MASS TRANSFER FROM SURFACE OF INITIAL SECTION OF WIND TUNNEL INTO A PARTIALLY SWIRLED STREAM

V. K. Shchukin, A. A. Khalatov, and Yu. F. Gortyshev

UDC 532.72:532.529.5

Mass transfer into a partially swirled stream from the surface of the initial section of a wind tunnel is studied experimentally. The experimental data for a swirler with φ_i = 45° and blades twisted according to the free vortex law for G_s/G_Σ = 0-0.5 are generalized in the form of the criterial equation (3). The dependence (10) is presented which makes it possible to determine the effect of partial swirling of the stream on the mass transfer law.

The swirling of a stream by blade swirlers considerably improves the mass output characteristics, but in some cases the excessive intensity of stream swirling in the entrance section of the channel is undesirable. In this case partial swirling of the stream, a diagram of which is presented in Fig. 1, can be used with high effectiveness to alter the mass output relationship along the length of the channel.

The stream twisted by the swirler interacts with the unswirled stream and partially expends its energy on swirling it, as a result of which it loses momentum. Conversely, the peripheral unswirled stream acquires a tangential velocity component and at a certain distance from the entrance to the channel one can obtain motion with rotation in the entire volume.

By varying the ratio of flow rates of the unswirled part of the stream and its swirled part through variation in the relative area of the slot ($\bar{F}_s = F_s/F_{tu}$) one can regulate the mass output law within the desired limits.

The working section on which the experimental study of mass output was conducted consists of a short cylindrical tunnel 170 mm long with an inner diameter of 80 mm, constructed out of 1Kh18N9T steel of low thermal conductivity.

The mass output consists in the process of evaporation from a thin liquid film covering the inner surface of the experimental section. The temperature of the film was measured with 11 Nichrome-constantan thermocouples 0.2 mm in diameter located in different cross sections on the inner surface of the tunnel (in two control sections three thermocouples each were mounted). The air temperature at the entrance was measured with a movable thermocouple. The air was heated to the assigned temperature in a three-section electric heater with a power of 36 kW.

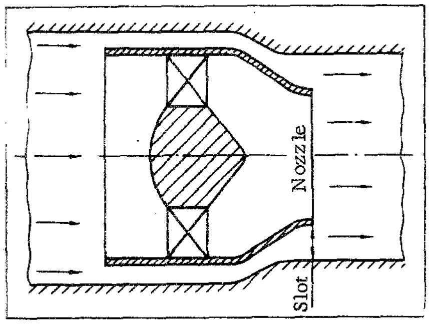

Fig. 1. Diagram of entrance assembly for partial swirling of stream.

The uniform continuous film was produced by a special distributor with 126 openings 0.8 mm in diameter and the unevaporated part of the liquid was gathered in a collector. The liquid supplied to the distributor was preliminarily heated in a thermostat. The amount of liquid evaporated was determined as the difference between the liquid supplied to the distributor (measured by a rotameter) and gathered by the collector (weighed on an analytical balance).

A preconnected section of variable length was installed between the working section and the swirler which made it possible

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 26, No. 2, pp. 197-203, February, 1974. Original article submitted July 25, 1973.

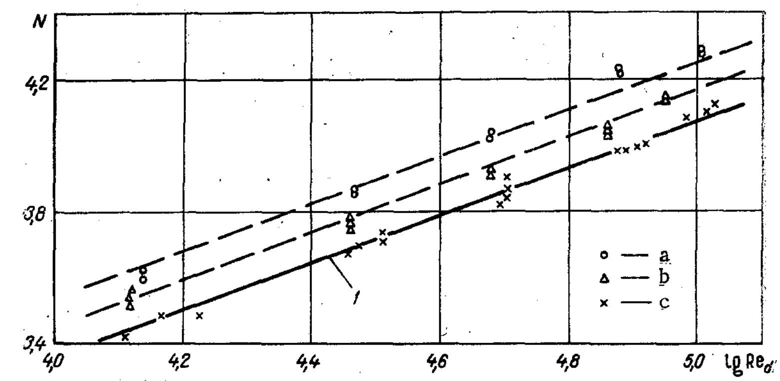

Fig. 2. Dependence of log $[Nu_D/0.023\ Sc^{0.4}\ (p/p-p_{vw})^{0.82}] =$ $= N$ on $f(\log Re_d)$: a) $\bar{F}_s = 0.2$; b) $\bar{F}_s = 0.5$ at $\varphi_i = 45°$, $\bar{x} = 1.0$; c) experimental data on mass output into an axial stream.

