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MULTIPLE SUBSONIC JET SYSTEM IN THE PRESENCE OF CROSS FLOW

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The series of three parallel subsonic turbulent jets issuing from circular nozzles into the cross flow was studied experimentally. Main characteristics of flow were found to be functions of the ratio of jet to stream momentum, the distance between the nozzles and the mode of orientation of series. Results of study at various flow conditions are presented.

NOMENCLATURE

x	coordinate parallel to the main stream direction,
y	coordinate in the jet direction at the outlet of nozzle,
z	coordinate normal to xy plane,
v_0	velocity of jet at the outlet of nozzle,
w	velocity of the main stream,
T_0	temperature of jet at the outlet of nozzle,
T_w	temperature of the main stream,
ΔT_0	excess temperature of jet at the outlet of nozzle,
ΔT	excess temperature in cross-section of the jet,
ΔT_m	excess of the maximum temperature in a cross-section of jet,
D_0	nozzle diameter,
D_E	equivalent diameter of series of nozzles,
D^*	equivalent diameter of series of jet in arbitrary cross-section,
S	distance between the nozzles,
I	complex parameter $T_w v_0/T_0 w^2$.

The behaviour of series of jets issuing at right angle into the stream is of interest for solution of many practical problems such as dispersion of effluents from chimney stacks, intensification of mixing processes in combustion chambers and chemical reactors VTOL aircraft, etc. Only few results have been reported in this field. Main bulk of information concerns single jet in the cross flow. Jet series were usually studied for chamber conditions [1—4] and results are of little use to understand physics of flow because of significant influence of walls.

In present study the system of three parallel subsonic jets discharging into the free cross flow was examined experimentally. Two modes of orientation of system were considered: a) series of nozzles with common axis normal to the direction of the main stream and b) series of nozzles with common axis parallel to the main stream. Geometry of the flow is presented in Fig. 1.

Experiments were carried out in low speed wind tunnel. The cross section of working part of tunnel was 1100 mm high by 900 mm wide and the length was

1000 mm. Jets were introduced through a 17 mm–diam. pipes with typical power shape profile of jet at the exit. Pipes were mounted on the plate and protruded 100 mm into the stream to eliminate the influence of boundary layer of the tunnel. Distance between the nozzles S/D_0 and initial jet to stream momentum ratio I varied in experiments taking values: $S/D_0=2$, 3, 5 and $I=4$, 16, 64. Value $I=\infty$ corresponds to stagnant environment. Because of great number of experimental points needed to cover flow area only detailed measurements of temperature at successive cross sections of flow were performed. Exess temperature at the orifice was $\Delta T_0=60°\text{C}$. The flow was studied up to distances 30 D_0 downstream.

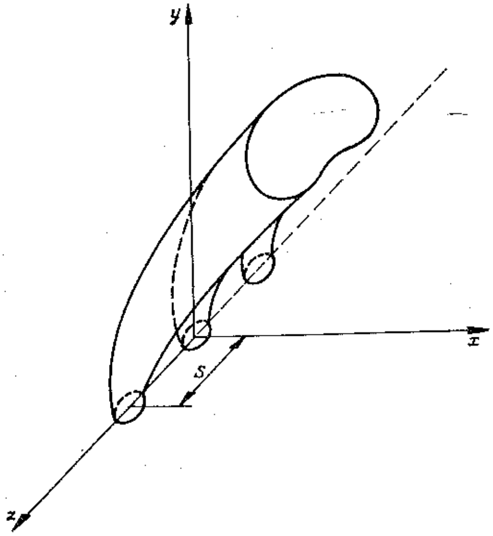
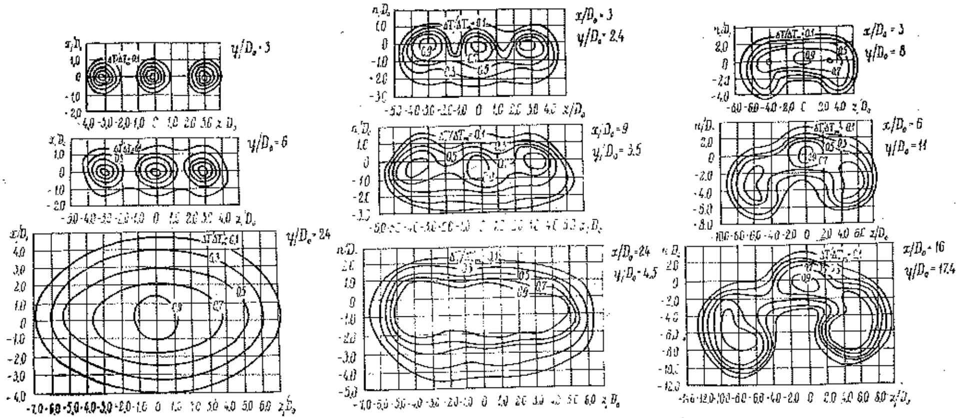


