



1,2

1

2

K. Hanjalic, M. Hadziabdic, B. Niceno, L. Vervisch, R. Sandberg

ССКЦ, 28 апреля 2016

# План презентации

## **1. О вычислительных кодах**

2. Введение

3. Незакрученная струя

4. Закрученная струя

5. Импульсная струя

6. Заключение

# О вычислительных кодах

**T-FlowS**



неструкт. сетки

конеч. объемы

2ой порядок

итер. решатели

DNS, LES, RANS

**PSI-BOIL**



структ. сетки

конеч. объемы

4ый порядок

итер. решатели

DNS, LES

**Nek5000**



неструкт. сетки

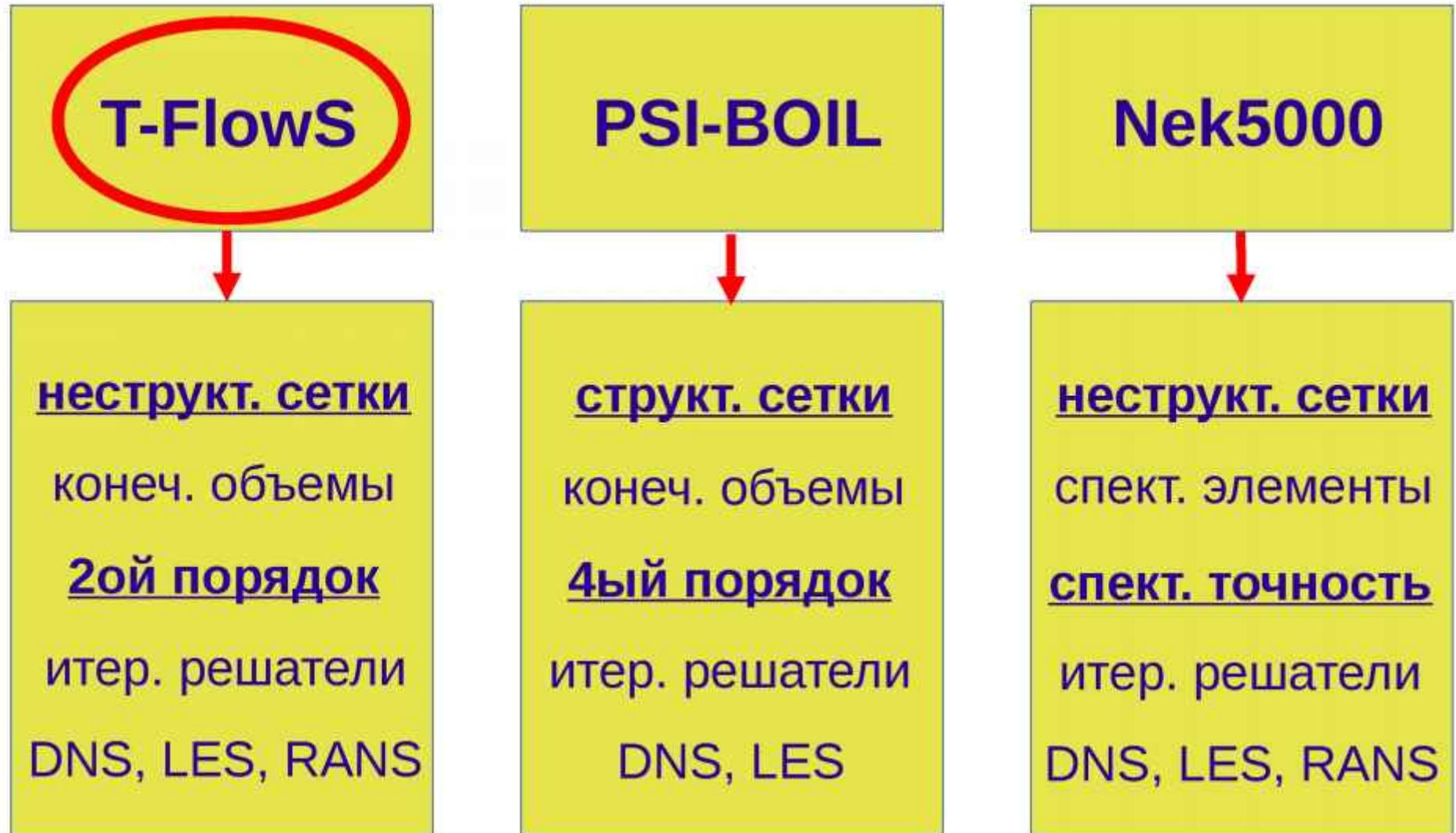
спект. элементы

спект. точность

итер. решатели

DNS, LES, RANS

# О вычислительных кодах



# О вычислительных кодах

**T-FlowS** -

(f90),

LES RANS (B. Niceno).

