MIXING OF A JET ARRAY WITH A TRANSVERSE STREAM IN A CHANNEL

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Universal empirical formulas are proposed for calculating, from the trajectories, the attenuation of velocity and temperature along the axis of a jet through a transverse stream in a channel.

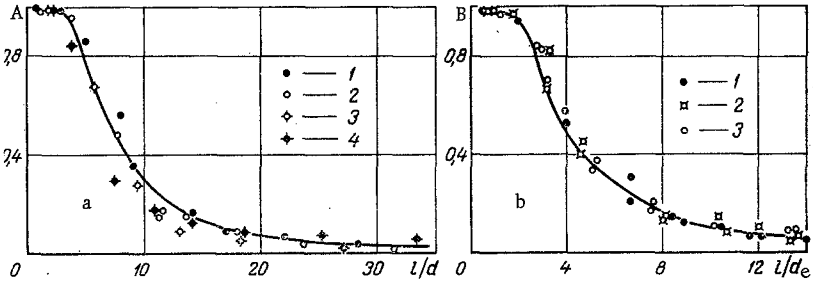
Various devices with jet injection of a gas into a drifting stream of air or another gas have found many applications in modern industry as, for example, mixing chambers, quenching baths, and gas burners. For the design and construction of such devices, it is of immediate interest to determine the heat and mass transfer between a jet array and a transverse stream in a channel.

Available data make it possible, with sufficient accuracy, to estimate the interaction zone between a jet array and a stream [1, 2] and to estimate the mixing rate between a single jet and a transverse stream [3, 4]. Meanwhile, there are no calculation formulas available which can be applied to the mixing of a jet array with a transverse stream.

The heat and mass transfer between a jet array and a stream was studied on a test stand where a uniform air stream could be produced in a rectangular channel and where an array of jets could be injected through the bottom. The stream velocity of 8 m/sec. The apparatus and the measurements have been described in detail earlier [2]. The test parameters were varied as follows: $q_{\mu c}$ from 4 to 36, s/d_e from 2 to 23.7, and H/d_e from 11.6 to 40.

Two flow modes will be analyzed here on the basis of test data: jet development and jet merging.

The first mode occurs when the spacing between jets $\bar{s}$ is rather wide (in our case $\bar{s} > 3.5$) and its characteristics are nearly those of a single jet. With appropriate modifications, formulas for a single jet can be used here. The velocity axis of a jet array is defined by the following equation:



conditions of jet development, (a) for $V_{2\mu}/V_1 = 10$, $\bar{s} = \infty$ (1), 16 (2), 8 (3), 4 (4), (b) for $V_{2\mu}/V_c = 6$, $\bar{s} = 23.7$ (1), 8.1 (2), 4 (3). Solid line represents values according to formula (3). $A = (V_{2m} - V_1 \sin\varphi)/V_{2\mu}$, $B = (V_{2m} - V_c \sin\varphi)/V_{2\mu}$.

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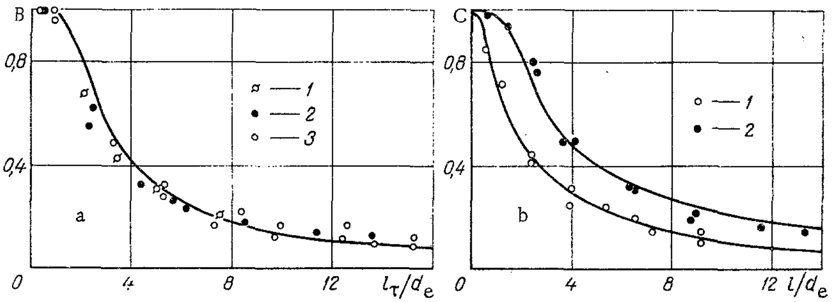

Fig. 2. Attenuation of excess temperature (a) with $\bar{s} = 4$: $q_{\mu c} = 4$ (1), 15.9 (2), 36.3 (3), attenuation of excess velocity (b) with $\bar{s} = 2$: $V_{2\mu}/V_c = 2$ (1), 4 (2), along the jet axis. Solid line represent values according to formulas (4) and (6) respectively. $B = (V_{2m} - V_c \sin\varphi)/V_{2\mu}$, $C = (T_{2m} - T_c)/(T_{20} - T_c)$.

$$\bar{x} = 0.43\,\frac{(\bar{y} + 0.59\,q_{\mu c}^{0.2})^3}{q_{\mu c}^{1.2}}\left[1 + 1.2\,\frac{(\bar{y} + 0.59\,q_{\mu c}^{0.2})^2}{q_{\mu c}^{0.4}\,\bar{s}^2}\right], \tag{1}$$

which indicates that the depth of jet penetration decreases as the relative jet spacing becomes narrower. The stream confinement in a channel is accounted for by the change from density ρ_1 and velocity V_1 of the oncoming stream to density ρ_c and velocity V_c of the mixture (in terms of the hydrodynamic parameter).

