$$\eta = \frac{T_0 - T_{a.w}}{T_0 - T_s}, \tag{1}$$

and there are many papers on this, of which the main ones are [1—4]. In all those papers, the studies were made under so-called idealized conditions, usually with the distinction of three parts: initial, transitional, and main, with different laws for η in terms of the basic dimensionless parameters m, Re_s, Θ, and x/s. Certain papers, such as [5—9] deal with the effects on the performance from a longitudinal pressure gradient, which can displace the flows in film cooling under real conditions.

In [5, 6] it was not found that there was any effect from flow acceleration on the performance of film cooling; in [7] a small effect was found on η from accelerated flow, but a correlation relationship was given for the η obtained under idealized conditions with the values of $\eta_{\Delta p}$ obtained in the presence of a longitudinal pressure gradient:

$$\eta = \eta_{\Delta P} \left[\frac{u_0(x)}{u_0(x=0)} \right]^{0.2}, \tag{2}$$

where $u_0(x)$ is the current value of the speed in the main flow, while $u_0(x = 0)$ is the speed of the main flow in the section x = 0, i.e., above the slot.

In [8], a method for calculating the boundary layer thickness in the presence of a longitudinal pressure gradient taken from [10] was used to perform a correction to the η for analogous conditions by substitution of the quantity

$$X = p^{-1} \int_0^x p dx, \tag{3}$$

where $p = [M/(1 + (k-1/2)M^2)]$, this replacing x in the parameter A_1 in $\eta = f(A_1)$, with

$$A_1 = m^{-1.25} \cdot Re_s^{-0.25} \cdot \Theta^{-1.25} \frac{x}{s}. \tag{4}$$

The recommendations in this last study were not compared with experiment.

In the conclusions of [9] it was stated that there was a considerable effect from flow acceleration on the performance of film cooling. In the relevant experiments, flow acceleration was only a secondary factor, while the mixing in the main was controlled by the angle of incidence of the main flow on the surface protected by the film. Under these conditions, film detachment may be more extensive than when the cooling agent is injected at an angle to the main flow [11].

We have obtained experimental evidence on the effects of a longitudinal negative pressure gradient on

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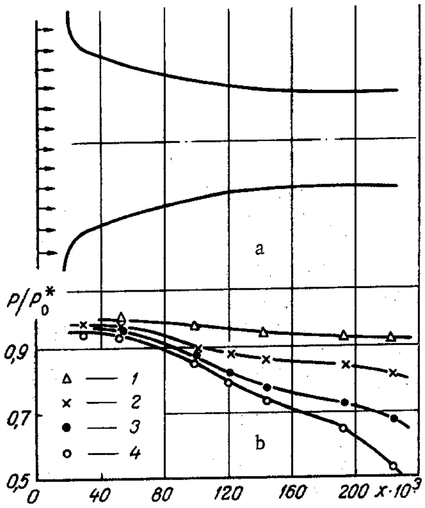

Fig. 1. a) Nozzle form; b) longitudinal pressure distribution for various $P_{k.min}/P_0^*$: 1) $P_{k.min}/P_0^*$ = 0.918; 2) 0.813; 3) 0.680; 4) 0.528. x, m.

the performance of film cooling under conditions similar to those in actual engines.

The tests were done with a static equipment that has been already described in detail [5]. The results were obtained on using air heated to 350-380°K, which was injected into a cold main flow (T = 310°K). The injection was performed through a tangential slot, and this resembled the devices for injecting secondary air into a boundary layer as used in [2, 4]. Almost adiabatic conditions were set up on the measuring plate with the equipment working. The coefficient of variation in the data for the cooling performance was 6-8% for the end of the main part.

The flow acceleration was produced by inserting a planar nozzle in the working part above the plate, the shape of this being shown in Fig. 1, which also shows the pressure distribution along the nozzle for various values of the ratio of the pressure at the inlet to the pressure in the narrow section $P_0/P_{k.min}$, and the corresponding Mach numbers in the narrow section $M_{k.min}$. The pressure ratio was varied mainly via P_0. The primary processing of the data was done in order to represent the values as a function of A_1 [5].

The tests were begun with a short series consisting of three operating conditions; in these tests, where the separation of the main flow was quite moderate (the velocity ratio $u_{0k.min}/u_0$ was of the order 2-3), the Mach number in the narrow section of the nozzle did not exceed 0.35. The other dimensionless parameters varied within the following limits: m = 0.4—1.0; Re_s = (2.5—3.75) $\cdot 10^3$; Θ = 1.19—1.22. Then one can neglect the effect of the compressibility on the process, which is a factor that often accompanies a flow in the presence of considerable negative pressure gradients. Figure 2 shows the results. The solid lines represent the experimental results under idealized conditions, in particular in the absence of flow acceleration [5]. The experimental results for the above series agree well with the curve for the main part obtained in the idealized case, while for the transitional part they even lie higher than the curve.

