LES predictions of round isothermal and heated jets

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Presentation outline

1. Introduction – experimental results on hot jets as a motivation to systematic LES studies
2. Numerical code applied – algorithms and discretization methods, subgrid model, boundary conditions
3. Numerical results and discussion:
   • Isothermal jet – influence of inlet turbulence intensity, shear layer thickness, mesh resolution, numerical scheme
   • Hot jet - influence of the density ratio, turbulence intensity, mesh resolution
4. Concluding remarks
Experimental part

*Variable density round jets – experimental results*

**Monkewitz et al. (J. Fluid Mech. 1990)**
- Critical density ratio $S_{cr} = 0.73$, below which self-exciting oscillations appear
- Two unstable modes exist: Mode I – $St_D = 0.3$ ($S < 0.73$), Mod II $St_D = 0.45$ ($S < 0.65$)
- Mode I disappears when the density ratio $S < 0.55$
- Mode II – axi-symmetric – vortex pairing process is observed

**Kyle i Sreenivasan (J. Fluid Mech. 1993)**
- Critical density ratio $S_{cr} = 0.6$
- Oscillating mode identical to Mode II (Monkewitz et al.)
- Boundary layer thickness - important governing parameter
- For thin boundary layer a *broadband* mode was observed
Experimental part

Experimental set-up

Main parameters of experimental set-up:
- nozzle area contraction ratio – 144
- turbulence intensity at the nozzle exit < 0.3%
- Reynolds number up to 20,000
- density ratio: $S = 0.5 - 1$
- boundary layer thickness: $D/\theta = 40 - 180$

Measuring equipment:
- hot-wire anemometer – 55M-DISA
- LDV – DANTEC – forward scatter mode

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Variable density round jets – mean and fluctuating velocity measurements (sample results: \( D/\theta = 56 \))

Experimental part

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Variable density round jets – frequency characteristics of the velocity field fluctuations (sample results: \(D/\theta = 56, S=1\))

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Variable density round jets – frequency characteristics of the velocity field fluctuations (sample results: $D/\theta = 56$, $S=0.7$)
Experimental part

Variable density round jets – frequency characteristics of the velocity field fluctuations (sample results: $D/\theta = 56$, $S=0.5$)

\[ S=0.5, \quad L/D=7, \quad D/\theta = 56.2, \text{ Mode II} \]

- a) $x/D=0.1$
- b) $x/D=0.667$
- c) $x/D=2.667$
- d) $x/D=2$
- e) $x/D=1.333$
- f) $x/D=2.667$
- g) $x/D=2$
- h) $x/D=4$
- i) $x/D=5.333$

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Main conclusions from experimental part

- According to stability theory critical density ratio is 0.7 which is close to the value established experimentally by Monkewitz et. al. (J.F.M., 1990) for the Mode I. However, the characteristic frequency which is far from the frequency of the Mode I, and close to the characteristic frequency of the Mode II. Hence it seems that the absolutely unstable mode predicted theoretically corresponds to the Mode II, observed by Monkewitz et al. in hot jet and by Kyle & Sreenivasan in helium-air jet.

- The characteristic frequency of the Mode I is $St_D=0.6$ while the vortex pairing process leads to the value $St_D=0.3$ observed by Monkewitz et al.

- The Mode I is not pertinent to variable density jet as it undergoes a continuous evolution from an unstable mode present in isothermal jet. It seems that there is only one absolutely unstable mode in variable density jet.

- There is a critical boundary layer thickness below which the absolutely unstable Mode II is not present while for the thin boundary layer the Mode I becomes more persistent, it is present even for the density ratio 0.5, and takes form of broadband oscillations.

- It is likely that the broadband mode observed by Kyle & Sreenivasan in helium-air jets is the same instability type as the Mode I but for thin boundary layer.
SAILOR (Spectral And Compact Differences High Order Code for LOw Mach NumbeR LES) computer code

**Code characteristic:**

- applicable to simple geometries
- prediction of turbulent variable/constant density flows by LES and DNS
- Cook&Riley (JCP, 1996) algorithm for low Mach number approximation of the Navier-Stokes equations
- various SGS models implemented:
  - Smagorinsky
  - Germano
  - filtered/selective structure function

*Fig. 1 Temperature isosurfaces (density ratio 0.7)*

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Numerical algorithm and discretization method:

- Projection method for pressure solution
  - Cartesian non-uniform meshes
  - Pseudospectral method in two directions based on the Fourier approximation (periodic boundary assumed)
  - $V_{th}$ order compact approximation in third direction (boundary closure: 3-4-6-4-3)
  - $III_{th}$ order low storage Runge-Kutta and Adams-Bashforth method implemented

Parallel computations:

- MPI library for data exchange
- Domain decomposition in direction where compact approximation is applied (require parallelisation of TDMA)
Boundary conditions:

- **inlet:**
  \( U_1, \rho_1 \) - velocity and density of the jet; \( U_2, \rho_2 \)
  - coflow velocity and density
  \( (U_2/U_1 = 0.05) \)

  \[
  U(x, y, z = 0, t) = \frac{U_1 + U_2}{2} + \frac{U_1 - U_2}{2} \tanh \left( \frac{R}{4\theta} \left( \frac{r}{R} - \frac{R}{r} \right) \right),
  \]

  \[
  \rho(x, y, z = 0, t) = \frac{\rho_1/\rho_2}{1 + (1 - \rho_1/\rho_2) \cdot (U - 1)}
  \]

- **outflow:** convective outflow

  \[
  \frac{\partial U}{\partial t} + V \frac{\partial U}{\partial z} = 0
  \]

  \[ p^{(1)} = 0 \]
### The governing parameters and the test cases considered

<table>
<thead>
<tr>
<th></th>
<th>$R/\theta = 10$</th>
<th>$R/\theta = 20$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$TI = 10^{-4} %$</td>
<td>A1 (S=1,0.8,06)</td>
<td>A2 (S=1,0.8,06)</td>
</tr>
<tr>
<td>$TI = 2%$</td>
<td>A3 (S=1,0.8,06)</td>
<td>A4 (S=1,0.8,06)</td>
</tr>
</tbody>
</table>

$TI$ – turbulence intensity at the inlet boundary  
$R$ - jet radius  
$\theta$ - momentum thickness
Mean and fluctuating profile of the axial velocity for S=1, R/θ=20, TI=2\% (left figure) and TI=10^{-4}\% (right figure)
Evolution of the spectrum of axial velocity component at the shear layer and the jet axis, $S=1$, $R/\theta=20$, $T_l=10^{-4}$ %, mesh $256\times160\times256$
Isosurface of the instantaneous Q-parameter
for $S=1$, $R/\theta=20$, $TI=10^{-4}$ % (left figure) and $TI=2\%$ (right figure),

mesh $256 \times 160 \times 256$

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Mean and fluctuating profile of the axial velocity for $S=1$, $R/\theta=10$, $TI=2\%$ (left figure) and $TI=10^{-4}\%$ (right figure)
Mean and fluctuating profile of the axial velocity for $S=1.0,0.8,0.6$, $R/\theta=20$, TI=2%, mesh 128x160x128 (left figure) and mesh 256x160x256 (right figure)
Mean and fluctuating profile of the axial velocity for \( S=1.0,0.8,0.6 \), \( R/\theta=20 \), \( T\ll 1=10^{-4} \% \), mesh 128x160x128 (left figure) and mesh 256x160x256 (right figure)
Isosurface of the instantaneous Q-parameter
$R/\theta=20$, $Tl=10^{-4}$ %, $S=0.8$ (left figure) and $S=0.6$ (right figure),
mesh 256x160x256

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Evolution of the spectrum of axial velocity component at the shear layer and the jet axis, $S=0.6$, $R/\theta=20$, $T_l=10^{-4}$ $\%$, mesh 256x160x256

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Mean and fluctuating profile of the axial velocity for \( S=1.0, R/\theta=20, \) \( TI=2\% \) (left figure) and \( TI=10^{-4}\% \) (right figure), For conservative and convective form of the non-linear term in N-S equtions

mesh 256x160x256

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Concluding remarks

1. Systematic studies of isothermal and heated round jet have been performed with particular attention devoted to the LES results quality due to mesh resolution and some numerical errors.

2. LES results are sensitive to mesh resolution and numerical errors in all the test cases in which strong large scale coherent vortices could develop.

3. No definitive answer whether absolute instability has been captured within current studies.

4. The influence of the subgrid model on coherent structures still remains as an open issue to be studied in near future.