EFFECT OF POROUS INJECTION AND SUCTION ON THE OPERATION OF A STALLED CONICAL DIFFUSER*

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The influence of porous injection and suction on the drag, pressure recovery, and efficiency of a conical diffuser in the stalled flow regime is studied experimentally.

Diffuser ducts are used for the efficient conversion of flow kinetic energy into potential energy [1, 2]. The prestall or slightly stalled flow regime in the diffuser has been found as the optimum from the stated point of view [3]. If the flow is further complicated by heat and mass transfer (as in drying, porous-cooling, and evaporation processes, as well as operations preliminary to boundary-layer control), the behavior of the flow and level of the diffuser characteristics change and are accessible to investigation and analysis only by experimental means.

The literature is almost completely devoid of data on conical diffusers with flow separation (stall) from the wall and with porous injection or suction. The experimental apparatus, experimental diffuser, measured quantities, and instrumentation for injection are described in detail in [4, 5]. For the suction experiments the VVN-3 vacuum pump operated as a pump, whereas for injection it operated as an air blower.

The primary (main) and secondary (suction or injection) air flows were subsonic ($M \leqslant 0.34$). The ranges of the experimental Reynolds numbers were $Re_0 \approx (0.5 \text{ to } 4.0)\cdot 10^5$ for the injection tests and $Re_0 \approx (1.0 \text{ to } 5.0)\cdot 10^5$ for suction. The injection rate $\overline{m}$ was varied from 0.00058 to 0.0292, and the suction rate $\overline{q}$ from 0.000585 to 0.0124. The diffuser inlet velocity was varied from 19 to 118 m/sec for injection and from 22.3 to 112.3 m/sec for suction. The expansion aspect ratio of the 12° diffuser was $n = 5.15$, and the constriction aspect ratio of the nozzle, which was profiled according to the Vitoshinskii equation [7], was $n = 10.5$. Injection was realized for a nonisothermal main flow, and suction for an isothermal main flow with a constant experimental temperature of 1 to 3°C. The main flow regimes and secondary flow rates were almost identical in injection and suction. The present article summarizes the results for one flow regime at the inlet to a 12° diffuser in order to facilitate their comparison.

The diffuser operation is characterized in the general case by the energy loss factor ζ (drag coefficient), pressure recovery C_p, and efficiency η. In processing the experimental data we found the distribution of these quantities along the diffuser. In the experiments the spent air from the diffuser was channeled into a cylindrical air duct for elimination from the laboratory.

The experimental data indicate an asymmetric flow sepration from the diffuser wall without injection or suction. The separation zone was determined by means of silk threads attached to a needle, which functioned as a holder and was moved along and across the flow by means of a special coordinating device. Injection or suction at the experimental rates had

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virtually little effect on the upstream or downstream position of the separation zone. However, the static wall pressure distribution changed considerably in both cases, affecting the aerodynamic characteristics of the duct; more will be said about this effect below. The boundary-layer suction in the diffuser obeyed the law

$$\bar{q}=(\rho_w v_w)/(\rho_0 \bar{u}_0)=\text{const.} \tag{1}$$

Suction according to (1) implies that the velocity of the sucked air as it entered the porous wall in the given experiment was practically constant over the entire inner surface of the diffuser. The injection law was

$$\bar{m}\approx(\rho_w v_w)/(\rho_1 u_1)\approx\text{const.} \tag{2}$$

Injection according to (2) over the entire inner surface of the diffuser was made possible by the configuration of the working section [4, 5]. The lengthwise distribution of the pressure recovery is determined from the experimentally measured distribution of the static pressure along the inner surface of the diffuser:

$$C_{p(x)}=(p_{2(x)}-p_0)/[(\rho_0/2)\,\bar{u}_0^2]. \tag{3}$$

Knowing the value of $C_{p(x)}$, in each test we determined the lengthwise distribution of the energy loss factor in suction [1, 6]:

$$\zeta_{(x)}=1-\frac{C_{p(x)}}{1-[(1-\bar{q})/n^2(x)]}, \tag{4}$$

and in injection:

