Dynamics of Multiple elevated Jets in Cross flow

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Abstract — **Introducing higher temperature inflows has proved to be one of the best solutions to higher power demands in the industry, namely in combustions chambers and turbine engines. The eventual drawbacks of such an initiative are the damages brought to the shielding engines as well as the generation of too much heated and/or toxic exhausts, likely to put the atmosphere at great risks (acid rain and fog strongly affecting fauna and flora).**

To cope with such intricate situations, it's highly recommended to track carefully the discharge of multiple jets in cross flows, under all possible affecting parameters. Such a consideration is likely to enlighten the different engendered mechanisms dynamic mixing and heat and mass transfer): their origins, their favorable conditions, their extent and how to control each of them.

For the matter, a variable number (twin and triple) of variably elevated (h=1, 2 and 5 cm) inline jet models are considered experimentally in the present work, in interaction with an oncoming cross flow generated within a laboratory wind tunnel, under different flow regimes (variable injection ratio).

A good comprehension of these experimental models is likely to provide a consistent data basis for later numerical simulations of similar small models or even larger real scale models available in the industry.

***Keywords*— multiple jets, cross flow, injection height, injection ratio, vortices.**

I. INTRODUCTION

Multiple jets in cross flow (MJICF) are frequently found in several applications and domains. An efficient control of the different mechanisms it engenders is consequently highly recommended to avoid hazardous behaviors and useless risks on operators and the sheltering environments.

MJICF are found in industrial applications such as film cooling of turbine blades and effusion cooling of combustors. In both applications the problem consists of introducing higher pressure ratios and higher temperature rises, to reach better performances of modern gas turbine engines.

MJICF are also of particular interest in the medical field in applications like blood injection during hemodialysis through one or more holes at the tip of a catheter, typically positioned at the superior vena cava [1].

Finally and not the least, liquid and gas MJICF are observed in environmental applications. In fact, waste waters generally need some chemical treatment and a serious control while being discharged through multiport diffusers into coast waters either because of their contents or of their thermal characteristics. Fume stacks, as well, need similar accurate handling when discharged in the atmosphere at high temperatures and or/containing reactive particles due to the eventual chemical reactions they engender.

In the open literature, multiple jets in cross flow were considered either globally by considering multiple, differently arranged, jets in cross flow, or gradually by concentrating on the single jet model physics and trying afterward to upgrade it to reach more realistic models. The earliest single jet in cross flow-studies available in the literature were carried out by Jordinson et al. in 1958 [2] and Gordier in 1959 [3] while the earliest multiple jets in cross-flow study dates back to 1971 where Ziegler and Wooler [4] generalized an analytical model initially dedicated for a single short and descending normal jet in crossflow. To reach their goal, they first solved the continuity and momentum equations to get the jet path. Then, they evaluated the jet velocity by replacing the jet with a sink-doublet singularity distribution, accounting for the entrainment of mainstream fluid and the blockage effect of the jet. They finally represented the influence of an upstream jet on a downstream jet in a multiple configuration by including a reduced mainstream velocity in the equations of motion. A satisfactory agreement was obtained in terms of jet centerlines and surface pressure distributions.

Briggs [5] tried to make an overview of the models available in the literature that predicted the rise of the bent-over plumes. The recent models were based upon the conservation equations for buoyancy and momentum or energy, and assumed that the mean horizontal speed of the plume in the bent-over stage essentially equals the ambient wind speed. Earlier models, on the other hand, made diverse assumptions about how the plume grows which gave rise to diverse expressions of the corresponding plume paths and

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final rise. The third and more recent collection of models that were reported by Briggs [5], made similar assumptions about how the plume grows in the initial stage of bent-over rise due to self generated turbulence, with the difference of the proportionality statement between the rise and the jet radius.

More realistic multi-source models were considered later by Briggs [6] to provide a simple enhancement factor for their plume rise in the case of bent-over buoyant plumes. For calm conditions, a crude but simple method was suggested for predicting the height of plume merge and subsequent behavior. Finally, it was suggested that large clusters of buoyant sources might give rise to concentrated vortices either within the source configuration or just downwind of it.

