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Water injection effects on hot supersonic jet noise

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Abstract The effects of temperature both on supersonic jet noise with water injection (used for noise reduction) and on the efficiency of the method are investigated. The location of injection varies from $1.5D$ to $15D$ while the other parameters remain fixed to their optimum values. One notices better overall noise level reductions by injecting close to the nozzle exit. Moreover spectral analysis emphasizes that attenuation in high and low frequencies depends on the location of injection. Finally, the jet temperature does not greatly affect the efficiency of this method as the measured attenuation is similar to that encountered with supersonic jets with ambiant temperature. To cite this article: Y. Marchesse et al., C. R. Mecanique 330 (2002) 1–8. © 2002 Académie des sciences/Éditions scientifiques et médicales Elsevier SAS

acoustics / waves / vibrations / fluid mechanics / supersonic jets / noise reduction / water injection / temperature effects

Effets de la température sur le rayonnement acoustique des jets supersoniques en présence d'injection d'eau

Résumé Cette étude est consacrée à l'application de l'injection d'eau dans les jets supersoniques comme moyen de réduction de bruit. L'efficacité de cette méthode est testée sur deux jets ayant des températures élevées. L'abscisse d'injection varie de $1{,}5D$ jusqu'à $15D$, les autres paramètres étant fixés à leur valeur optimale. Une bonne réduction du bruit global est mesurée lorsque l'eau est injectée près de la sortie de tuyère. L'analyse spectrale montre des atténuations différentes en hautes et basses fréquences selon l'abscisse d'injection. Finalement, la température ne paraît pas jouer un rôle prédominant dans l'efficacité de la réduction de bruit par injection de masse. Pour citer cet article : Y. Marchesse et al., C. R. Mecanique 330 (2002) 1–8. © 2002 Académie des sciences/Éditions scientifiques et médicales Elsevier SAS

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Version française abrégée

La technique d'injection de masse est étudiée dans le cas de jets supersoniques ayant des vitesses identiques pour des temperatures différentes (Tableau 1). Le système d'injection d'eau est composé d'une

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couronne pourvue de huit injecteurs (Fig. 1). L'injection est effectuée aux abscisses 1,5 ; 5 ; 10 et 15 diamètres de tuyère en aval de la sortie de buse. Le champ acoustique est mesuré à l'aide de 15 microphones placés en quart de cercle centré à l'aplomb de la tuyère au sol.

On note des réductions importantes de niveaux de puissance acoustique dans le cas des deux jets testés lorsque l'eau est injectée près de la sortie de tuyère ($\Delta \sim 2{,}5$ dB). Au fur et à mesure que cette injection est effectuée en aval, la réduction s'en trouve diminuée (Tableau 2). De plus, la réduction du bruit est différente selon le type de sources présentes dans le jet. En effet, lorsque le jet présente un système de cellules de chocs, il est nécessaire d'injecter au plus près de la sortie de tuyère afin de réduire la contribution acoustique de la première cellule de choc. Dans le cas contraire, celle-ci rayonnant fortement, la réduction de bruit est faible. Pour des jets parfaitement détendus, la source principale se situe à proximité de la fin du cône potentiel, ainsi une injection en amont de cette abscisse entraîne une réduction notable du bruit.

L'étude de la directivité indique des réductions de bruit identiques pour les deux jets à savoir de fortes réductions observées dans la direction amont lorsque l'injection est effectuée dans les premières abscisses. Dans le cas d'injection plus en aval, le processus de réduction de bruit est inefficace et on note même une augmentation de bruit dans la direction amont due à l'impact de l'eau sur le jet d'air (Fig. 2).

Une analyse spectrale est ensuite menée. Les effets de l'injection d'eau sur le spectre dépendent alors de l'angle d'observation.

De façon générale, on observe une réduction de bruit en hautes fréquences d'autant moins efficace que l'injection se fait loin de la sortie de tuyère. En effet, les petites structures générées au début de la couche de mélange sont alors de moins en moins impliquées dans le processus de réduction de bruit. Le niveau des basses fréquences est quant à lui difficilement réduit. En effet, une bonne décélération des grosses structures responsables du rayonnement d'ondes de Mach est alors nécessaire et ceci est atteint pour une injection proche de la sortie de buse.