$$\zeta_{(x)}=1-\frac{C_{p(x)}}{1-[(1-\bar{m}(x)/n^2(x)]}. \tag{5}$$

The local efficiency of the diffuser in suction is found from the expression

$$\eta_{(x)}=C_{p(x)}/C_{p\bar{q}(x)}, \tag{6}$$

in which $C_{p\bar{q}(x)}$ is the lengthwise-local ideal pressure recovery of the diffuser in suction, as defined by the equation [6]

$$C_{p\bar{q}(x)}=1-[(1-\bar{q})/n_{(x)}^2]. \tag{7}$$

For injection, analogously, the local efficiency is given by the relation

$$\eta_{(x)}=C_{p(x)}/C_{p\bar{m}(x)}, \tag{8}$$

in which $C_{p\bar{m}(x)}$ is the lengthwise local ideal pressure recovery of the diffuser in injection, as defined by the equation

$$C_{p\bar{m}(x)}=1-[(1+\bar{m}_{(x)})/n_{(x)}^2]. \tag{9}$$

The values of $C_{p(x)}$ in (6) and (8) are determined from (3) for the test using suction and injection. The lengthwise distribution of the pressure recovery in the diffuser as a function of the injection and suction rates is given in Fig. 1. The dashed curves correspond to ideal recovery calculated according to (7) and (9). It is evident from a comparison of the curves in Figs. 1a and 1b that the effects of porous injection and suction on the pressure recovery in a diffuser differ qualitatively as well as quantitatively. The recovery decreases in the injection case, more so as the relative injection flow rate $\bar{m}$ is increased. Thus, for small values of m = 0.0006 to 0.0048 we observe an almost uniform reduction of the recovery: $C_{p(x)}$ decreases from 0.76 ($\bar{m}$ = 0) to 0.68 ($\bar{m}$ = 0.0048), i.e., an eightfold increase in $\bar{m}$ decreases $C_{p(x)}$ by a factor of 1/1.12 at the exit cross section. Further increasing $\bar{m}$ to 0.0140, i.e., by a factor of 2.92, lowers the value of $C_{p(x)}$ at the exit to $\approx$ 0.425, i.e., by 1/1.6.

Consequently, porous injection lowers the pressure recovery in the diffuser, uniformly at low injection rates and more intensely as the latter are increased. Thus, injection of

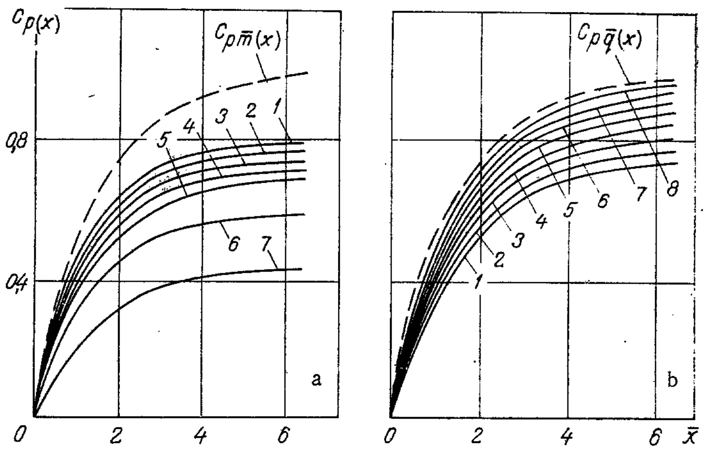

Fig. 1. Lengthwise distribution of pressure recovery in 12° diffuser ($Re_0 \approx 10^5$). a) Injection: 1) $\bar{m}$ = 0; 2) 0.0006; 3) 0.00124; 4) 0.00248; 5) 0.0048; 6) 0.00918; 7) 0.0140. b) Suction: 1) $\bar{q}$ = 0; 2) 0.000603; 3) 0.00113; 4) 0.00196; 5) 0.00268; 6) 0.00506; 7) 0.0088; 8) 0.0124. All quantities are dimensionless.

