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Determination of the Air Velocity in the Free Stream Flowing out of a Cylindrical and Two-Gap Skewed Jet (Dual Slot Die)

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Abstract
This paper presents the theoretical basis for the determination of the field of velocity of the free air stream flowing out of a cylindrical and two-gap skewed jet. Based on this, calculation of the air velocity distribution in the stream's axis was carried-out. Good agreement was achieved between the values of theoretical and experimental results obtained. The theoretical dependences were adapted to the jets applied in textile technologies. A formula is given for the calculation of the velocity distribution of air flowing out from the two-gap skewed jet applied in the melt-blown method. The correctness of the formula given is certified by the results computed as well as by those of the measurements.

Key words: *circular stewed jet, two-gap skewed jet, air velocity.*

Introduction

Many textile technologies apply a stream of air flowing out from a jet for the formation and transport of fibres or threads. The outlet channel of the jet has in its cross-section a mostly circular or rectangular profile. In the former there are circular or axial-symmetric jets [7], and in the latter there is a gap [8]. The classic theory for a turbulent free stream [1] was adapted to the stream flowing out from the jets applied in textile machines. These jets consist of a central element for the guiding of ready or formed yarns (fibres).

This paper presents the results of theoretical calculations as well as measurements of air velocity using a pressure probe (Pitot) for both types of jets. Theoretical knowledge of the field of air velocity is required for proper selection of the flow parameters of modern textile technologies that use pneumatic jets [7, 8].

Application of the calculation of velocity distributions of air flowing out from jets allows to avoid expensive experimental investigations, and it can be used in the design process of new types of devices.

Circular axial-symmetric nozzle

The outflow of air from a circular jet to the open space generates a turbulent free stream. In the classic consideration of this problem [1, 4], it is assumed that the pressure in the full stream is constant and close to that in the surrounding environment. The range occupied by the free stream increases proportionally to the distance from the outlet. At the outflow from a circular bore, the range occupied by the free stream has the profile of a cone, which is shown in ***Figure 1***.

A free stream is described in the classic theory of flow. Air flows out from the outlet channel at a mean velocity V_o. On the axis of the jet at the initial interval l_1, the velocity is constant and equal to the velocity V_0. At distances from the channel outlet that are greater than l_1 and on the axis of jet, the velocity decreases. Theoretically the free stream has the profile of a cone with a top angle α_s. The top of this cone is placed at point O (pole), that is at distance l_0 from the outlet. On the boundary of the stream and the surrounding, theoretically stationary air, the axial velocity V_x decreases to nil. Here a turbulent exchange of mass takes place that causes a continuous increase in the stream mass of the free stream, caused by the transverse component of the air velocity.

According to Abramovitch theory [1], in the cross-section II-II, that is at the distance l_1 from the jet outlet, the stream of air volume flowing in the free stream is 2.13 times greater than the stream supplied to the jet. From the point of constant assumed pressure in the free stream, this phenomenon can be explained by the turbulent exchange of impulses in the zone of contact between stationary and non-stationary air, which is called the mixing zone. To a certain extent the modern consideration of a turbulent free stream [3] explains these phenomena. Micro whirls occurring on the border (periphery) of a

