Effect of Two Inline Jets' Temperature on The Turbulence They Generate Within a Crossflow

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***Abstract*—Consideration is given in the present work to the interaction of twin tandem inclined jets of variable temperature with an oncoming crossflow. This consideration is carried out numerically by means of the finite volume method and is validated by confrontation with experimental data depicted on the same geometric replica by means of the Particle Image Velocimetry (PIV). The numerical model is actually obtained by the resolution of the Navier Stokes conservation equation system by means of the turbulent Reynolds Stress Model (RSM). A non uniform grid system was applied and was particularly tightened in the vicinity of the jet nozzles in order to describe well the near field mechanisms. In this paper, we intend to focus more precisely on the exploration of the different shear stress components' behavior along the whole domain. This will give an overall idea about the established turbulence that is best way to characterize well the occurring mixing process. The latter acquires a primordial importance due to its presence in various applications and its dependence in various parameters. The efficiency of the meant applications is actually mainly equivalent to that of the mixing process itself. Since in most of the applications there is a constant need of higher temperatures, we propose here to evaluate the impact of this parameter on the generated turbulence and then on the mixing process.**

Mixing process, shear stress, turbulence, twin jets, vorticity.

I. Introduction

"Jets in crossflow" is a common theme in the realm of fluid dynamics and heat and mass transfer. It was largely investigated in the literature but rather in the case of single and multiple jet configurations. The intermediate twin jet configuration was on the contrary significantly less considered in spite of its great relevance. In fact, its understanding is likely to predict the usefulness or uselessness of emitting further jets in the handled applications. The latter are mainly industrial and academic and include the traditional chimney stack exhaust, the V/STOL aircrafts, the injection of fuel within combustion chambers, the film cooling of turbine blades, the discharge of liquid effluents through piping systems, etc…

In the literature the double jet in crossflow configuration was most of the time considered in the context of comparisons. The varied parameter was either the arrangement of the double jets; tandem, side by side, opposite, etc..; or the number of the emitted jets by confronting the double configuration to the single and/or the multiple cases. Works that have dealt exclusively with the inclined jet configuration are very scarce in the literature. That of Ohanian *et al.* [1] consisted in numerical investigations of two turbulent planer jets in a cross flow and aimed at evaluating the impact of two main parameters: the velocity ratio and the jets' spacing. These parameters were determinant in the jets' throw distance as well as on their coupling which highly affect the mixing and diffusion processes in the interacting zone. Radhouane *et al.* [2] devoted a similar exclusive exploration for twin inline elliptic jets in crossflow in order to evaluate the same phenomenon: the mixing and diffusion processes. For the matter they considered different initial streamwise inclination emission angles and noted their consequences on the resulting heat and mass transfer taking place between the different interacting flows.

Makihata *et al.* **[3]** chose rather to compare the inline twin jet configuration to the single one. The jets were emitted at an inclination angle of 45°, placed following an interval ratio of 0.8 and respond to a variable injection ratio. Their paper was based upon experimental and theoretical predictions of buoyant and non-buoyant jets in a uniform crossflow. The adopted finite difference method gave a satisfying model that allowed detailing the near field dynamics. An experimental consideration of both configurations; twin and single jets in crossflow; was carried out later by Ibrahim *et al.* [4] by means of the particle image velocimetry (PIV). This work aimed essentially at evaluating the impact of the injection ratio on the different jet features such as the jet trajectory, penetration and deflection, the mass entrainment approximation based on the jet trajectory, the windward and leeward jet spread, the size, location and magnitude of the reverse flow region, the turbulent kinetic energy, etc… which allowed to observe a striking resemblance between the tandem and single jet evolutions.

Isaac *et al.* [5] carried out a larger consideration by comparing twin jet configuration to both single and multiple jet cases. That was carried out experimentally by means of hot wire anemometry on vertical jets placed at a distance of 4 nozzle diameters in a wind tunnel using a jet-to-crossflow ratio equivalent to 2. The comparison concerned the extent of the different jets' trajectories and the velocity and turbulence flow details at several cross sections. The initial jet conditions proved to be determinant on the corresponding trajectories but had no impact ton the turbulent parameters themselves.