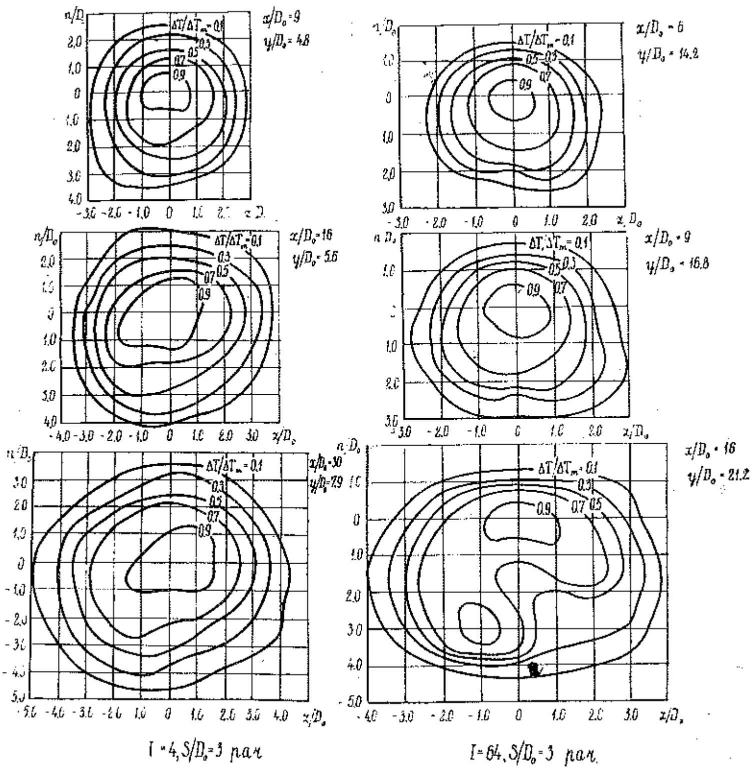
FIG. 1.

Specific features of the flow can be illustrated by Figs. 2, 3, where temperature profiles at different cross sections for various flow conditions ($S/D_0=3$) are presented. Evolution of flow field produced by series of jets in quiescent environment, presented in Fig. 2a is of quite regular nature. The shape of isolines is undertaking transformation from isolated circles to single ellipse nad later to single circle. The process is a result of successive redistribution of shear stresses taking place when turbulent mixing zones of separate jets are merging. The only parameter is important here — S/D_0 which determines the distance where actual interaction starts. Detailed study of such flow was performed by ALEXANDER et al. [6].



$I=\infty$, $S/D_0=3$ $I=4$, $S/D_0=3$ norm. $I=64$, $S/D_0=3$ norm.

FIG. 2.



I = 4, S/D0 = 3 par.

I = 64, S/D0 = 3 par.

FIG. 3.

Imposition of the cross flow makes flow picture significantly more complicated. Now, the flow pattern depends not only on value of S/D_0 but also in value of I and mode of orientation of series. Profiles for normal orientation are presented in Figs. 2b, c and for parallel orientation in Figs. 3a, b. In both cases I has values $I=4.64$. It is obvious from Figs. 2b, c that evolution of profiles is different for different values of I. General regularities remind these of a single jet in the cross wind [5]: conservative shape of cross sections without noticeable deformation at low values of I and typical kidney shape of cross sections with lateral maxima caused by secondary vortex flow at high values of I. No such difference can be observed in Figs. 3a, b for parallel orientation of series. Temperature profiles at $I=4$ as well as at $I=64$ are almost of regular circular shape.

