Effect of an electric field on the response of a liquid jet to a pulse type perturbation

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Abstract. In this work we analyze the influence of an electric field on the response of a circular liquid jet excited by a pulsed signal externally imposed to the mean flow. The influence on the limits of the wavepacket and on the growth rate are established showing that the electric field spreads and destabilizes a pulse type perturbation.

1. Introduction

In an unstable flow the response to a pulsed disturbance can be characterized by two important parameters, the growth rate of the perturbation and the velocity of propagation of the disturbance in the flow. Concerning this last parameter prior research work has established [1] that an electric field reduces the velocity of propagation, making possible in theory to control with an electric field the absolute or convective nature of the instability in a jet. However with this analysis neither the spreading of the wave packet nor the growth rate at the different streamwise stations as a function of time can be specified.

The objective of this work is to establish the influence of an electric field on the boundaries of the wavepacket and on the growth rate of the disturbances as a function of time for the different axial coordinate positions.

2. Description

The geometry of the problem we have analysed is a circular jet coaxial with a cylindrical electrode at a different electric potential. We have considered the following simplifying hypothesis: -The surface of the liquid jet is an electrical equipotential. -The magnetic and gravitational effects can be disregarded -The jet is inviscid, incompressible and isothermal -There is no mass transfer between the jet and the surrounding atmosphere.

-All streamwise stations have the same plug velocity profile independent of the axial coordinate in the basic state.

We will analyze the motion resulting in this basic flow from a pulse input following a linear analysis. Considering a pulse perturbation giving rise to two-dimensional travelling wave modes of the type

$$\Psi(r,z,t) = \Phi(r)e^{i(kz-\omega t)}$$

with both k and ω complex values, Gaster [2] deduced that in any ray z/t within the wave packet (z being the axial coordinate of the jet, t: interval of time elapsed after the application of the pulsed signal) the response is dominated by a specific complex wave number k^* and the wave motion appears to grow in space and time with an amplification rate

$$-\left[k_i^* \frac{z}{t} - \omega_i(k^*)\right] t$$

where k^* is obtained from the conditions on the group velocity

$$\frac{\partial \omega_r}{\partial k_r}(k^*) = \frac{z}{t}$$

$$\frac{\partial \omega_i}{\partial k_i}(k^*) = 0$$

and where the dispersion equation defines the behavior of ω in terms of k. The set of four equation constituted by these and the corresponding equations resulting from the splitting of the dispersion equation in its complex and real part enables to obtain for any z/t ray the values of k^* and of $\omega(k^*)$ and consequently the growth rate for any z/t ray. By representing the growth rate as a function of the ratio z/t it is possible to obtain the boundaries of the wave packet that can be defined by the rays z/t along which the amplification is zero.

In the following paragraph we show results obtained from the dispersion equation obtained in [1]. Considering only the axisymmetric case and disregarding the effect of the sourrounding atmosphere the equation $\mathrm{D}(k,\omega,We,Eue) = 0$ establishes the relationship between the complex wavenumber k, the complex frequency ω, the Weber number $We = \frac{\rho U_0^2 \quad a}{\gamma}$ (the ratio between inertial and surface tension forces) and the Electric Euler number $Eue = \frac{\epsilon_0 E_n^2}{\rho U_0^2}$ (the ratio between the electric forces and inertial forces). In these expressions $\rho, U_0, a, \gamma, \epsilon_0, E_n$ are respectively the liquid density, the mean jet velocity, the jet radius, the interfacial tension, the dielectric constant in vaccum and the electric field at the jet surface.

2.1. Results and Discussion

The set of equations cited above has been solved numerically for different convective unstable flows (the ray $z/t = 0$ is not involved by the perturbation propagation).

Figure 1 shows the non dimensional growth rate (non dimensionalized with the jet radius and jet velocity) as a function of z/t (non dimensionalized with jet velocity) for different Weber Numbers. We can see that as the Weber number increases the boundaries of the wavepacket get closer and that the maximum growth rate corresponds to the ray $z/t = 1$. A propagation upstream of the pulse source occurs when the ray $z/t = 0$ has a positive growth rate (absolute unstable flows) and this occurs for low velocity jets and at Weber number of 3.1 in agreement with [3]. Analyzing these figures it can be concluded that inertial forces stabilizes a pulse type perturbation and leads to a more compact pulse propagation. The effect of surface tension forces is the opposite. Figure 2 shows the non dimensional growth rate as a function of the non dimensional ratio z/t for different Eue. The symmetry of the spreading along the non dimensional ray $z/t = 1$ is kept even when an electric field is applied but the pulse type perturbation may propagate upstream if the electric field is intense enough . It can be observed that larger electrical Eue (larger electric fields) lead to a more spread pulse, as the boundaries of the wavepacket are more separated. The effect of the electric forces differs from that of inertial forces: they destabilize a pulse type perturbation but lead to a more spread pulse propagation.