The latest work having dealt with different number of emitted jets belongs to Maidi *et al.* [6] that compared twin tandem and side by side jets in crossflow to single and triple

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normal square configurations. This comparison was conducted numerically by means of direct numerical simulations (DNS) where the jets responded to the following conditions: an injection ratio of 2.5 and a Reynolds number of 225, based on the free-stream quantities and the jet width. This study allowed correlating the behavior of the developed vortical structures; mainly the counter rotating vortex pair (CVP) to the jet nozzles' spacing.

The earliest comparison between different arrangements of a double jet configuration was carried out by Ziegler *et al.* [7]. It has been followed by many others but the most recent one is for sure that of Kolar *et al.* [8] where it was similarly question of tandem and side by side oriented twin jets in crossflow.

In the present work, we propose to give a more extensive consideration to the twin inline jets and more particularly to their double turbulent interaction: both with each others and with the mainstream. Such an approach has been tackled by several authors but never in the case of a double jet in crossflow. It was for example explored by Khan *et al.* [9] while tracking experimentally the evolution of a single vortex generating jet within a water channel. The data obtained by three-component laser Doppler velocimetry (LDV) showed many interesting features of the flow such as the deficit of streamwise momentum in the vortex core, the thinning of the boundary layer on the downwash side of the vortex, the thickening of the boundary layer on the upwash side, etc… These observations were drawn mainly from plots of the turbulent kinetic energy and the tangential turbulent shear stress distributions. The same experimental procedure was adopted by Johnson *et al.* [10] and the same features were evaluated but under changing geometric inlet conditions of the jet-holes. The impact of this factor appears only in the near field and is reflected on the higher attained turbulence levels and the development of the dominant vortical structures. This is believed to result both from flow separation and free shear layer instability inside the jet-hole.

The shear stress distributions were also evaluated by Ahmed *et al.* [11] in the case of the injection of triple inline rectangular jets in crossflow within a coal-fired power station boiler. This study stated the major impact of the observed turbulence in enhancing the gas and fuel mixing process.

II. NUMERICAL PROCEDURE

Fig. 1 represents the geometric replica to model that has been considered both experimentally and numerically.

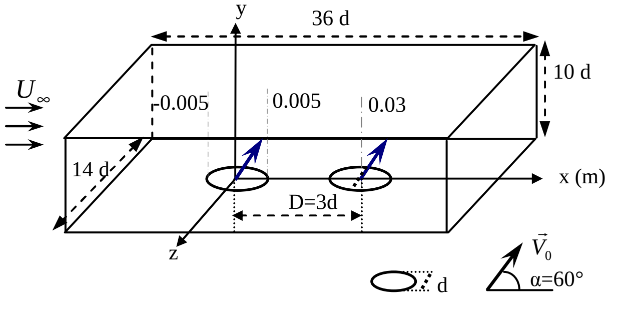

Fig. 1 Scheme of the handled configuration

A Cartesian coordinate system was adopted and it origin was placed within the upstream jet nozzle to account for the possible asymmetry of the resulting flowfield in spite of the symmetry of the geometry.

Consideration is given to a steady, three-dimensional, incompressible and turbulent flow. The Navier stokes conservation laws are then written as follows:

$$\frac{\partial\left(\bar{\rho}\,\tilde{u}_i\right)}{\partial x_i}=0 \qquad (1)$$

$$\frac{\partial\left(\bar{\rho}\,\tilde{u}_i\,\tilde{u}_j\right)}{\partial x_j}=-\frac{\partial \bar{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu\frac{\partial \tilde{u}_i}{\partial x_j}-\rho\,\overline{u_i'' u_j''}\right)+\left(\bar{\rho}_\infty-\bar{\rho}\right)g\delta_{ij} \qquad (2)$$

$$\frac{\partial\left(\bar{\rho}\,\tilde{u}_j\,\tilde{T}\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\frac{\mu}{Pr}+\frac{\mu_t}{\sigma_t}\right)\frac{\partial \tilde{T}}{\partial x_j}\right] \qquad (3)$$

$$\frac{\partial\left(\bar{\rho}\,\tilde{u}_j\,\tilde{f}\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\frac{\mu}{Sc}+\frac{\mu_t}{\sigma_f}\right)\frac{\partial \tilde{f}}{\partial x_j}\right] \qquad (4)$$

