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ACTIVE FLOW CONTROL BY COUNTERCURRENT JETS

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The paper presents the results of experimental analysis of the flowfield in slightly heated countercurrent round jets. The velocity measurements were carried out by means of hot-wire anemometry (a combined CTA-CCA system for temperature compensation). The instantaneous signals collected during the experiment were digitally processed and used for determination of the statistics of velocity and temperature fields including frequency characteristics. The results revealed that the fluid aspiration at the jet periphery significantly influences large-scale structures naturally existing in the flow and being responsible to a great extent for the mixing and entrainment in the free flow. The aspiration intensity was found as the key parameter deciding about the way the reverse flow either inhibits or enhance transport processes.

Key words: countercurrent jets, jet stability, flow control, coherent structures

Notations

D	–	diameter
E	–	mean voltage
f	–	frequency
I	–	aspiration intensity, $-U_2/U_1$
L	–	extension collar length
r	–	radial coordinate
Re	–	Reynolds number of internal jet, U_1D_1/ν_1
St	–	Strouhal number based on internal jet parameters, fD_1/U_1
T	–	mean temperature
t	–	temperature fluctuation
U	–	mean axial velocity
u	–	axial velocity fluctuation

w – suction slot width, $(D_2 - D_1)/2$
x – axial coordinate (attached at the exit plane of internal nozzle)
α – extension collar divergence half-angle
ΔT – overheat, $T_1 - T_2$
ν – kinematic viscosity coefficient

Subscripts
1 – denotes the main jet
2 – denotes the aspirated reverse flow
am – denotes ambient conditions

Superscripts
$(\cdot)'$ – denotes standard deviation of fluctuations

Abbreviations
CTA – Constant Temperature Anemometer (measuring velocity)
CCA – Constant Current Anemometer (sensing temperature)
HWA – Hot Wire Anemometer

1. Introduction

Dynamics of free round jets is a subject of continuous scientific interest in recent decades resulting in a number of publications. The reason of such an interest is the applicability of that type of flow to many practical flow configurations. Recent investigations have been mainly devoted to the improvement of transport processes which are essential in such industrial flows as gas burners, jet engines, drying chambers, fluidized beds, etc. Although there is a number of known techniques leading to the improved mixing (e.g. swirling or crossflows), scientists do not give up in looking for new more effective and more efficient ways of active control of the flow.

One of the most recent attempts aimed at the enhancement of transport processes are the variable-density jets, i.e. jets issuing to the surroundings of considerably different (higher) density. Results of a number of experiments showed very intensive oscillations of flow field parameters (i.e. velocity, pressure) characterising the absolute instability phenomenon. The concept of absolute instability, originally proposed by Landau and Lifshitz (1959) assumes the development of a small perturbation in time, in contradiction to convective instability being developed in space. The nature of this type of instability decides about its intensive character as predicted theoretically and proved by experimental investigations. The results of research studies that have been carried out since early eighties showed clearly that heated air jets (e.g. Monkewitz *et al.*, 1990) as well as helium jets (studied by Kyle and Sreenivasan, 1993) revealed very intensive oscillations of all flow parameters leading to significant mixing enhancement.

As the variable-density jets can rather exist only in a natural way (i.e. their artificial establishment would be too expensive), the so-called countercurrent jets were proposed as an alternative method of active flow control. The idea is to generate an annular (for round nozzles) reverse flow applied to the outer region of the main stream, which was shown theoretically by Jendoubi and Strykowski (1994) to be effective in enforcing the absolute instability. The original experiment conducted by Strykowski and Niccum (1991) revealed the great potential of that way of flow stimulation in terms of intensification of transport processes. The phenomenon had unfortunately a local character, i.e. intensive mixing took place in a limited space of the flow, and additionally was compensated by flow "laminarization" (i.e. damping of turbulent fluctuations) in the remaining jet regions.

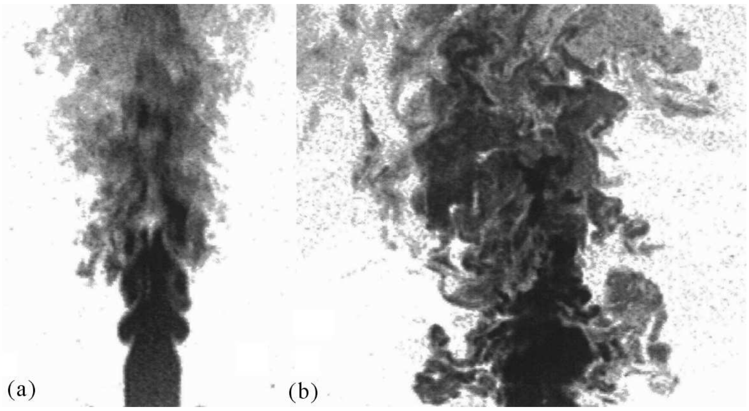

Fig. 1. Influence of aspiration on jet spreading rate: (a) no aspiration applied, (b) aspiration intensity $I = 0.36$ (Bogusławski *et al.*, 1999)