Regarding experiments to confirm the theoretical predictions one must consider a convective flow and it is possible either to have an image of a jet region including the pulse or to study the radius evolution as a function of time as the pulse passes through a fixed station with an experimental setup as described in [4]. By these experiments a three dimensional graph of the radius as a function of the axial position and time $r(z,t)$ can be obtained for either t constant or z constant, and from this graph a set of points of growth rate as a function of z/t easily deduced. Figure 3 shows a diagram of the propagation of the perturbation. The figure represents the perturbation at two different times in the z-t domain with the lines identified by $(z/t)_I$ and $(z/t)_{II}$ indicating the head and tail ray limits of the wavepacket boundary. Outside the region delimited by this two rays the perturbation is dampened and it is amplified inside it. The pulsed perturbation can be generated with a square signal of low frequency applied to a piezoelectric that excites the jet but it should be mentioned that measurements should be undertaken in positions where there is no interaction between two successive pulses. Looking at figure 3 it can be easily deduced that to satisfy this for a jet of a lenght L (or for the largest distance pulse source-streamwise station observed) the time elapsed between the excitation of two successive pulses should be larger than the interval $\Delta t_{\min}$ given by

$$\Delta t_{\min} = L \left(1 - \frac{(z/t)_I^{-1}}{(z/t)_{II}^{-1}} \right) (z/t)_I^{-1}$$

As example for a water jet of a radius of $100\mu m$, $We = 5$ and $Eue = 0.5$ at a distance L of 1 cm this time should be larger than about 11 ms.

3. Conclusions

In a jet excited by a pulse type perturbation the effect of electric forces is different from the action of inertial and surface tension forces. An increase in inertial forces stabilizes a pulse type perturbation in z/t rays but leads to a more compact pulse propagation, while an increase of surface tension forces leads to an opposite effect. Our results indicate that the effect of an electric field stressing the jet surface on the response to a pulse type perturbation is to increase the separation of the boundaries of the wavepacket (even upstream for large enough electric fields) and also to increase the growth rate at which the perturbation is amplified in each ray z/t. This action is reduced for high Weber number jets (or large jet velocities).

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References

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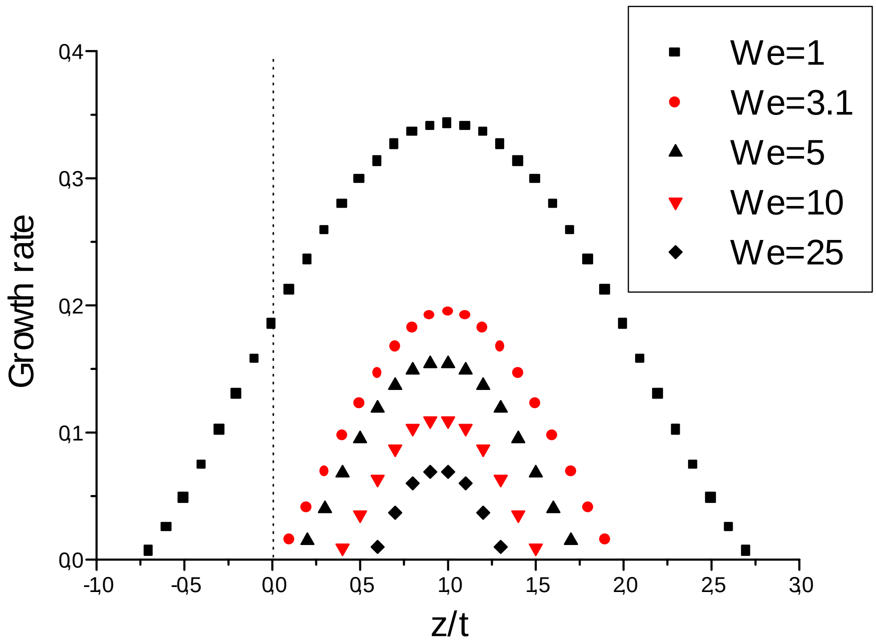

Figure 1: Non dimensional absolute growth rate as a function of z/t for different Weber Numbers