Dans la direction amont, les meilleures réductions sont obtenues pour le jet non parfaitement détendu suite à une baisse de la contribution des sources liées au réseau d'ondes de choc (Fig. 3). On note des réductions moindres dans la direction aval quelles que soient les conditions du jets (Fig. 4). En effet, cette région du jet est dominée par le rayonnement d'ondes de Mach difficilement altérable par l'injection d'eau.

Ces expériences mettent en valeur des influences négligeables de la température vis à vis de l'efficacité de la méthode de réduction de bruit par injection de masse. En effet, les réductions ainsi obtenues sont équivalentes à celles mesurées dans les jets supersoniques froids dans les conditions optimales d'injection. La température joue néanmoins un rôle dans la structure aérodynamique du jet (longueur du cône potentiel, accroissement de la couche de mélange) et ainsi dans la répartition des sources acoustiques. L'injection d'eau doit alors être adaptée pour impliquer ces sources dans le processus de réduction de bruit.

1. Water injection in hot supersonic jets

Studies related to the attenuation of jet noise have received attention in order to reduce the acoustic levels in the vicinity of space launchers. Indeed, the noise emitted by the rocket motors during lift-off is able to injure the payload [1].

This noise reduction can be achieved by modifying the parameters at the origin of the flow (diameter, coaxing flows), or by acting on the exhaust flow downstream of the nozzle exit (water injection). It appears that this last method is well adapted to supersonic jets as it does not penalize the efficiency of the jet engine. Nevertheless, previous work [2,3] has emphasized the importance of the injection conditions (angle of injection, location of injection, mass flow rate).

The main objective of water injection is to reduce the velocity of the jet through momentum transfer between the liquid and the gaseous phases. The jet noise associated with the jet velocity is then attenuated. However, the mechanisms involved in this noise reduction are complex. The injected water jet is rapidly broken down by the high speed gaseous stream producing a spray of droplets. Partial vaporization takes place by heat transfer. Moreover, injecting cold water in a hot air stream would lead to an increase of the jet density via a decrease of the jet temperature. This process would increase the acoustic contributions of the Reynolds stresses $\rho u_i u_j$. Unfortunately, one can not separate these two processes associated with water injection which have opposite effects.

According to previous work, one notices that the noise reduction is higher in supersonic jets rather than in subsonic conditions. This can be explained by the fact that the reduction of velocity is better in the former case. Furthermore, Zoppellari [3] shows that the more important reduction is reached in the case of non-perfectly expanded jet. Thus water injected in the mixing layer disrupts the efficiency of broadband noise generation associated with shock cells.

One notices that none of this work has yet studied strictly the influence of temperature on the efficiency of the water injection method. The present study proposes another set of experimental results to observe the main effects of temperature on the process of noise reduction. The first part of the study consists of introducing the operating conditions and the experimental set-up.

The effect of water injection on acoustic power is described in Section 4. Finally, studies of directivity and spectral analysis are carried out for a better understanding of the influence of temperature on the noise reduction process.

2. Jet test conditions

Water injection method has been tested on two jets with the same exhaust velocity for different temperatures (Table 1) (T_s is the static temperature). These jet conditions allow studies of temperature effects independent of those related to velocity.

The length of the potential core of a high speed jet may be estimated by the relation:

$$\frac{L_c}{D} = 3.45\left(1 + 0.38 M_j^2\right) \tag{1}$$

where D and M_j are respectively the nozzle diameter and the perfectly expanded Mach number. Using this estimate it is possible to define the location of water injection with respect to the potential core.

3. Experimental set-up

Experiments are carried out on the MARTEL facility [4] which operates with a curved-shaped convergent–divergent nozzle with a 50 mm exit diameter. This geometry is designed to provide a perfectly expanded jet without shock cells for stagnation pressure $P_i = 30$ bar and stagnation temperature $T_i = 1900$ K (jet 1 in Table 1). When stagnation conditions differ from the former values, jets are non-perfectly expanded and shock cells appear in the flow generating acoustic sources [5].

This modifies the aerodynamic structure and the type of acoustic sources in the jets tested. In the case of perfectly expanded jets, two mechanisms are responsible for noise radiation: mixing noise and Mach wave emission. The first radiates throughout the direction of observation, while Mach wave emission is merely

Table 1. Jet test conditions.