Особенности:

- ◆ Продвинутое RANS модели
- ◆ Различные подсеточные LES модели
- ◆ Гибридные RANS/LES модели
- ◆ Пристеночные функции
- ◆ Сопряженный теплообмен

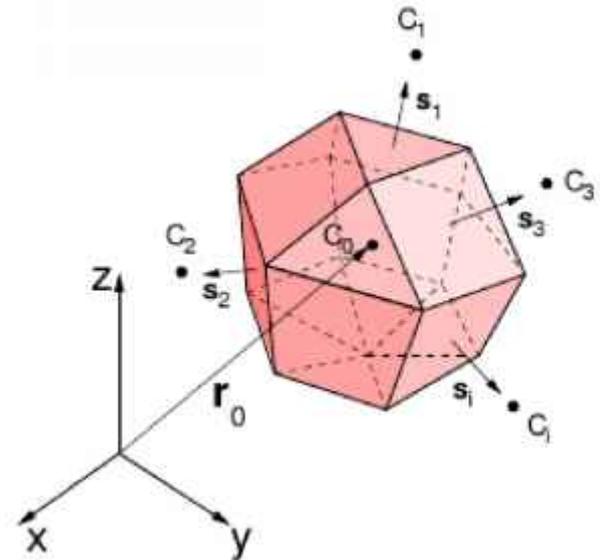
## О вычислительных кодах

$$\int_V (\mathbf{r} - \mathbf{r}_0) dV = 0,$$

$$\int_S \mathbf{u} \cdot \mathbf{n} dS = 0,$$

$$\frac{\partial}{\partial t} \int_V \mathbf{u} dV + \int_S \mathbf{u} (\mathbf{u} \cdot \mathbf{n}) dS =$$

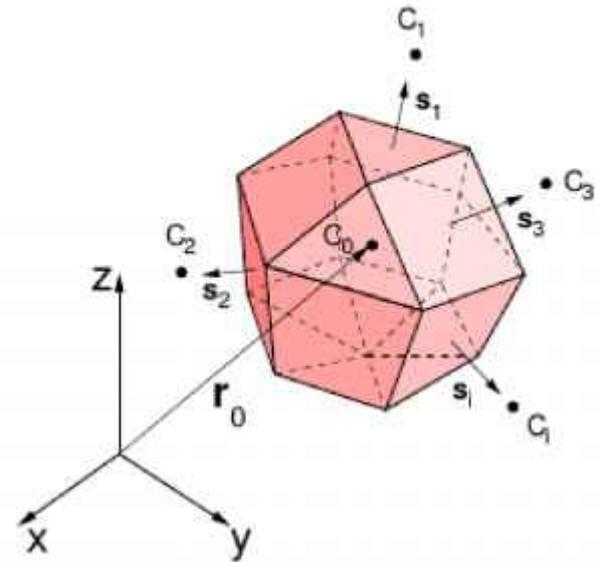
$$- \int_V \nabla p dV + \int_S \nu (\nabla \mathbf{u} + \nabla \mathbf{u}^T) \mathbf{n} dS,$$