TABLE 1. Temperature Distribution in Diffuser Boundary Layer

$\bar{m}=0$; $x/d_0=1{,}23$; $T_w=407$ °K ($Re_0 \approx 10^5$)

Δ, mm	0,25	0,5	1,5	2,5	3,5	5	7
T, °K	415	419	421,3	422,6	423,6	427	427

$\bar{m}=0{,}0140$; $x/d_0=1{,}23$; $T_w=304{,}7$ °K ($Re_0 \approx 10^5$)

Δ, mm	0,25	0,5	1,5	2,5	3,5	5	7	10	14	20	26
T, °K	354,9	361	368,9	378,6	387,2	398	407,3	413,5	416	423	423

order 1.5% lowers the recovery by a factor of 1/1.78 relative to noninjection. Porous injection therefore deteriorates the operation of the diffuser, bearing in mind that its principal function is to maximize the exit value of the pressure recovery. However, injection is necessary in a number of situations, for example, to protect the structural elements of thermally stressed mechanisms against overheating, and therein lies the main object of injection, to reduce the temperature of a working surface. Table 1 lists the values of T_w for zero injection and for $\bar{m}$ = 0.0140 for a given duct cross section. We see that 1.4% injection of a homogeneous coolant lowers the wall temperature by 102.3°C, the air temperature falling off abruptly with the thickness of the thermal boundary layer.

Suction creates an altogether different picture (Fig. 1b). It increases the pressure recovery over the entire length. It is evident from the graph that the recovery increases with $\bar{q}$, and, unlike injection, this growth is practically uniform (the values of $\bar{m}$ and $\bar{q}$ were varied in almost equal measure from one test to another). It is seen that 1.24% suction of the air frozen in the boundary layer brings the pressure recovery to its ideal value in the diffuser, i.e., significantly improves the operation of the diffuser. Thus, for $\bar{q}$ = 0 we have $C_{p(x)}$ = 0.75 at the inlet cross section; for $\bar{q}$ = 0.0124 we have $C_{p(x)}$ = 0.98 at the same cross section. The growth ratio of $C_{p(x)}$ is 1.31.

Note that injection at the same rate ($\bar{m}$ = 0.0140) lowers the recovery by 1/1.79. Consequently, injection has a more pronounced effect on the flow than suction. This disparity is possibly due to dissimilar laws governing injection and suction of air through the wall. However, injection tests that we conducted on the same diffuser with the admission of coolant through the wall at T_w = const showed that the pressure variation along the length differs very little from the tests described above. Consequently, the influence of the law governing

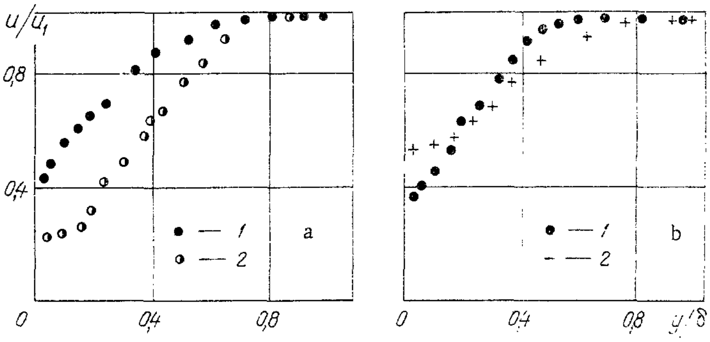

Fig. 2. Velocity distribution in diffuser boundary layer with injection and suction ($Re_0 \approx 10^5$; $\alpha = 12°$; $x/d_0 = 1.23$). a) Injection: 1) $\overline{m} = 0$; 2) 0.0140. b) Suction: 1) $\overline{q} = 0$; 2) 0.0124. All quantities are dimensionless.

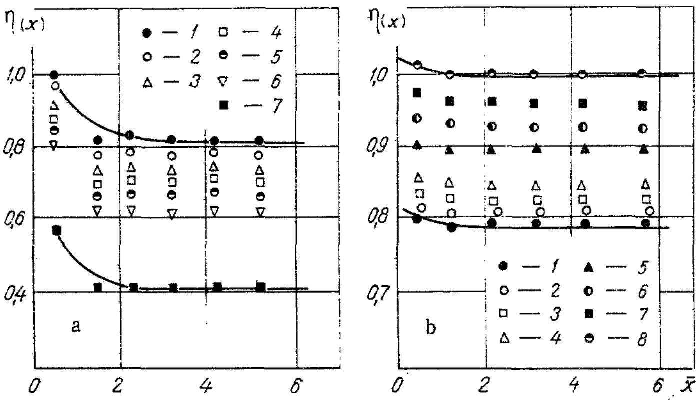

Fig. 3. Lengthwise efficiency distribution in a 12° diffuser ($Re_0 \approx 10^5$). a) Injection: 1) $\overline{m}$ = 0; 2) 0.0006; 3) 0.00124; 4) 0.00248; 5) 0.0049; 6) 0.00918; 7) 0.0140. b) Suction: 1) $\overline{q}$ = 0; 2) 0.000603; 3) 0.00113; 4) 0.00196; 5) 0.00268; 6) 0.00506; 7) 0.0088; 8) 0.0124. All quantities are dimensionless.