Total enhancement of mixing processes in the free jet was achieved by the application of an extension tube put on the external nozzle as shown by Strykowski and Wilcoxon (1993). The results of later studies (e.g. Bogusławski *et al.*, 1999; Asendrych, 2000) confirmed the necessity of application of the extension tube of a sufficient length to ensure global intensification of the mixing. As it is shown in Fig. 1 (images obtained by smoke visualization – courtesy Bogusławski *et al.*, 1999) the flow pattern stimulated with the reverse flow is significantly affected when the aspiration intensity (being the ratio of bulk velocities of the reverse and main streams) is sufficiently strong. While natural (not stimulated) jet reveals a regular shape being the result of convectively developing shear-layer instability in the near-nozzle region (see Fig. 1a), the jet influenced by reverse stream is highly disrupted (see Fig. 1b).

One can easily observe the existence of the so-called side-jets (portions of the fluid ejected in the transverse directions) being the evidence of absolute instability, and leading to the substantial increase of the spreading rate of the jet. The available literature data prove that the countercurrent jet is a very promising flow configuration allowing for flow control, in particular for mixing enhancement being of special importance for combustion systems. An improved mixing of combustion substrates (being the crucial factor for diffusion flames) should enable more effective burning of lean fuels (e.g. nitrogen-diluted gases) and lead to significant reduction of pollutants emission (like soot, carbon monoxide and nitrogen oxides). The existing data (e.g. Lonnes *et al.*, 1998) also indicate the need of optimisation of nozzles geometry (suction gap width, length and divergence angle of the extension tube etc.) as well as further studies on the mechanism governing the phenomenon. The continuous progress in numerical treatment of turbulent flows is still to poor to correctly predict some more complex flow configurations, which indicates the importance of experimental investigations. That is the case of countercurrent jets for which CFD simulations based on conventional turbulence modelling (i.e. RANS – Reynolds-Averaged Navier Stokes) show significant qualitative discrepancies with experimental data (see for instance Bogusławski *et al.*, 2002).

As the most recent application of countercurrent jets, the thrust vectoring of jet engines exhaust should be mentioned. A number of studies have been conducted in this field (e.g. Dores *et al.*, 2006) proving that the mechanical thrust vectoring can be replaced by fluidic control provided that the technique is optimised in terms of the range of thrust angles.

2. Experimental facility and measurement technique

The experiment was performed with the use of an open vertical wind tunnel equipped with a system of two concentric nozzles (shown in Fig. 2) mounted at its outlet. The tunnel with the built-in settling chamber (making the flow quiet and disturbance-free) was supplied with air by a compressor producing the main stream. The space between the nozzles was connected to the collector and then to the aspiration fan producing the reverse flow. Both flow driving devices were operated independently allowing for free control of the flow rates and, in turn, for precise setting of the aspiration intensity, which is the key parameter of the conducted research work. The tunnel provided also the possibility to heat the main jet thanks to the built-in system of electric heaters. The electric power installed in the facility allowed for overheat up to 50 degrees for the Reynolds number applied during the reported experiment. The corresponding density ratio of about 0.85 did not allow one to reach the absolute instability limit which, according to the literature data, varies within the range 0.73-0.75 depending on flow configuration (see e.g. Kyle and Sreenivasan, 1993; Bogusławski, 2002). It was not, however, intended to enhance the mixing by absolute instability due to variable density as the main target of the work was to study the influence of reverse stream on the jet behaviour.

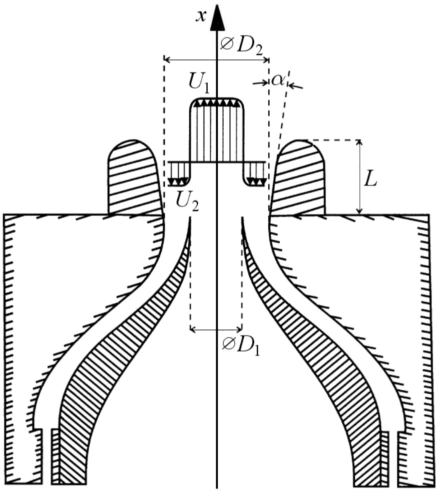

Fig. 2. Geometry of the countercurrent nozzle and exit velocity profile

The system of concentric nozzles was designed following the original study of Strykowski and Wilcoxon (1993) with the following geometrical parameters:

- inner nozzle exit diameter $D_1 = 40\,\mathrm{mm}$
- outer nozzle internal diameter $D_2 = 2D_1 = 80\,\mathrm{mm}$
- extension tube height $L = D_1$
- suction slot width $w = D_1/2$
- divergence angle $\alpha = 7^\circ$.