The above discussed semi empirical of Briggs [6] together with a further one developed by the same author [7] were reconsidered by Anfossi et al. [8] in an attempt to develop a new model based on "virtual" stack concept, able to provide estimates of maximum plums height for stacks of different emission conditions. A simplified expression was first compared to Briggs' models for equal heights and emissions. A new model was then confronted with experimental data relative to stacks of different heights with a general satisfactory agreement. Finally, a comparison was carried out with reference to the empirical expression of Montgomery et al.[9] which gave a correction factor for ground level concentrations for multiple sources and analogue ones derived from the models of Briggs [6, 7] and Anfossi et al.[8].

Overcamp [10] tried to investigate the plume rise enhancement and merge process in the case of two to four stacks models. The plumes frequently merge as they rise, and the rise is enhanced when the resultant plume rises higher than the individual plumes would have separately. The study included three major parts, namely a laboratory study on the interaction of line thermal pairs released in various configurations to determine the dynamics of plume merging, a wind tunnel study of plume rise from one to four stacks to measure plume rise enhancement and an analysis of field data to determine if plume rise enhancement is observed for actual power plant plumes.

To complete the above cited work, Overcamp [11] added three further studies that investigated the effect of the number of stacks and of the azimuthal angle between the direction of the wind and the line of stacks on plume rise enhancement. In the first study, observations were made of the merger and motion of thermal pairs: thermal pairs released in one-above-the other configurations merged more rapidly and moved faster than thermal pairs released in a side-by-side configuration. In the second study, plume rise measurements were made in a wind tunnel for plumes from two to four stacks. For a given number of plumes, the rise was higher for smaller azimuthal angles. The third study was an analysis of a large experimental data that lacked of observations which made the results inconclusive for cases with two to four plumes. Nevertheless, the ten plume cases showed higher rise and the rise was larger for smaller azimuthal angles.

Zanetti [12] considered the discharge of industrial hot pollutants into ambient air. The pollutants, emitted from smokestacks or chimneys, possess an initial vertical momentum. Both factors (thermal buoyancy and vertical momentum) contributed to increasing the average height of the plume above that of the smokestack. This process ends when the plume's initial buoyancy is lost by mixing with air.

Finally consideration was given to triplet inline jets in cross flow by Radhouane et al. in the context of an experimental study dedicated to the effect of first the injection height [13] and then both the injection height and ratio [14] over the engendered dynamic mixing and the induced vortical structures.

With regards to the abovementioned references, we see how important the issue of the elevated jets in environmental cross flows is. Since most jets were considered side by side in the open literature, we propose in the present to enrich the documentation on multiple inline jets in environmental cross flows. We particularly intend to emphasize on the combined effect of three parameters, namely the injection number, ratio and height over the jets' rise and merge, in addition to the subsequent accompanying phenomena and processes like the wake vortices and the final jets' fading.

II. EXPERIMENTAL SET UP

The experiments were carried out in a wind tunnel at the university institute of the industrial thermal systems (IUSTI), a joint research unit between the University of Provence (Aix-Marseille) and the Mediterranean University in Marseille, France. The jets handled in the present paper are emitted from elliptical cross-sections with d and $D = d/\sin\alpha$ as small and great diameters, respectively. In fact, the jets are emitted from 60° inclined discharging nozzles that were razed at different levels from the ground. The jets are placed three great diameters apart and tandem toward the oncoming cross flow; and are sent according to jet to cross-flow velocity ratio inferior to one ($R < 1$).

