Pulsation Amplitude Influence on Free Shear Layer of a Vertical Pulsating Jet in Laminar Regime

Nawel Khaldi, Salwa Marzouk, Hatem Mhiri, and Philippe Bournot

***Abstract*—In this study, we are proposed to find out the restrictions of the free shear layer approximations for a permanent vertical jet and a pulsed vertical jet in laminar regime by using a numerical calculation code. For this, we considered a two-dimensional air plane jet resulting in a quiescent environment. At the exit of the nozzle, the pulsating flow is imposed with a uniform temperature T_0 and a velocity $u=u_0+a*\sin(wt)$. The effect of the important governing parameters, such as the pulsation amplitude, the Reynolds and Grashof numbers on the flow behavior are investigated in detail. The numerical results show that the free shear layer approximations are suitable for a permanent jet in different regions; however, these approximations remain valid for a pulsed jet only in the plume region.**

***Index Terms*—Free shear layer, laminar, numerical, plane jet, pulsation amplitude, pulsed.**

I. Introduction

Due to the fact of their diverse aspects and their applications, typical jet flows present a constant interest. Indeed, many applications are met in industry such as pulverization, cooling by film, aeronautic propellers, welding, etc. However, the characteristics of such a flow are not yet defined precisely what has stimulated considerable interest from researchers.

In 1959, Sato [1] showed that the pulsed jet becomes unstable for Reynolds numbers higher than 50 and a Strouhal number equal to about 0.17. Favre *et al*. [2] treated experimentally the influence of high pulse amplitude on the symmetric axis jet development. They showed that the periodic perturbations are amplified for a distance twice to three times the nozzle diameter, then decrease to disappear, for a distance close to 10 diameters beyond the degenerated vortex and are accompanied by a very significant increase in the turbulent intensity.

Chambers *et al.* [3], [4] have found, using an experimental study of a disturbed air jet, that for some frequencies, the turbulent intensity and Reynolds stress increase in the jet region. Further downstream of the nozzle, the acoustic perturbation has no effect on the quantities of the flow. An experimental study was carried out by Thomas *et al*. [5] to determine the effects of a periodic acoustic perturbation on a two-dimensional turbulent jet. They showed that the rate of the jet expansion is larger for Strouhal numbers ranging between 0.34 and 0.42. This is in agreement with those reported by Kaiser [6] and Chambers *et al.* [3], [4].

Mhiri *et al*. [7] have studied numerically the influence of the emission profiles on a steady free jet (isothermal or non-isothermal). They have accomplished an accurate description for the different regions of the jet and showed that the emission profiles affect the flow in the jet region (in the nozzle vicinity), while in the plume region (far from the nozzle), where the buoyancy forces are preponderant, these emission profiles no longer affect the flow parameters.

In the same context, a numerical study was carried out by Marzouk *et al.* [8] to reveal the influence of an initial perturbation on the dynamic and thermal quantities of a plane jet in laminar regime. They showed that for an isothermal plane jet and for a fixed pulsation amplitude, the fluctuations disappear at a distance close to X=30 for very low Strouhal numbers (St=0.1), while for a fixed Strouhal number these fluctuations disappear completely at a distance closer to X = 10. Beyond this distance, the centerline velocity obtained for a pulsed jet coincides with a non-pulsed one. Marzouk *et al*. [9] proposed later a numerical study of the Strouhal numbers and pulsation amplitudes influence on an isothermal or heated plane jet in turbulent regime and in a forced convection mode. Their results show that the pulsation influence is particularly observed in the jet zone and that the introduction of a disturbance to the flow involves the appearance of fluctuations in the vicinity of the nozzle which persist at larger distances for small Strouhal numbers.

Recently, Kriaa *et al.* [10] conducted a numerical study of a free pulsed plane jet with variable density in unsteady and laminar mode. It was shown that the pulsation affects the flow particularly in the vicinity of the nozzle and that the Strouhal number has no influence on the flow mixture degree, while the pulsation amplitude affects the mixture and, consequently, the concentration core length.

