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# Aerodynamic and Thermal Characteristics of a Hot Jet in Parallel Flow

F. Satta and G.Tanda†

*DIME, Università degli Studi di Genova, via Montallegro 1, I-16145, Genova, Italy*

†*Corresponding Author Email: giovanni.tanda@unige.it*

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## ABSTRACT

This paper presents an experimental investigation of the aerodynamic and thermal characteristics of a round jet of hot air, injected through a nozzle into a parallel air flow, simulating a hot streak. Experiments were performed by imposing the same total pressure, established by means of a five-hole probe, for the mainstream and the jet at nozzle exit. Time-averaged temperatures at different points over planes downstream of the nozzle exit section were measured by thermocouple rakes. Experimental data, presented in a non-dimensional form, provide a representation not correlated to individual maximum jet temperature and Reynolds number, in the respective fields of variation. The attenuation of the hot jet strength is reported as a function of the normalized axial coordinate for the various operating conditions considered. Results obtained for the hot jet discharged into a parallel flow are compared with data obtained for the hot jet spreading into stagnant air.

**Keywords**: Hot jet; Hot streak; Temperature profile.

## NOMENCLATURE

| | |
|---|---|
| $D$ | nozzle diameter, m |
| $H$ | test section height, m |
| $L$ | nozzle length, m |
| $p$ | pressure, Pa |
| Re | Reynolds number |
| $u$ | velocity, m/s |
| $T$ | temperature, K |
| $W$ | test section width, m |
| $x, y, z$ | horizontal, vertical and axial coordinates, m |
| $\alpha$ | yaw angle, deg |
| $\gamma$ | pitch angle, deg |
| $\theta$ | dimensionless temperature |

***Subscripts***

| | |
|---|---|
| *axial* | axial |
| *dyn* | dynamic |
| *hj* | hot jet (at nozzle exit) |
| *ref* | reference |
| *t* | total |
| $\infty$ | mainstream |

## 1. INTRODUCTION

Turbulent jets are employed in a wide variety of engineering devices. In the cases where the jets are located far from solid walls, they are classified as free shear flows. In other cases solid walls are present and significantly affect the flow and heat transfer (Bejan, 2013). For both situations, the jet can spread into a stagnant flow or interact with a parallel or cross-flow. Free-shear hot jets are encountered in several environmental and engineering applications. In particular, in gas turbine engines, free-shear jets are of interest in the turbine blade film cooling and to simulate the hot streaks exiting the combustor, which induce large and dangerous variations in turbine inlet temperature. Jet/wall interactions (jet impingement) find applications in internal cooling of turbine blades, materials packaging and electronics cooling.

Due to the great practical relevance of the above topics, many experimental, numerical and theoretical studies have been undertaken. Most of the literature is concerned with hot jet impingement (Carlomagno and Ianiro, 2014) and the jet mixing in cross-flow (Margason, 1993, Pleasniak and Cusano, 2005) or into a medium at rest (Abramovich, 1963, Abdel-Rahman, 2010). The mixing of a hot jet into a parallel, cold flow received less attention from the phenomenological point of view, but its study was specifically addressed to conditions occurring in modern gas turbine engines. In fact, during the last decade, a considerable amount of literature papers has been devoted to computational and experimental studies of the migration of hot jets discharged into a parallel flow entering turbine stages (see, for instance, Jenkins *et al*., 2004, Jenkins and Bogard, 2005, Jenny *et al*., 2012, and Qureshi *et al*., 2012). To experimentally reproduce a non-uniform temperature field at the turbine inlet, a temperature distortion generator (or hot streak generator) has to be appropriately designed. This device introduces an air flow at higher temperature than the mainstream with the requirement of a total pressure profile across the section downstream of the hot streak generator as much uniform as possible. To successfully design a hot streak generator able to reproduce a non-uniform temperature field at the turbine inlet, a clear understanding of the fundamental mechanisms involved in the convection and the migration of the hot jet (or hot streak) through a parallel air flow is necessary.

Figure 1 shows a schematic representation of a turbulent hot jet discharged into a medium at constant temperature and velocity. The part of the jet in which there is a core of potential flow is termed the initial region. In this region, the centerline velocity and temperature are very close to the exit values and practically independent of axial coordinate. At a certain distance from the nozzle exit, due to the transverse transfer of momentum and heat, the region with a continuous distribution of velocity and temperature (the jet boundary layer) increases and both centerline velocity and temperature decrease with the axial coordinate (transitional region). Further downstream, the variations in velocity and temperature along the transverse direction, taken ad different axial coordinates, attain the same geometrical shape (fully developed or main region).

