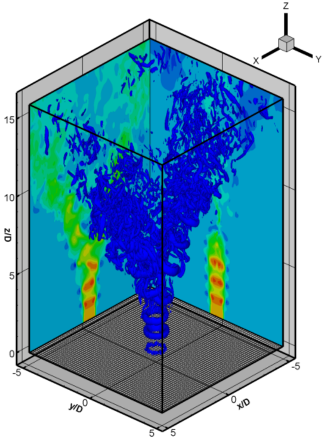
Numerical Analysis of the Excited Jets Using Large Eddy Simulation - Parametric Study

Artur Tyliszczak and Andrzej Bogusławski
Institute of Thermal Machinery
Częstochowa University of Technology
http://www.imc.pcz.czest.pl

Presentation plan

Flow characteristic, solution method, goal of the research.

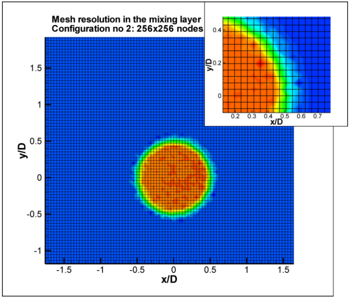
- Isothermal bifurcating turbulent jet:
  - Reynolds number: $4300, 10000, 20000$;
  - momentum thickness: $10, 20, 40$;
- Solution method: Large Eddy Simulation with *Filtered Structure Function* subgrid model
- Goal of the research:
  - application of LES to physically complex phenomenon;
  - analysis of the influence of axial+helical excitation with different forcing parameters:
    - varying amplitude;
    - varying Strouhal number;



Isosurface of Q parameter and axial velocity contours.

Computational mesh and numerical algorithm

- Computational domain and mesh:
  - Configuration no 1:
    dimensions: $8D \times 8D \times 16D$
    mesh: $128 \times 128 \times 160$ ($\approx 2.6 \cdot 10^6$)
  - Configuration no 2:
    dimensions: $10D \times 10D \times 16D$
    mesh: $256 \times 256 \times 160$ ($\approx 10.5 \cdot 10^6$)



- Numerical method (in-house SAILOR code):
  - Projection method for the pressure-velocity coupling
  - Time integration: Runge-Kutta III order (low storage)
  - Spatial discretization in the axial direction: *VI* order compact difference - boundary closure: $3 - 4 - 6 - 4 - 3$
  - Spatial discretization in the directions perpendicular to the jet axis: pseudospectral Fourier method with dealiasing by $3/2$ law
- Parallel efficiency ≈ 1.7 (comparing computational time on 4 and 8 processors)

Boundary conditions

- Inlet:

$$u(x,y,z=0,t) = \frac{U_1+U_2}{2} + - \frac{U_1-U_2}{2}\,\mathrm{tgh}\left(\frac{R}{4\theta}\left(\frac{r}{R}-\frac{R}{r}\right)\right)$$

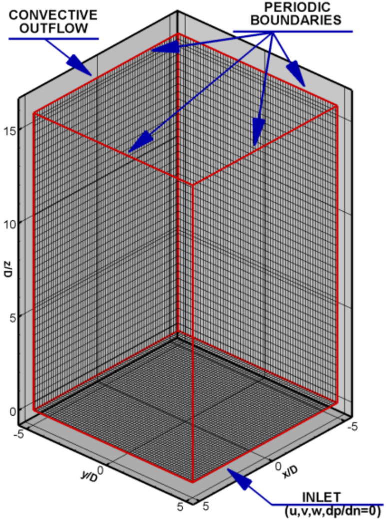
  U_1 - velocity in the jet axis;
  U_2 - coflow velocity ($U_2/U_1 = 0.05$)

- Outflow: convective outflow

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

$$p = 0$$

- inlet turbulence intensity (TI): white noise with amplitude equal to $0.0, 0.025, 0.05 U_1$

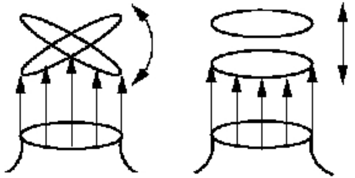


Axial and helical excitation (forcing)