to study the mass output from the surface of the working section at different distances from the swirler. In order to exclude the effect of the hydrodynamics of the film on the mass output the experimental and preliminary sections had independent arrangements for producing the film and collecting the unevaporated part of the liquid.

A subsonic conical nozzle with an exit diameter of 60 mm was mounted at the exit from the working section to prevent the inflow of air into the experimental section from the surrounding medium. A special bypass assembly constructed in accordance with the diagram presented in Fig. 1, which was mounted between the receiver and the experimental section, was used to produce the regulated partial swirling of the stream. To eliminate the nonuniformity in the velocity profiles of the axial and swirled streams the bypass section was assembled using special technological collars. The position of the nozzle with the swirler relative to the channel axis was regulated by four movable screws. Tests which were conducted for a study of the structure of the isothermal stream established that nonuniformity of the velocity field is practically absent in the channel beyond the bypass section. A study of the stream structure during total swirling [1] showed that the velocity field after the swirler is also uniform. The thickness of the edge separating the main and swirled streams was made small enough (about 0.5 mm) to prevent vortex formation. The bypass assembly with a set of inserts and regulating collars makes it possible to vary the flow rate of the unswirled part of the gas in a broad range without changing the total flow rate of the gas.

The study was conducted on four inserts with area ratios $\bar{F}_s = 0.1,\ 0.2,\ 0.3$, and 0.5.

The bypass assembly was preliminarily calibrated to determine the flow rate of the unswirled part of the gas. We note that because of spontaneous redistribution of the quantity of gas passing through the bypass assembly the ratio of flow rates of the unswirled part of the gas (G_s) to the total flow rate through the experimental section (G_Σ) remains practically constant in the range of Re_d studied for a specific slot area but essentially depends on the value of F_s.

The program of experiments included a study of the effect of the Reynolds number on the mass exchange with partial swirling of the stream for different ratios $\bar{F}_s$ and the effect of the relative distance of the working section from the swirler ($\bar{x} = x/d$).

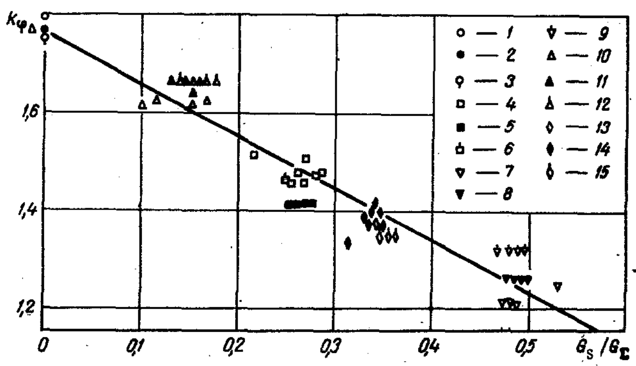

Fig. 3. Generalizing dependence $k_{\varphi\Delta} = f(G_s/G_\Sigma)$: 1) $\bar{x} = 1$, 2) 7, 3) 11 at $\bar{F}_s = 0$; 4) $\bar{x} = 1$, 5) 7, 6) 11 at $\bar{F}_s = 0.2$; 7) $\bar{x} = 1$, 8) 7, 9) 11 at $\bar{F}_s = 0.5$; 10) $\bar{x} = 1$, 11) 7, 12) 11 at $\bar{F}_s = 0.1$; 13) $\bar{x} = 1$, 14) 7, 15) 11 at $\bar{F}_s = 0.3$; $\varphi_i = 45°$; $n = 1$; $\bar{F}_s = 0$–0.5.