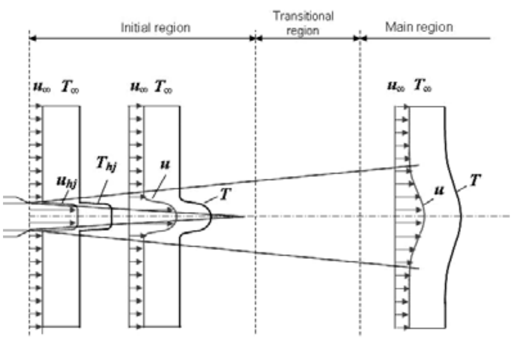


**Fig. 1. Diagram of a hot jet in parallel flow.**

In the present study, experiments were carried out to determine the aerodynamic and thermal characteristics of a round hot-air jet, formed by discharge from a nozzle into a translational air flow parallel to the hot jet direction. The temperature profiles of the hot jet at several locations downstream of the nozzle exit section as the result of interactions with the mainstream are presented and discussed in a non-dimensional form, in order to allow a generalized use of these data for both design of hot-streak generators or simulation of different blade internal cooling configurations.

Since the main focus of this research was to investigate the thermal mixing between the jet and the mainstream, the experiments were designed with the constraint of imposing the total pressure for the mainstream and the jet at the nozzle exit.

## 2. Experimental Setup And Procedure

The experimental facility, shown in Fig. 2, consisted of a variable speed fan, a 15 kW electric heater, a settling chamber, a contraction with a thermally insulated tube (20 mm-diameter) and a stainless steel cylindrical nozzle, aligned with the mainstream. The mainstream mass flow rate, controlled by a variable speed fan, was kept at ambient temperature (about 295 K), while the jet coming out from the nozzle (the hot jet) was heated in the 343−383 K range.

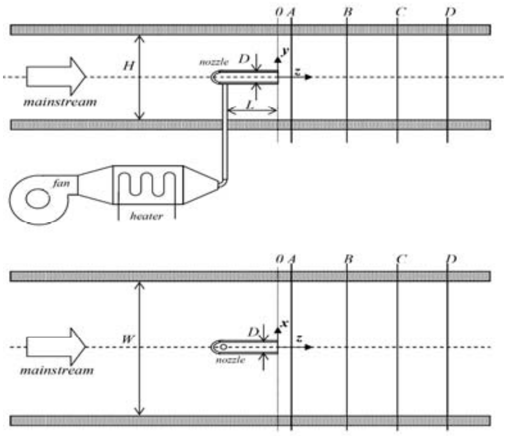


**Fig. 2. Schematic (side and top views) of the wind tunnel and cylindrical nozzle. Dimensions not to scale.**

The nozzle had a 21 mm inner diameter $D$, a 2 mm thickness and a 125 mm length $L$ in the mainstream direction (measured from the supporting duct exit to the nozzle exit), while the vertical section of the duct supporting the nozzle had a 10 mm inner diameter and a 2 mm thickness, to minimize the dimension of the wake shed from the support.

The nozzle was centered with respect to the horizontal and vertical dimensions of the rectangular inlet duct (the test section), which were $W$ = 1000 mm and $H$ = 210 mm, respectively. Additional tests were performed with a 10mm-inner-diameter nozzle to investigate the effects induced by the nozzle dimension. The exit section of the nozzle was contoured in order to minimize the wake generation and the associated total pressure non-uniformities immediately downstream of the nozzle.