For all these numerical resolutions [7]-[10], the authors used the free shear layer approximations which consist in ignoring the lateral velocity. These approximations may put in default the discovered results especially in the case of a pulsed jet where the longitudinal velocity increases the entrainment of the surrounding air on the jet zone which increases the heat exchange between the jet and the ambient conditions. Therefore, this numerical study proposes a new approach that does not consider these approximations, in order to test their validity for a pulsed plane jet resulting in a

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quiescent environment.

II. Mathematical Formulation

A. Assumptions

The considered jet is issued from a rectangular plane nozzle into a quiescent surrounding. The thickness of the nozzle is assumed very small compared to its width in order to neglect the edge effects and have a two-dimensional vertical jet; the jet and the ambient environment are constituted of the same fluid (Fig.1).

The considered fluid is air, assumed Newtonian and incompressible; its density varies linearly with the temperature in the term containing the buoyancy force, it is considered constant elsewhere, according to the Boussinesq approximation.

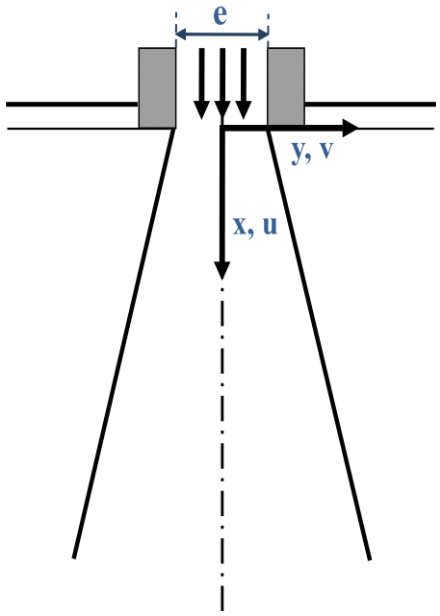

Fig. 1. Coordinates system of the free jet.

B. Governing Equations

Given the above assumptions, in a Cartesian coordinates system (Fig.1), the mass, momentum and energy equations of a plane vertical jet in laminar regime, can be written as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

$$\rho\frac{\partial u}{\partial t}+\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial P}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\rho g \quad (2)$$

$$\rho\frac{\partial v}{\partial t}+\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial P}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \quad (3)$$

$$\rho c_p\frac{\partial T}{\partial t}+\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \quad (4)$$

The associated boundary and ejection conditions to the equations (1)–(4) are described as:

$$x>0\quad\begin{cases}\dfrac{\partial u}{\partial y}=v=\dfrac{\partial T}{\partial y}=0\,;y=0\\ u,T\longrightarrow 0\,;y\longrightarrow\infty\end{cases} \quad (5)$$

$$x=0\quad\begin{cases}\bullet\ \text{if } 0\le y<0.5e\\ v=0, T=T_0\\ u=u_0\text{, Permanent jet}\\ u=u_0+\text{a*}\sin(2\pi\, u_0\text{St}*t/e)\text{, Pulsed jet}\\ \bullet\ \text{if } 0.5e\le y\le 2\\ u=v=T=0\end{cases} \quad (6)$$

III. Numerical Method

In this work, equations (1)–(4) associated to the conditions equations (5) and (6) were solved numerically by a finite volume method.

The discretization domain was meshed by dividing it into spacing quadrilateral cells (Fig. 2). The used mesh is non uniform in both longitudinal and transversal directions; indeed, according to *X* direction, the calculation step is taken very thin in the nozzle vicinity. Then, a little further, we increase its value to finally adopt a larger step for higher longitudinal coordinates in order to be able to go further in the jet. In the transversal direction, the calculation step is taken very thin near the symmetry axis where steep variations in velocity and temperature are expected.

The temporal resolution was as such one pulsating period is divided by 120 time steps.

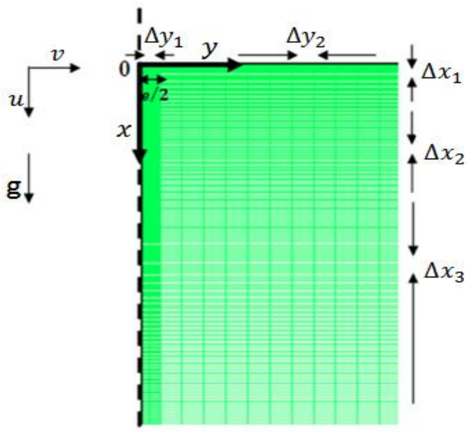

Fig. 2. Computational grids of the free jet.

