INVESTIGATION OF THE APPARENT MASS OF A SUPERSONIC JET ESCAPING FROM A NOZZLE INTO OFF-DESIGN MODES

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Results are presented of an experimental investigation of the dependence of the apparent mass on the number M_a at the nozzle exit, on the off-design factor n, and the distance $\bar{x}$ from the nozzle exit.

The apparent mass is the difference between the discharge at some section of the jet and the discharge through the nozzle. Direct measurement of the discharge in the cross section of a supersonic off-design jet is associated with known difficulties. The measurement of the apparent mass of an off-design supersonic jet is reduced herein to the measurement of the air discharge in a pipeline, which significantly raises the measurement accuracy. The investigation is conducted by two different methods, and this permitted a rise in the confidence of the results.

The experimental setup whose diagram is pictured in Fig. 1 was used for conducting the experiments by the first method.

The apparatus consists of the receiver A and the chamber B. The pressure P_0 in the receiver 2 ahead of the nozzle 14 is built up by using the valve 1 to which air is supplied with a pressure of 200 kg/cm^2. The prssure P_0 is measured by the manometer 4 to ± 0.2 kg/cm^2 accuracy. The model housing 13 is mounted in the nozzle. An extension 10, on which a diaphragm 11 is fastened with an appropriate seal, is mounted on the down-flow endface of the model. The working length of the model $\bar{L}$ is changed by using the extension, i.e., the jet length $\bar{x}$ under investigation. To assure uniform delivery of the air drained to the jet, the whole space of the chamber is separated into two cavities by the cylindrical perforated wall 9 with a large quantity of fine orifices. The dissector 8 serves this same purpose by hindering the formation of a directed jet from the pipeline 7 into the chamber. The chamber is connected to the receiver by means of the pipeline 7 in which the stopcock 3 to regulate the air discharge is set, and by means of the measuring

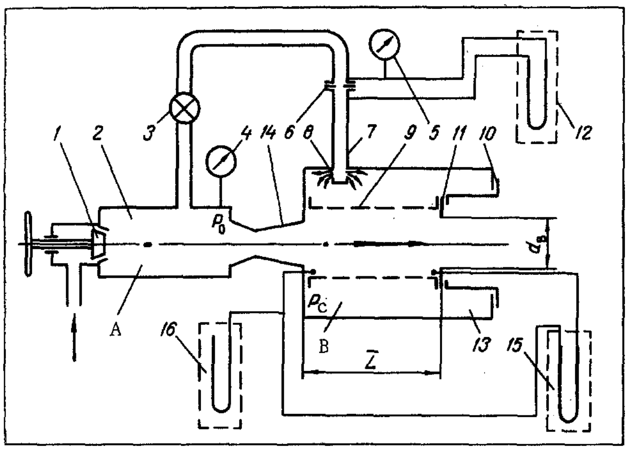

Fig. 1. Diagram of experimental set-up No. 1.

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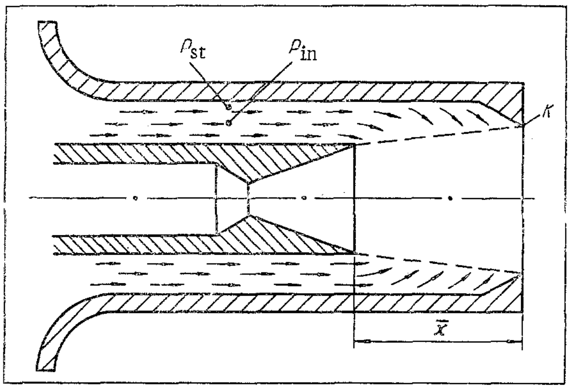


Fig. 2. Diagram of experimental setup No. 2.

plate 6 to measure the discharge through it. The pressure drop at the plate was measured by the differential manometer 12 and the pressure ahead of the plate by the manometer 5, with a ± 0.02 kg/cm^2 measurement accuracy. The pressure in the chamber P_c was measured by an alcohol manometer 16, and the pressure drop along the chamber which indicates the presence of accompanying flow, by the differential manometer 15. The choice of the orifice size in the diaphragm was subject to specific conditions, which will be examined below.

The method of conducting the experiment was the following.

As is known, as a jet propagates in a chamber, rarefaction forms there due to the ejection properties of the jet. In unit time the jet entrains a quantity of mass from the chamber which equals the apparent mass in the length $\bar{L}$. By opening the stopcock 3 air in a quantity equal to that which has been entrained by the jet can be delivered into the chamber through the pipeline 7. In this case the pressure in the chamber should evidently be atmospheric, and therefore, an accompanying or counter flow should not exist since $\Delta P = P_N - P_c = 0$. The air discharge measured at this instant through the measuring plate 6 will equal the apparent mass of the jet in the length $\bar{x} = \bar{L}$ being propagated in the medium at rest. The measurement of the axial drop in the space between the jet and the perforated wall, performed by the differential alcohol manometer 15, is a gage of the presence of an axial stream along the jet.