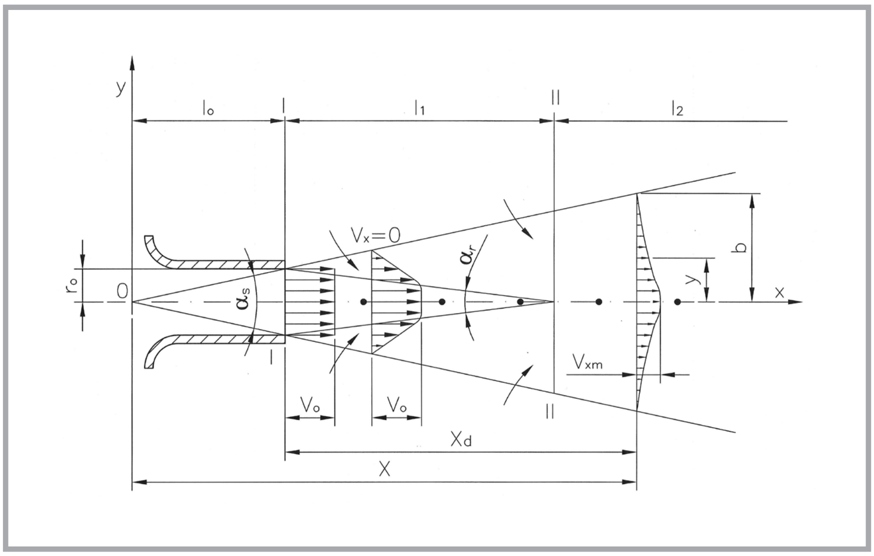

Figure 1. *Schematic view of the outflow of air from the turbulent free stream of a circular jet;* ***Denotations****:* V_o *- air velocity at the outlet from the jet channel,* V_{xm} *- maximum air velocity in the assumed cross-section of the stream, O - pole,* r_o *- radius of the outlet channel of the jet,* l_o *- distance of the pole from the nozzle outlet (theoretical),* l_1 *- interval of the stream with its core, where* $V_{xm} = V_0$*,* l_2 *- initial interval of the stream with a decreasing velocity, b - width (radius) of the stream at any cross-section (is measured),* X_d *- distance of the control plane from the end of the jet,* α_s *- stream angle,* α_r *- angle of the stream core at constant velocity, • - measuring points, X - distance of the control plane from the pole.*

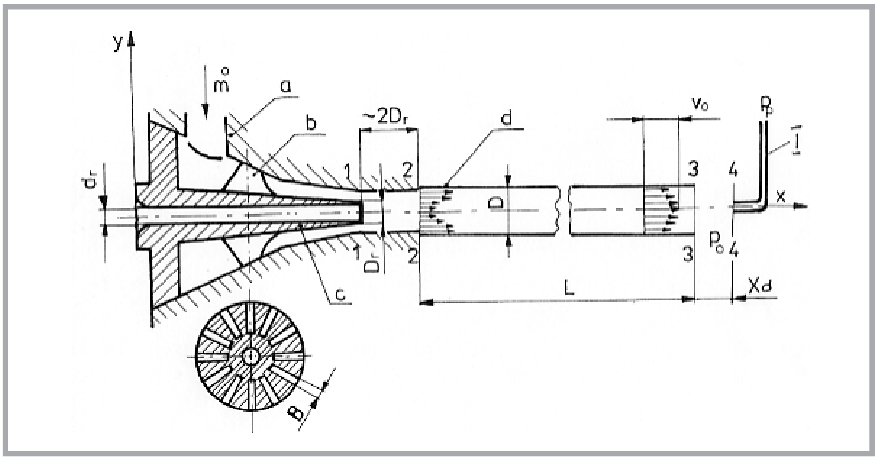

Figure 2. *Geometry of the circular nozzle with a cylindrical outlet channel applied in this investigation;* ***Denotations****: a – body of nozzle, b – guide ring, c – central pipe, d – cylindrical outlet channel of diameter D_{2r}= 8 mm, D_r = 3.6 mm d_r = 3 mm, B = 1.5 mm, I – Pitot probe for the measurement of air velocity, 1, 2, 3, 4 – control cross-sections, p_0 – ambient pressure, p_p – measuring pressure, L – length of outlet channel, m – stream of the mass.*

free stream generate a suction effect in this stream. In a free circular stream coherent structures occur [3]. The basic dimensions connected to the geometry of a free stream, given by Abramowicz [1], can be calculated from the following formula:

The pole distance

$$l_0 = 0.29\ r_0/a \qquad (1)$$

Initial interval

$$l_1 = 0.67\ r_0/a \qquad (2)$$

where: according to [1], a = 0.066 ÷ 0.076 is an experimental coefficient for jets of a circular cross-section. For a higher initial turbulence, the value of coefficient a = 0.089.