The introduction of the fluctuating functions and variables requires the use of a turbulent closure model. The RSM (Reynolds Stress Model) second-order model was chosen for its ability to model the turbulent features developed in the near field and whose exploration constitutes our main goal in this paper. The introduction of this model leads to the resolution of the following equation:

$$\underbrace{\frac{\partial}{\partial x_k}\left(\bar{\rho}\tilde{u}_k\overline{u_i'' u_j''}\right)}_{C_{ij}}=\underbrace{\frac{\partial}{\partial x_k}\mu\frac{\partial}{\partial x_k}\left(\overline{u_i'' u_j''}\right)}_{D_{ij}^L}\underbrace{-\bar{\rho}\left[\overline{u_i'' u_k''}\frac{\partial \tilde{u}_j}{\partial x_k}+\overline{u_j'' u_k''}\frac{\partial \tilde{u}_i}{\partial x_k}\right]}_{P_{ij}}+D_{ij}^T+G_{ij}+\phi_{ij}+\varepsilon_{ij} \qquad (5)$$

where C_{ij} is the convective term, and D_{ij}^L, P_{ij}, D_{ij}^T, G_{ij}, ϕ_{ij}, ε_{ij}, respectively, the molecular diffusion, the stress production, the turbulent diffusion, the buoyancy production, the pressure strain and the dissipation rate of the turbulent kinetic energy [12].

The equations of the turbulent kinetic energy (k) and of the dissipation rate of the kinetic energy (ε) associated with the second-order model are defined as follows:

$$\frac{\partial\left(\bar{\rho}\tilde{u}_j k\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+\frac{1}{2}\left(P_{ii}+G_{ii}\right)-\bar{\rho}\,\varepsilon \qquad (6)$$

$$\frac{\partial\left(\bar{\rho}\tilde{u}_j\,\varepsilon\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+C_{\varepsilon 1}\frac{1}{2}\left(P_{ii}+C_{\varepsilon 3}G_{ii}\right)\frac{\varepsilon}{k}-C_{\varepsilon 2}\,\bar{\rho}\,\frac{\varepsilon^2}{k} \qquad (7)$$

For more information concerning the constants introduced in the different equations see reference [13]

The resolution of the two last equations is quite delicate as further nodes are needed in the near field in order to model well the corresponding mixing mechanisms. To overcome this problem, we opted for a non uniform grid system particularly tightened near the jet nozzles. The discretized equations are then solved by means of the finite volume method.

III. RESULTS AND DISCUSSION

The validation of the numerically elaborated model is realized by confronting the calculated results to data depicted experimentally by means of the particle image velocimetry (PIV) technique. Both the twin jets and the crossflow are assumed to contain air.

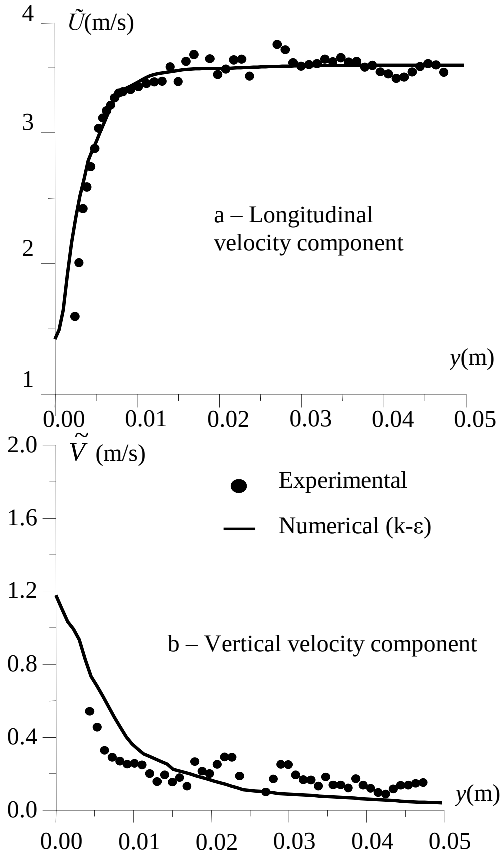

Fig. 2 Confrontation of the longitudinal and vertical velocity distributions in the symmetry plane, within the upstream jet location (x=0 mm)