A five-hole probe was traversed horizontally and vertically to determine the distribution of total pressure in a plane located 55 mm downstream of the nozzle exit. Thermocouple rakes, consisting of

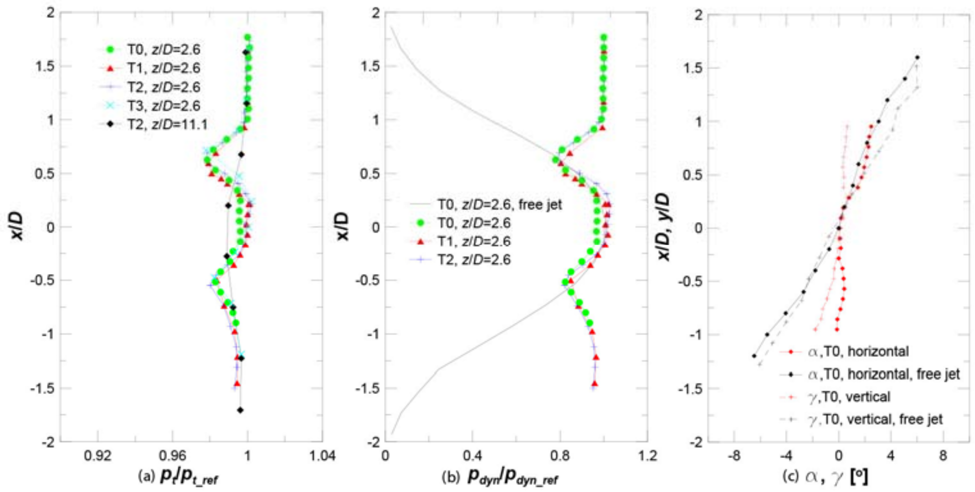


**Fig. 3. (a) Total pressure, (b) dynamic pressure and (c) angle distributions measured downstream of the exit section of the hot jet with *D* = 21 mm. Mainstream air temperature = 295 K, air jet temperature conditions: T0 = 295 K, T1 = 343 K, T2 = 363 K, T3 = 383 K.**

T-type, stainless-steel-sheathed thermocouples, pre-calibrated to ± 0.1 K, were used to measure the hot jet profile in several planes downstream of the nozzle exit. Thermocouples had a 0.5 mm sheath diameter and the junctions directly exposed to the airflow in order to assure a fast time response. The rake traversing was accomplished by means of a carriage system running both horizontally and vertically along a steel track. Temperature readings from the thermocouple rake and thermocouples placed in the mainstream were acquired using a National Instruments data acquisition unit and time-averaged over a 5 s time span.

In order to make this investigation representative for hot-streak migration in gas turbine engines, the experiments were conducted by imposing a conserved total pressure downstream of the nozzle. This assumption is consistent with similar literature investigations dealing with the migration of simulated hot streaks (Jenkins *et al*., 2004, Jenkins and Bogard, 2005, Qureshi *et al*., 2012). According to the conserved total pressure criterion, the mainstream and the exit jet velocities were nominally uniform in the case of unheated jet, while the exit velocity of the heated jet was expected to slightly increase from its nominal value (with no heating) due to the density reduction. A nominal velocity of 15 m/s was set for the majority of experiments, resulting in a Reynolds number Re, based on the nozzle inner diameter (21 mm), of $2.1 \times 10^4$. Additional tests were carried out at Re = $1.0 \times 10^4$, obtained either with the same nozzle diameter (21 mm) and a reduced velocity (7 m/s) for jet and mainstream, or with the same velocity of 15 m/s and the nozzle diameter reduced to 10 mm. The mainstream turbulence intensity was kept fixed at 1% for all cases.

For the purpose of comparison, temperature profiles of the hot jet were measured even in the case of the absence of mainstream, thus simulating the condition of a hot jet discharged into a stagnant air environment.

A normalized temperature ratio $\theta$ was found to be appropriate for the presentation of results. The normalized ratio was based on the peak jet temperature $T_{hj}$ (measured at the nozzle exit and varying in the 343−383 K range) and the mainstream temperature $T_\infty$ (= 295 K), as follows

$$\theta = (T - T_\infty) \,/\, (T_{hj} - T_\infty) \qquad (1)$$

The overall fixed and variable error components of uncertainty of the time-averaged temperatures have been accurately evaluated. This evaluation included the measuring system uncertainty plus all those associated with system disturbances (heat conduction effects along the thermocouple wires) and system-sensor interactions (heat radiation and convection between the probe junction and the environment). In particular, variable errors have been estimated by means of a set of 30 observations at a representative test condition. For instance, considering a hot jet temperature at the nozzle exit of 363 K and a mainstream temperature of 295 K, the fixed and variable errors in the peak time-averaged jet temperature, evaluated five diameters downstream of the nozzle exit, were ± 0.6 K and ± 0.8 K, respectively. Based on the root-sum-square combination of fixed and random uncertainty components, the 95% confidence estimate of the overall uncertainty in $\theta$ measurements was found to be ± 0.02.