The rate of heat and mass transfer between a jet array and a stream is estimated from the attenuation of velocity and temperature along the jet axis. The attenuation of excess velocity $(V_{2m} - V_1 \sin\varphi)/V_{2\mu}$ does not depend on the relative jet spacing, neither in the case of a low jet height in the channel (Fig. 1a, with data from [1] appropriately converted) nor in the case of appreciable congestion of jets at the channel passage section. In the latter case, velocity V_1 must be replaced by velocity V_c of the mixture (Fig. 1b). Thus, the sought relation must be of the form

$$\frac{V_{2m} - V_c \sin\varphi}{V_{2\mu}} = f\left(\frac{l}{d_e}, \frac{\rho_2}{\rho_c}, \frac{V_{2\mu}}{V_c}\right). \tag{2}$$

A specific functional relation can be borrowed from the generalizations pertaining to a single jet. Using the relation in [3], we obtain

$$\frac{V_{2m} - V_c \sin\varphi}{V_{2\mu}} = 1 - \exp\left[-\frac{0.34\,q_{\mu c}}{\sqrt{\rho_2/\rho_c}\,(l_v/d_e)^2}\right]. \tag{3}$$

Based on analogous considerations, we obtain a relation describing the attenuation of excess temperature along the temperature axis:

$$\frac{T_{2m} - T_c}{T_{20} - T_c} = 1 - \exp\left[-\frac{1.64}{\sqrt{\rho_2/\rho_c}\,(l_\tau/d_e - 1)^{1.1}}\right]. \tag{4}$$

It is to be noted that formula (3) approximates both our test data and the data in [1], i.e., it applies up to $q_\mu = 400$. As to formula (4), the effect of q_μ on the rate of temperature attenuation along the axis is very small throughout our test range and remains quantitatively within the magnitude of measurement error (Fig. 2a). For this reason, the effect of q_μ could not be discerned. At large values of q_μ, according to the data in [1, 4], its effect is more pronounced and formula (4) is not applicable when $q_\mu > 36$.

One must bear in mind, when using formulas (3) and (4), that the peak velocity and the peak temperature do not coincide, owing to the effect of adjacent vortex pairs [2].

The second mode occurs when the relative spacing between jets is narrow ($\bar{s} < 3.5$). The merger of jets near the orifice has an appreciable effect on the characteristics of mass transfer between jets and stream, approaching those of a plane jet.

It is entirely valid to treat such a merging jet array as some equivalent plane jet with the same cross section area and the same velocity at the orifice. On the other hand, the confinement of the stream can here also be accounted for by a change from stream parameters to mixture parameters. With such a representation, it is possible to calculate the characteristics of a jet array by an appropriate modification of formulas pertaining to a plane jet. For the velocity axis of such an array we have the equation

$$\bar{x} = 0.24 \frac{\bar{s}^{1.5}}{q_{\mu c}} \bar{y}^{2.5}, \tag{5}$$

which indicates that, unlike in the first mode, the penetration depth increases as the jet spacing s becomes narrower.

The velocity attenuation can be calculated by the formula

$$\frac{V_{2m} - V_c \sin\varphi}{V_{2\mu}} = 1 - \exp\left[-1.5 \frac{\sqrt{q_{\mu c}}}{\bar{s}\bar{l}_v}\right]. \tag{6}$$

Calculations according to (6) are compared in Fig. 2b with test data for $\bar{s} = 2$.

It is to be noted that relations (5) and (6) are applicable when up to 75% of the channel height ($<0.75H$) is covered with jets.

In the jet development mode, therefore, the effect of structural parameters (jet spacing and channel height) on the heat and mass transfer between a jet array and a transverse stream in a channel is small. In the jet merger mode, on the other hand, a narrower relative jet spacing slows down the mass transfer between jets and stream and a zone of circulating currents is formed behind the jets.

NOTATION

ρ	is the density;
T	is the temperature;
V	is the velocity;
$V_{2\mu}$	is the jet discharge velocity;
d	is the orifice diameter;
$d_e = \sqrt{\mu}d$	is the equivalent diameter;
μ	is the discharge coefficient;
s	is the spacing between jets;
H	is the channel height;
l_V	is the length of velocity wave;
l_T	is the length of temperature wave;
x, y	are the longitudinal and transverse coordinates;
$q_\mu = \rho_2 V_{2\mu}^2/\rho_1 V_1^2$	is the hydrodynamic parameter;
φ	is the angle between y-axis and a tangent to the jet axis;

$\bar{s} = s/d_e$;

$\bar{l} = l/d_e$;

$\bar{x} = x/d_e$;

$\bar{y} = y/d_e$.

Subscripts

1	refers to oncoming stream;
2	refers to jet in the orifice;
c	refers to mixed flow;
m	refers to axis.

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