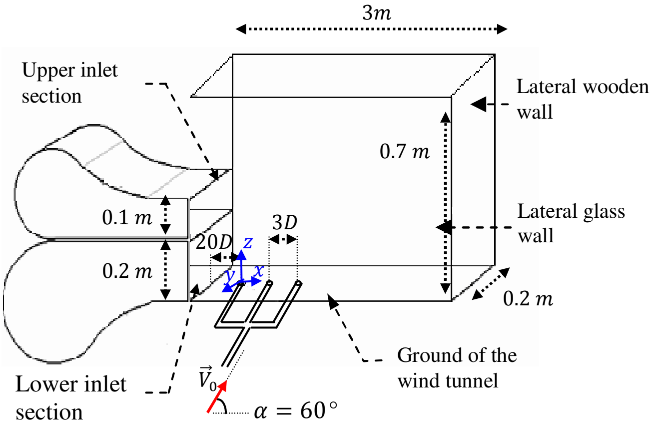


Fig. 1 Experimental setup associated with the Cartesian coordinate system

As illustrated in Fig.1 the leading injection nozzle is placed 20 great diameters apart from the wind tunnel inlet section in order to avoid the transition zone of the mainstream entrance and therefore stay away from the boundary layer influence as illustrated in previous papers in the case of twin inline jet in cross flow [15].

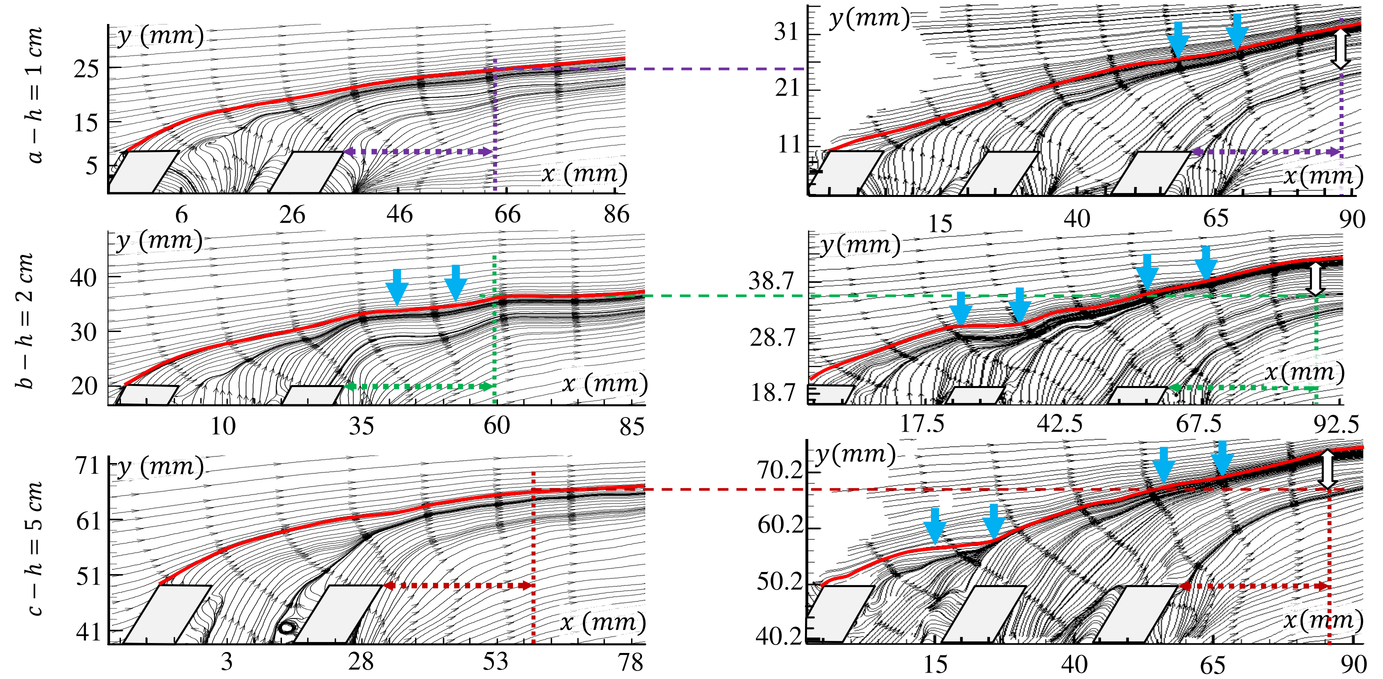
Measurements were depicted by means of Coupled Charge Device (CCD) images together with a two-component Particle Image Velocimetry (PIV) technique, in the symmetry plan $z = 0$; which allowed a non intrusive, instantaneous and mean bi-dimensional dynamic diagnosis of the resulting flow field for a given injection ratio inferior to one.