## 3. RESULTS AND DISCUSSION

The hot jet characteristics have been investigated both thermally and aerodynamically in several measuring planes, shown in Fig. 2 and labelled as A, B, C and D, where a Cartesian coordinate system is introduced, and each position along *x*, *y*, and *z* axes has been normalized by the inner diameter of nozzle *D*.

Figure 3 shows the total pressure, dynamic pressure and yaw/pitch angle distributions measured at a non-dimensional distance of $z/D$ = 2.6 from the nozzle exit plane.

The total pressure, measured along a horizontal traverse centered in the vertical direction (Fig. 3a), shows a uniform distribution of $p_t$ inside the jet ($-0.3 < x/D < 0.3$) at all the tested jet temperatures.

The value of total pressure inside the jet has been fixed to be equal to the free-stream value ($p_{t\_ref}$), in order to minimize the flow distortion induced by the presence of the nozzle. Non-uniformities in the total pressure distributions are hence confined to the region next to $x/D = \pm\ 0.5$, where the wake shed from the nozzle is present. The difference with the external value is smaller than 3% of the reference total pressure and drops to less than 1% in the measuring plane at $z/D$ = 11.1, where the wake of the nozzle is no longer distinguishable. The comparison of the distributions measured for the different jet temperatures (conditions T0, T1, T2, T3) shows that the effect of this parameter on the total pressure distributions is negligible.

The total pressure distributions measured along the vertical traverse, centered along the horizontal traverse (here not shown to not threaten the plot readability), have been found to be almost overlapped with those along horizontal traverses, demonstrating a good axial-symmetry of the jet.

In Fig. 3b the distributions of the dynamic pressure $p_{dyn}$ (made non-dimensional by the dynamic pressure $p_{dyn\_ref}$ measured in the free-stream for the jet at the ambient temperature surrounded by a parallel air flow) are shown in order to allow the comparison with the free-jet, developing in the absence of the mainflow. It is clear how at $z/D$ = 2.6 the dynamic pressure at the center of the free jet is very similar to the one measured at the center of the jet when the mainstream flow is present. Also for what concerns the dynamic pressure distributions, the effect of the jet temperature is negligible, which means that a slight difference in the flow velocity will occur due to the density decrease associated with the temperature increase.

Figure 3c displays the distribution of the yaw angle ($\alpha$) measured in a horizontal traverse, and of the pitch angle ($\gamma$) measured in a vertical traverse, at $z/D$ = 2.6 for the free jet (without the mainstream) and for the jet at the ambient temperature surrounded by a parallel air flow. The angle distributions clearly show that the free jet is characterized by a very good symmetry, being the two angle distributions rather overlapped. Moreover, as expected, the free jet spreads out more rapidly as compared with the jet confined by the mainstream, as demonstrated by the much smaller angle values measured when the mainstream flow is present, and as it will be further supported by the thermal investigations.

Once verified the aerodynamic characteristics of the hot jets, the thermal field has been investigated. The distributions of the normalized temperature ratio $\theta$ at three axial stations are reported in Fig. 4. At each station $z/D$, both horizontal and vertical temperature profiles were insensitive to the jet maximum temperature $T_{hj}$. This result found for a hot jet in a parallel flow is consistent with those shown in the pioneering paper by Wilson and Danckwerts (1964), who found, for a hot-air jet in stagnant air, the similarity between $\theta$ profiles and normalized $z/D$ axial coordinate, regardless of the individual $T_{hj}$ value.