# О вычислительных кодах

$\phi$  — некоторое скалярное поле

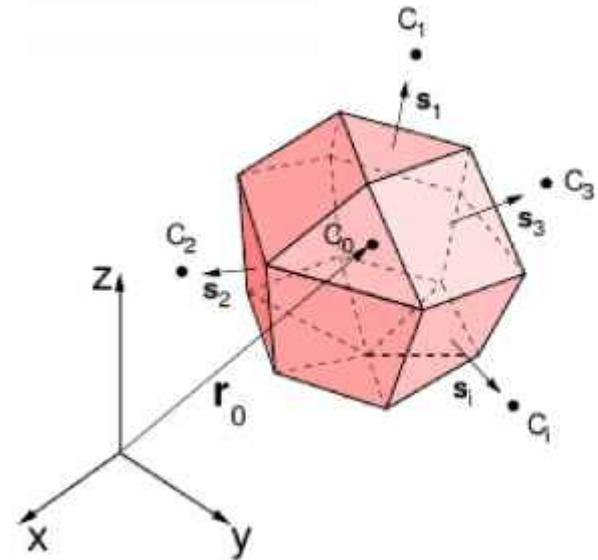
$$\int_V \phi dV \approx \phi_0 \Delta V$$



$$\left( \frac{\partial}{\partial t} \int_V \phi dV \right)^{n+1} \approx \frac{\Delta V}{\Delta t} \left( \frac{3}{2} \phi^{n+1} - 2\phi^n + \frac{1}{2} \phi^{n-1} \right), \quad \left| D_t \right.$$

$$\int_S \phi(\mathbf{u} \cdot \mathbf{n}) dS \approx \sum_{\text{faces}} \bar{\phi}_j F_j, \quad F = \overline{\mathbf{u} \cdot \mathbf{n} \Delta S}. \quad \left| \text{Conv.} \right.$$

# О вычислительных кодах



$$\int_S \nabla \phi \cdot \mathbf{n} dS \approx \sum_{\text{faces}} \left( \overline{\nabla \phi \cdot \mathbf{n} \Delta S} \right)_j,$$

Diff.

$$D_t^{n+1} + Conv^{n+1} = Pres^{n+1} + Diff^{n+1},$$

fully  
implicit  
scheme

# О вычислительных кодах

Связь скорости и давления осуществляется при помощи алгоритма SIMPLE

$$D_t^{n+1} + Conv^{n+1} = Pres^{n+1} + Diff^{n+1},$$

fully  
implicit  
scheme

$$\mathbf{u}^{n+1} = \underline{\mathbf{u}^*} + \delta \mathbf{u}, \quad p^{n+1} = \underline{p^*} + \delta p,$$

corr.

$$\delta \mathbf{u} = -\Delta t \nabla \delta p,$$

$$\Delta \delta p = \frac{1}{\Delta t} [\nabla \cdot \mathbf{u}^*], \quad \int_S \nabla \delta p \cdot \mathbf{n} dS = \frac{1}{\Delta t} \int_S \mathbf{u}^* \cdot \mathbf{n} dS.$$