III. RESULTS AND DISCUSSION

We propose to start our discussion with the description of the established dynamic field due to its close and direct dependence on the thermal field and the induced mass transfer. Whether single or in group, when the jets interact with the surrounding cross flow, they generally result in four main vortical structures: the horseshoe vortices and counter-rotating vortex pair, known as CVP, that are present in the transverse plane, and the leading edge/shear layer vortices and wake/upright vortices that develop in the symmetry plane.

Figure 2 provides streamlines of double and triple inline jets discharged from different levels from the tunnel ground $(h = 1, 2\ and\ 5\ cm)$ under an injection ratio inferior to 1 $(R < 1)$. Our objective consists of evaluating the impact of the jets' number and elevation level over the their progression among the surrounding domain, in terms of rise, bending, merge and fading; all of which are closely implied by the established vortices, and highly affecting on their turn the induced heat transfer. Generally, as they rise, the jets expand in accordance with the adopted injection ratio, and block more or less consistently the oncoming mainstream, inducing a bow shock ahead of the first injection orifice as already observed by Chen et al. [16] in the case of a triple jet in cross flow configuration. According to the same authors [16], the bow shock produces an adverse pressure gradient and forces the approaching boundary layer to separate with an oblique separation shock. In Fig.2, the bow shock appears as a separation continuous line between the evolving jets and crossflow regions that reaches progressively higher levels as the jets are sent from higher injection nozzles. It also rises higher when more jets are discharged, as indicated by the double sided arrows in Fig.2-II, evaluated three great diameters downstream of the rear jet nozzle). The separation line appears more smoothly curved in the case of twin inline jets even if both twin and triple jet configurations are observed under almost the same injection ratio, inferior to one. Actually in a double jet configuration the leading edge jet is consistently flattened by the oncoming cross flow. Once flattened it merges with the downstream evolving jet, and they keep on rising together before fading.