the suction of air from the boundary layer in the given tests is clearly inconsequential. The behavior of the static pressure and velocity profile in injection are the same in our tests as in [8], indicating the qualitatively identical influence of porous and obstructive injection in the given studies.

Our experimental data on the pressure recovery in the diffuser without injection or suction agree qualitatively and quantitatively with the data of [9] for an 8° diffuser with fully developed inlet flow, as well as with the recovery data of [6], in which $C_{p(x)}$ is shown to increase with slotted suction in a circular 10° diffuser with aspect ratio n = 4. When a slot is placed in the prestall zone, the behavior of $C_p(\overline{x}; \overline{q})$, as in our experiments, approaches the ideal ($\overline{q}$ is the relative flow of air through the slot).

Injection or suction changes the shape of the velocity profile in the diffuser cross sections. Figure 2 gives the velocity distribution in the boundary layer with suction and injection for a fixed cross section $(x/d_0) = 1.23$ and the maximum injection and suction rates. It is seen that injection makes the velocity profile (in the prestall zone) much shallower; its development is analogous to what happens with an increase in the longitudinal positive pressure gradient [2]. In suction (Fig. 2b), conversely, the profile becomes much fuller, tending to equalize and thus affecting the pressure recovery. An analogous filling-out of the velocity profile in slotted suction has been established in [6], in which a loss of axial symmetry on the part of the flow at the diffuser exit is noted.

The efficiency of the diffuser with injection and suction is given in Figs. 3a and 3b as a function of length in the diffuser. It is seen that for uncomplicated hydrodynamic con-

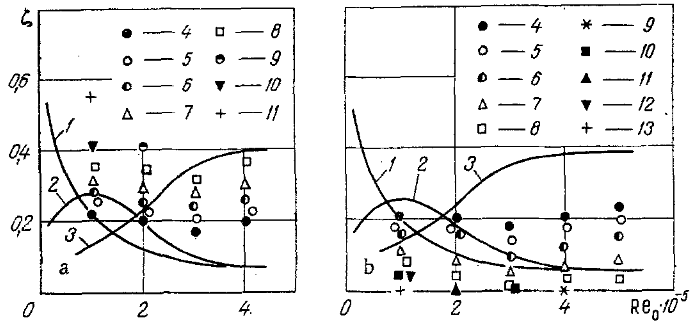

Fig. 4. Total drag coefficient at diffuser exit versus Reynolds number and injection or suction rate ($n \approx 5.15$; $M_0 \leqslant 0.28$). Deich et al. [1] (curves 1-3): 1) $\alpha = 10°$; 2) 15°; 3) 20°. a) Our data, with injection: 4) $\bar{m} = 0$; 5) 0.0006; 6) 0.0012; 7) 0.0024; 8) 0.0048; 9) 0.0072; 10) 0.00918; 11) 0.0140. b) Our data, with suction: 4) $\bar{q} = 0$; 5) 0.0006; 6) 0.0011; 7) 0.002; 8) 0.0026; 9) 0.0036; 10) 0.00506; 11) 0.00603; 12) 0.0088; 13) 0.0124. All quantities are dimensionless.

ditions the diffuser efficiency is at the 0.8 level except in the inlet section, where its value is somewhat higher. The latter occurrence is clearly attributable to the fact that the maximum longitudinal pressure gradient occurs in precisely that section of the duct; farther downstream this gradient decreases. Injection and suction alter the efficiency values radically, injection decreasing it abruptly and suction increasing it. Thus, injection at the rate $\bar{m} = 0.0140$ decreases the efficiency from 0.8 to 0.4 near the exit; suction, conversely, causes the efficiency to increase with the relative flow rate of sucked air: $\eta_{(x)} \approx$ 0.78 to 0.82 at $\bar{q} = 0$, and $\eta_{(x)} \approx 1.0$ at $\bar{q} = 0.0124$, i.e., the efficiency of the diffuser operation becomes equal to its efficiency at ideal pressure recovery. We note that the injection and suction, respectively, exhibit an almost equidistant behavior relative to the efficiency distribution for uncomplicated hydrodynamic conditions.