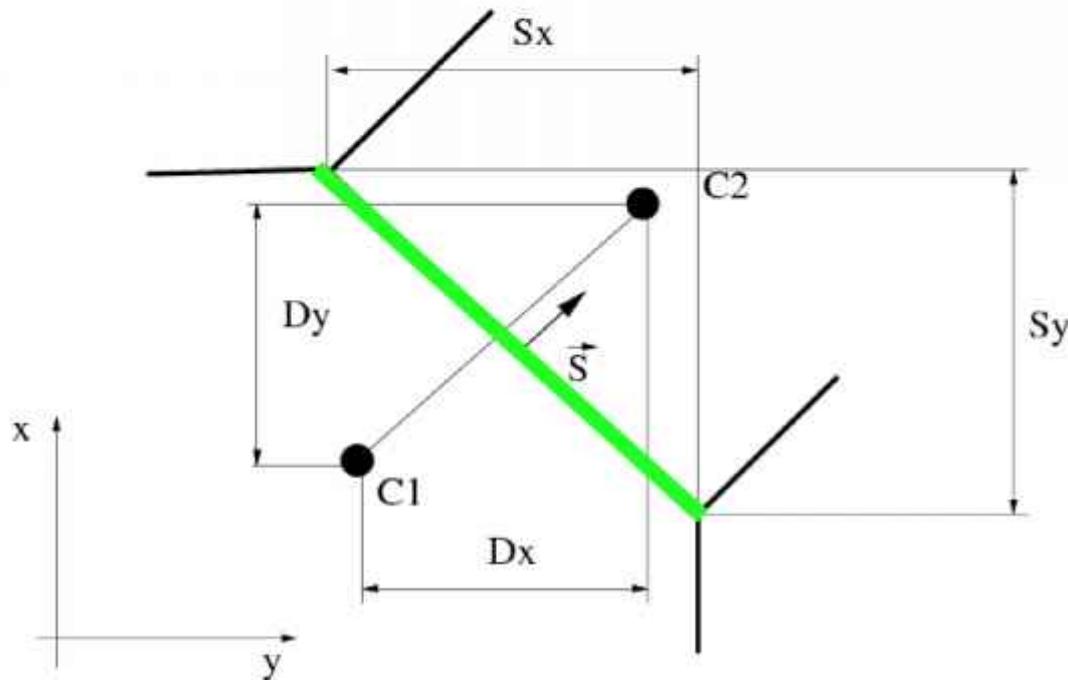
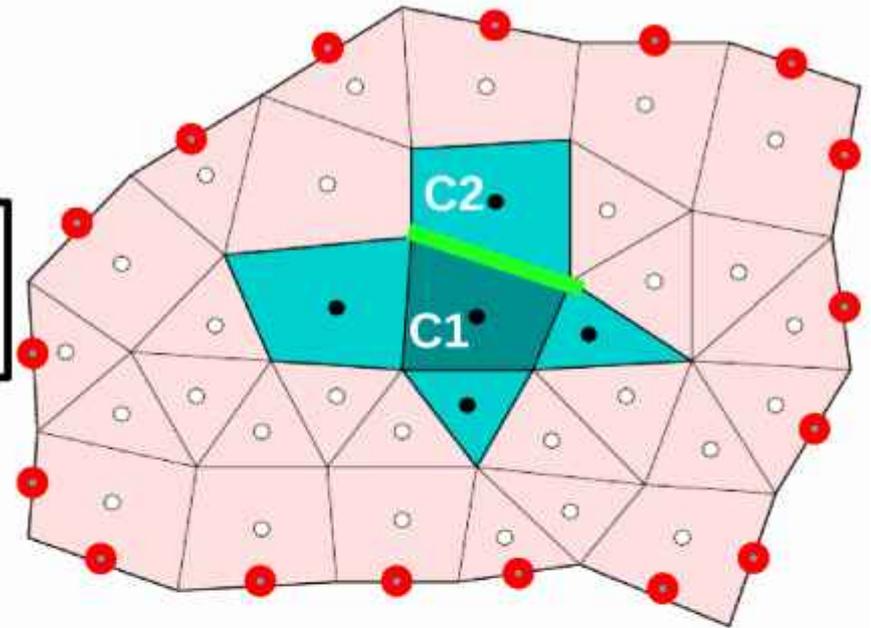
# О вычислительных кодах