It results from the considerations mentioned above that for the types of jets assumed and velocities of air flowing out, it is required to determine the value of coefficient a experimentally, which is the subject of this paper.

For determination of the theoretical geometry of the stream, its angle α_s is defined by the dependence:

$$\alpha_s = 2 \cdot \text{arctg}\ r_0/l_0 = 2 \cdot \text{arctg}\ a/0.29 \quad (3),$$

whereas the core angle is derived from

$$\alpha_r = 2 \cdot \text{arctg}\ r_0/l_1 = 2 \cdot \text{arctg}\ a/0.67 \quad (4).$$

These angles, in the case of the nozzle investigated (***Figure 2***) and on the basis of the value of coefficient experimentally determined a = 0.08, are:

$$\alpha_s = 30° \text{ and } \alpha_r = 14°.$$

Applying nozzles for the pneumatic weft pick-up on confuz or looms or equipped in sinkers [8], it is important to calculate the distance X_d of the nozzle outlet from the first sinker, the reason being that the full stream is contained in an area of width b (see ***Figure 1***). The value X_d can be calculated from the formula:

$$X_d = b/3.4a - 0.29r_0/a \qquad (5)$$

From the point of view of textile technology, the most important is the distribution of air velocity along the axis of the nozzle. As the observation shows, fibres or threads during pneumatic transport are in the region of maximum air velocities; hence on the axis of the stream. This fact, to a certain extent, shakes assumptions regarding the stability of static pressure in the cross-section of a free stream; hence the fibres or thread is always placed in the field of the lowest pressure. As the measurements show, the transverse gradient of static pressure is inconsiderable, and the assumption of the equality of pressures in the stream with ambient pressure can be accepted.

The velocity along the axis of the outlet channel of the nozzle at a distance $x > l_0 + l_1$ can be calculated, according to [1], from the formula:

$$V_{xm} = const/x \qquad (6)$$

where:

$$x = x_d + l_0$$

$$const = 0.96\ V_0\ r_0/a \qquad (7)$$

As shown in equation (6), the velocity along the axis of the stream is inversely proportional to the distance x.

The velocity distribution at any point of the control cross-section of width (radius) b is possible to calculate, according to [1], with the use of equation (8).

$$V_x = V_{xm}\left[1 - \left(\frac{y}{b}\right)^{\frac{3}{2}}\right]^2 \qquad (8)$$