A great area contraction ratio of the internal nozzle (~ 100) was applied in order to ensure a uniform mean velocity distribution and very low turbulence intensity (below 0.5% when referenced to the exit bulk velocity) at the exit plane. The main flow was kept unchanged during the reported experiment and can be characterized with the following parameters:

- Reynolds number based on the internal stream $\mathrm{Re} \approx 20000$
- jet overheat (temperature difference between the main jet at the exit plane and surrounding air) $\Delta T \approx 40\,\mathrm{K}$ giving the density ratio 0.88
- aspiration intensity expressed as the ratio of bulk velocities of the reverse flow and internal stream $I = 0$ to $I = 0.45$.

The measurements were carried out with the use of a DANTEC$^{\mathrm{TM}}$ 2-channel hot-wire anemometer 55M-type with details shown schematically in Fig. 3. A constant current channel was used to follow the instantaneous temperature of the medium which could be then introduced to the response equation of the constant temperature channel for recovering the instantaneous velocity. The operation of HWA channels was described by the following system of equations

$$
\begin{aligned}
E_{CTA}^2 &= A(1+BT)(1+C\sqrt{U}) \\
E_{CCA} &= E_0 + c_T T
\end{aligned}
\qquad (2.1)
$$

where: A, B, C, E_0, c_T – constants determined during calibration.

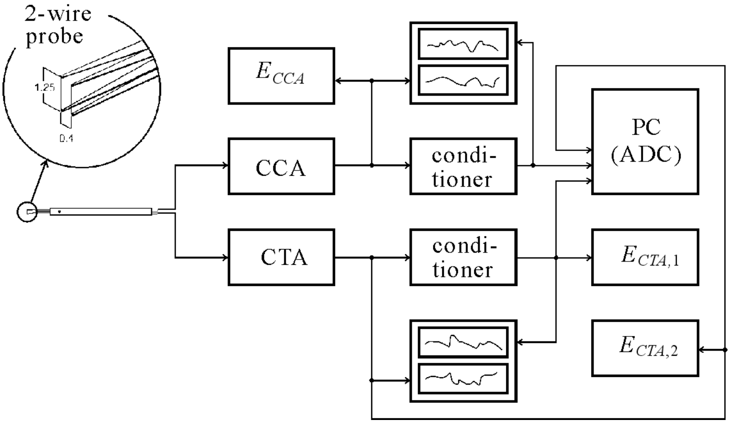

Fig. 3. Scheme diagram of measuring equipment

For measurements, a DANTEC$^{\mathrm{TM}}$ 2-sensor probe was used with tungsten wires of lengths 1.25 mm positioned in parallel at the distance approximately 0.4 mm (see Fig. 3), allowing for the assumption of point measurements. Instantaneous voltage signals were sent from the probe to HWA bridges and then through signal conditioners and analogue-to-digital converter to the personal computer memory. In order to monitor the experiment, all signals were visualized by oscilloscopes, and their average values were controlled by mean voltage meters. Signal processing, i.e. recovering the instantaneous temperature and velocity values as well as evaluation of statistical moments and spectral density functions, was performed completely digitally.

3. Characteristics of the flow field in non-isothermal countercurrent jets

3.1. Mean and fluctuating velocities

The measurements were carried out on the jet centreline starting from the exit plane of the inner nozzle up to the axial distance $x/D_1 = 12$. Figure 4a presents the influence of the aspiration intensity on the axial distribution of mean velocity. The reference distribution ($I = 0$ – no aspiration applied) seems to be typical for free round jets revealing the presence of the potential core of the flow of the length of about $4D_1$. For low aspiration rates ($I \leqslant 0.1$), the reverse stream does not affect the mean velocity field. The effect of flow stimulation starts to be visible for the velocity ratio $I = 0.2$ (one could say that for $I = 0.173$, however, the corresponding data points deviate from the reference values less than the measurement accuracy) and for growing aspiration, the reduction of mean velocity becomes more and more pronounced. For instance: at the position $x/D_1 = 4$ (the end of the potential core for the reference case, i.e. $U = U_1$) the aspiration intensity $I = 0.25$ leads to a very slight velocity reduction to $U = 0.97U_1$ approximately, while for $I = 0.434$ local speed decreases to the half of the exit level. The flow stimulation is also responsible for the shortening of the potential core (reduced from the length of $4D_1$ down to $1.5D_1$ for the strongest aspiration applied) being the clear evidence of the suction impact on the jet near-exit region.