The experiments to determine the apparent mass were conducted in this order. A pressure P_0 corresponding to the number M_a and the off-design factor n which was determined by means of the relationship

$$P_0 = \frac{nP_N}{\pi(M_a)}$$

was built up ahead of the nozzle.

Furthermore, air was delivered to the chamber through the pipeline 7 until the rarefaction H in the chamber was zero. At this time the discharge through the pipeline 7 was measured. By using the extension, the dependence

$$q = \frac{Q_{app}}{Q_n} = f(M_a, n, \bar{x})$$

could be obtained in the nozzle.

The size of the holes in the diaphragm d_B was selected in conformity with data in [2] in such a way that when the stopcock 3 was closed the rarefaction H in the chamber was not greater than 0.01 kg/cm^2, which afforded the possibility of assuring high accuracy in measuring H.

The accuracy of measuring the apparent mass in the method considered is determined mainly by the accuracy of measuring the pressure in front of the measuring plate and the pressure drop on it, which is evidently sufficiently high.

Measurements of the apparent mass on the apparatus whose diagram is shown in Fig. 2 were carried out as checks. Here, the nozzle mounted at the end of a long pipe was placed in a diffuser. Because of turbulent exchange with the surrounding medium in a length $\bar{x}$ the air jet annexes a definite quantity of air and, hence, a rarefaction is produced in the annular channel between the pipe and the diffuser, which is the reason for air from the surrounding space flowing into the channel through the smooth entrance. The air discharge in the channel depends on the efficiency of the turbulent exchange on the section $\bar{x}$, particularly on the number M_a, but the quantitative aspect of this dependence is not generally evident. The fact is that the whole air discharge flowing through the annular channel can provisionally be separated into two parts. One part is the quantity of air which annexes the section of the jet of length $\bar{x}$, and the other produces an external accompanying stream flowing in the annular gap between the diffuser wall and the outer boundary of the jet. The problem is to extract the apparent mass of the jet from the total quantity of air flowing through the annular gap. It was solved thus.

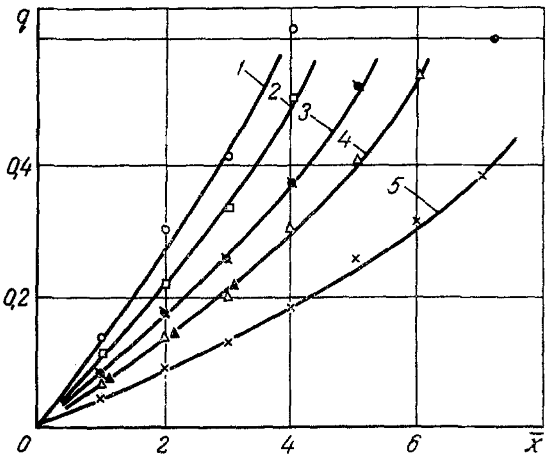


Fig. 3. Dependence of the relative apparent mass on the distance from the nozzle exit for $M_a = 2.53$: 1) n = 0.5; 2) 0.6; 3) 0.8; 4) 1.0; 5) 1.6.

The measurements were made at the time when the jet touched the point K of its outer boundary (Fig. 2). It was assumed, as is usually done, that the static pressure in the jet boundary layer on the section $\bar{x}$ equals the pressure in the annular channel. Up to this time the pressure at the point K has been less than the static pressure in the channel because of acceleration of the stream near the exit section of the diffuser. The difference between the static pressure in the annular channel and the pressure at the point K was measured by using an inclined alcohol differential manometer. The discharge through the annular channel which was equal to the apparent mass of the jet in the length $\bar{x}$ was determined by means of the measured total and static pressure in the channel (at a distance from the entrance to it which would assure maximum equilibration of the velocity field) at a time when the difference between the pressure at the point K and the static pressure in the channel became positive. Measurements by this method were conducted only for $M_a = 2$ and $M_a = 3$, for a rated jet (n = 1) and relatively small values of $\bar{x}$. The experimental data were processed in the form

$$q = \frac{Q_{app}}{Q_0} = f(M_a, \bar{x}),$$

where Q_{app} is the apparent mass of the jet in the section $\bar{x}$ for n = 1, and Q_0 is the discharge through the nozzle for n = 1.

The experiments were carried out with cold air. The nozzle assured $M_a = 1.0$, 1.53, 2.03, 2.53, and 3.01 would be obtained. The jet length under investigation was between $\bar{x} = 0$–7. The air discharges were computed by the method in [1].