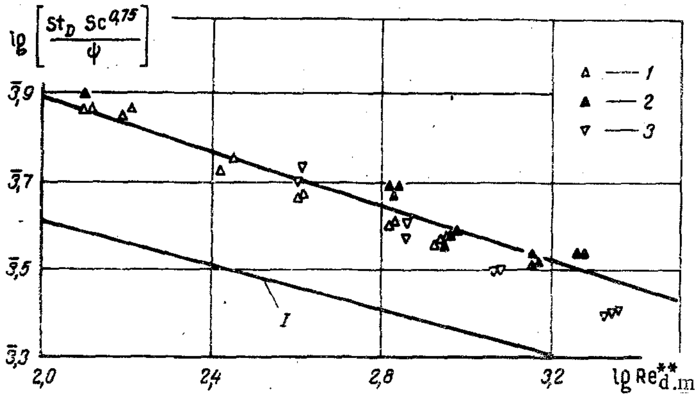

Fig. 4. Dependence $St_D = f(Re^{**}_{d.m})$: 1) $\bar{x} = 1$; 2) 7; 3) 11 at $\varphi_i = 45°$, $\bar{F}_s = 0.3$.

A blade swirler with an initial swirl angle (at the surface of the tunnel) of $\varphi_i = 45°$ and with blade profiling according to the free vortex law ($w_\varphi r$ = const) was used in the experiments.

The study was conducted in the range $Re_d = 1.26 \cdot 10^4 - 1.2 \cdot 10^5$ for three x and four slot sizes (F_s).

In the treatment of the experimental data the local mass exchange coefficient was related to the difference in the mean integral partial pressures of water vapor at the surface of the film and in the stream

$$\beta_p = \frac{g_w}{F_w(p_{vw} - p_{ve})}. \tag{1}$$

In such a treatment the local values of β_p (for a tunnel 12 diameters long) are found as the average value of β_p for the working section (two diameters long).

The physical constants in the local number $Nu_D = \beta d/D_{12}$ (here $\beta = \beta_p R_v T_w$) were calculated for the average air temperature in the tunnel, while the number $Re_d = wd/\nu_e$ was calculated from the mean flow rate velocity of the air in the tunnel after subtraction of the velocity of motion of the film.

Experimental data treated in this way for the mass output into a partially swirled stream for two slot sizes ($\bar{F}_s = 0.2-0.5$) are presented in Fig. 2. Experimental data on the mass output into an axial stream are plotted with the symbol X in the figure as calibration points. The line 1 is constructed for an axial stream from L. D. Berman's empirical dependence [2] corrected to the case of the initial section of the tunnel using the coefficient ε_e [3]. It is seen from Fig. 2 that the experimental calibration data are well described by line 1.

The excess along the ordinate of the experimental points above line 1 represents the coefficient of intensification of mass transfer during partial swirling of the stream $k_{\varphi\Delta} = Nu_{D\Delta}/Nu_{D_0}$ (Nu_{D_0} is the Nu_D number for an axial stream).

With an increase in the relative area of the slot the intensity of mass output decreases and approaches the case of an axial stream, which is explained by attenuation of the swirling because of the increase in $\bar{G}_s = G_s/G_\Sigma$.

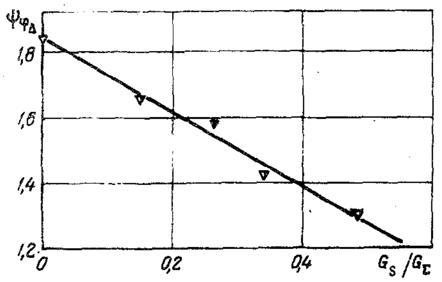

Fig. 5. Degree of intensification in mass output law. $\varphi_i = 45°$; n = 1; $\bar{F}_s = 0-0.5$.

The effect of the Schmidt number and the transverse flow of material on the mass output coefficient is taken here just as in the case of axial flow as $Sc^{0.4}$ and $(p/p-p_{vw})^{0.82}$, respectively [2].