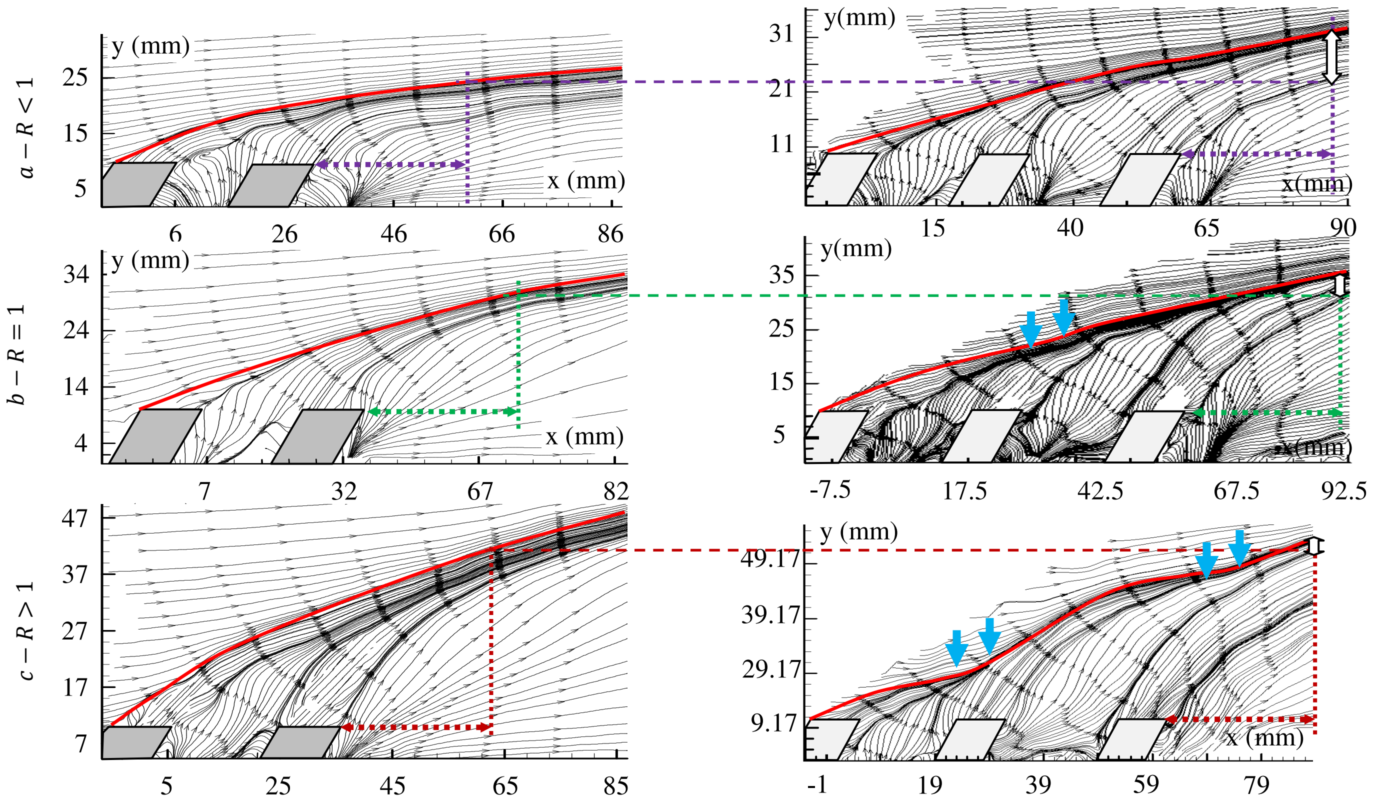
When a third jet is discharged, it rises and merges farther downstream with the upstream already merged first two jets. The moment the three of them merge, the resulting plume is "straightened", which changes the smooth curved profile of the separation line (Fig. 2-II). The separation line contains consequently quasi-stages relative to the corresponding discharged jets that are more emphasized and apparent when the jets are sent from higher levels from the ground (indicated by arrows in Fig. 2). The second important features to comment on the present streamlines are the wakes of the discharging nozzles, where the streamlines seem to be sent from either a reattachment point or line, particularly when the jets are sent close to the ground (Fig. 2-a).



I) double jet configuration

II) triple jet configuration

Fig. 2 Streamtraces under variable heights in the twin (I) and triple (II) jets configurations under R<1.



I) double jet configuration

II) triple jet configuration

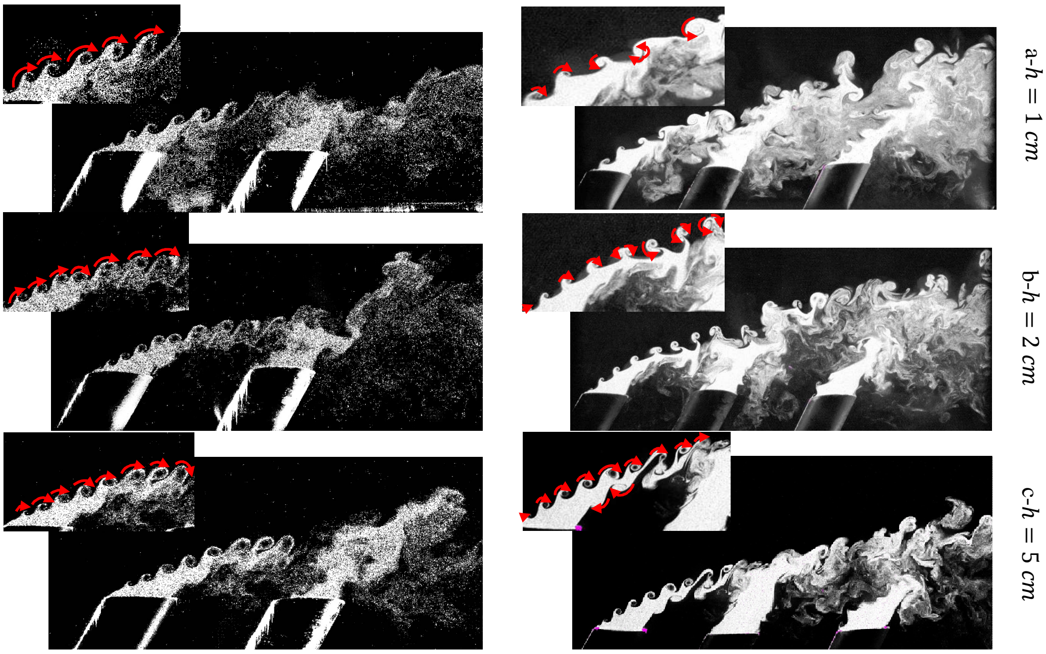
Fig. 3 Streamtraces under variable injection height in the twin (I) and triple (II) jets configurations under h=1cm.