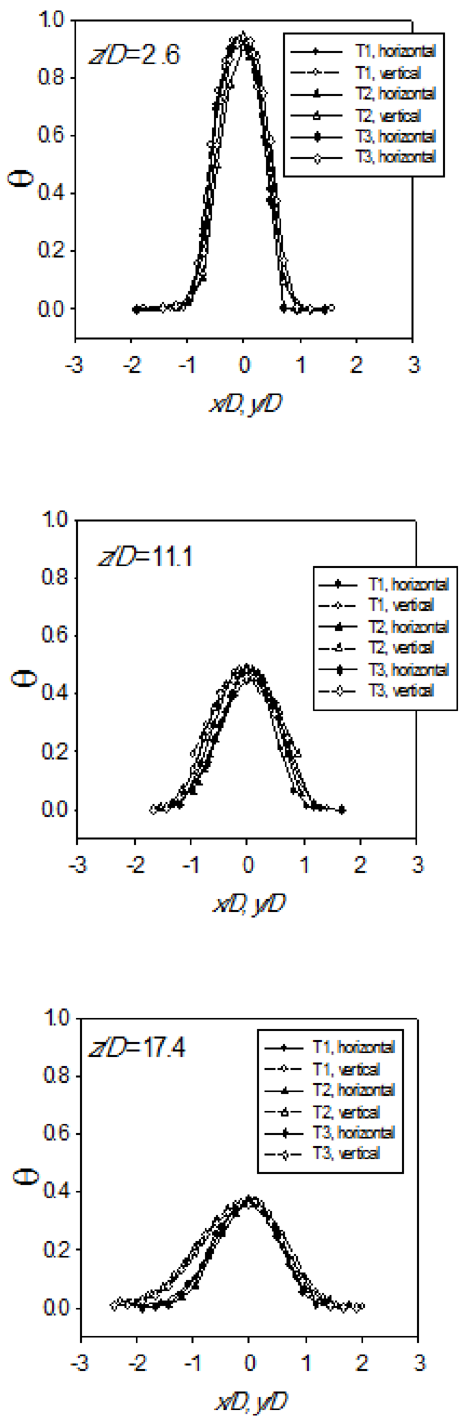


**Fig. 4. Normalized temperature profiles of the hot jet at different axial positions: effect of jet temperature.**

Since at a given axial plane horizontal and vertical profiles are almost coincident, the hot jet was supposed to be circular and featured by a thermal diffusion to the mainstream practically uniform in the radial direction. The only exception is represented by the vertical $\theta$ profiles at the largest *z/D* value, where a not-negligible asymmetry probably indicates the influence of the aerodynamic wake induced by the nozzle support.

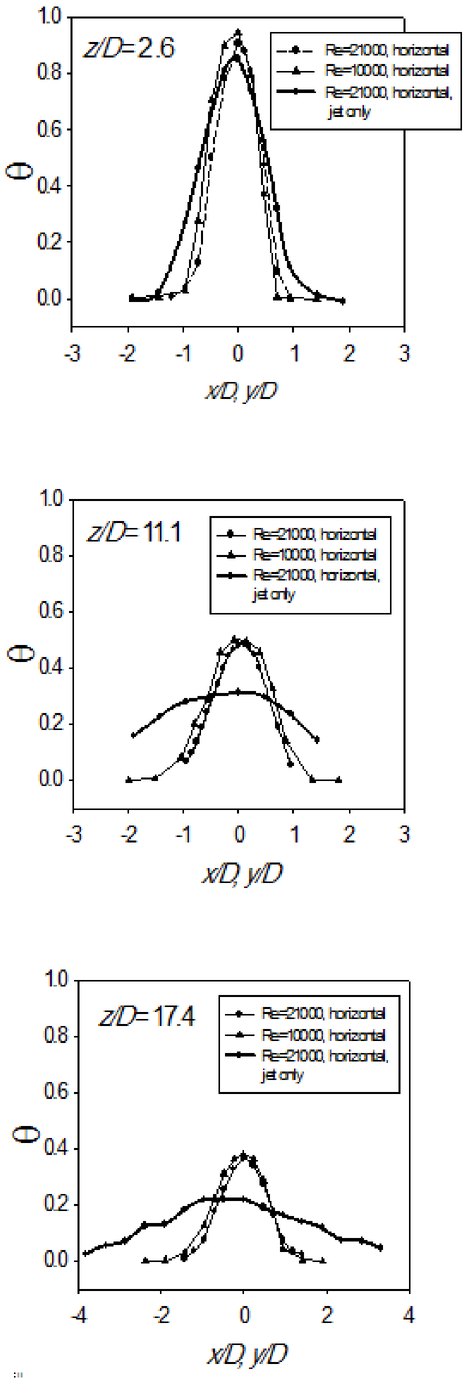


**Fig. 5. Normalized temperature profiles of a hot jet at different axial positions: effects of Re number and no-mainstream.**