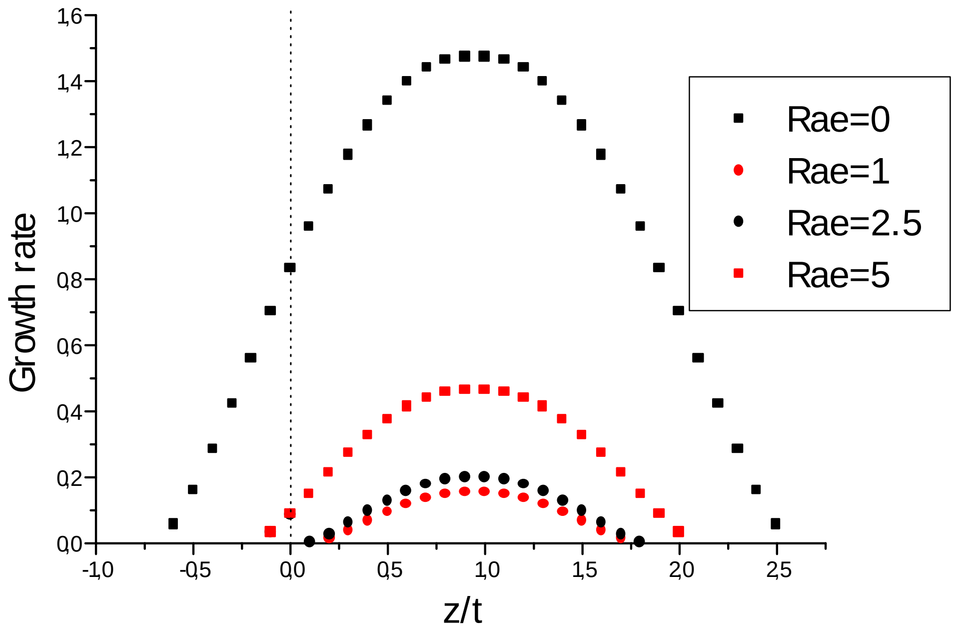

Figure 2: Non dimensional absolute growth rate as a function of z/t for different Eue Numbers.We=5.

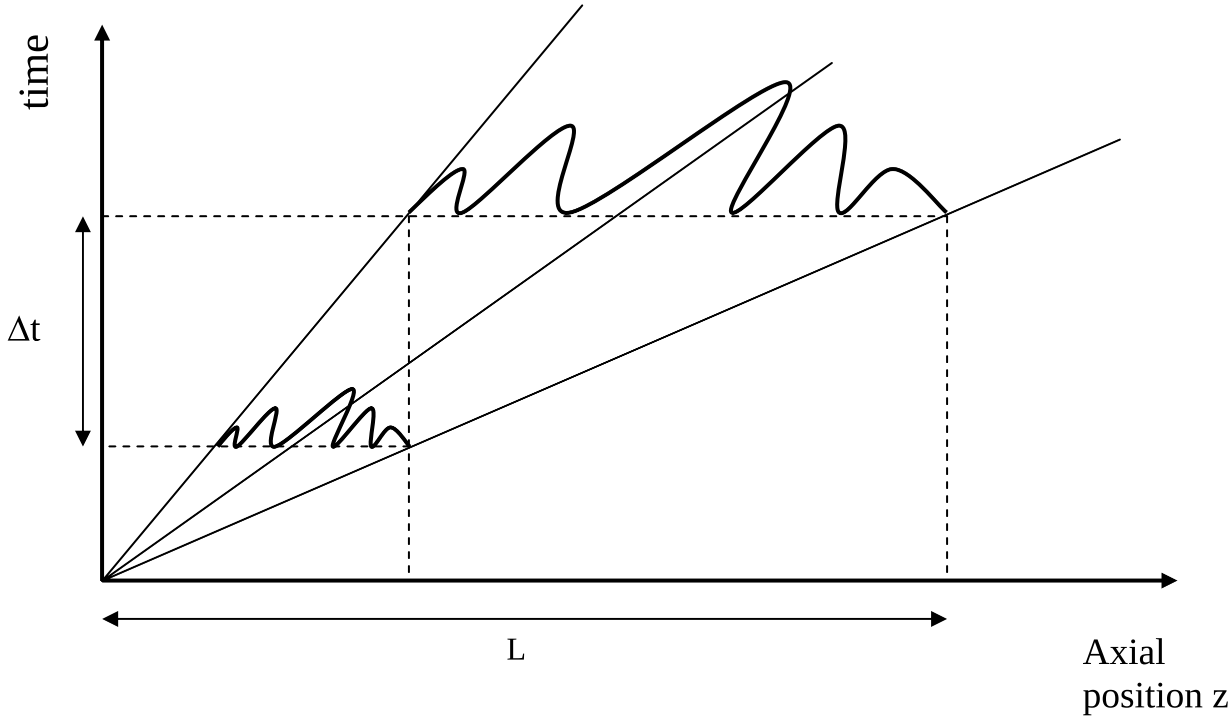

Figure 3: Scheme of the pulse propagation.