These points or lines take place in the wake regions where wake vortices originate from the downstream cross flow shear layer [17, 18]. The induced vorticity results from the injection of the wall boundary layer where the boundary layer fluid has been "lifted-off" and wrapped around the jets [17]. Fric and Roshko [18] attribute the boundary layer fluid "lifting-off" or "sucking up" to the pressure gradient discussed by Chen et al. [16] which is actually the origin of the vertical momentum and a tornado-like structure, also said wake or upright vortices that will entrain a proportional amount of fluid with reference to the injection ratio [19].

To come back to the goal above fixed in the beginning, namely evaluating the joint effect of both the injection height and ratio, we propose in Fig. 3 to present the streamlines of double and triple inline jets discharged from $h = 1cm$ from the tunnel ground, but under a variable injection ratio: $R > 1$, $R = 1$ and $R > 1$. For a given number of discharged jets (whether double or triple jets), we note that increasing the injection height and ratio have similar effects: a further rise for the different jets which postpones their merge and later their fading. Actually, increasing both parameters results in their "liberation" from their attachment to the ground, reducing their bending and the wakes created between the ground and their lower peripheral edges. This is demonstrated in the figure through the progressively more straightened bow shocks under increasing ratios. When three jets are discharged, the global more pronounced rise is maintained over the bow shock, with however the apparition of the stages, more particularly under the highest ratios. Once again, this is due to the more "consistent" effect of the evolving jets towards the mainstream.

Nevertheless, we note that at a similar location from the rear jet (the second jet in the double configuration and the third jet in the triple configuration), the bow shock does no longer reach higher levels: the interaction zone is no longer deep vertically as in Fig. 2 under increasing injection levels (smaller vertical double sided arrows). Actually, this could be justified by the fact that increasing the injection height "protects" the jets from the attachment effect without changing their trajectories; while increasing the injection ratio "strengthens" the jets to cross deeper vertically the mainstream. As a consequence they are liberated from the attachment effect to the ground but also forced to change direction, to adopt a more straightened one.

At present, we propose to detail the effect of the same parameters on the different stages of the jets' emission both in double and triple jets' models. A particular concern is dedicated to the vortices developed on the periphery of the rising jets and their wakes. In Fig. 4, an injection ratio inferior to 1 is considered for jets discharged at the same previously adopted levels from the ground ($h = 1, 2\ and\ 5\ cm$). Since the injection ratio is inferior to one, it's obvious to note the clockwise sense of rotations of the vortices, even if more obvious on the periphery of the first jet majorly. However, what is interesting to observe is the merge process that takes place farther from the injection cross-section as the jets are sent farther from the ground.