бежим по внутренним  
ячейкам

```
do c = 1, NC  
end do
```

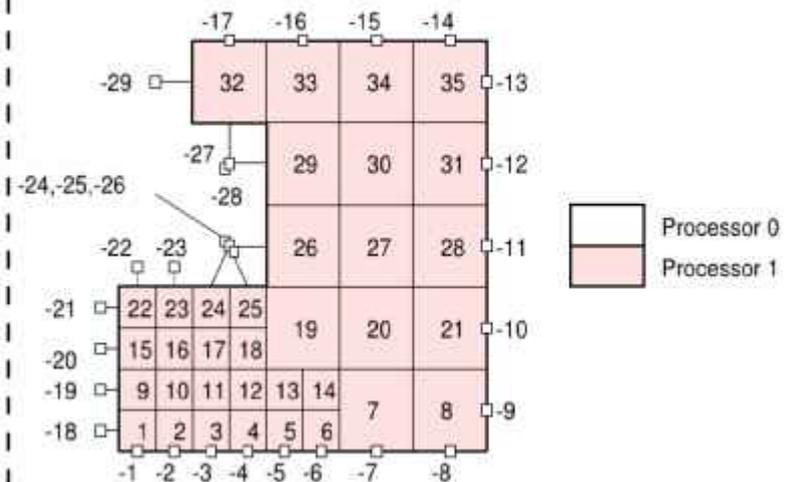
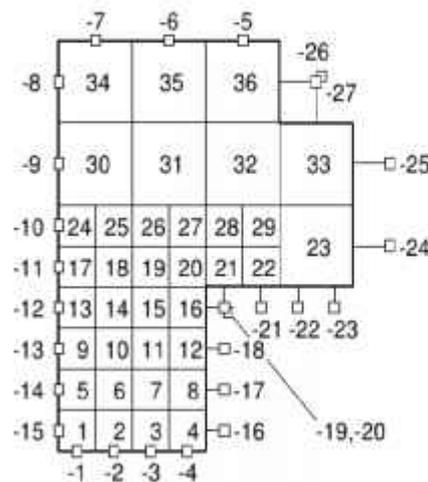
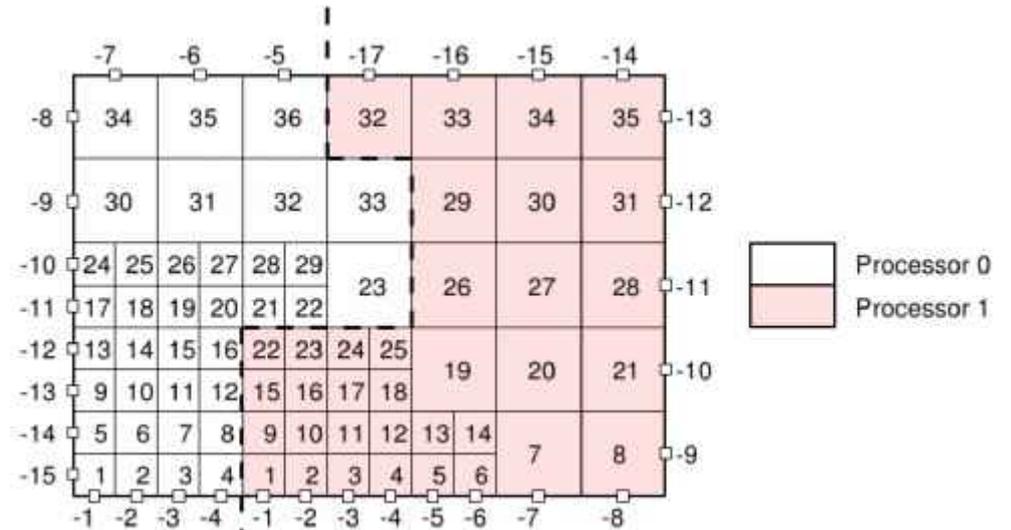
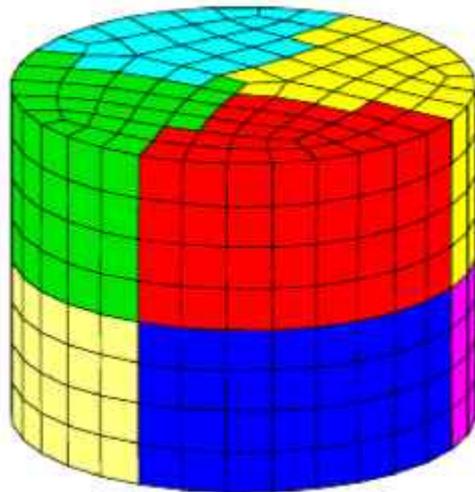
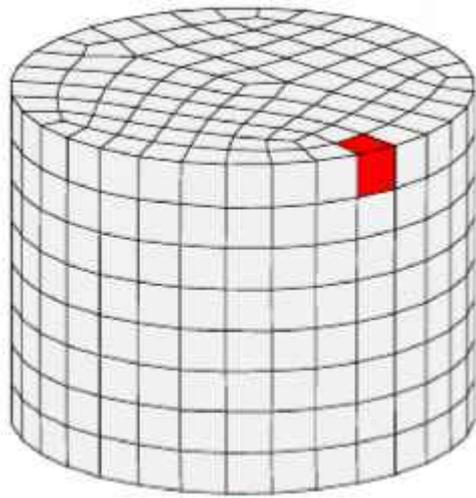
бежим по всем  
ячейкам

```
do c = -NbC, NC  
end do
```