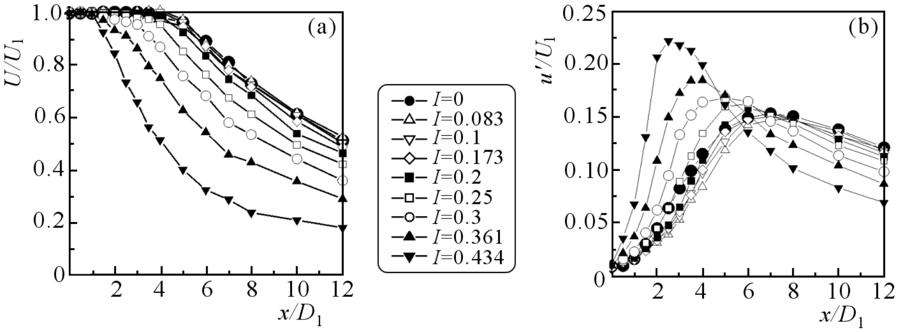

Fig. 4. The influence of aspiration intensity on axial distribution of mean velocity (a) and intensity of turbulent velocity fluctuations (b)

Figure 4b presents the longitudinal evolution of standard deviation of axial velocity fluctuations determined at the same locations as mean velocities. The impact the aspiration has on the turbulent intensity is more complex than for the mean flowfield. For low suction intensities, the reverse flow noticeably inhibits turbulent activity which is manifested by a slight decrease of turbulent fluctuations in the downstream distances from the nozzle exit $x/D_1 =$ 2-5 and the accompanying shift of the maximum of $u'/U_1 = f(x/D_1)$ distributions in the downstream direction. These effects are most pronounced for the suction ratio $I = 0.083$ for which the maximum is located at $x/D_1 = 8$ (while for not stimulated jet at $x/D_1 = 7$) and takes the value of 0.148 (being reduced from the initial one equal to 0.153). Further increase of the suction intensity is associated with an inverse tendency, i.e. turbulent fluctuations grow gradually, while the peak of the axial distribution travels upstream, and for the maximum aspiration ($I = 0.434$) it is located at $x/D_1 = 2.5$ and reaches the level 0.225. For the aspiration intensity $I \cong 0.2$ the $u'/U_1 = f(x/D_1)$ distribution reaches roughly its original shape (i.e. for no stimulation applied), so the aspiration intensity range $I =$ 0-0.2 can be called as a "laminarization" regime.

In order to validate the present experiment, the results of the mean velocity measurements were compared to the available literature data and presented in Fig. 5 in a form of the reduced velocity versus aspiration intensity at a selected measuring point, namely $x/D_1 = 5$ at the jet centreline. As the reference, the results of Strykowski and Wilcoxon (1993) as well as Bogusławski *et al.* (1999) are cited. Additionally, Fig. 5 includes the former own data obtained for isothermal conditions (Asendrych, 2000) at the same experimental facility.

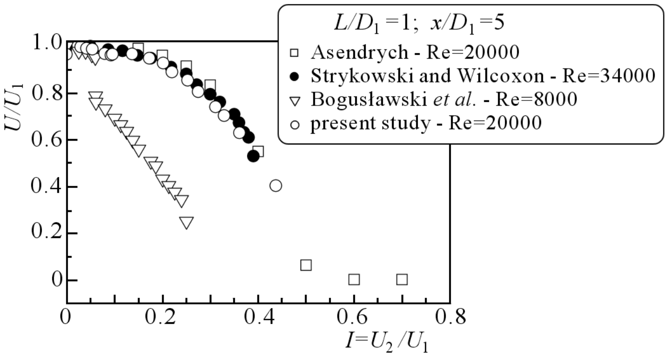

Fig. 5. The influence of aspiration intensity on mean velocity decay

Variation of the mean velocity measured during the experiment (empty circles in Fig. 5) agrees very well with the original research of Strykowski and Wilcoxon (1993) (solid circles in Fig. 5) in the entire range of applied suction intensity. An excellent agreement was also found between the data corresponding to iso- and nonisothermal conditions (empty squares and circles, respectively) proving there is no influence of density difference (for the applied value of 0.88) on the jet development. A significant deviation from all the mentioned distributions was observed, however, for the results of Bogusławski *et al.* (1999), which indicates a dramatic drop of the mean velocity for the aspiration intensity exceeding $I \approx 0.06$. The reason for these discrepancies can be, however, explained by the differences in the nozzles design in reported investigations, being the crucial factor for the jet instability origin and development. The work of Bogusławski *et al.* (1999) was conducted with the use of a tube jet, which resulted in a parabolic velocity profile and relatively high turbulence intensity at the exit plane, while the remaining studies incorporated contoured nozzles ensuring a flat velocity profile and very low fluctuations level. The data from Fig. 5 indicate that the stream development is strongly influenced by the exit-nozzle conditions and that the jet control cannot be done effectively without careful nozzle design.