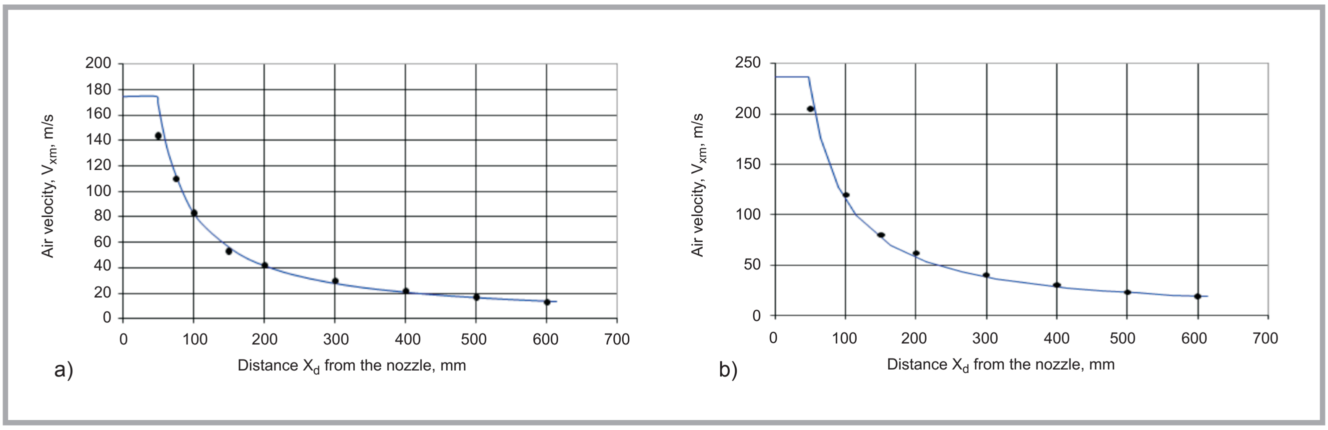

Figure 3. *Theoretical run of the air velocity along the axis of a turbulent free stream versus the distance from the nozzle. Initial velocity V_0= 175 m/sec (a) and V_o= 237 m/sec (b). For comparison purposes, points mark the results of the measurements, by means of a probe, carried out by the authors.*

Comparison of the results of calculations and measurements of the air velocity in an axial-symmetric nozzle

The geometry of the nozzle with a cylindrical outlet channel investigated is shown in ***Figure 2***.

Theoretical calculations and measurements were carried out for two values of the initial velocity of air flowing out from a nozzle: 175 m/sec and 237 m/sec.

The nozzle was part of a pneumatic loom of the type P-125 equipped with an outlet channel of 100 mm length and 8 mm diameter.

The value of Reynolds number in the range of velocities investigated was about 125×10^3, indicating the turbulent flow. The velocity V_{xm} was calculated as a function of variable X_d by means of equation (6). The value of constant a was assumed as 0.08, as shown in ***Figure 1***.

$$X = X_d + l_0 \qquad (9)$$

For practical purpose, the dependence $V_{xm} = F(X_d)$ is given in ***Figure 3.a***.

As shown in ***Figure 3.a***, the theoretical run of the maximum velocity along the

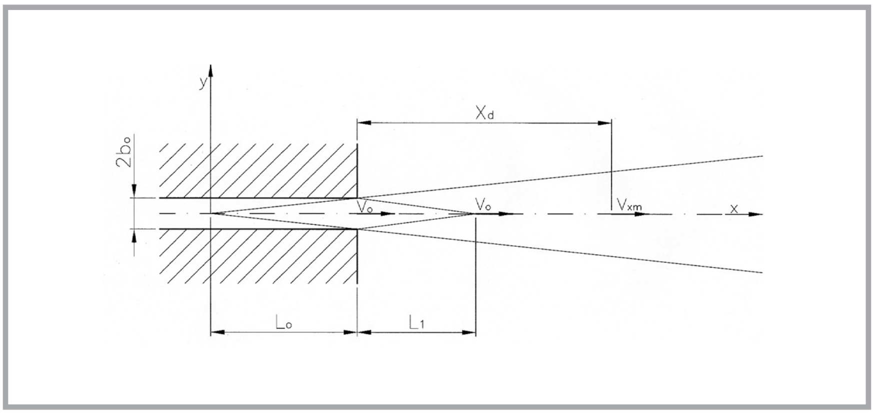

Figure 4. *Schematic flow of steam from a flat gap nozzle.* ***Denotations****:* b_0 *– half of the initial width of the stream,* V_0 *– initial velocity at the outlet of the nozzle,* V_{xm} *– maximum velocity at every cross section of the stream,* L_o *– pole distance (theoretical),* L_1 *– origin interval with the stream core, where* $V_{xm} = V_0$*.*

axis of a turbulent air stream flowing out from a nozzle of circular cross-section (***Figure 2***), calculated from equation (6), is very close to the run measured.

Flat, gap nozzle

A simplified scheme of the flow of air from a flat gap nozzle is shown in ***Figure 4***.

A gap nozzle differs from a nozzle of circular cross-section in its profile. The transverse dimensions of a gap nozzle are generally much smaller than its longitudinal dimensions. This results from the fact that the length of the gap is substantially larger than its width, which means that the flow of air from a gap nozzle differs from the flow of a nozzle of circular cross-section.