Fluent 6.2 is used as a tool for numerical solution of the governing equations. First order upwind discretization scheme is selected for momentum and energy equations. The discretized equations were solved following the Simple algorithm. The maximum residual of all variables was 10^{-7} in the converged solution.

IV. Results and Discussions

Our numerical results have been written in properly dimensionless form to be compared with those established with free shear layer approximations [7], [8]. The used dimensionless variables are the following:

$$(X,Y)=\frac{(x,y)}{e},(U,V)=\frac{(u,v)}{u_0},\theta=\frac{T-T_\infty}{T_0-T_\infty},\tau=\frac{t\,u_0}{e}$$

A. *Permanent Vertical Plane Jet*

The Fig. 3 presents the centerline velocity evolution of the free isothermal jet for various Reynolds numbers. In the vicinity of the nozzle (X = 3), the velocity remains constant and equal to that of the ejection; then, outside this region, the velocity decreases progressively throughout the axis.

In order to compare our results with those obtained by Mhiri *et al.* [7] for the case of an isothermal permanent jet, we present on Fig.4, the longitudinal distributions of the modified centerline velocity given by the relation $U_{cm} = \frac{U_c}{Re^{1/3}}$.

The latter shows that our results coincide with those of [7] for different Reynolds numbers in different regions of the jet. This demonstrates the validity of the free shear layer approximations in different regions for the case of an isothermal permanent jet.

The Fig. 5 shows the longitudinal distributions of the centerline velocity (Fig. 5(a)) and the modified centerline temperature expressed as $\theta_{cm} = \theta_c \times (Re/Gr)^{0.25}$ (Fig. 5(b)), according to the modified distance X_m defined by $X_m = X \times (Gr^3/Re^7)^{0.25}$. The results are presented in the case of the air (Pr = 0,71).

As it can be seen on Fig. 5, the obtained results coincide with those of [7] in different regions of the jet and for different Grashof numbers, which enables us to deduce that the free shear layer approximations remain also valid in different regions of the heated permanent jet.

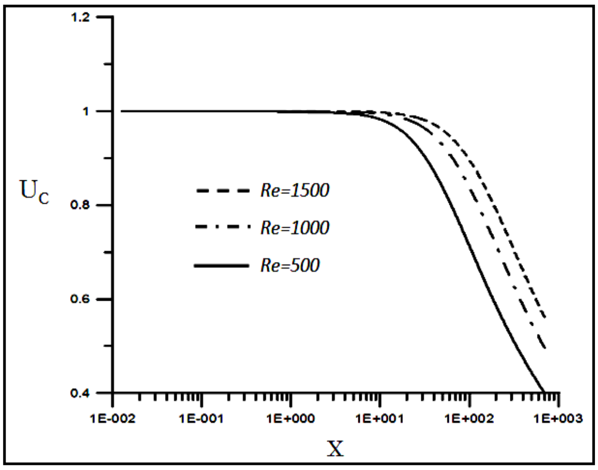

Fig. 3. Influence of Reynolds number on longitudinal distribution of the centerline velocity.

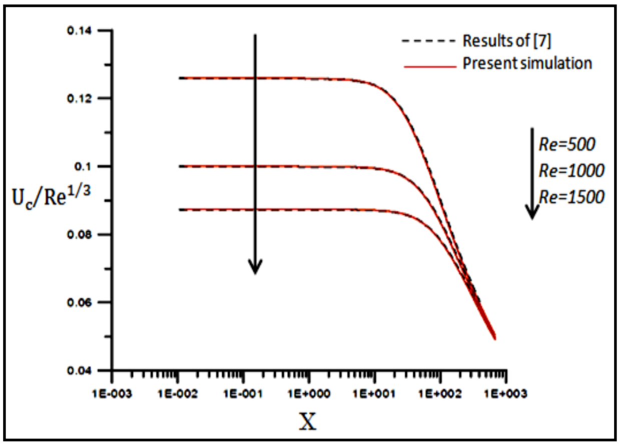

Fig. 4. Influence of Reynolds number on longitudinal distribution of the modified centerline velocity.