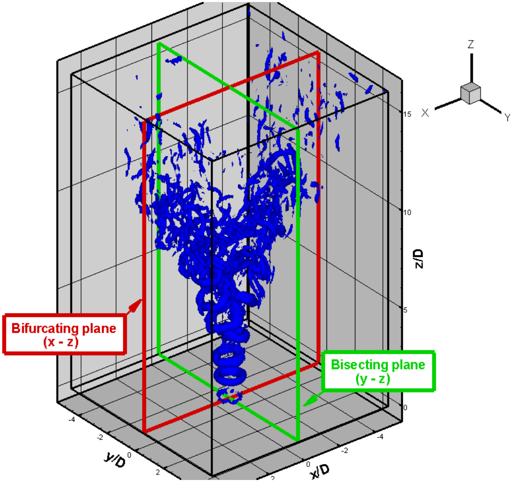
- Excitation parameters:
  - Inlet axial velocity: $u(\vec{x},t) = u_{mean}(\vec{x}) + u_{noise}(\vec{x},t) + u_{excit}(\vec{x},t)$
  - Excitation:

$$u_{excit}(\vec{x},t) = A_a \sin\left(2\pi St_a \frac{U_1}{D} t\right) + A_h \sin\left(2\pi St_h \frac{U_1}{D} t + \frac{\pi}{4}\right) \sin\left(\frac{\pi x}{R}\right)$$

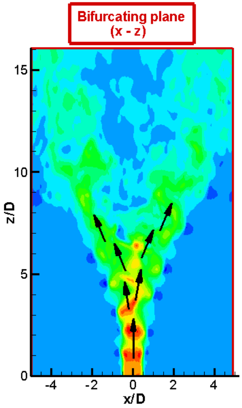
- Known excitation effects:
  - for combination of axial and helical forcing with integer ratio St_a/St_h with $St_a = 0.3 \div 0.7$ the bifurcating jets occur (confirmed experimentally and numerically)
  - for non-integer ratio St_a/St_h blooming jets are observed (confirmed experimentally)



Definition of bifurcating and bisecting planes



Instantaneous Q criterion and definition of the bifurcating and bisecting planes



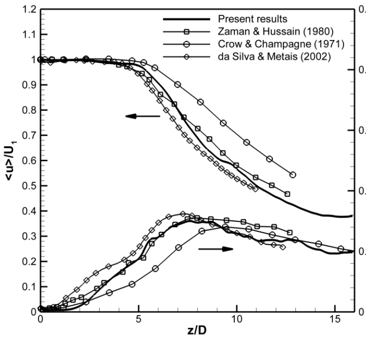
Instantaneous axial velocity presented in the bifurcating plane $(x - z)$ - plane of the helical excitation

Code verification

Comparison of experimental and computational data: natural and axially excited jet

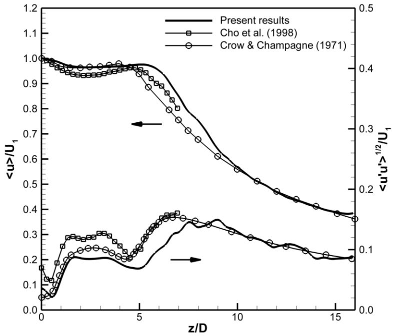
Experimental data: Crow & Champagne (1971), Zaman & Hussain (1980)
Experimental data: Crow & Champagne (1971), Cho & Choi (1998)
Numerical data: da Silva & Metais (2002)

Non-excited jet



Axial forcing only

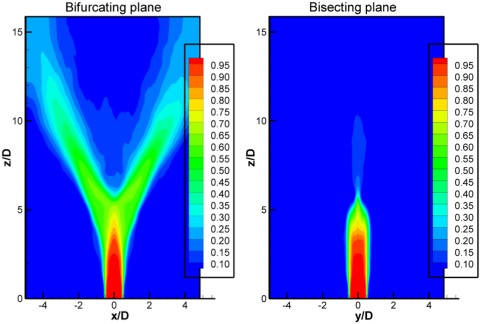
$A_a = 0.05U_1$, $St_a = 0.5$



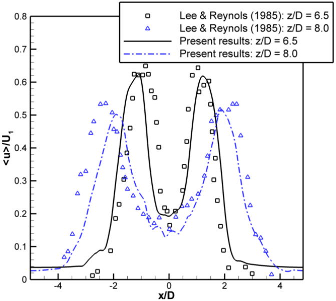
Mean and fluctuating axial velocity along the jet axis