The distribution of maximum velocity along the direction of flow is calculated, according to [1], from the following formula:

$$V_{xm} = V_0 \cdot \frac{1.2}{\sqrt{\frac{a \cdot X_d}{b_0} + 0.41}} \qquad (10)$$

where:
$a = 0.1$
X_d - distance of the control plane from the end of the jet.

Dependence (10) is valid for the distribution of the velocity of air flowing out from a single flat gap nozzle. Formula (10) is considered for $X_d > L$ and $X_d = 10\ b_0$ because in such a case, according to (10), $V_{xm} = V_0$.

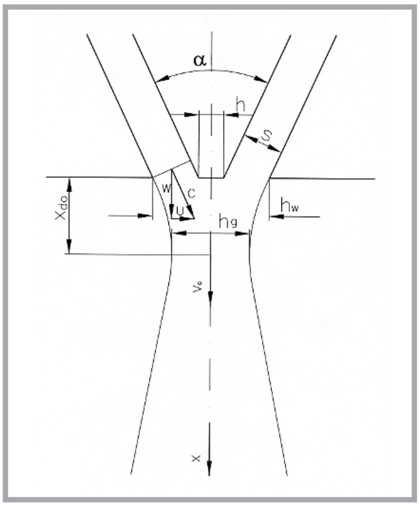

Figure 5. *Layout of a two gap skewed nozzle, with basic dimensions;* ***Denotations****: S - width of a single gap, α - angle of inclination of the nozzle channels, h - width of the internal insert,* h_w *- width of the outlet channel,* h_g *- contraction of the stream, C - velocity of air in the gaps, W - axial component of the velocity, U - transverse component of the velocity,* V_0 *- calculated velocity at distance* X_{d0}*,* X_{do} *- distance at hg,* α_s *- angle of the stream.*

Comparison of the results of calculations and measurements of the air velocity in a two gap skewed nozzle

The results of theoretical calculations and experimental investigation of the velocity distribution of air flowing out from two gap nozzle inclined at a certain determined angle are presented below. Such a nozzle is called a two gap inclined nozzle. The lay-out of the nozzle considered is shown in ***Figure 5***.

Air flows out from a single gap at a mean velocity C. This velocity can be divided into two components i.e. axial W and transverse U, with values:

$$W = C \cos \alpha/2$$
$$U = C \sin \alpha/2 \qquad (11)$$

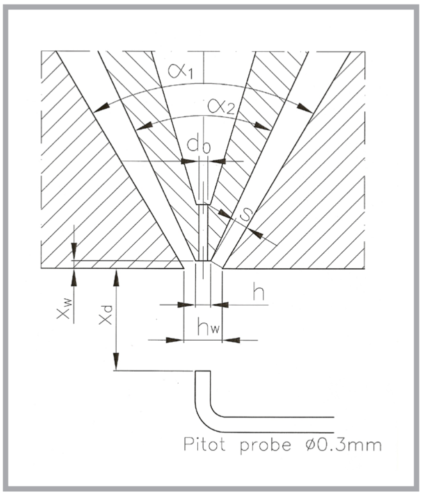

Figure 6. *Layout of the two-gap nozzle, with basic dimensions. (Pitot probe Ø 0.3 mm);* ***Denotations****:* $\alpha_1 = 60°$, $\alpha_2 = 50°$, $s = 0.5$ *mm,* $h = 0.6$ *mm,* $h_w = 1.6$ *mm,* $x_w = 0.5$ *mm,* $d_0 = 0.5$ *mm.*