A. *Pulsed Vertical Plane Jet*

In this part, we will discuss the effect of the pulsation amplitude on the dynamical and thermal quantities of the flow. The validity of the free shear layer approximations for the pulsed plane jet will be also examined.

The Fig.6 presents the influence of Reynolds number on the modified centerline velocity of an isothermal pulsed jet for pulsation amplitude of 3%. This figure enables us to notice that at the instant $t = \frac{9T}{4}$, the pulsation creates fluctuations in the jet zone; the amplitude of these fluctuations is higher for low Reynolds numbers, which leads us to deduce that the impact of the pulsation is more important when the flow is in a slow movement.

It is also noticed that our results coincide with those of Marzouk et al. [8], for different Reynolds numbers, only in the region of the established regime, whereas a significant difference between our results and those established by [8] is observed in the jet zone and the intermediate region. Free shear layer approximations are thus suitable for an isothermal pulsed jet only in the established region.

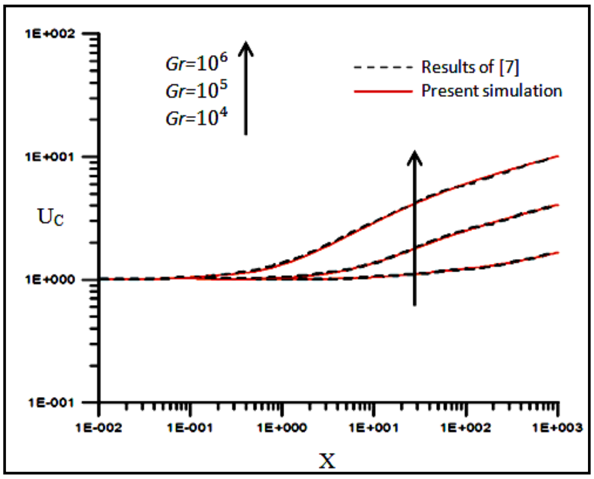

Fig. 5 (a). Influence of Grashof number on longitudinal distribution of the centerline velocity; Re=1500.

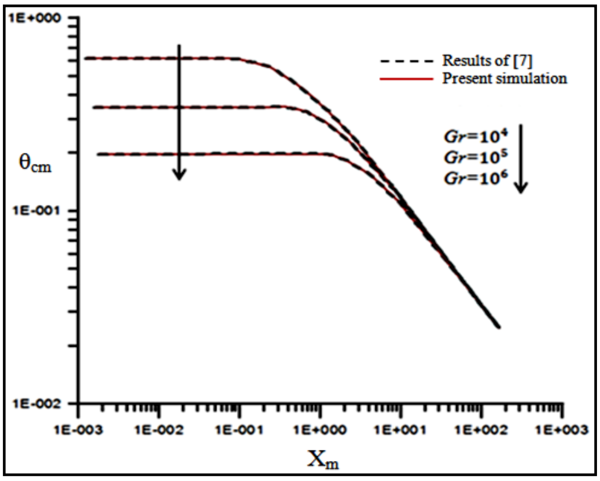

Fig. 5 (b). Influence of Grashof number on longitudinal distribution of the modified centerline temperature; Re=1500.

B. *Pulsation Amplitude Influence on Isothermal Pulsed Jet:*

The evolution of the longitudinal distribution of the jet centerline velocity for various pulsation amplitudes is given in Fig. 7. The later shows that the introduction of a disturbance to the flow involves the appearance of oscillations which amplitudes increase with of the pulsation one. It is also noticed that our results coincide with those of Marzouk *et al.* [8], for different amplitudes of pulsation, and that, only in the region of the established regime. Nevertheless, these approximations are no longer valid in the region closer to the nozzle, especially for high pulsation amplitudes. Indeed in the nozzle vicinity, the increase in the pulsation amplitude produces more important ejection velocity than that of the permanent jet; this acceleration associated with a higher entrainment of the surrounding air makes the lateral velocity more significant. These results show that free shear layer approximations are suitable for an isothermal pulsed jet only for low pulsation amplitude (A<3%).