3.2. Mean and fluctuating temperatures

As a complement to the results of velocity field measurements, the corresponding data are presented in Fig. 6 for the temperature field. Although one could expect that the distributions of both quantities should lead to similar conclusions, it was decided that the temperature data would also be included in the analysis. The reason is that single-wire CTA measurements in the region of high turbulence intensity may be significantly biased. As shown by Bogusławski (2002), the axial distribution of mean velocity at the jet centreline revealed a local minimum as long as the experiment was done with the use of laser-doppler anemometry, while the hot-wire measurements did not show this feature. That uncertainty of the 1-channel CTA system is attributed to its actual sensitivity to all velocity components (contributing to the cooling effect) being interpreted as the response of the main one only. The temperature as a scalar is, in principle, free from such a bias.

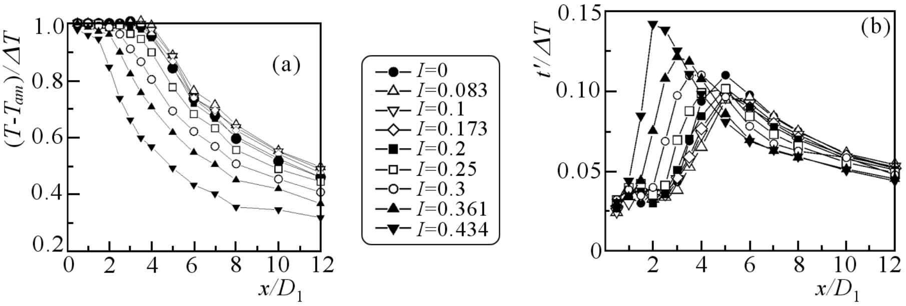

Fig. 6. The influence of aspiration intensity on axial distribution of mean temperature (a) and intensity of turbulent fluctuations of temperature (b)

The temperature profiles both for mean (Fig. 6a) as well as fluctuating component (Fig. 6b) reveal shapes similar to velocity distributions, but their evolutions are much more pronounced. For the "laminarization" regime (i.e. for suction intensity $I = 0\text{-}0.2$) mean temperatures noticeably exceed the reference curve for no stimulation applied, which was not the case for velocity measurements (compare Fig. 4a). The reduction of temperature fluctuation intensity is also much more sensitive to aspiration, which is manifested by the 15-percent drop of the $t' = f(x/D_1)$ maximum for the suction intensity change from $I = 0$ to $I = 0.083$. For the aspiration intensity greater than 0.2, the data from Fig. 6 indicate intensification of the mixing, which is associated with a rapid drop of the mean temperature (see Fig. 6a) and elevation of the peak of turbulent temperature fluctuations accompanied by their shift towards the nozzle exit (see Fig. 6b).

Temperature field measurements, fully consistent with velocity distributions, much more clearly reveal the existence of two flow control regimes, i.e.:

- laminarization, and
- enhanced mixing

regimes with the frontier corresponding to the suction ratio of about $I = 0.2$.

3.3. Frequency spectra of velocity fluctuations

The instantaneous signals collected during the experiment were also utilised to get frequency characteristics of the velocity field. As it was suggested by Strykowski and Wilcoxon (1993), the aspiration of the flow exerts an impact on the shear-layer instability resulting finally in modified development of large-scale structures dominating the free jets. In order to have a reference for the suction-influenced frequency representation of the flow studied, the power spectral density functions were first determined for the case with no aspiration applied. The results are presented in Fig. 7 for selected space locations at the jet centreline, in particular at distances $x/D_1 = 0.5$, 1, 2, 3, 4 and 5 downstream the main nozzle exit.