The effects of the Reynolds number and of the absence of mainstream on normalized temperature profiles are reported in Fig. 5. Passing from Re = $2.1\times10^4$ to $1.0\times10^4$ (obtained by maintaining the same nozzle diameter, while reducing mainstream and jet velocities by about 50%) does not significantly alter the $\theta$ distributions at every axial station. It is worth to notice that most of literature dealing with round free jets (see for instance, Abdel-Rahman, 2010 and Mi *et al*., 2013) seems to agree that, if the Reynolds number is greater than $10^4$, the radial spread of the velocity field and the decay of the centreline velocity in the downstream direction are independent of Reynolds number. As the temperature distribution is closely related to the velocity field (Bejan, 2013), a similar conclusion is expected to be reached for hot free jets, even if temperature diffuses more rapidly than velocity. To the Authors' knowledge, no literature data are available for the Reynolds effect on temperature distributions of a hot jet in parallel flow; although restricted only to two Reynolds numbers, the present data are likely to suggest that normalized temperature profiles tend to be Reynolds-number independent even for hot jets in parallel flow at relatively high Reynolds numbers.

Normalized temperature profiles obtained with no mainstream are characterized by a larger thermal diffusion towards the radial direction; as a consequence of the increased dispersion of the jet, the temperature distribution, at a given axial position, exhibits a more uniform shape with respect to the case of the jet mixed to a parallel flow.

Figure 6 shows the distribution of the normalized temperature on the axis of the jet. Results obtained for both nozzle diameters and Re number values are considered. Immediately downstream of the nozzle exit section (*z/D* < 5), the normalized peak temperature of the jet is still very close to its maximum (i.e., the value recorded at the centreline of the exit section); here the jet characteristics match those of the nozzle exit, as it occurs in the initial region, whose extension typically lasts up to 6 diameters for a free jet (Abdel-Rahman, 2010). As the normalized axial distance *z/D* is increased up to about 10, peak temperature markedly decays as a result of thermal diffusion towards the surrounding mainstream. However, at *z/D* = 11, the peak value of $\theta$ is still close to 50% of its maximum value. As the axial distance is further increased, peak temperature still decreases but the slope is noticeable reduced and the fully developed turbulent conditions (for which similarity of the temperature profiles is maintained downstream) are supposed to be approached. At the farthest station from the nozzle exit (*z/D* = 24.3), a normalized peak value of 0.27 was recorded. The normalized peak temperature values for the free jet (with no mainstream) are lower than that recorded, at the same axial locations, in the presence of the mainstream. The parallel flow surrounding the hot jet reduces the spreading extent in the radial direction (as stated in the comment to Fig.5) and allows the jet to travel at longer distances in the mainstream direction.

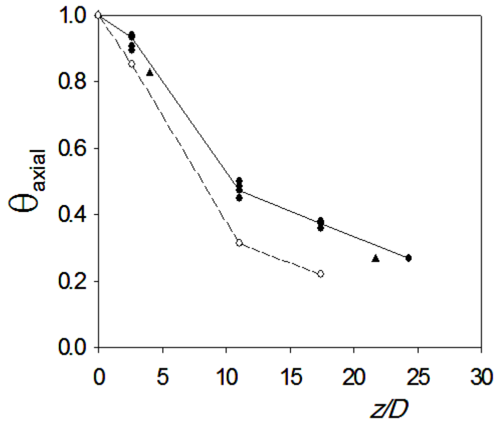


**Fig. 6. Axial decay of normalized temperature. Closed circles: *D* = 21 mm, closed triangles: *D* =10 mm, open circles: *D* = 21 mm, no-mainstream.**

## 4. Concluding Remarks

The aerodynamic and thermal characteristics of a hot-air jet injected into a parallel air flow have been experimentally investigated. The jet passed through a cylindrical nozzle used as a hot streak generator. Radial and axial thermal diffusion of the jet, in terms of an appropriate normalized temperature, were found to be uncorrelated to maximum jet temperature and Reynolds number, in the respective fields of variation. The strength of the hot jet is attenuated by 50% within the first ten diameters from the nozzle exit and by a further 50% after about 25 diameters from the exit section. The comparison with data obtained for a hot jet discharged into stagnant air showed that parallel flow surrounding the hot jet reduces the spreading extent in the radial direction and permits to the jet to travel at longer distances in the mainstream direction.

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