Comparison of experimental and computational data: bifurcating jet

Simulation parameters: $A = 5\% \rightarrow A_a = A_h = 0.05U_1$, $St_a = 0.5$, $St_a/St_h = 2.0$
Averaging time: $40D/U \div 200D/U$



Mean axial velocity in the bifurcating plane and bisecting plane



Mean axial velocity along the radial direction in the bifurcating plane at 6.5 and 8.0 diameters from the nozzle

Type and range of analyzed parameters

Simulation parameters:

1. influence of the Reynolds number: $Re = 4300$, $Re = 10000$, $Re = 20000$ with $D/\Theta = 40$, turbulence intensity $TI = 5\%$, forcing amplitude $A = 5\%$
2. influence of the momentum thickness: $D/\Theta = 10$, $D/\Theta = 20$, $D/\Theta = 40$ with $Re = 20000$, turbulence intensity $TI = 5\%$, forcing amplitude $A = 5\%$
3. influence of the forcing frequency: $St_a = 0.3 \div 0.7$ with $D/\Theta = 40$, turbulence intensity $TI = 5\%$, forcing amplitude $A = 5\%$ presented only for Reynolds number: $Re = 20000$
4. influence of the forcing amplitude and turbulence intensity: $A = 1.0\%$, $A = 2.5\%$, $A = 5.0\%$ for $TI = 0\%$, $TI = 2.5\%$, and $TI = 5\%$ with $Re = 20000$, $D/\Theta = 40$

Type and range of analyzed parameters

Simulation parameters:

1. influence of the Reynolds number: $Re = 4300$, $Re = 10000$, $Re = 20000$ with $D/\Theta = 40$, turbulence intensity $TI = 5\%$, forcing amplitude $A = 5\%$
2. influence of the momentum thickness: $D/\Theta = 10$, $D/\Theta = 20$, $D/\Theta = 40$ with $Re = 20000$, turbulence intensity $TI = 5\%$, forcing amplitude $A = 5\%$
3. influence of the forcing frequency: $St_a = 0.3 \div 0.7$ with $D/\Theta = 40$, turbulence intensity $TI = 5\%$, forcing amplitude $A = 5\%$ presented only for Reynolds number: $Re = 20000$
4. influence of the forcing amplitude and turbulence intensity: $A = 1.0\%$, $A = 2.5\%$, $A = 5.0\%$ for $TI = 0\%$, $TI = 2.5\%$, and $TI = 5\%$ with $Re = 20000$, $D/\Theta = 40$

Type and range of analyzed parameters

Simulation parameters:

1. influence of the Reynolds number: $Re = 4300$, $Re = 10000$, $Re = 20000$ with $D/\Theta = 40$, turbulence intensity $TI = 5\%$, forcing amplitude $A = 5\%$
2. influence of the momentum thickness: $D/\Theta = 10$, $D/\Theta = 20$, $D/\Theta = 40$ with $Re = 20000$, turbulence intensity $TI = 5\%$, forcing amplitude $A = 5\%$
3. influence of the forcing frequency: $St_a = 0.3 \div 0.7$ with $D/\Theta = 40$, turbulence intensity $TI = 5\%$, forcing amplitude $A = 5\%$ presented only for Reynolds number: $Re = 20000$
4. influence of the forcing amplitude and turbulence intensity: $A = 1.0\%$, $A = 2.5\%$, $A = 5.0\%$ for $TI = 0\%$, $TI = 2.5\%$, and $TI = 5\%$ with $Re = 20000$, $D/\Theta = 40$