We should note that for all the $\bar{F}_s$ and $\bar{x}$ studied the exponent on the number Re_d is equal to 0.8.

The experimental data on $k_{\varphi\Delta}$ as a function of the relative flow rate of the unswirled part of the stream ($\bar{G}_s$) are described with satisfactory accuracy (Fig. 3) by the equation:

$$k_{\varphi\Delta} = 1.77 - 1{,}1\,\frac{G_s}{G_\Sigma}. \tag{2}$$

It is seen from Fig. 3 that the intensification of mass output into a partially swirled stream decreases linearly with an increase in the parameter $\bar{G}_s$. The bypassing, apart from the swirler, of 50% of the total discharge of air through the experimental section leads to a decrease of 46% in the intensification of mass output.

We note that the intensification of mass output into a partially swirled stream is almost independent of the dimensionless distance of the working section from the swirler ($\bar{x}$) and is described by Eq. (2) in the entire range of variation in x studied.

Using the coefficient $k_{\varphi\Delta}$ of intensification of mass transfer all the experimental data for the swirler in the range of Re, $\bar{F}_s$, and $\bar{x}$ studied are described by a single dependence

$$\mathrm{Nu}_D = 0.023\, k_{\varphi\Delta}\, \varepsilon_e\, \mathrm{Sc}^{0.4} \left(\frac{p}{p - p_{vw}}\right)^{0.82} \mathrm{Re}_d^{0.8}, \tag{3}$$

which describes practically all the results of the experimental study with an accuracy of ±12%. Thus, Eq. (2) makes it possible to reduce the data obtained to the conditions of an axial stream.

To bring out the effect of partial swirling of the stream on the mass output law the experimental data were treated in the form of the dependence $\mathrm{St}_D = f(\mathrm{Re}^{**}_{d.m})$. Here

$$\mathrm{St}_D = \frac{g(1 - z_w)}{\rho_e w (z_w - z_e)}; \quad \mathrm{Re}^{**}_{d.m} = \frac{\int_0^x g\,dx}{\rho_e v_e (z_w - z_e)}.$$

The results of this treatment for the slot $\bar{F}_s = 0.3$ are represented in Fig. 4. The effect of the Schmidt number is taken as the same as in an axial stream ($\mathrm{Sc}^{0.75}$).

The value ψ in Fig. 4 represents a parameter which takes into account the effect of nonisothermy and extraneous blowing on the mass transfer law. It is calculated from an expression obtained in [4]:

$$\psi = \left(\frac{2}{\sqrt{\frac{h_w}{h_e}} + 1}\right)^2 \left(\frac{\sqrt{\frac{c_{pw}}{c_{pe}}} + 1}{\sqrt{\frac{m_e}{m_w}} + 1}\right)^2 \left(1 - \frac{b_1\psi}{b_{cr}}\right)^2. \tag{4}$$

An equation for the calculation of b_{cr} under the corresponding conditions is presented in [4]. We note that for the conditions of the experiments conducted the parameter ψ had a value of the order of 0.9 - 1.05 and that extraneous blowing had the predominant effect on it.

The experimental data for $\bar{F}_s = 0.3$ can be generalized by the dependence

$$\mathrm{St}_D = \frac{0.0346}{\mathrm{Re}^{**0.319}_{d.m}\,\mathrm{Sc}^{0.75}}\,\psi, \tag{5}$$

which also reflects the conditions of entry in addition to the effect of partial swirling of the stream. In the given experimental apparatus the entrance assembly is a cone with an aperture angle of 34°. The experiments on an axial stream showed that the conditions of entry can be taken into account by the coefficient

$$k = \frac{1.89}{\mathrm{Re}^{**0.069}_{d.m}}, \tag{6}$$

which agrees satisfactorily with the corresponding results on heat transfer [5, 6].

Since the coefficient k is obtained in a comparison with a plate it includes the properties of the initial section of the tunnel connected with acceleration of the stream.