This shows the air blown into a turbulent boundary layer does not have any effect on the film cooling when there is acceleration as regards the main part, i.e., we confirm the results of [5, 6]. It is virtually impossible to produce large flow accelerations at small M, i.e., when one can neglect the effects of the compressibility on the aerodynamic characteristics. For this purpose, one needs to have very low flow speeds at the input to the nozzle.

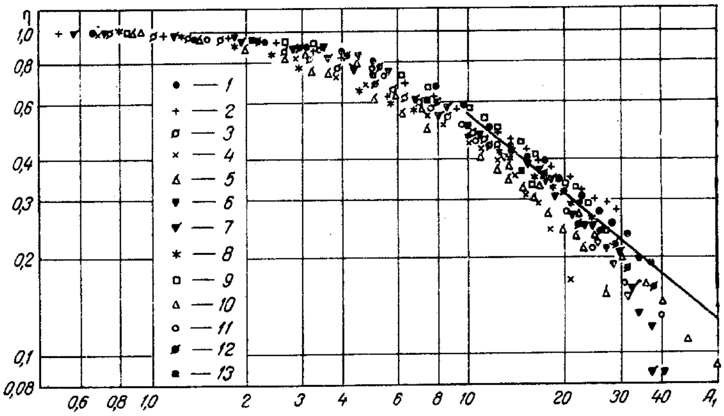

Fig. 2. Experimental results on cooling performance: 1) M = 0.35; m = 0.40; 2) 0.27 and 0.50; 3) 0.27 and 1.0; 4) 1.0 and 1.0; 5) 1.0 and 0.83; 6) 1.0 and 0.3; 7) 1.0 and 0.59; 8) 0.49 and 0.96; 9) 0.76 and 0.88; 10) 0.80 and 0.26; 11) 0.83 and 0.33; 12) 0.63 and 0.63; 13) 0.47 and 0.52.

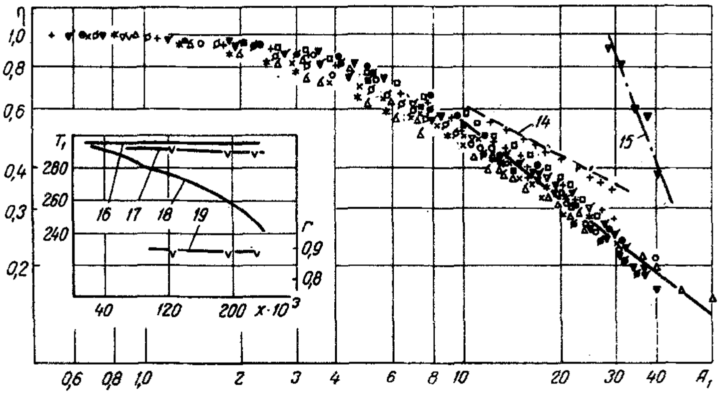

Fig. 3. Generalization of the data on film cooling performance: 1-13) as Fig. 2; 14) from (2); 15) from (3); 16) stagnation temperature in flow along nozzle; 17) adiabatic wall temperature; 18) thermodynamic temperature of flow along nozzle; 19) recovery factor. T in °K, x in m.

Then we performed three series of experiments on the effects of considerable flow acceleration, which differed in height of the slot for injection. We used in sequence slots of heights s = 1.0, 1.75, and 3.75 mm. In all we examined 53 sets of working conditions, which differed in injection coefficients and in velocity ratios at the start and end of the nozzle. The velocity ratios corresponded to $P_{k.min}/P_0^*$ from 0.95 to 0.528, which provided $M_{k.min}$ at the narrow section of the nozzle from 0.47 to 1.0.

The basic dimensionless parameters varied within the following limits in these runs: m = 0.265-1.04; Θ = 1.14-1.3; Re_s = (3.44-25.0)$\cdot 10^3$; $M_{k.min}$ = 0.43-1.0. Figure 2 shows some of the experimental results. It is clear that there is a loss of cooling performance as the Mach number increases for the narrow section of the nozzle, this applying to the main part, where the effects of acceleration and compressibility should be greater.

We applied (2) and (3) to the experimental results from all four series. The broken line in Fig. 3 approximates the observed η from the first series as represented via (2) for $u_0^{k.min}/u_0$= 2.5; the curve lies above the idealized one for the main part, which shows that this relationship cannot be used here. The dot-and-dash curve was obtained by using the recommendations of [8] with (3) to process the data; the resulting corrected η lie considerably above the performance curve for the idealized case.

