Effects of Reynolds number and aspect ratio on the opposed-jet flow instability

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Abstract

The effects of Reynolds number and aspect ratio on the distinct resulting flow regimes in an unbounded opposed-jet configuration are analyzed. For nozzle separations of *h≥9d* where *d* is the nozzle diameter, the steady symmetric solution becomes unstable and loses its symmetry. As a result, the opposed jets start to deflect periodically with a fixed frequency and increasing amplitude, until a chaotic behavior is reached. For large aspect ratios, no periodic patterns appear in the transition between the unstable steady solution and the chaotic solution. For the case of nozzle separation equal to 10 diameters, a new type of instability has been found at *Re≥1000*. This instability appears as capillary waves in the outgoing jets and can be inhibited by turbulent mechanisms.

Introduction

Counterflowing jets may exhibit different stable configurations, depending on many parameters such as the jet velocity, inlet geometry and separation, or boundary conditions. Different kind of flows can be observed in the opposed-jet configuration [1-3]: a symmetric single steady state, a stable state with the stagnation point near one of the injectors, a “deflecting jet” oscillatory flow, a symmetric state with capillary waves, or a timedependent chaotic flow with vortex shedding. The objectives of this study are: (i) to characterize the pressure and velocity profiles for the stable solution, for different values of the aspect ratio and the Reynolds number, (ii) to identify the critical parameter values leading to the instability for the deflecting jets, and (iii) to analyze the effects of turbulence in the inhibition of the capillary waves instability.

Implementation

Dimensionless Navier-Stokes equations have been solved for an unbounded, two-dimensional, isothermal single phase flow. The CHARM differencing scheme have been used in a *100x100* non-uniform grid. Cartesian coordinates have been used, with the injection along the horizontal direction. Laminar model and KECHEN turbulence model have been compared. Nozzle separations ranged from *5* up to *50* nozzle diameters, and Reynolds number ranged from *Re=10* up to *Re=2000*.

Results

Opposed jets start to develop until a steady state is reached. For *h<9d*, the steady solution is stable, independently of *Re*. For *9d≤h<20d*, the steady solution destabilizes and the jets start to deflect periodically.with a fixed frequency ω. A bifurcation diagram with *Re* and *h/d* as continuation parameters is presented in Figure 1.

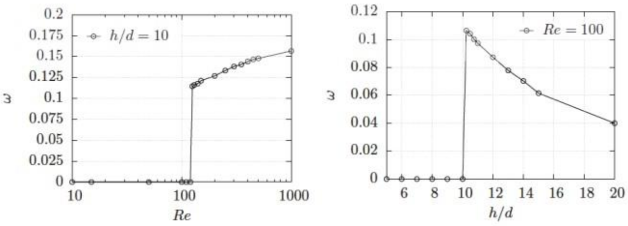

Fig. 1: Left: Bifurcation diagram for *h/d=10* with *Re* as a continuation parameter. Right: Bifurcation diagram for *Re=100* with *h/d* as a continuation parameter.

For *h>20d*, the transition from the steady state to the chaotic behaviour is no longer periodic (Figure 2). The deflection still exists, but with an unpredictable behaviour.

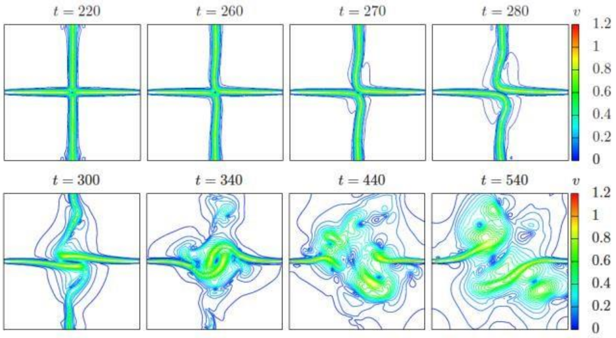

Fig. 2: Transition to instability without periodic oscillations for opposed jets with *h/d=50* and *Re=500*.

At high Reynolds numbers, *1000≤Re≤2000*, capillary waves have been observed in the outgoing vertical jets, which become superposed to the deflection instability (see Figure 3).

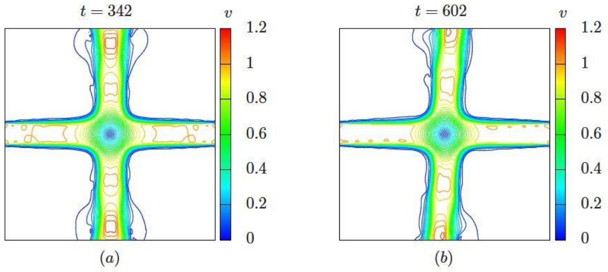

Fig. 3: Velocity contours of laminar opposed jets for *Re=2000* and *h/d=10*. (*a*): Capillary waves instability. (*b*): Capillary waves superposed to deflecting jets oscillation.

This kind of capillary waves are inhibited by turbulent mechanisms, as can be seen in Figure 4, in which the vertical component of the velocity at a fixed point is plotted as a function of time, for *h/d=10*. In Fig. 4 (Left), the time evolution of the opposed-jet flow can be observed: for *t<100* time units, the jets develop until a steady state is reached (*100<t<350*). For *t>350*, the solution destabilizes following a periodic motion with increasing amplitude, until at *t>650* the solution becomes chaotic.

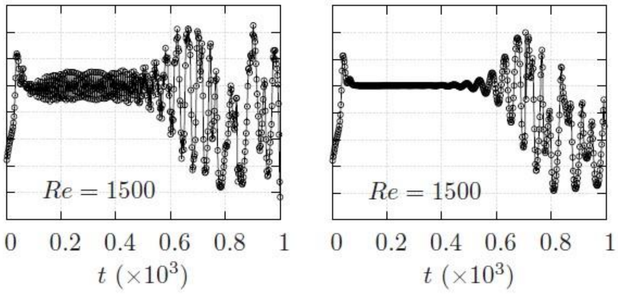

Fig. 4: Left: laminar case (with capillary waves). Right: turbulent case (without capillary waves).

Conclusions

The main conclusions of this study can be stated within the following points:

- For nozzle separations lower than 10 nozzle diameters, the symmetric solution is stable, independently of *Re*.
- For nozzle separations of 10 nozzle diameters, three stable solutions have been found in the laminar case:
    - For *Re<125*, symmetric solution.
    - For *Re≤125<1000*, deflecting jets.
    - For *Re≥1000*, deflecting jets with capillary waves.
- The capillary wave instability becomes inhibited by turbulent mechanisms.

References

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