Tableau 1. *Conditions des jets testés.*

Jet	V_j (m/s)	P_i (bar)	T_i (K)	T_s (K)	L_c/D
1	1700	30	1900	860	14
2	1700	17	2100	1100	11

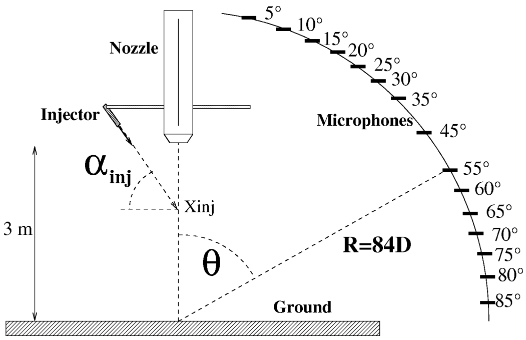

Figure 1. Experimental set-up.
Figure 1. *Configuration expérimentale.*

Table 2. Influence of water injection on acoustics power level – jet 1 ($V_j = 1700$ m/s, $T_s = 860$ K), jet 2 ($V_j = 1700$ m/s, $T_s = 1100$ K).

Tableau 2. *Influence de l'injection d'eau sur le niveau de puissance acoustique – jet* 1 ($V_j = 1700$ m/s, $T_s = 860$ K), *jet* 2 ($V_j = 1700$ m/s, $T_s = 1100$ K).

Jet 1				Jet 2			
Injection	X_{inj}/D	L_W (dB)	Δ (dB)	Injection	X_{inj}/D	L_W (dB)	Δ (dB)
no		160		no		158	
yes	1.5	157.5	2.5	yes	1.5	156	2.7
yes	5	158.9	1.1	yes	5	157.4	0.6
yes	10	158.5	1.5	yes	10	157.8	0.2
yes	15	159.8	0.2	yes	15	158	0

measured in the downstream direction. In contrast, when the jet is nonperfectly expanded, both screech and shock-associated noise are generated by shock cells and mainly radiate in the upstream direction. For these reasons, noise reduction is not explored on two supersonic jets which are identical but their temperature.

The MARTEL facility is semi-anechoic. The floor is not acoustically treated and the reflected waves are taken into account in the computation of the acoustic power L_W. Far field sound pressure spectra have been measured with 15 $1/4''$ microphones located on a quarter circle of radius $R_{SS} = 4.2$ m ($84D$) centered at the point where the jet impinges on the ground on the nozzle axis (Fig. 1).

The water injection system is composed of a ring coaxial with the air jet and includes 8 injectors. The angle of injection α_{inj} is kept constant and equal to 45 degres (zero angle corresponds to the direction normal to the jet axis). It appears that a small mass flow rate of water is sufficient to reduce shock-associated noise but an important reduction of mixing noise requires higher levels of injections. The ratio of the mass flow rate of injected water to air jet mass flow rate is chosen as $Q_w/Q_a = 2$. Several injection locations from $X_{inj} = 1.5D$ to $15D$ have been tested. The minimum value is determined by the presence of the nozzle lip.

4. Supersonic jet noise with water injection

4.1. Acoustics power level

Results are gathered in Table 2 where Δ corresponds to the difference between the level without injection and the level with injection ($\Delta > 0$: attenuation, $\Delta < 0$: amplification).

When there is no injection, the noise radiated by jet 1 is more important than the noise of jet 2. This former presents a higher temperature, and thus a lower density, for the same jet velocity. Hence, the acoustic contribution of the first term in Lighthill stress tensor ($\rho u_i u_j$) decreases [6].

Experiments indicate that the best attenuations are obtained by injecting close to the nozzle exit, whatever the jet conditions. In this case, the momentum transfer process affects both the low and high frequency sound sources. When the injection location is moved downstream, the reduction is lower. In that case, the high frequency sound production is not affected since its source is located within the first diameters downstream the nozzle.

However one notices that the attenuation obtained with the two jets are different. The reduction observed for $X_{\text{inj}} = 5D$ decreases strongly for jet 2 compared to the result obtained for $X_{\text{inj}} = 1.5D$. Actually when the injection takes place at 5 diameters downstream, the first shock cell is no longer involved in the process of attenuation and so it radiates strongly. At contrast, for jet 1, water injection at $X_{\text{inj}} = 10D$ still results in good reduction ($\Delta \sim 1$ dB). This jet presents only mixing noise generated at $7 \sim 10$ diameters downstream the nozzle exit. Water injection then effectively alters the structures responsible of low frequency noise while injection in the downstream region at 10 diameters leads to a small decrease of jet noise.