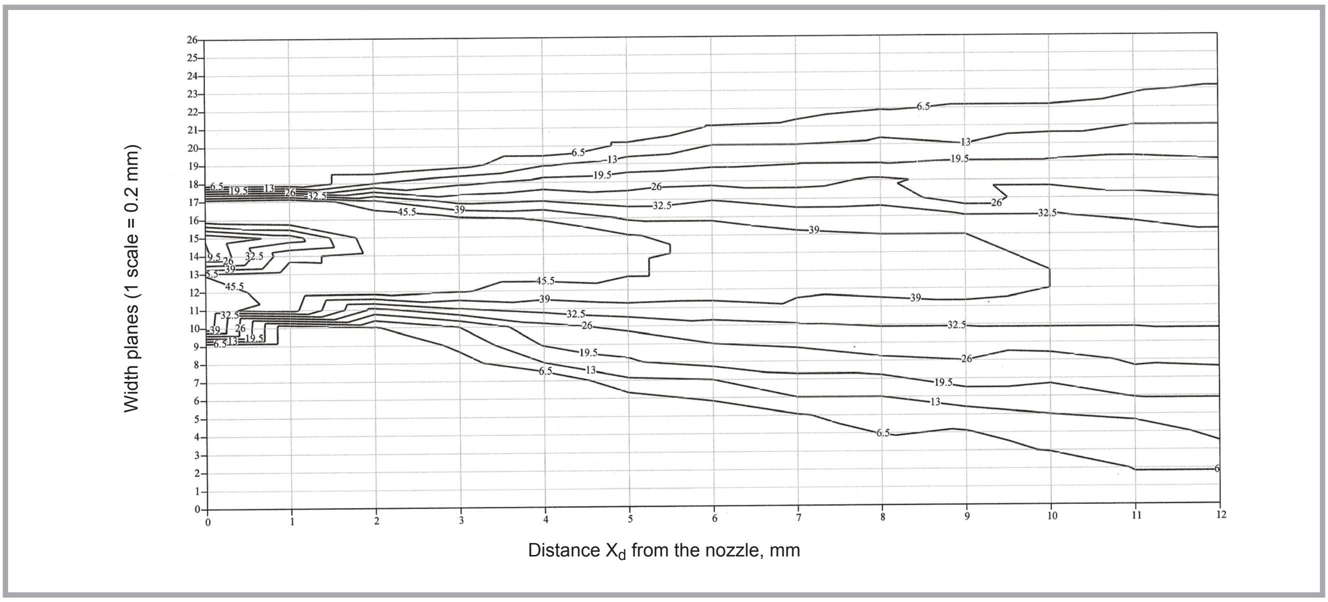

__Figure 7.__ Isotachs of the free stream flowing out from a two gap slanting nozzle.

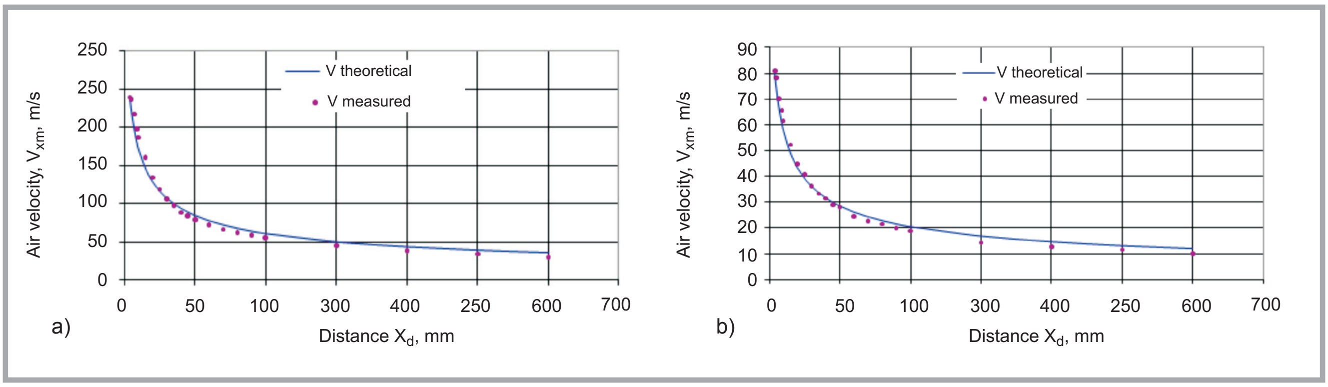

__Figure 8.__ Chart of the distribution of air velocities along the axis of the nozzle at V_0 = 50 m/s (a) and V_0 = 80 m/s (b).