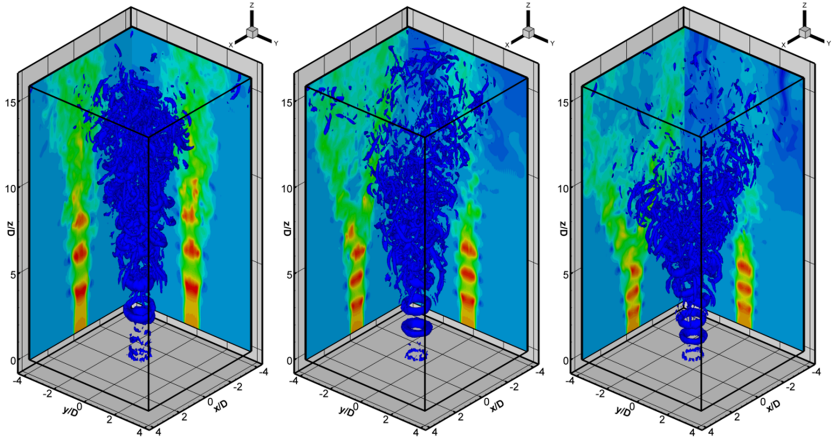
Type and range of analyzed parameters

Simulation parameters:

1. influence of the Reynolds number: $Re = 4300$, $Re = 10000$, $Re = 20000$ with $D/\Theta = 40$, turbulence intensity $TI = 5\%$, forcing amplitude $A = 5\%$
2. influence of the momentum thickness: $D/\Theta = 10$, $D/\Theta = 20$, $D/\Theta = 40$ with $Re = 20000$, turbulence intensity $TI = 5\%$, forcing amplitude $A = 5\%$
3. influence of the forcing frequency: $St_a = 0.3 \div 0.7$ with $D/\Theta = 40$, turbulence intensity $TI = 5\%$, forcing amplitude $A = 5\%$ presented only for Reynolds number: $Re = 20000$
4. influence of the forcing amplitude and turbulence intensity: $A = 1.0\%$, $A = 2.5\%$, $A = 5.0\%$ for $TI = 0\%$, $TI = 2.5\%$, and $TI = 5\%$ with $Re = 20000$, $D/\Theta = 40$

Analysis of the influence of forcing frequency

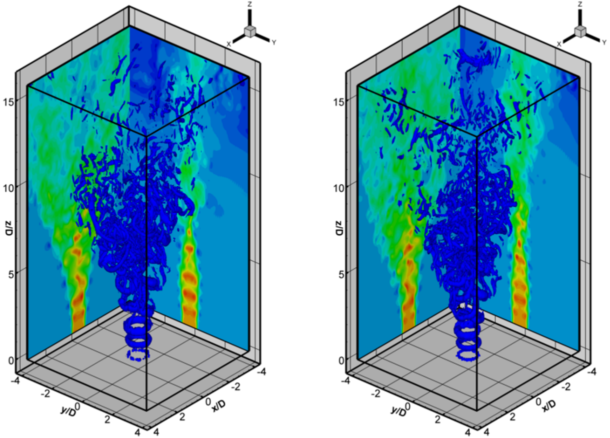
Simulation parameters: $St_a = 0.3, 0.4, 0.5, 0.6, 0.7$; $St_a/St_h = 2.0$, $A_a = A_h = A = 5.0\%$, $TI = 5\%$, $Re = 20000$;



Instantaneous isosurfaces of Q parameter and contours of axial velocity in the bifurcating and bisecting planes

Analysis of the influence of forcing frequency (continued)

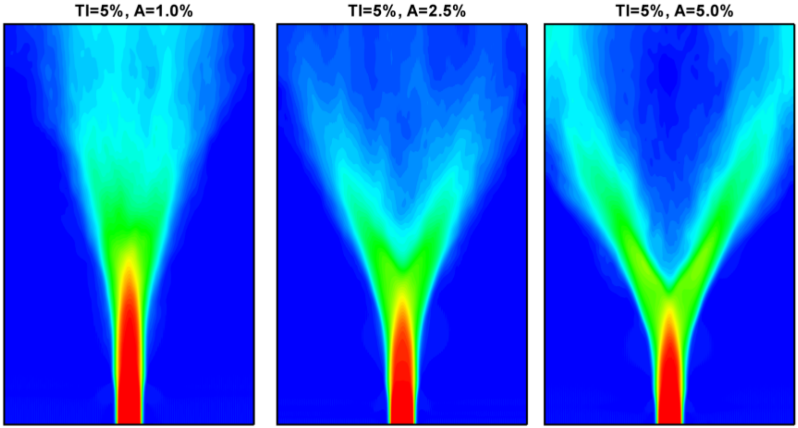
Simulation parameters: $St_a = 0.3, 0.4, 0.5, 0.6, 0.7$; $St_a/St_h = 2.0$, $A_a = A_h = A = 5.0\%$, $TI = 5\%$, $Re = 20000$;