Both flows were seeded: the jets with glycerin particles and the mainstream with oil droplets. This procedure allows a better track of the jets during the mixing process. Different parameters were experimentally varied but the confrontation case corresponds to an injection ratio of R=1.29, a jet spacing of D=3d and an initial jet inclination of α=60°. The distribution of both the longitudinal and the vertical velocity components were plotted on the symmetry plane and within the upstream jet location (fig. 2). The longitudinal component seems to be well reproduced along the y coordinates. The slight discrepancy detected in the vicinity of y=20 mm may originate from the transition between the first jet plume and the surrounding transverse flow. A slightly weaker agreement is noted on the vertical velocity component distribution. It may result from a non uniformity in the jet seeding; even if the latter was regulated by a pumping system.

We can state then that the RSM model reproduces satisfyingly the handled geometry. Now that it is validated, our replica can even be generalized in order to approach better the real and large scale conditions. For that, we propose to introduce a non reactive fume within the jet nozzles. It is composed as follows: 76.9% N_2, 20.9% CO_2, 18% O_2 and 0.4% SO_2. We also varied the gradient between the interacting flow temperatures; the mainstream's one being maintained constant.

These assumptions and the remaining boundaries are summarized in the table 1. These conditions will remain the same for the rest of the paper. Only the injection ratio changes and becomes R=2 for a better observation of each of the jets before they bend and combine under the main flow's impact.

Table 1. Boundary conditions and fume composition

Injection Nozzles	$u=v_0\cos\alpha$, $v=v_0\sin\alpha$ T_0=variable	$k=10^{-3}v_0^2$ $\varepsilon=k^{3/2}/0.5d$
Crossflow	$u=v_0$, $v=0$ T_∞=303.15K	$k=\varepsilon=0$
Fume Composition	N_2:76.9%, CO_2:20.9%, O_2:1.8%, SO_2:0.4%	

We propose at present to track the evolution stages of the turbulence generated by the different flows' interactions. This examination may be carried out by plotting the distribution of the velocity components, by drawing the vorticity field or by evaluating the shear stress components themselves since they constitute together the basis of the generated turbulence. Of course, we will also and above all evaluate the impact of the imposed temperature gradient on their evolution stages.

As a primer step, this paper will be dedicated only to the tangential $\overline{u'v'}$ shear stress component distribution. To cover the entire domain, we considered four characterizing zones that were chosen in function of the jet nozzle locations. This dividing gave rise to the following zones: the center of the upstream and downstream jets, the mid-distance of the jet nozzles and finally far downstream (at x=50 mm). The distribution of the $\overline{u'v'}$ component presents both negative and positive portions. The sign adopted by the plotted profiles is likely to provide a thorough idea about the nature of the occurring mechanisms and their location with reference to the different interacting flows. Globally when $\overline{u'v'}$ is negative, that means that we are within the wake region developed downstream of the evolving jets. It is on the contrary positive when we reach the top side of the jets: at the interface of the interacting flows (Ahmed *et al.* [11]). Khan *et al.* [9] found out a further condition to the possible negativity of this feature. It consists in the crossing of the thinned and thickened portions of the boundary layer. Otherwise, the same authors [9] stated that the enhancement of the $\overline{u'v'}$ stress component is not simply due to the augmentation of the normal $\overline{u'u'}$ or $\overline{v'v'}$ stress values but also and essentially to the presence of the vortices embedded in the boundary layer.