The effects of jet temperature do not appear clearly in these results as the observed attenuation is similar in the two jets when the conditions of injection are optimal. Actually, the sound attenuation according to the location of injection essentially depends on the type of sources in the jet.

Moreover, there are no significant differences between these results above and those obtained with cold supersonic jets. In the two cases, one observes higher noise reductions when the injection is made close to the nozzle exit.

4.2. Directivity

Semi-anechoic ambiance and microphones configuration used here are not suited to the study of directivity. This do not appear clearly in the results obtained (Fig. 2) but spectral analysis (Section 4.3) shows signs of the impact of the jet on the ground. Nevertheless, it allows us to comment the main influence of injection particularly in the upstream and downstream direction.

Results are similar whatever the jet conditions (Fig. 2). In the downstream direction, one always notices an attenuation, but less so when water is injected downstream. This is due to the fact that the large structures are less and less involved in the process of noise reduction.

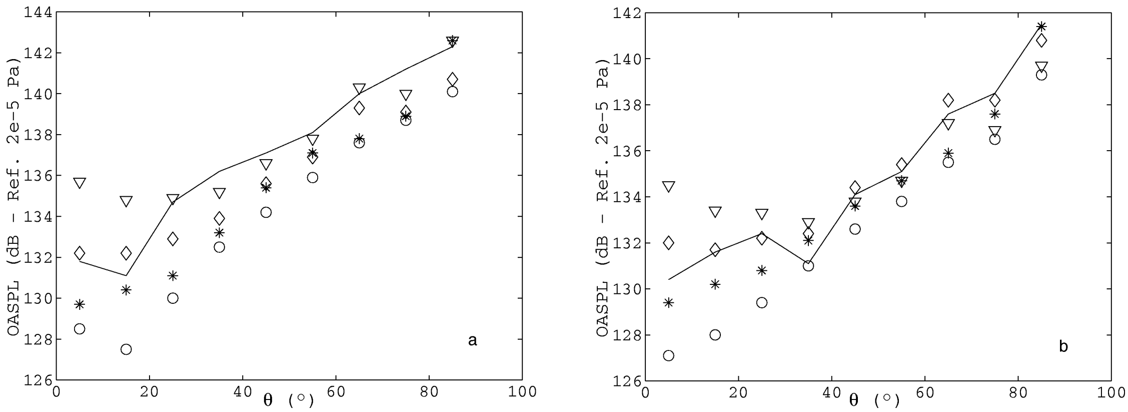

Figure 2. Effects of water injection on acoustic directivity, jet 1 (a) ($V_j = 1700$ m/s, $T_s = 860$ K) and jet 2 (b) ($V_j = 1700$ m/s, $T_s = 1100$ K). (-): without injection, ($\circ$): $X_{\text{inj}} = 1.5D$, ($*$): $X_{\text{inj}} = 5D$, ($\diamond$): $X_{\text{inj}} = 10D$, (∇): $X_{\text{inj}} = 15D$.

Figure 2. *Influence de l'injection d'eau sur la directivité du rayonnement acoustique, jet* 1 (a) ($V_j = 1700$ m/s, $T_s = 860$ K) *et jet* 2 (b) ($V_j = 1700$ m/s, $T_s = 1100$ K). (-) : *sans injection,* ($\circ$) : $X_{\text{inj}} = 1{,}5D$, ($*$) : $X_{\text{inj}} = 5D$, ($\diamond$) : $X_{\text{inj}} = 10D$, (∇) : $X_{\text{inj}} = 15D$.

In the upstream direction, noise reduction is sizable when injection takes place in the first five diameters. In contrast, for injection downstream of this location, the attenuation is small and one even notices an increase of jet noise due to the water impact on the air stream.

4.3. Spectral analysis

Present acoustic sources radiate at different frequencies in various directions. The effects of water injection thus depend on the angle of observation.

Noise reduction obtained in high frequencies mainly depends on the location of injection whatever the angle of observation. When the injection is downstream, high frequencies are less attenuated.