The experimental results and calculated η of [7, 8] thus indicate that the latter cannot be used to take into account the effects of a negative pressure gradient on the cooling performance. On the other hand, if the flow acceleration is considerable and the velocities are high, which corresponds to large M, one cannot use the results of [5, 6], which apply for small pressure gradients.

Of course, at high flow speeds the stagnation temperature differs from the temperature measured at the wall, and the following is the stagnation temperature measured in the layer near the wall:

$$T^* = T + A\frac{u^2}{2gc_p}. \tag{5}$$

The following is the expression for the temperature measured at the wall in the cooling case:

$$T_{a.w} = T + rA\frac{u_0^2}{2gc_p}, \tag{6}$$

and then

$$T^* - T_{a.w} = (1-r)A\frac{u_0^2}{2gc_p},$$
$$T^* = T_{a.w} + (1-r)A\frac{u_0^2}{2gc_p}. \tag{7}$$

The experimental data were therefore worked up as

$$\eta = \frac{T^* - T_0}{T_s - T_0} = f(A_1),$$

and to calculate T* we used the recovery factors derived from a special experiment with the equipment. The method of deriving the r is fairly simple and consists in comparing the stagnation temperature of the flow in the vessel with the measured temperature at the wall. The experimental results are shown on the left in Fig. 3 and they correspond well with the values obtained from the following theoretical relationship [12]:

$$r = \sqrt[3]{\mathrm{Pr}}. \tag{8}$$

Therefore, we used r = 0.89 in the subsequent processing. Figure 3 shows that the results for the main part agree well with the cooling performance curve obtained under idealized conditions [5]. The maximum spread in the experimental results in relative terms was ±15%.

Then the following relationship can be used for film cooling with considerable flow acceleration and high M:

$$\eta = \frac{T_{a,w} + (1-r)\,\dfrac{u_0^2(x)}{8380c_p} - T_0}{T_s - T_0} = 3.47A_1^{-0.8}. \tag{9}$$

Note also the increase in the length of the initial part by a factor of about 1.5, which agrees with the results of [9] for small flow accelerations.

The results for the transition part with the nozzle at $A_1 \leq 5$ lie above the η for the idealized case. We were unable to discover the reason for this.

These results indicate that a negative longitudinal pressure gradient does not reduce the efficiency of film cooling, and that (9) can be used to calculate η for the main part under these conditions.

NOTATION

u is the velocity, m/sec;
ρ is the density, kg/m^3;
μ is the dynamic viscosity, kg·sec/m^2;
T is the temperature, °K;
c_p is the specific heat at constant pressure, kcal/kg·deg;
P is the pressure, N/m^2;
s is the height of slit, m;
x is the distance from injection point, m;
m is the injection coefficient;
Θ is the ratio of temperatures of injected and main flows;
Re_s is the Reynolds number calculated from the parameters of main flow and height of slit;
M is the Mach number;
r is the recovery coefficient;
η is the film cooling efficiency.

Subscripts

s refers to parameters of injected flow;
0 refers to parameters of main flow;
a, w refers to wall parameters under adiabatic conditions;
* refers to parameters of stagnated flow;
K refers to parameters in narrow section of confuser.

LITERATURE CITED

1. K. Wieghart, ATY 24536. Original in Deutsche Luftfahrtforschung, Forschungsbericht, 1900 (1943).
2. R. Seban, Trans. ASME, series C, No. 4 (1960).
3. S. S. Kutateladze and A. I. Leont'ev, Teplofizika Vysokikh Temperatur, No. 2 (1963).
4. I. T. Shvets, E. P. Dyban, and V. M. Repukhov, Izv. VUZ, Aviats. Tekh., No. 4, (1968).

5. V. A. Zysin and M. S. Zolotogorov, Izv. VUZ, Énergetika, No. 5 (1971).
6. R. Seban and L. Beck, Teploperedacha, No. 3 (1962).
7. I. Hartnett, R. Birkebak, and E. Eckert, International Heat Transfer Conference, part IV, No. 81 (1961).
8. I. Stollery and A. El-Ehwany, International Journal of Heat and Mass Transfer, 8, No. 1 (1965).
9. W. Carlson and E. Talmor, International Journal of Heat and Mass Transfer, 11, No. 11 (1968).
10. B. Stradford and G. Beavers, ARG, R8, M3207 (1964).
11. E. P. Dyban, E. G. Popovich, and V. M. Repukhov, Inzh.-Fiz. Zh., 20, No. 2 (1971).
12. A. A. Gukhman and N. V. Ilyukhin, Principles of Heat Transfer in High-Speed Gas Flows [in Russian], Mashgiz, Moscow (1951).