We propose to check these and further observations by paying extensive consideration of what occurs within the different characterizing zones one by one in the sense of the oncoming crossflow. The first location to consider coincides with the upstream jet nozzle that shields the upstream jet core. The wake region has then not developed yet. Nevertheless, two striking features already developed: the initial $\overline{u'v'}$value is both non null and negative; even if very weak (fig. 3-a). According to Ahmed *et al.* [11], this non zero value might occur due to the diffusion transport occurring in the cross stream directions from regions of peak generation. Concretely, this diffusion transport in spite of our location within the first jet core may originate from a pressure gradient. This pressure gradient exists between the evolving jet and the oncoming mainstream and is particularly significant due to the direct confrontation of both flows. It is so important that it may be able to push the environing flow within the jet nozzle and result in a significant diffusion process.

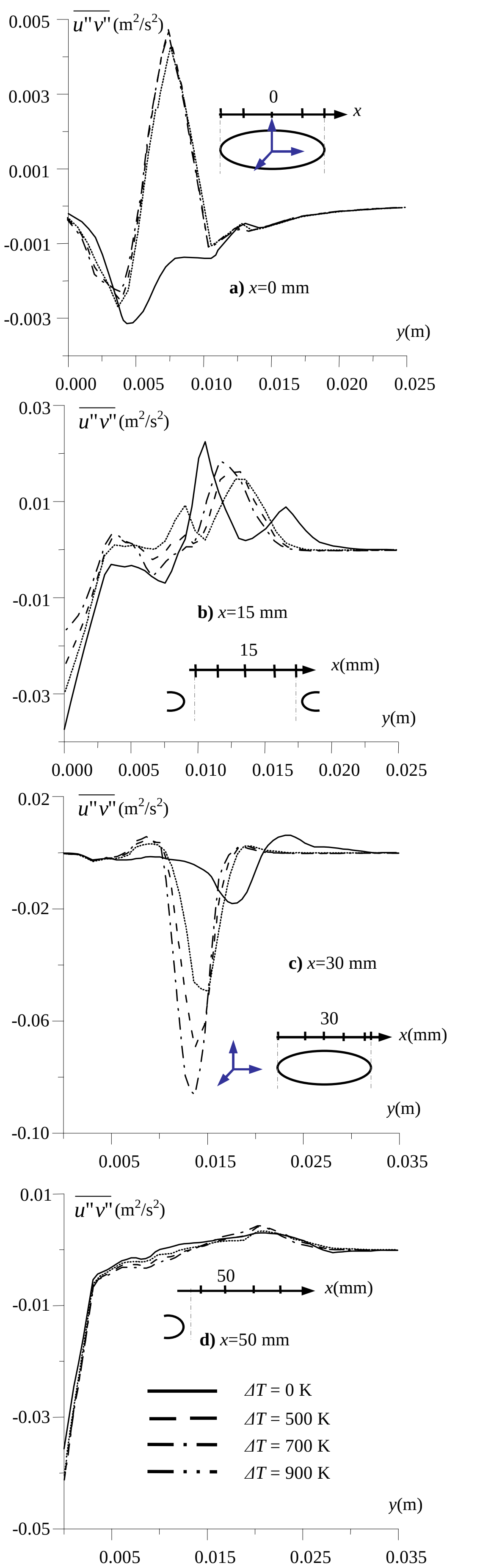

Fig. 3 Impact of the temperature gradient on the vertical distribution of the tangential $\overline{u''v''}$ shear stress component

The second feature to note is the negative trend of the $\overline{u'v'}$ profile that is simply a direct consequence of the diffusion transport. In fact when emitted, the jets constitute an obstacle to the free progression of the main flow. The latter is then blocked at the base of the rear jet column which engenders a significant velocity and pressure gradients. The main flow is consequently bound to accumulate, go backward or to be aspired by the jet nozzle. Whatever the adopted mechanism, a sensible deceleration and/or recirculation of the flow take place which comforts the negative trend of the examined stress component evolution. The $\overline{u'v'}$ distribution accuses then a sudden augmentation. This augmentation occurs departing from y=4 mm and attains its maximum at y=7 mm. The latter position coincides with the interface between the mainstream and the evolving rear jet: where the confrontation of the interacting flows attains its utmost. Plotting such a distribution in successive longitudinal positions is likely to delimitate the leeward border of the emitted jet.