Spreading of jet series and decay of axial temperature presented in Figs. 4, 5 permit to draw some quantitative conclusions about the flow. Spread of the jets was determined as change of the diameter of some equivalent round jet which can be calculated [5] as

$$D^* = \sqrt{\frac{4F}{\pi}}, \tag{1}$$

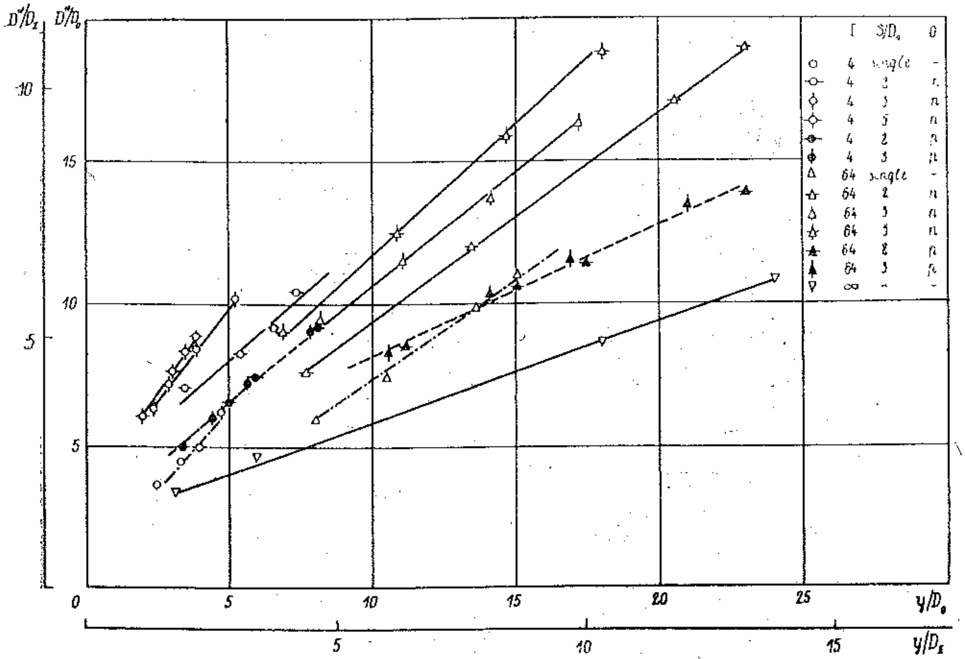


FIG. 4.

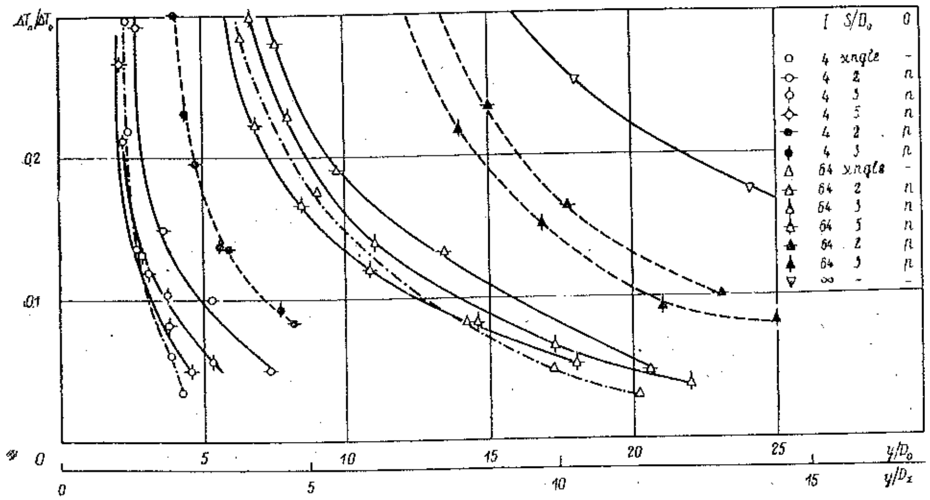


FIG. 5.

where F is the area enclosed by isotherm $\Delta T=0{,}1\ \Delta T_m$. In Fig. 4 D^* is plotted as a function of y. In such representation the spread of series of jets may be aproximated as well as for a single jet in the cross wind by linear function with various angle coefficients.

There are two possible ways of plotting the results for series of jets: a) all dimensions are non-diemnsionalized with respect to nozzle diameter D_0, b) all dimensions are non-dimensionalized with respect to equivalent diameter of three nozzles D_Σ. Last way is more justified for merging flows. D_Σ is determined as

$$D_\Sigma = 1{,}73\, D_0 \tag{2}$$

Both representations are shown in Figs. 4–6.