The data collected in Fig. 7 indicate the existence of large-scale organised motion with a relatively well defined shedding frequency, developing convectively in the shear layer. The fundamental mode of coherent vortices characterized by the Strouhal number $\mathrm{St} = 0.84$ dominates in the near-nozzle region, i.e. $x/D_1 \leqslant 1$ (see Fig. 7a,b). In further downstream locations, these oscillations quickly disappear (at $x/D_1 = 2$ the spectral peak $\mathrm{St} = 0.84$ is hardly visible), and due to the pairing phenomenon they give birth to the subharmonic mode with the dimensionless frequency $\mathrm{St} = 0.42$ keeping its coherence up to the axial location $x/D_1 = 5$. It is worth to note that the "child" mode is much more energetic than the fundamental one and contributes, to a great extent, to the momentum transfer and entrainment processes taking place in the flow.

The frequency characteristics of the flow are strongly modified if suction at the jet periphery is applied. Figure 8 presents the velocity spectra versus aspiration intensity determined at the selected measuring point located $x/D_1 = 1$ downstream the nozzle exit at the jet centreline for the following

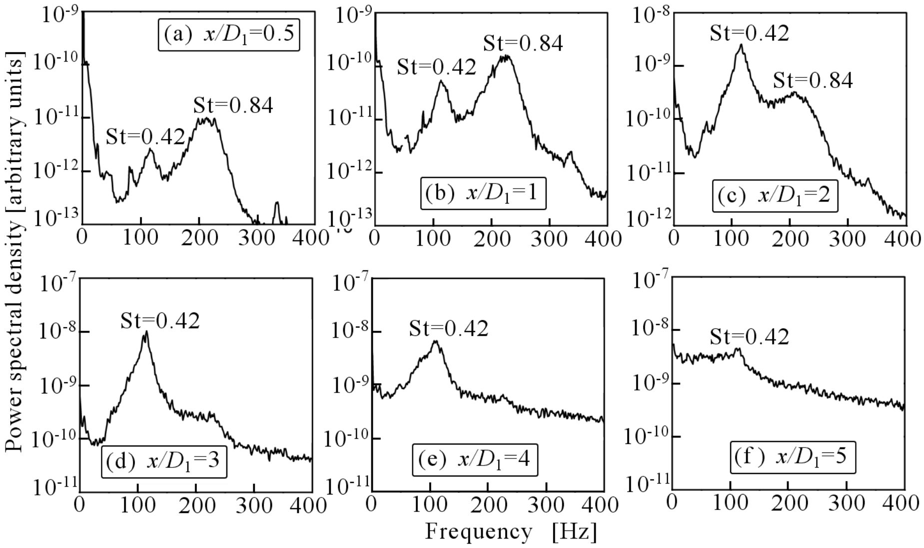

Fig. 7. The evolution of the power spectral density function of velocity fluctuations along the jet centreline for natural flow conditions (no aspiration)

values of suction intensity: $I = 0$, 0.055, 0.103, 0.145, 0.231, 0.304. The initial distribution (Fig. 8a) corresponding to the not stimulated jet ($I = 0$) reveals the "coexistence" of both instability modes indicated by spectral peaks St = 0.84 (fundamental mode) and St = 0.42 (subharmonic mode). For increasing aspiration intensity, the fundamental mode is consecutively inhibited (see Fig. 8b,c,d) and finally disappears (see Fig. 8e). As the turbulence intensity of turbulent motion is roughly constant for I = 0-0.3 (see Fig. 4b for $x/D_1 = 1$), the reduction of the fundamental mode results in transfer of power to the subharmonic instability mode being the dominating one for both flow regimes, i.e. "laminarization" ($I \leqslant 0.2$) as well as "enhanced mixing" ($I > 0.2$) ones.

The evolution of the spectral power density function of velocity fluctuations presented in Fig. 8 may be interpreted as subharmonic amplification of the fundamental instability mode enforced by fluid aspiration. The increase of reverse flow intensity above $I \approx 0.4$ (not shown in Fig. 8) leads to disappearance of dominant spectral peaks (the peaks become hardly recognised). The flow stimulation becomes so strong that the large-scale vortices can no longer maintain their coherence and they are completely destroyed, partly feeding the reverse stream (note the reduction of the jet potential core for high aspiration intensities, Fig. 4a). Further substantial growth of turbulent fluctuations accompanying the decay of organised motion (see Fig. 4b for $x/D_1 = 1$) is related to purely random motion.