Herein, we have to note that the introduction of the gradient between the different flows' temperatures affected only slightly the level of the attained negative peak whereas it was determinant for the positive one. It was even absent under the isotherm case which shows how this parameter is essential for the evolving of the rear jet and its resistance towards the flattening effect of the crossflow. We can then presume that in absence of temperature gradient, the upstream jet was totally flattened by the mainstream which canceled any interface between them. Once we go beyond of the interacting zone of the rear jet and the environing flow (increasing y coordinates), we reach the steady zone that did not witness any perturbation: the uniform crossflow where no interaction occurred which justifies the absence of turbulence production (the stress components are null there). The vanishing of this component was not affected by the temperature gradient in the present zone whereas it will be in the following ones due to the further and more significant mechanisms that are going to take place.

The second jet nozzle shields a behavior that shares many common points with the one adopted previously. These points are even similar at the first evolution stages and consist in the negative and then the positive portions of the plotted profiles. After that and starting from y≈10 mm, we assist to a different behavior that seems very dependant in the imposed temperature parameter. It consists in a tough decline that is deeper for the increasing temperature gradients. The amplitude of this decline, its origin and its extent may be explained with reference to fig. 4. The latter represents the contours of the $\overline{u'v'}$ shear stress component on the symmetry plane (z=0) under the isotherm and two non isotherm cases: the minimum (ΔT=500 K) and the maximum (ΔT=900 K). It shows the development of a significant zone where the tangential shear stress is negative as soon as we introduce the temperature gradient between the interacting flows. This negative stress zone is actually generated by the trapping and then accumulation of the flow both under the top side of the downstream jet and the leeward side of the upstream one.

In fact, the flow contained between the twin jet nozzles has no ability to flee the injection plate and progress with the environing flow.

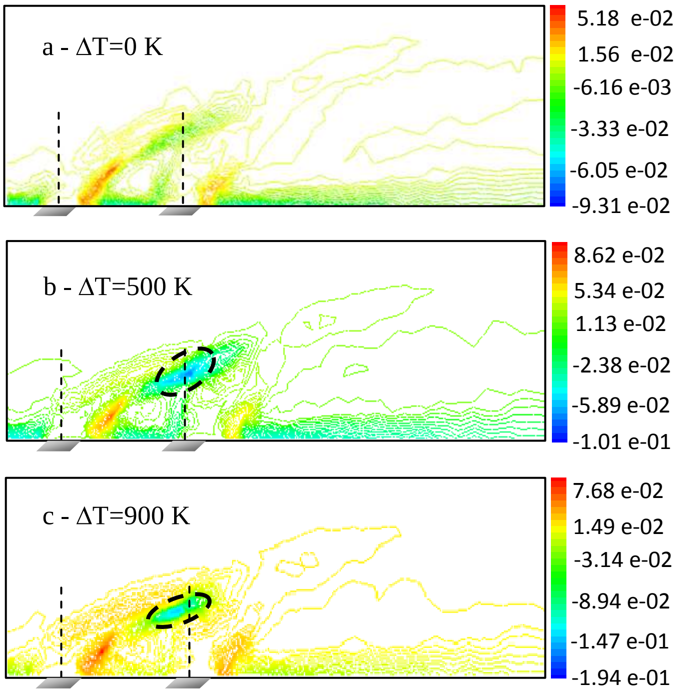

Fig. 4 Contours of the $\overline{u'v'}$ (m^2/s^2) shear stress component on the symmetry plane under the isotherm, ΔT=500 K and ΔT=500 K cases

It is on the contrary constrained to remain between the injection plate from below and the twin jet borders from the other sides (encircled in fig.4-b and c): that's why we say that it is trapped. Since there is a conservation of the momentum quantity, the trapped flow is bound to re-circulate indefinitely and/or to flee laterally. It's probably both of the mechanisms that take place.

Another striking feature is to note concerning this negative peak. It consists in its delay as the temperature gradient climbs. This delay is simply due to the further impulsion of the most heated jets which engenders a further crossing of the domain. The strong turbulence zone will consequently be shifted away in the longitudinal direction which results in the shifting of its corresponding peak. The initial inclination of the jet emission is a supplementary factor that enhances the peak shifting. As soon as this highly turbulent zone is crossed, a further positive peak is accused. It is less pronounced than the first one despite originating from the same phenomenon: the interface between the rear jet and the environing flow. It is however less marked due to the interaction of the mainstream with the extent of the rear jet and not the just emitted and then still strong jet.