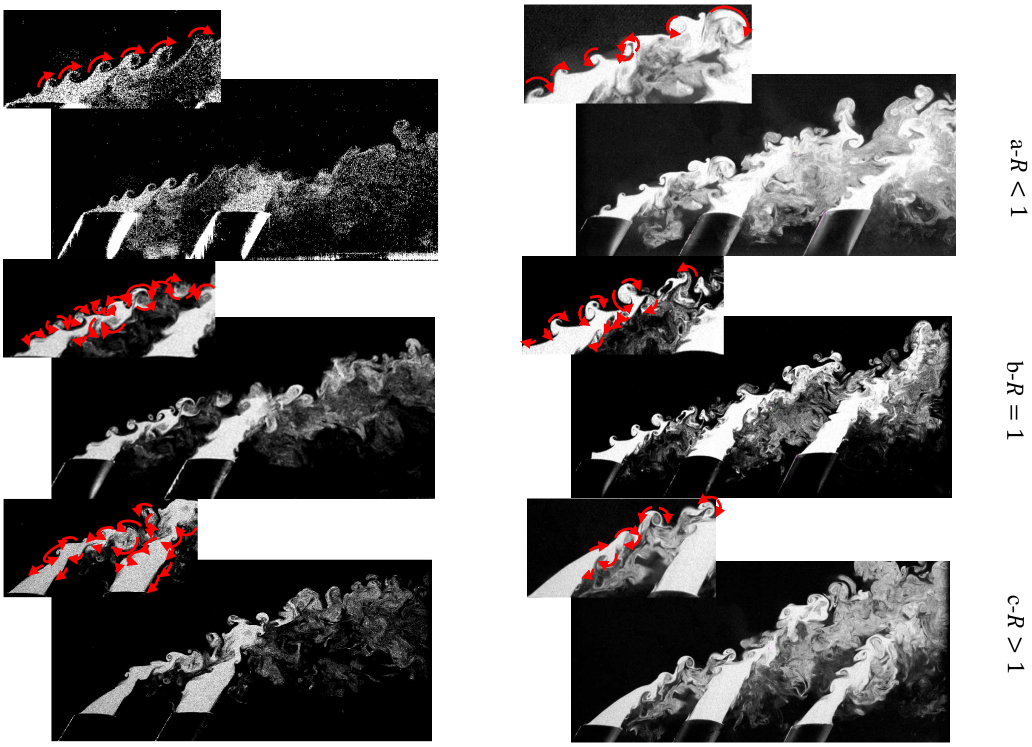
I) double jet configuration

II) triple jet configuration

Fig. 4 CCD images of twin (I) and triple (II) jets configurations under a variable height under R<1

In fact the jets are freed from the attachment effect to the ground which enables them to cross deeper the domain before bending and merging. When more jets are discharged, the stages already observed on the streamlines of Fig. 2 are found back here as soon as the upstream expanded jets join the downstream just emitted jets.

The effect of the increasing injection ratio appears in Fig. 5 through the change in the rotation sense of the leading edge vortices, from clockwise to anticlockwise, both in the double and triple jet configuration. It also results in a reduced wake due to the decreasing attachment to the ground.



I) double jet configuration

II) triple jet configuration

Fig. 5 CCD images of twin (I) and triple (II) jets configurations under a variable injection ratio for h=1 cm

However, it promotes a further vertical rise of the jets, reducing their downstream expansion, and then accelerating their streamwise fading.

IV. CONCLUSIONS

Consideration was given in the present study to multiple (double and triple) inline inclined and variably elevated jets in cross flow. The measured experimental data mainly showed that:

- Increasing the number of the emitted jets and their height implies a shaped change in the bow shock, the line separating the emitted jets and the cross flow: from smoothly curved to staged line.
- When the jets are discharged closer to the ground (decreasing h), attachment points or lines take place in the wake of the jet nozzles, due to the lifting-off of the boundary layer fluid around the jets, due on its turn to a pressure gradient.
- Multiplying the number of the emitted jets postpones their merge process deeper vertically and streamwise, without affecting the sense of rotation of the shear layer peripheral vortices.
- Increasing both the injection height and ratio liberates the jets from the attachment to the ground, reducing their bending and the wakes created between the ground and their lower peripheral edges, but for different reasons.
- Increasing the injection height “protects” the jets from the attachment effect without changing their trajectories as they are already sent far from the ground.
- Increasing the injection ratio “protects” the jets from the attachment effect by “strengthening” them, and then straightening their direction to cross deeper vertically rather than streamwise the mainstream.