The experimental data on the dependence of the total drag coefficient at the diffuser exit section on the inlet flow regime (Re_0) with injection and suction are presented in Fig. 4. Also shown for comparison are data on the drag coefficients for conical diffusers characterized by total angles of 10, 15, and 20° without injection or suction [1]. It is seen that the energy loss factor of the diffuser depends on the number Re_0, the diffuser angle, and the injection and suction rates, where the former increases and the latter decreases this factor. Clearly, our experimental data without injection or suction agree qualitatively with the data of Deich et al. [1].

Without injection or suction (Figs. 4a and 4b) the diffuser ensures 78 to 82% utilization of the flow kinetic energy input. Injection diminishes the percentage utilization of that energy, ensuring only 46% at the maximum rate $\bar{m} = 0.0140$. Conversely, boundary-layer suction increases the percentage utilization of the kinetic energy input to the diffuser, bringing it to 100% at the maximum relative rate $\bar{q} = 0.0124$, i.e., the diffuser performance becomes extremely efficient from the standpoint of its prime function: pressure recovery.

NOTATION

α, total diffuser angle in deg; $n = (F_2/F_1)$, diffuser (expansion) aspect ratio, or $n = (F_1/F_2)$, nozzle (constriction) aspect ratio; F_1, F_2, inlet and exit cross sections of duct in either case, in m^2; $M = (\bar{u}_0/a)$, Mach number; $\bar{u}_0$, mean longitudinal main flow velocity at inlet to experimental section in m/sec; a, speed of sound in m/sec; $Re_0 = (\bar{u}_0 d_0/\nu_0)$, Reynolds number formed with respect to inlet diameter and main flow parameters at inlet; d_0, inlet inside diameter of diffuser in m; ν, kinematic viscosity coefficient in m^2/sec; $\bar{m}$, relative injection mass flow rate; $\bar{q}$, relative suction mass flow rate; ζ, drag coefficient (energy loss); C_p, pressure recovery; η, diffuser efficiency; v, transverse flow velocity in m/sec; u, longitudinal component of main flow velocity in m/sec; ρ, density of flow in kg/m^3, p, static wall pressure in N/m^2; y, distance measured perpendicularly to porous wall in given cross section, in m; δ, dynamic boundary-layer thickness in m; Δ, thermal boundary-layer thickness in m; x, distance measured from diffuser inlet section along longitudinal axis, in m; $\bar{x} = (x/d_0)$, dimensionless longitudinal coordinate; T, absolute temperature in °K. Indices: 0, diffuser inlet; 1, upper boundary of boundary layer; w, inner surface of duct; x, value of coordinate x; 2, static pressure to coordinate x downstream from inlet at the wall.

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CALCULATING TURBULENT NONISOTHERMAL JETS

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Experimental and calculated data concerned with the propagation of turbulent nonisothermal jets are compared.

Semiempirical methods of calculating nonisothermal turbulent jets, as a rule, well depict the qualitative flow pattern for T_0 = var and the influence of the overheating parameter $\omega = T_0/T_\infty$ on the velocity, temperature, etc., distributions [1-5]. With an appropriate choice of the numerical values of the empirical constant (or relationships) we can achieve a satisfactory quantitative agreement between experimental and calculated data. In connection with this, when evaluating the area of application of various calculation methods and their effectiveness – the capability of being used for sufficiently accurate predictive calculation of the characteristics of nonisothermal jets – the question of "universality" of the experimental constants which complete any semiempirical calculation system is important. First and foremost the question is about determining the degree of influence of the overheating parameter on the empirical coefficients and about estimating the calculation error connected with the assumption about their independence of ω.

In Table 1 we have presented, for a number of calculation schemes, the numerical values of experimental constants that are necessary for calculating velocity and temperature fields. These data, obtained on the basis of processing results of measurement in turbulent jets of variable density, are taken from [1-5].

The results of a calculation carried out for the distribution of the characteristic quantities along the axis of the jet are shown in Fig. 1. In Fig. 1a-c, for three values of

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