As it can be seen from Fig. 4 the rate of spread of normaly oriented series (solid lines) is higher than of parallel series (dashed lines). For the same mode of orientation the rate of spread is higher for lower values of I and higher values of S/D_0

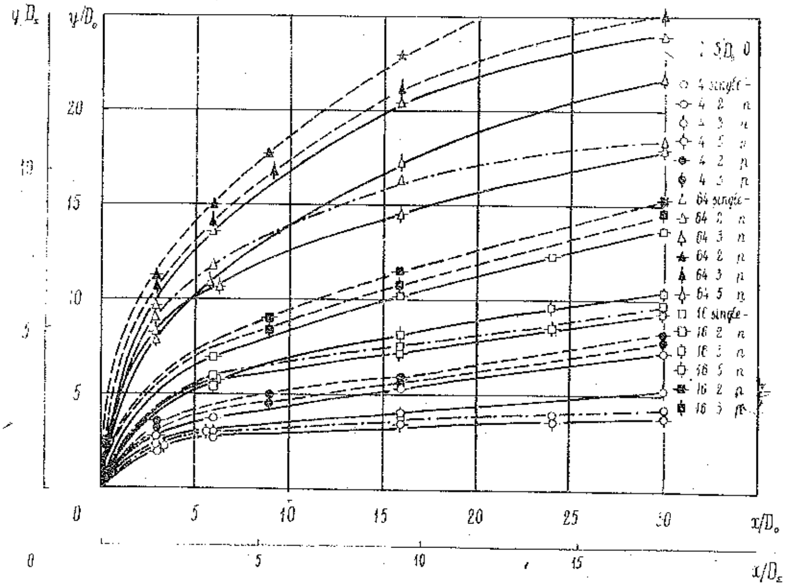


FIG. 6.

although for parallel orientation dependence on S/D_0 is rather weak. For normal orientation the rate of spread of system is higher than of single jet in both representations: $(D^*/D_0, y/D_0)$ and $(D^*/D_\Sigma, y/D_\Sigma)$. Parallel system spreads at almost the same rate and for some regimes even lower than single jet.

Decay of axial temperature is presented in Fig. 5. The axis of flow was defined as a locus of maximum temperatures in cross sections. Regularities of decay are in accordance with data on spreading of jets. Curves of decay in Fig. 5 are dispersed correspondingly to values of I and S/D_0. The higher is I and smaller S/D_0, the slower is decay. Decay of temperature of normal system is significantly more rapid than of parallel system. Curves of decay for normal system are close to the curve of single jet in $(\Delta T_m/\Delta T_0; y/D_0)$ representation but when $(\Delta T_m/\Delta T_0, y/D_\Sigma)$ is used decay of temperature of system is more rapid. Decay of temperature of parallel system in $(\Delta T_m/\Delta T_0, y/D_0)$ representation is slower than of single jet and in $(\Delta T_m/\Delta T_0, y/D_\Sigma)$ coordinates the curves are rather close.

Data on spreading and decay of axial temperature of series of jets show that in different regimes the rate of turbulent mixing is various. It results in different penetrations of jets.

Trajectories of jets are presented in Fig. 6. It is possible to see from graph that qualitative dependence on parameter I is the same as for a single jet. There is difference between the shapes of trajectories of single jet and series of jets. Developement of single jet is more homogeneous. As for series of jets their regularities are different before and after merging point. Penetration abilities of system after merging of jets increase significantly. Penetration of parallel system is deeper than of normal system and for some regimes deeper than of a single jet. Increasing of S/D_0 reduces penetration for all regimes.

Presented results show that, when a series of jet are issued into the cross wind, most favorable conditions for delaying mixing process and getting maximum penetration would be parallel orientation of the series with short distance between the jets. Vice versa, for acheaving maximum mixing rate, normal orientation with sufficient distance between the jets will be the best.

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STRESZCZENIE

UKŁAD KILKU STRUMIENI PODDŹWIĘKOWYCH W PRZEPŁYWIE KRZYŻOWYM

Zbadano doświadczalnie szereg złożony z trzech równoległych poddźwiękowych burzliwych strumieni wypływających z dysz kołowych i wchodzących w przepływ krzyżowy. Wykazano, że główne charakterystyki przepływu są funkcjami stosunku strumienia do momentu strumienia, odległości między dyszami i sposobu orientacji szeregu. Przedstawiono wyniki badań dla różnych warunków przepływu.

Резюме

СИСТЕМА НЕСКОЛЬКИХ ДОЗВУКОВЫХ СТРУЙ В ПОПЕРЕЧНОМ ПОТОКЕ

Ряд из трех параллельных дозвуковых турбулентных струй, истекающих из круглых сопел в поперечный поток, был изучен экспериментально. Основные характеристики потока оказались зависящими от отношения импульса струи к потоку, расстояния между соплами и типа ориентации ряда. Приводятся результаты исследования при различных условиях течения.

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