The temperature gradient in this location generates on the contrary a less significant turbulence; this is yet understandable. In fact, the jet that is heated further has already spread within the domain and once it reaches this far position (y≈19 mm), it is no longer likely to generate turbulence anymore. The weaker turbulence produced under the isotherm case is then likely to be preserved later which delays the final vanishing of the resulting flow turbulence.

Between the twin jet nozzles (fig. 3-b), the profile of the $\overline{u'v'}$ shear stress component begins directly with a significant negative value. This is due to the already described high perturbation taking place due to the trapped flow between the jet columns. If we re-consider fig. 4, we can see that a high shear stress is found also near the injection plate and corresponds to the wake region of the upstream jet. This zone is highly affected by the imposed temperature of the jets. In fact, heating more the jets enables them to flee farther the injection plate before bending. A less significant wake region and less prominent vortices are consequently generated at the base of the jet columns. When the imposed temperature gradient decreases, the rear jet is on the contrary flattened more significantly creating a more pronounced wake region and more embedded vortices. This observation is reflected on the scale of the minimum values attained by the $\overline{u'v'}$ component at mid distance between the jet nozzles. It is in the vicinity of -5e-02, -3e-02 and -2e-02 respectively under the isotherm, ΔT=500 K and ΔT=900 K cases.

Once we go out of the wake region, we get into a weak turbulence zone which justifies the less significant variations along the $\overline{u'v'}$ distribution. This zone corresponds to the steady crossflow that remained re-circulating out of reach of all the boundaries: both jets' borders and the injection plate. The most significant peak is attained at the vicinity of y=11 mm and corresponds as previously mentioned to the reaching of the interface between the extent of the rear jet and the environing crossflow. The extent of the upstream plume is still significant, that's why the range of the attained peak is high with reference to the one attained at the downstream jet location (0.02 m^2/s^2 here and 0.005 m^2/s^2 farther). The temperature gradient affects in this location the number of the intermediate peaks that is sensibly reduced when the jets are heated further. The attained peaks are on the contrary preserved longer when the temperature of the jets is lowered resulting in a later vanishing of the resulting flowfield's turbulence.

The impact of the imposed temperature gradient is however sensibly reduced far downstream both on the departing value, the vanishing moment and the intermediate variations. The latter are summed in a simple increasing with a moderate slope. The only peak is attained at the vicinity of y=20 mm, location at which develops the interface between the combined jet plumes and the mainstream. The corresponding level is approximately similar to the one attained at the rear jet wake region.

We see then that the gradient between the jets and the mains flow temperatures enables the jets to flee farther from the injection wall. This helps generating weaker wake regions at the base of both jet columns but on the same time results in a stronger negative shear stress zone (even if less staggered on space) confined between the jets' borders and the injection plate. Finally, since heating the jets accelerates their spreading within the environing crossflow; it naturally results in an earlier vanishing of the resulting flowfield's turbulence.

IV. Nomenclature

Symbol	**Description**	**Unit**
d	Jet Nozzle Diameter	m
D	Nozzles' Spacing	m

f	Mass Fraction	No unit
g	Gravitational Acceleration	m/s^2
G_k	Term of production due to buoyancy forces	$kg/(m\ s^3)$
k	Kinetic Energy of Turbulence	m^2/s^2
D	Center-to-Center Distance	m
P_k	Term of production due to the mean gradients	$kg/(m\ s^3)$
R	Velocity Ratio	No unit
S_{ij}	Mean Strain Rate	No unit
T	Temperature	K
U_∞	Crossflow Velocity	m/s
V_0	Injection Velocity	m/s
u_i, u_j	Velocity components along the i and j directions	
u, v, w	Velocity components along x, y, and z directions	m/s
x, y, z	Cartesian Coordinates	m
	Greek Symbols	
ρ	Volume mass	Kg/m^3
β	Thermal Expansion Coefficient	No unit
ε	Dissipation Rate of the Turbulent Kinetic energy	No unit
μ	Kinetic Viscosity	kg/(m s)
μ_t	Turbulent (or eddy) Viscosity	kg/(m s)
α	Injection Angle	°
δ_{ij}	Kronecker symbol (=1 if i=j and 0 if i≠j	No Unit
	Subscripts	
∞	Conditions in Crossflow	No unit
0	Exit Section of the Jet	No unit
	Superscripts	
–	Reynolds average	No unit
˜	Favre average	No unit