Now that the effect of the injection height, ratio and number were explored, we can consider more realistic cases including the temperature parameter, and see how it can affect the generated dynamic and thermal fields.

REFERENCES

[1] J. Froust and D. Rockwell, “Flow structure associated with the multiple jets from a generic catheter tip”, *Exp Fluids* vol.42, pp 513-530, 2007. Doi:10.1007/s00348-006-0249-z

[2] R. Jordinson, “Flow in a jet directed normal to the wind”. R&M No. 3074, Brit. A R C, 1958.

[3] R.L. Gordier, “Studies on Fluid Jets Discharging Normally into Moving Liquid”. St. Anthony Falls Hyd. Lab., Tech. Paper, No. 28, Series B, 1959.

[4] H. Ziegler and P.T. Wooler, “Multiple Jets Exhausted into a Crossflow”. *J. Aircraft*, vol. 8(6), pp. 414-420, 1971

[5] G.A. Briggs, “Discussion on chimney plumes in neutral and stable surroundings”, *Atmospheric Environment*, vol. 6, pp. 507-510, 1972

[6] G.A. Briggs, “Plume rise from multiple sources”. Proc. of Cooling Tower Environment symposium, university of Maryland, pp.161-179, 4-6th March 1974.

[7] G.A. Briggs, “Plume rise predictions. Lectures on air pollution and environemental impact analysis” , pp. 59-111, 1975

[8] D. Anfossi, G. Bonino, F. Bossa and R. Richiardone, “Plume rise from multiple sources: a new model”, *Atmospheric Environement*, vol. 12, pp. 1821-1826, 1978.

[9] T.L. Montgomery, W.B. Norris, F.W. Thomas and S B. Carpenter, “A simplified technique used to evaluate atmospheric dispersion of emissions from large plants”, *J. Air Poll. Control Ass*. Vol. 23, pp. 388-457, 1973

[10] T.J. Overcamp, “ Plume rise from two or more adjacent stacks”, Report N° PPRP-67 (PB-83-179036), Power Plant Siting Program, State of Maryland, National Technical Information Service, Springfield, VA, 1982

[11] T.J. Overcamp and T. Ku, “Plume rise from two or more adjacent stacks”, *Atmosphenc Enrironment*, vol. 22(4), pp. 625-637, 1988.

[12] P. Zannetti, “Plume rise, Air Pollution Modeling”, DOI: 10.1007/978-1-4757-4465-1_5, 1990

[13] A. Radhouane, N. Mahjoub Saïd, H. Mhiri, P. Bournot, "Wind tunnel experiments of multijets in cross flow: Effect of the injection ratio", *Experimental Thermal and Fluid Science*, vol.105, pp.234-246, 2019

[14] A. Radhouane, N. Mahjoub Saïd, H. Mhiri, P. Bournot, " Dynamics of the flow field induced by multiple elevated jets in crossflow", Proceeding of the *8th International Congress on Design and Modeling of Mechanical* Systems(CMSM’2019-ID127), Hammamet, Tunisia, 2019

[15] A. Radhouane, N. Mahjoub Saïd, H. Mhiri, P. Bournot and G. Le Palec, “Twin inclined jets in crossflow: experimental investigation of different flow regimes and jet elevations”, *Environ Fluid Mech* vol.16(1), pp.45-67, 2016.

[16] P. Chen, S. Li, S. Luo and Z. Ni, “Flow visualization on lateral multiple jet interaction with freestream”, *J of Flow Control, Measurement and Visulization*. vol.2, pp. 7-11, 2014

[17] Y. Yao, and M. Maidi, “Direct numerical simulation of single and multiple square jets in cross-flow”, *Journal of Fluids Engineering*, vol. 133(3), pp:031201(1)- 031201(10), 2011

[18] T.F. Fric and A. Roshko, “Vortical structure in the wake of a transverse jet”, *J. Fluid Mech*, vol.279, pp:1-47, 1994

[19] S.H. Smith and M.G. Mungal, “Mixing, structure and scaling of the jet in crossflow”. *J Fluid Mech* , vol.357, pp.83–122, 1998