C. Pulsation Amplitude Influence on Heated Pulsed Jet:

In this part, all results are presented for Pr = 0.71 and at $t = \frac{9T}{4}$. The Fig.8 represents the longitudinal distributions of the modified centerline velocity given by the relation $U_{cm} = U_C \times (Fr/Re)^{0.25}$ according to the modified distance expressed as $X_m = X/(Fr^3 \times Re)^{0.25}$ for various Reynolds numbers and by maintaining the other parameters fixed ($A = 10\%; St = 0.3$). The same figure illustrates also a comparison between our results and those of [8] in a mixed convection mode (Fr = 20).

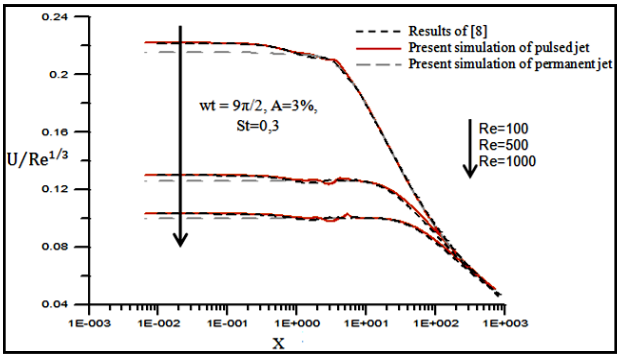

Fig. 6. Influence of Reynolds number on longitudinal distribution of the modified centerline velocity.

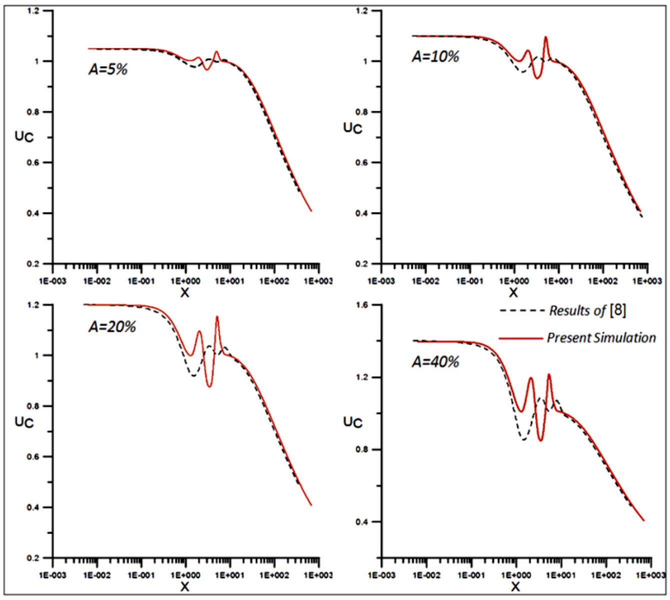

Fig. 7. Influence of Pulsation amplitude on longitudinal distribution of the centerline velocity; Re=500, St=0.3, wt = 9π/2.

The obtained results are in accordance with those of [8], and that, only in the plume region. A significant difference between results is observed in the region closer to the nozzle. Indeed, the approach considered by Marzouk et al. [8] consisting in ignoring the lateral velocity, explains the observed difference between results in the jet region and the intermediate zone.

The Fig. 9 illustrates the longitudinal distributions of the centerline velocity (Fig. 9 (a)) and the centerline temperature (Fig. 9 (b)) in a mixed convection mode (Fr = 20) for various pulsation amplitudes values. This figure shows that the centerline velocity and temperature present oscillations which amplitudes increase with the pulsation one. The increase of thermal gradient between the jet and the ambient environment (low Froude numbers) involves oscillations of higher amplitudes accompanied by a widening of the dissipation region of these oscillations. The heating is thus a significant factor for the study of a pulsed jet behavior.

On the other hand, the obtained results coincide with those of Marzouk *et al.* [8], for different pulsation amplitudes, only in the plume region, which enables us to conclude that free shear layer approach remains valid for the heated pulsed jet only for low pulsation amplitude.