Line 1 in Fig. 4 is the standard law for a plate [7]

$$\mathrm{St}_{D_0} = \frac{0.0128}{\mathrm{Re}^{**0.25}_{d.m}\,\mathrm{Sc}^{0.75}} \left(\frac{\mu_w}{\mu_e}\right)^{0.25}. \tag{7}$$

Taking the coefficient k into account, the excess of the experimental points above line 1 represents the degree of intensification in the mass output law due to the partial swirling of the stream

$$\psi_{\varphi\Delta} = \left(\frac{\mathrm{St}_D}{\mathrm{St}_{D_0}}\right)_{\mathrm{Re}^{**}_{d.m} = \mathrm{idem}}. \tag{8}$$

The experimental data on $\psi_{\varphi\Delta}$ for different values of $\overline{F}_s$ (Fig. 5) are satisfactorily described by the linear dependence

$$\psi_{\varphi_\Delta} = 1.84 - 1.13\frac{G_s}{G_\Sigma}. \tag{9}$$

Note that experimental points for the corresponding swirler with total swirling of the stream ($G_s/G_\Sigma = 0$) are also plotted in Fig. 5.

With allowance for $\psi_{\varphi\Delta}$ practically all the experimental data in the ranges of $\overline{x}$, $Re^{**}_{d.m}$ and $\overline{F}_s$ investigated ($\overline{x} < 12$, $Re^{**}_{d.m} = 120$–2500, $\overline{F}_s = 0$–0.5) are described with an accuracy of ±15% by a single dependence

$$St_D = \frac{0.0128}{Re^{**0.25}_{d.m}\, Sc^{0.75}}\, k\psi \cdot \psi_{\varphi_\Delta} \left(\frac{\mu_w}{\mu_e}\right)^{0.25}. \tag{10}$$

Thus, the following were revealed as a result of the experimental study conducted:

a) the effect of the number Re_d and the relative flow rate $\overline{G}_s$ on the intensity of mass output into a partially swirled stream ($\varphi_i = 45°$, $n = 1$); it is established that $k_{\varphi\Delta}$ is practically independent of the relative distance $\overline{x}$;

b) the effect of partial swirling of the stream on the mass output law.

NOTATION

b_1	is the blowing parameter;
D_{12}	is the coefficient of diffusion;
F_w	is the surface area of evaporation;
g_w	is the amount of liquid evaporated in working section;
ε_e	is the correction to initial section;
m	is the molecular weight;
μ	is the dynamic viscosity;
h	is the enthalpy;
Nu_D	is the diffusion Nusselt number;
R	is the universal gas constant;
r	is the current radius;
ρ	is the density;
$Re^{**}_{d.m}$	is the Reynolds number based on thickness of displaced mass;
St_D	is the diffusion Stanton number;
c_p	is the heat capacity;
T	is the temperature;
z	is the relative concentration;
ν	is the kinematic viscosity.

Subscripts and Superscripts

s	are the slot parameters;
tu	are the tunnel parameters;
w	are the conditions at wall;
e	are the conditions in stream;
v	are the vapor parameters;
Δ	are the parameters of partially swirled stream.

LITERATURE CITED

1. V. K. Shchukin, A. A. Khalatov, and V. G. Letyagin, Heat and Mass Transport [in Russian], Vol. 1, Minsk (1972).
2. L. D. Berman, Teploénergetika, No. 5 (1956).
3. I. T. Alad'ev, Izv. Akad. Nauk SSSR, Otd. Teplofiz. Nauk, No. 11 (1951).
4. A. I. Leont'ev and E. G. Zaulichnyi, Inzh.-Fiz. Zh., 19, No. 4 (1970).
5. P. N. Romanenko and N. V. Krylova, ibid., 7, No. 4 (1964).
6. V. K. Fedorov, Heat and Mass Transport [in Russian], Vol. 3, Moscow—Leningrad (1963).
7. S. S. Kutateladze and A. I. Leont'ev, Heat and Mass Exchange and Friction in Turbulent Boundary Layer [in Russian], Énergiya, Moscow (1972).