The theoretical transverse components *U* have the same values but opposite directions, which causes that both components are reduced. Air flows out from a channel of width h_w - *h* at velocity *W*.

However, in reality, because of the presence of elements of width h and the turbulent exchange of impulses between the streams and the contraction of the stream, the axial velocity of air becomes equal at a certain distance X_{d0} from the nozzle. This results from the measurements that are discussed in chapter 6 of this paper.

The respective magnitudes of the nozzle investigated are as follows:

$$X_{d0} = 1.2\, h_w,\ h_g = 0.8\, h_w,$$

$$l_1 = 2.5\, h_w,\ \alpha = 15°.$$

Considering the dependencies given above, formula (10) should be modified to form:

$$V_{xm}=V_0\cdot\frac{1.1}{\sqrt{\frac{a\cdot X_d}{b_0}+0.41}} \qquad (12)$$

where: $b_0 = 0.5\, h_g = 0.4\, h_w$, $a = 0.1$.

For $x_{d0} = 2.5\, h_w$ the distribution of maximum velocity is $V_{xm} = V_0$.

Formula (12) is valid for $x_d > 2.5\, h_w$.

Comparison of the results of calculations and measurements of the air velocity in the axis of a two-gap nozzle

Figure 6 shows the geometry of the nozzle applied for the formation of fibres from melted polymers.

The total pressure in the free stream flowing out from a two gap slanting nozzle was measured by a Pitot probe. The air velocity at the measuring points was calculated on the assumption that the static pressure is constant in the stream. The flow (izotachs) was visualised on this basis (***Figure*** *7*).

The asymmetry of flow resulting from the lack of geometrical symmetry (precision of machining) of the nozzle is shown in ***Figure*** *7*. Theoretical parameters of the stream can be approximately determined on the basis of ***Figure*** *7*. Hence, the following value of $l_1 \sim 2.5\, h_w$, $h_g \sim 0.8\, h_0$, and $\alpha_s \sim 15°$ can be established. The largest velocities of air occur on the axis of the nozzle at a distance larger than 2 mm. The aerodynamic shadow of the internal insert visible in ***Figure 5*** can be observed at a closer distance from the nozzle. The values of theoretical velocities calculated from equation (12) and experimental values are shown in ***Figures 8.a***, respectively.

The results of theoretical calculations are shown as a continuous line, highlighting

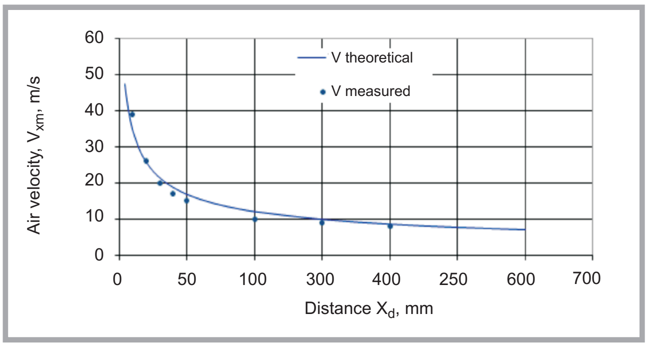

Figure 9. *Comparison of the runs of velocities along the axis of the stream flowing out from a two gap nozzle at an air velocity of V_0=50 m/s.*