V. Conclusion

Consideration was given in this paper to the influence of the temperature of two inclined inline jets on their interaction with an oncoming uniform crossflow, the temperature of the latter being kept constant. In an aim to evaluate the impact of the temperature on the whole mixing process, we proposed to track the particular evolution of the $\overline{u'v'}$ tangential shear stress component along the domain. This consideration was made possible thanks to the modeling of the handled geometry by means of the finite volume method together with the RSM second order turbulent model.

The conclusions drawn from the present study are summarized in the following key notes:

- The augmentation of the temperature gradient enables them to cross deeper vertically the domain before tilting under the flattening effect of the crossflow.
- The most heated jets generate weaker wake regions at the base of both jet columns but a stronger confined turbulence zone.
- The augmentation of the temperature gradient engenders an earlier vanishing of the resulting flowfield's turbulence.

References

[1] T. Ohanian, H.R. Rahai, , "Numerical investigations of multi turbulent jets in a crossflow", AIAA 2001-1049, 2001.

[2] A. Radhouane, N. Mahjoub Saïd, H. Mhiri, G. Le Palec, P. Bournot, "Impact of the initial streamwise inclination of a double jet emitted within a cool crossflow on its temperature field and pollutants dispersion", Heat and Mass Transfer, Springer, 09.01.2009, 45(6), pp. 805-823

[3] T., Makihata, Y., Miya, "Trajectories of single and double jets injected into a crossflow of arbitrary velocity distribution," J. Fluids Eng., 101, 1979, pp. 217-223.

[4] I.M. Ibrahim, E.J. Gutmark, "Dynamics of single and twin circular jets in crossflow". 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 2006.

[5] K.M. Isaac, A.K. Jakubowski, "Experimental study of the Interaction of Multiple Jets with a Cross Flow." AIAA Journal, 23(11) , 1985, pp. 1679- 1683

[6] M. Maidi, Y. Yao, "Numerical visualization of vortex flow behavior in square jets in crossflow", Journal of visualization, 11(4) , 2008, pp. 319-327

[7] H. Ziegler, P.T. Wooler, "Multiple Jets Exhausted into a Crossflow," J. Aircrafl, 8(6), 1970, pp. 414-420.

[8] V. Kolar, E. Savory, H. Takao, T. Todoroki, S. Okamoto, N. Toy, "Vorticity and Circulation Aspects of Twin Jets in Cross-Flow for an Oblique Nozzle Arrangement", Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 220(4) , 2006, pp.247-252

[9] Z. U. Khan, J. P. Johnston, On vortex generating jets, International Journal of Heat and Fluid Flow 21, 2000, pp.506-511

[10] J.P. Johnston, B.P. Mosier, Z.U. Khan, Vortex generating jets; effects of jet-hole inlet geometry, International Journal of Heat and Fluid Flow 23, 2002, 744–749

[11] S. Ahmed, J. Hart, J. Nikolov, C. Solnordal, W. Yang, J. Naser, The effect of jet velocity ratio on aerodynamics of a rectangular slot-burner in the presence of cross-flow, Experimental Thermal and Fluid Science 32, 2007, 362–374

[12] R. Schieste, B.E Launder, "Modélisation et simulation des écoulements turbulents", Hermès, Paris, France, 1993.

[13] N. Mahjoub, H. Mhiri, S. Golli, G. Le Palec, P. Bournot, 'Three dimensional numerical calculations of a jet in an external crossflow: application to pollutant dispersion", ASME J. of heat transfer, 2003,125.