Experiments show that it is difficult to reduce the noise generated by large structures at low frequency as it is necessary to strongly diminish the velocity of these structures. An injection downstream at 15 diameters from the nozzle is inefficient. This observation would confirm that the main sources in a supersonic jet are located upstream of the potential coretip.

4.3.1. *Upstream direction*

One first of all observes on spectra (Fig. 3) a low frequency broadband peak ($f \sim 400$ Hz) due to the impact of the jet on the ground. This peak desappears when microphones are centered on the nozzle exit using absorbing material on the ground. However, this configuration is not recommended here as the characteristic of the absorbing material varies with water.

There are no dominant acoustic sources radiating in the upstream direction for a perfectly expanded jet. A good attenuation is then obtained with a large decrease of the jet velocity leading to an efficient reduction of the mixing noise (Fig. 3a).

In the case of the non-perfectly expanded jet, spectra is dominated by a single broadband peak at a frequency of around 4 kHz (broadband shock-associated noise); this is not the case for jet 1. It does not appear clearly in the 1/3 octave frequency representation (Fig. 3b) which is chosen in this paper for a better estimation of the reduction.

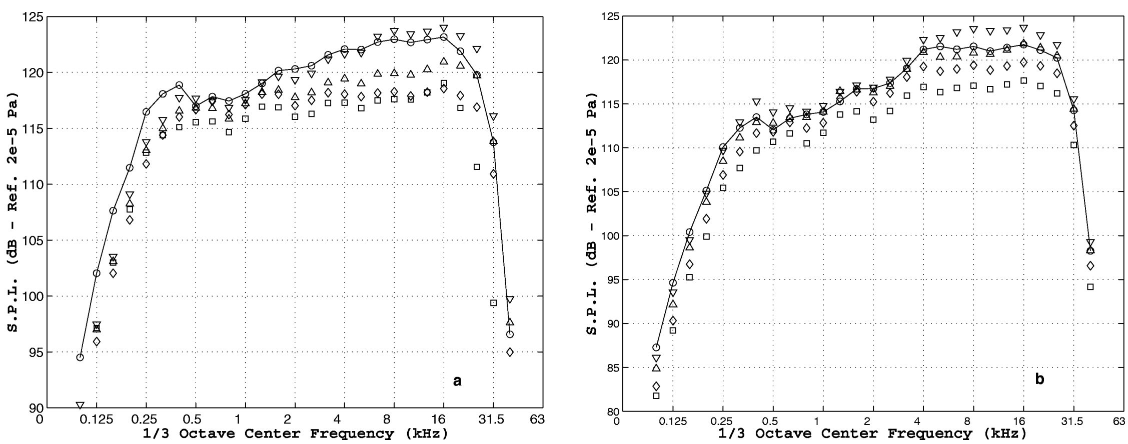

Figure 3. Effects of water injection on the noise level in upstream direction, $\theta = 25°$, jet 1 (a) ($V_j = 1700$ m/s, $T_s = 860$ K), jet 2 (b) ($V_j = 1700$ m/s, $T_s = 1100$ K). (○): without injection, (□): $X_{\text{inj}} = 1.5D$, (◇): $X_{\text{inj}} = 5D$, (△): $X_{\text{inj}} = 10$D, (▽): $X_{\text{inj}} = 15$D.

Figure 3. *Influence de la température sur le niveau sonore dans la direction amont,* $\theta = 25°$, *jet* 1 (a) ($V_j = 1700$ m/s, $T_s = 860$ K), *jet* 2 (b) ($V_j = 1700$ m/s, $T_s = 1100$ K). (○) : *sans injection,* (□) : $X_{\text{inj}} = 1{,}5D$, (◇) : $X_{\text{inj}} = 5D$, (△) : $X_{\text{inj}} = 10D$, (▽) : $X_{\text{inj}} = 15D$.