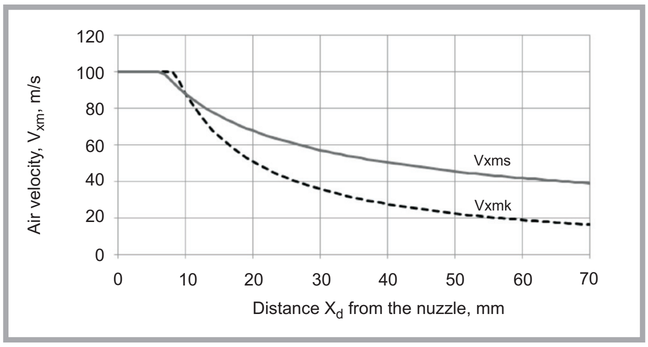

Figure 10. *Comparison of the runs of velocities along the axis of the free stream flowing out from circular and two gap slanting nozzles.*

good agreement with the results of measurements.

A comparison between the results of measurements and the theoretical calculations is given in [5]. Theoretical calculations were carried out with the aid of the computer program FLUENT 6.2.16 Manual, which is a very modern program allowing to determine fields of pressures, velocities and temperatures from a system of differential equations, such as:

- an equation for the flow continuity,
- an equation for the momentum in the direction of the axis y (***Figure 4***),
- an equation for the momentum in the direction of the axis x,
- an energy equation,
- an equation for the energy of turbulent motion,
- a dissipation equation.

The model of flow k - ε was applied, where k is the energy of turbulence and ε - the dissipation of turbulence. According to [4]

$$k = 0.06\,(W^2 + U^2) \qquad (13)$$

$$\varepsilon = 0.06\,(W^2 + U^2)/S \qquad (14)$$

were:
W - axial component of the velocity,
U - transverse component of the velocity,
S - width of a single gap.

In ***Figure 8.b*** the continuous line shows the run of velocities along the axis of a two gap nozzle calculated from formula (12), as well as the run calculated with the aid of the program FLUENT (points). It can be seen that the theoretical calculations carried out by means of both methods show good agreement. The comparison of the runs in ***Figures 8.b and 9*** shows good agreement between the theoretical calculations and the measurements.

Comparison of the runs of air flowing out from circular and two-gap slanting nozzles

As shown above, the runs of air flowing out from circular and two-gap slanting nozzles are determined by theoretical equations (6) and (7), which are in agreement with the runs that were determined experimentally.

The assumption of the equal cross sections of both nozzles allows for comparison of the runs described .

The following were assumed:
V_0 =100 m/s,
r_0 = 1.13 mm then b_0 – 1.0 mm.

This comparison is shown in ***Figure 10***.

Figure 10 shows that the run of velocities along the axis of a circular nozzle, V_{xmk}, is characterised by larger decreases than in the case of a two-gap slanting nozzle, $\boldsymbol{V_{xms}}$, which reaches more than 80% of the initial velocity at a distance x_d = 70 mm. A similar decrease was found for the velocity in the axis of a two-gap slanting nozzle - 60%. The stream has a larger velocity than that flowing out from a two-gap slanting nozzle at a distance $x_d \leq$ 10 mm in the initial phase only. Both curves cross at the point in which the velocity in the axis of both nozzles is smaller than the maximum velocity at about 20%.

Conclusions

1. The velocity distribution of air flowing out from a circular nozzle can be determined from dependencies (6) and (7) on the assumption of known velocity V_0 and a = 0.08.
2. The velocity distribution of air flowing out from a two-gap nozzle can be calculated from formula (12) when value V_0 = C is known.
3. The stream angle α_s for a skewed two-gap nozzle is about 15°, which is two times smaller than in the case of a circular nozzle.
4. The run of velocity along the axis of a circular nozzle is characterised by a larger decrease than in the case of a two-gap slanting nozzle, except in the initial zone where $x_d \leq b_0$.
5. The theoretical calculations carried out by means of the modern program FLUENT confirm the correctness of the calculations of the velocity distribution of air flowing out from a two-gap nozzle based on formula (12).

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