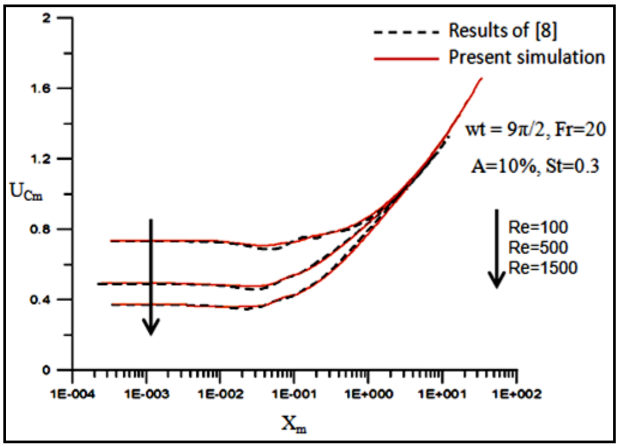

Fig. 8. Influence of Reynolds number on longitudinal distribution of the modified centerline velocity.

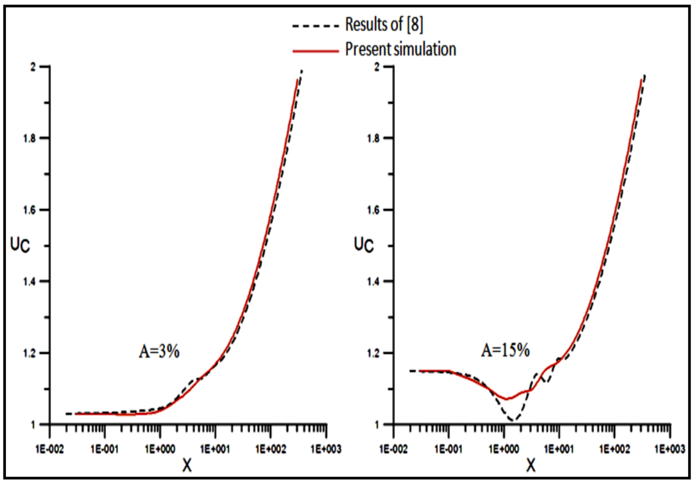

Fig. 9 (a). Influence of Pulsation amplitude on longitudinal distribution of the centerline velocity; Re=100, St=0.3, Fr=20, wt = 9π/2.

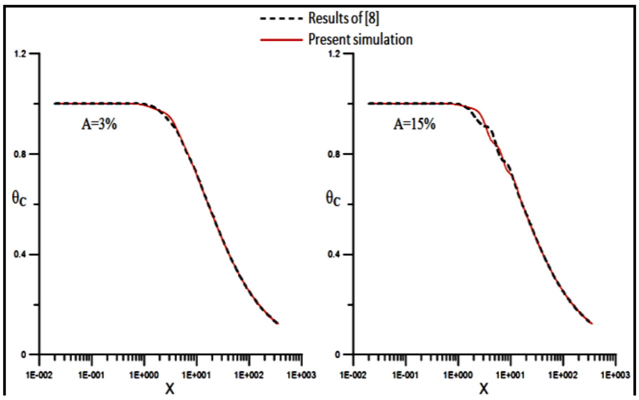

Fig. 9 (b). Influence of Pulsation amplitude on longitudinal distribution of the centerline temperature; Re=100, St=0.3, Fr=20, wt = $9\pi/2$.

V. Conclusion

In this work, we have studied in a laminar regime, the momentum and the heat transfer in a free vertical plane jet subjected to a sinusoidal disturbance. This numerical study has proposed a new approach that does not take into consideration the free shear layer approximations in order to test their validity for a permanent vertical jet and a pulsed vertical jet resulting in a quiescent environment. It was shown that the free shear layer approximations are suitable for a permanent jet in its different regions and for different Reynolds and Grashof numbers. It was also found that in the case of pulsed jet, these approximations remain valid in different regions of the isothermal or the heated jet, and this, only for high Strouhal numbers ($St \geq 1$) and for low pulsation amplitude ($A<3\%$) . Otherwise, these approximations remain valid for a free pulsed jet only in the plume region.

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