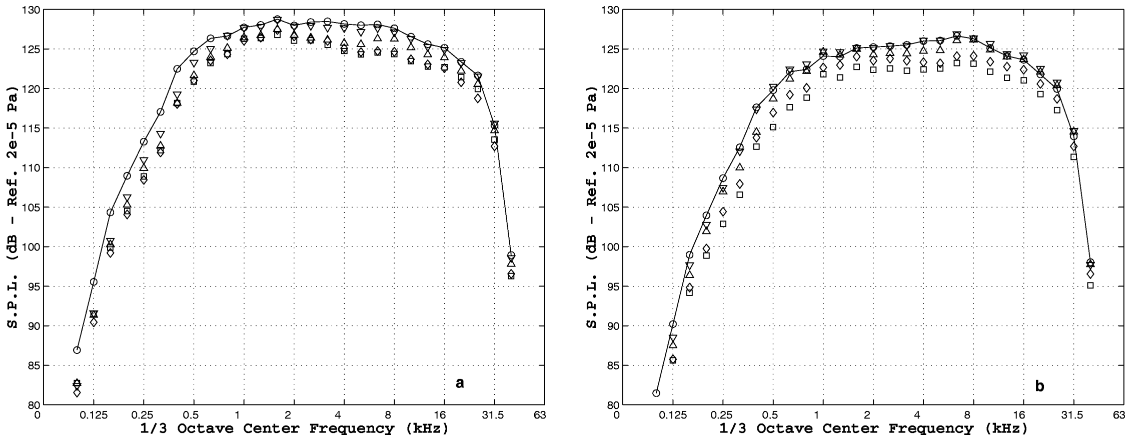

Figure 4. Effects of water injection on the noise level in downstream direction, $\theta = 65°$, jet 1 (a) ($V_j = 1700$ m/s, $T_s = 860$ K), jet 2 (b) ($V_j = 1700$ m/s, $T_s = 1100$ K). (○): without injection, (□): $X_{\text{inj}} = 1.5D$, (◇): $X_{\text{inj}} = 5D$, (△): $X_{\text{inj}} = 10D$, (▽): $X_{\text{inj}} = 15D$.

Figure 4. *Influence de la température sur le niveau sonore dans la direction aval,* $\theta = 65°$, *jet* 1 (a) ($V_j = 1700$ m/s, $T_s = 860$ K)*, jet* 2 (b) ($V_j = 1700$ m/s, $T_s = 1100$ K). (○) : *sans injection,* (□) : $X_{\text{inj}} = 1{,}5D$, (◇) : $X_{\text{inj}} = 5D$, (△) : $X_{\text{inj}} = 10D$, (▽) : $X_{\text{inj}} = 15D$.

The quality of the noise reduction strongly depends on the destruction of the sound generation process associated with the shock cells. When injection takes place downstream of the location of the first shock cells ($X_{\text{inj}} > 5D$), noise reductions in high frequencies are low compared to those obtained when the water is injected close to the nozzle exit ($X_{\text{inj}} = 1.5D$) (Fig. 3b).

4.3.2. *Downstream direction*

As we expected, the turbulent mixing noise, that contributes to the broadband region around 1 kHz, is higher for jet 1 (Fig. 4a) [5]. This is due to a lower temperature leading to a higher value of the density in the term $\rho u_i u_j$.

A lower noise reduction is observed in the downstream direction as compared to that measured in the upstream direction. Indeed, large structures in the jet are responsible for Mach wave emission in this direction. Noise reduction essentially depends on the efficiency of the velocity decrease. This process is reached for jet 1 when water is injected at 15 diameters as the low frequencies are attenuated (Fig. 4a).

The reduction of the low frequencies in jet 2 depends on the injection location (Fig. 4b). Actually, the higher temperature leads to a decrease both of the length of the potential core and the growth rate of the mixing layer [7]. Therefore large structures are generated in the mixing layer region where their energy is too low to radiate strongly. Thus, an injection at this location involves structures that do not have a dominant acoustic contribution leading to a limited noise reduction.

5. Conclusion

This study allows us to verify the efficiency of water injection method to reduce noise from hot supersonic jets. As in the case of cold supersonic jets, the more important reduction are obtained when water is injected near the nozzle exit, thus all acoustic sources are affected by the water injection. When the jet is non perfectly expanded, the contribution of the source tied up with the presence of shock cells is strongly reduced.

It appears that the jet temperature does not greatly affect the process of noise reduction as no difference in results is observed with the two jets in optimal configuration. Nevertheless, it appears that the temperature parameter is at the origin of the modification of the aerodynamic structure of the jet (length of the potential core, growth rate of the mixing layer). Thus the location of injection should be adapted to involve the main sources in the jet.

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