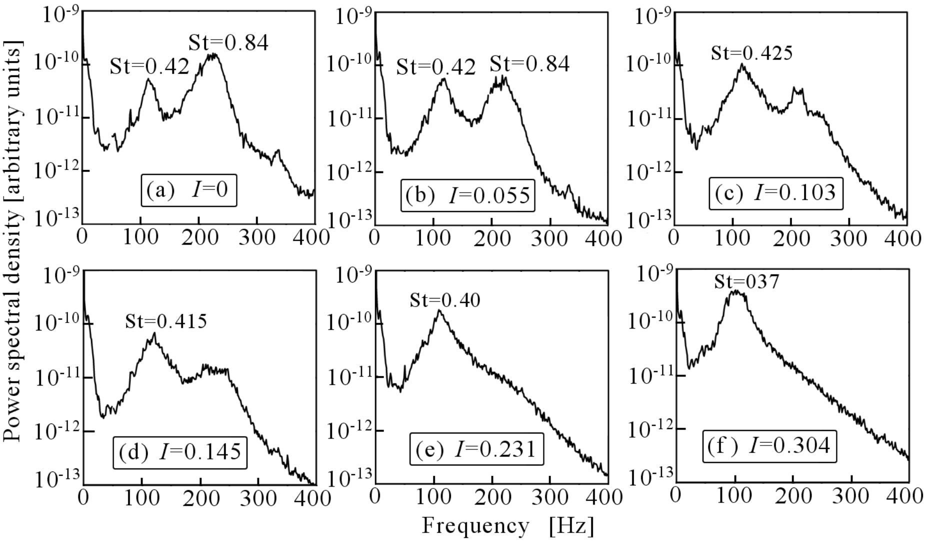

Fig. 8. The influence of the aspiration intensity on spectral density functions of velocity fluctuations at the point located at the jet centreline, $x/D_1 = 1$

Strykowski and Wilcoxon (1993) drew similar conclusions from results of spectral analysis, although their spectra were not so convincing as in the present work. Both instability modes detected in the reported research had a character of rather wide-band processes, and the relatively high turbulent background level made it difficult to recognise frequencies (Strouhal numbers) and to justify the presented reasoning. As a possible reason of such unclear frequency characteristics in the investigations by Strykowski and Wilcoxon (1993), much lower (than in the present experiment) internal nozzle contraction ratio could be pointed out to be responsible for the thicker boundary layer exiting the nozzle which leads, in turn, to worse conditions for the instability development.

The results of spectral analysis presented in Fig. 8 reveal also quite a noticeable relation between the shedding frequency of coherent structures and the intensity of flow aspiration. Figure 9 presents variation of the Strouhal number of the subharmonic (dominating) form of organised motion determined in its coherence region, i.e. for $x/D_1 \leqslant 4$. The data collected in Fig. 9 clearly indicate, that the reverse stream leads to a decrease in the shedding frequency of oscillations if the suction intensity exceeds $I \approx 0.15$, so it roughly corresponds to the "enhanced mixing" regime $(I > 0.2)$ where the $\mathrm{St} = f(U_2/U_1)$ relationship has strong decreasing tendency. For the highest aspiration intensity $(I = 0.45)$ still indicating some detectable spectral peaks, the frequency is reduced by approximately 30% when compared to the not stimulated flow. Such a change of the shedding frequency of coherent vortices may be explained

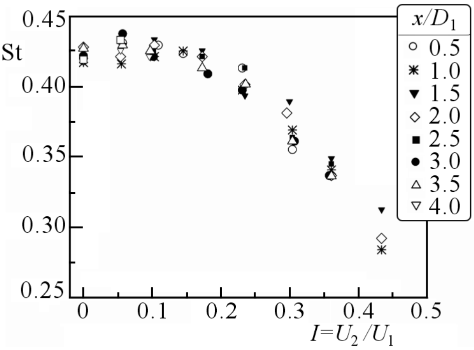

Fig. 9. The influence of the aspiration intensity on the Strouhal number characterising the subharmonic form of coherent motion

by deceleration of the shear layer in the near-nozzle region which influences also the developing instability in further downstream distances. An alternative explanation of the tendency observed in Fig. 9 employs the linear stability theory describing in a simple manner the mechanism of organised motion generation and its spatial development. According to that theory, the flow exposed to a random disturbance supports and amplifies only selected frequency modes giving birth to the organised vorticity. The solution of the stability theory relates the dominating frequency with other flow parameters including the momentum thickness of the boundary layer exiting the nozzle. The application of the reverse flow at the jet periphery leads to the modification of transverse velocity profiles in this region which are, in principle, characterised by increased values of the boundary layer thickness (Asendrych and Drobniak, 2002). According to the linear stability theory, the shedding frequency is inversely proportional to the momentum thickness, so application of the countercurrent external flow may lead to a decrease of Strouhal number as shown in Fig. 9.