Let us examine the results of the experimental investigations which are presented in Figs. 3-5. As is seen from an examination of the curves in Fig. 3, the quantity q depends practically linearly on $\bar{x}$ for small $\bar{x}$, where the smaller the off-design factor the closer this dependence is to the linear. For a constant value of $\bar{x}$ the apparent mass diminishes as the off-design factor grows. For large $\bar{x}$, as is known, this dependence is linear for the main part of the jet (for a rated jet in every case). The intensity of the apparent mass process grows as the off-design factor of the escape diminishes.

It is seen from Fig. 4 that the apparent mass depends linearly on the magnitude of the inverse power of the off-design factor, where the angular coefficients depend on the distance from the nozzle exit, which increases as $\bar{x}$ grows. The lines q = f(1/n) pass through the origin.

The dependence of q on the number M_a (Fig. 5) is linear in $1/M_a$ where it may be assumed that for $1/M_a = 0.22$ the apparent mass tends to zero at all distances from the nozzle exit.

The black symbols on all the graphs represent the results of measurements using the method with the diffuser, and the open symbols by using the chamber with the perforated wall. As is seen from an examination of the curves, the measurements by both methods agree completely.

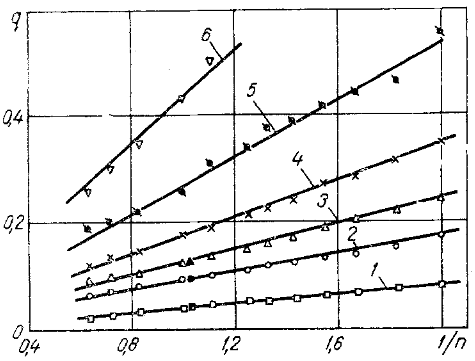
The experimental results obtained for a distance $\bar{x} = 0$–5 from the nozzle exit (which is of value for a specific class of problems referring to the base pressure) are approximated well by the formula

$$q = \left(\frac{0.408}{M_a} - 0.09\right)\frac{\bar{x}}{n}, \qquad (1)$$

and for the distance $\bar{x} = 0$–7 by the formula

$$q = \frac{1}{n}(0.375\bar{x} + 1.2 \cdot 10^{-4} \exp \bar{x})\left(\frac{1}{M_a} - 0.22\right). \qquad (2)$$

It is interesting to analyze (1). For $\bar{x} \to 0$, $q \to 0$, and for $\bar{x} \to \infty$, $q \to \infty$. Furthermore, for $n \to \infty$, which corresponds to jet propagation in a vacuum, $q \to 0$. This is natural since in this case the apparent mass does not generally exist ($P_N = 0$).



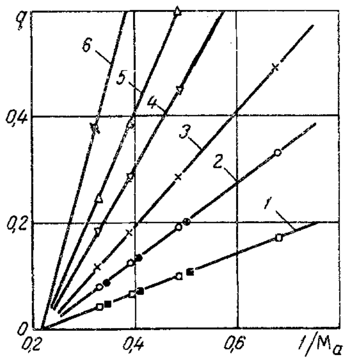


Fig. 4 Fig. 5

Fig. 4. Dependence of the relative apparent mass on the off-design factor for $M_a = 3.01$: 1) x = 1; 2) 2; 3) 3; 4) 4; 5) 5; 6) 7.

Fig. 5. Dependence of the relative apparent mass on the Mach number for n = 1 [1-6) see Fig. 4].

For $n \to \infty$ (because $P_a \to \infty$) $q \to 0$. This also does not contradict the physical sense since here (for a finite value of M_a) $P_0 \to \infty$, and therefore $Q_0 \to \infty$. Hence, the apparent mass (for finite P_N) is small compared with Q_0.

The case $n \to 0$ can be realized for $P_a \to 0$ and $P_N \to \infty$. In the first case $Q_0 \to 0$ and naturally $q \to \infty$. In the second case ($P_N \to \infty$) the apparent mass will be large compared with the finite Q_0. Finally $q \to 0$ when $((0.408/M_a)-0.09) \to 0$, i.e., $M_a \to 4.55$.

It is seen from the analysis performed on (1) that it does not contradict the physical sense of the phenomenon under consideration in all possible limit cases.

NOTATION

M_a	is the Mach number at the nozzle exit;
$n = P_a/P_N$	is the off-design factor of the escape from the nozzle;
P_a	is the static pressure at the nozzle exit;
P_N	is the atmospheric pressure;
P_0	is the stagnation pressure ahead of the nozzle;
Q_0	is the discharge through the nozzle for the rated escape mode (n = 1);
Q_n	is the discharge through the nozzle for the off-design escape mode ($n \neq 1$);
Q_{app}	is the apparent mass;
$q = Q_{app}/Q_n$	is the relative apparent mass;
$\bar{x} = x/d_a$	is the distance from the nozzle exit;
d_a	is the diameter of the nozzle exit section;

$\pi(M_a) = 1/(1 + (k-1)M_a^2/2)^{1/k-1}$.

LITERATURE CITED

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