Instantaneous isosurfaces of Q parameter and contours of axial velocity in the bifurcating and bisecting planes

Analysis of the influence of forcing amplitude

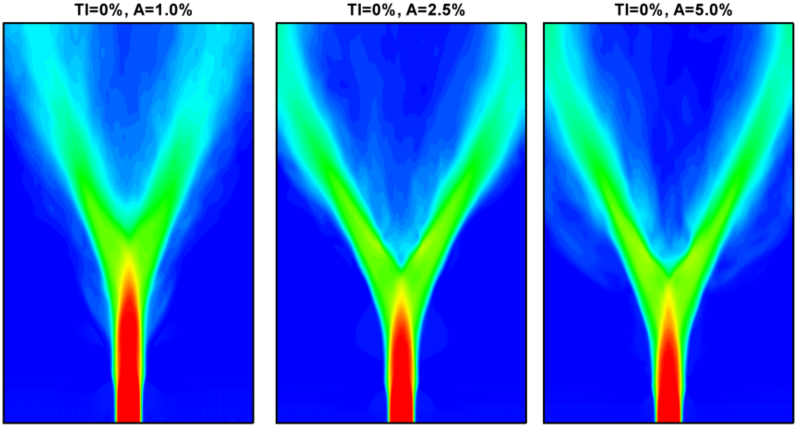
Simulation parameters: $A_a = A_h = A = 1.0\%, 2.5\%, 5.0\%$, $TI = 5\%$, $St_a = 0.5$, $St_a/St_h = 2.0$; Averaging time: $100D/U$



Mean axial velocity in the bifurcating planes

Analysis of the influence of forcing amplitude (continued)

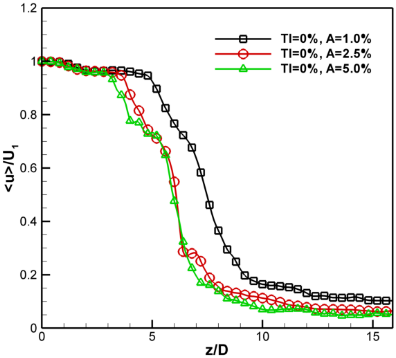
Simulation parameters: $A_a = A_h = A = 1.0\%, 2.5\%, 5.0\%$, $TI = 0\%$, $St_a = 0.5$, $St_a/St_h = 2.0$; Averaging time: $100D/U$

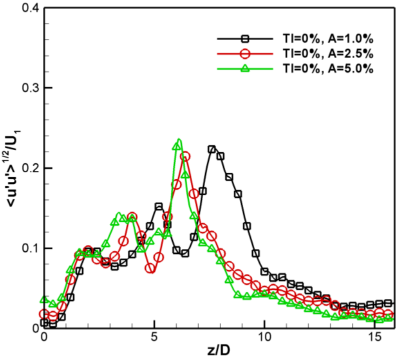


Mean axial velocity in the bifurcating planes

Analysis of the influence of forcing amplitude (continued)

Simulation parameters: $A_a = A_h = A = 1.0\%, 2.5\%, 5.0\%$, $TI = 0\%$, $St_a = 0.5$, $St_a/St_h = 2.0$; Averaging time: $100D/U$





Mean and fluctuating axial velocity along the jet axis

Conclusions:

- The LES computations show that the excitation (forcing) parameters determine the jet behavior. In particular:
  - bifurcating jets are observed when the forcing amplitude is of the same order (or higher) as the turbulence intensity at the jet inlet
  - bifurcating jets are observed when the forcing frequency is close to the preferred mode frequency (in our case $St = 0.44$); considerably bellow this value the jet seems to be unaffected by excitation; considerably above this value the spreading rate of the jet increases but the bifurcation phenomena also vanishes
- The LES computations performed (but not presented) show that:
  - the excited jets are independent of the Reynolds number (if it is high enough)
  - neither the bifurcation phenomenon nor increased spreading rate were observed for thick momentum thickness ($D/\Theta = 10$)

Part of the work was performed within FAR-Wake project (No. AST4-CT-2005-012238) within 6th Framework Program