4. Summary

The paper presents an experimental study devoted to flow field characteristics in nonisothermal countercurrent round jets. The results of the research revealed that the reverse flow established at the main jet periphery may substantially change the flow pattern, proving that it can be utilised for the active flow control. As the key parameter, the aspiration intensity (the ratio of bulk velocities of the reverse stream and the main jet) was found with its critical value around 0.2 distinguishing between two flow regimes. For a low suction intensity (i.e. below 0.2), the transport processes were noticeably inhibited, which was more pronounced for the temperature field. The application of a strong aspiration (exceeding 0.2) resulted in a substantial gain of turbulent activity manifested by the elevation of turbulent intensity maxima and their upstream shift with the corresponding reduction of the jet potential core. The spectral analysis of velocity fluctuations showed that the flow stimulation leads to a modification of the characteristics of large-scale vortical structures, in particular to degradation of the fundamental mode and simultaneous amplification of the subharmonic form created as a result of the pairing phenomenon. The well defined shedding frequency of organised motion was found to be affected by the aspiration intensity which seems to be in agreement with the linear stability theory.

Acknowledgements

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References

1. Asendrych D., 2000, Intensification of transport processes in free round countercurrent flows, *Cieplne Maszyny Przepływowe "Turbomachinery"*, **117**, II, 27-32
2. Asendrych D., Drobniak S., 2002, Experimental analysis of the flowfield in non-isothermal countercurrent jets, *Advances in Turbulence*, **IX**, 839
3. Asendrych D., Favre-Marinet M., 2004, Diffusion of jets with annular counterflow and small diameter ratio, *AIAA Journal*, **42**, 11, 2385-2387
4. Bogusławski A., 2002, *Absolute and Convective Instability in Free Round Variable Density Jet*, seria Monografie, Politechnika Częstochowska
5. Bogusławski A., Asendrych D., Drobniak S., Kubacki S., 2002, CFD simulations of concentric jets with external counterflow, *QNET-CFD Network Newsletter*, **1**, 3, 27-30
6. Bogusławski A., Favre-Marinet M., Abdulwahab A., 1999, Controle des jets par ecoulement a cont-courant, *CRA Cad. Sci. Paris*, **327**, Serie IIb
7. Dores D., Madruga Santos M., Krothapalli A., Lourenco L., Collins E., Alvi F., Strykowski P., 2006, Characterization of a counterflow thrust vectoring scheme on a gas turbine engine exhaust jet, *3rd AIAA Flow Control Conference, AIAA Paper*, 2006-3516
8. Jendoubi S., Strykowski P.J., 1994, Absolute and convective instability of axisymmetric jets with external flow, *Phys. Fluids*, **6**, 9, 3000-3009

9. Kyle D.M., Sreenivasan K.R., 1993, The instability and breakdown of a round variable-density jet, *J. Fluid Mech.*, **249**, 619-664
10. Landau L., Lifshitz E.M., 1959, *Fluid Mechanics*, London, Pergamon
11. Lonnes S., Hofeldt D., Strykowski P.J., 1998, Flame speed control using a countercurrent swirl combustor, *AIAA Paper 98-0352*
12. Monkewitz P.A., Bechert D.W., Barsikow B., Lehman B., 1990, Self-excited oscillations and mixing in a heated round jet, *J. Fluid Mech.*, **213**, 611-639
13. Strykowski P.J., Niccum D.L., 1991, The stability of coutercurrent mixing layers in circular jets, *J. Fluid Mech.*, **227**, 309-343
14. Strykowski P.J., Wilcoxon L.G., 1993, Mixing enhancement due to global oscillations in jets with annular counterflow, *AIAA Journal*, **31**, 3, 564-570

Sterowanie przepływem przy zastosowaniu strugi przeciwbieżnej

Streszczenie

W pracy zaprezentowano wyniki badań eksperymentalnych pola przepływu w lekko nieizotermicznych strugach przeciwbieżnych. Pomiary prędkości zostały przeprowadzone z użyciem 2-kanałowego układu termoanemometrycznego (układ stałotemperaturowy CTA z kompensacją temperatury kanałem stłoprądowym CCA). Sygnały pomiarowe zarejestrowane w trakcie eksperymentu były następnie poddane obróbce cyfrowej w celu uzyskania statystyk pól prędkości i temperatury, obejmujących również rozkłady widmowe turbulentnych fluktuacji. Uzyskane wyniki wykazały, iż zastosowanie przepływu zwrotnego na obrzeżach strugi głównej modyfikuje znacząco charakterystyki zorganizowanych struktur wirowych, występujących w przepływie w sposób naturalny i odpowiedzialnych w dużym stopniu za podsysanie czynnika z otoczenia oraz jego wymieszanie ze strugą główną. Obraz pola przepływu okazał się być silnie zależny od intensywności odsysania, która w zależności od poziomu może prowadzić do wytłumienia lub intensyfikacji procesów transportu promieniowego.

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