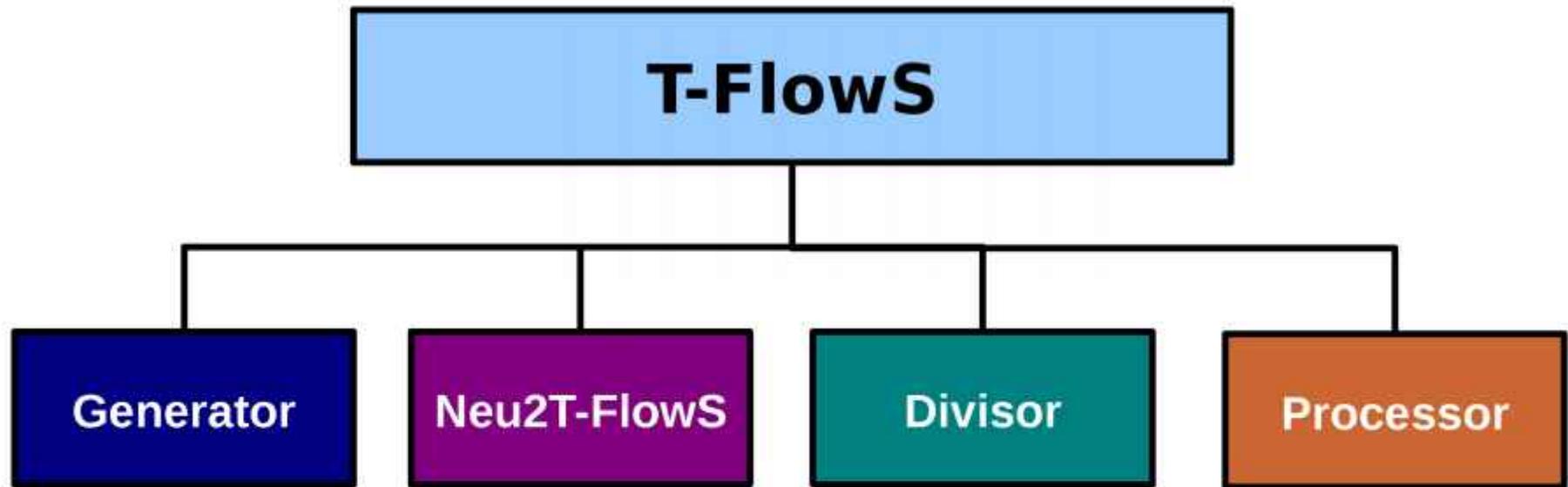


```
do s=1,NS  
  c1=SideC(1,s)  
  c2=SideC(2,s)  
  if(C2 > 0) then  
    внутренняя ячейка  
  else  
    внешняя ячейка  
  end if  
end do
```

# О вычислительных кодах



# О вычислительных кодах

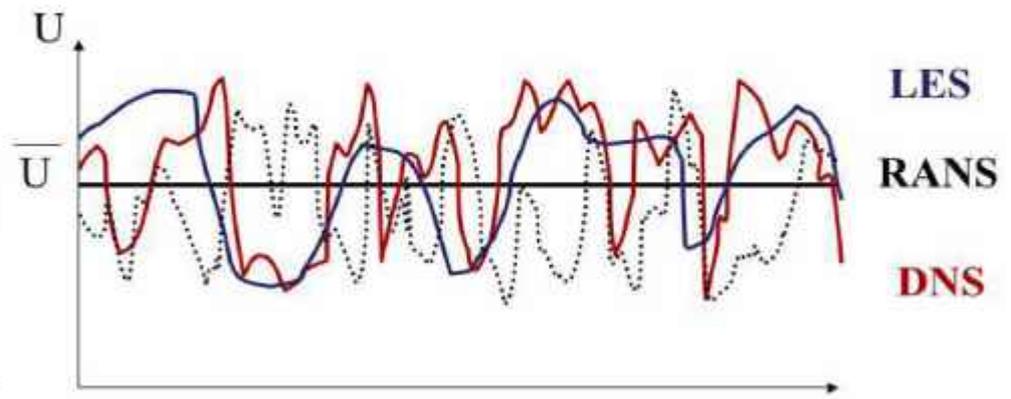
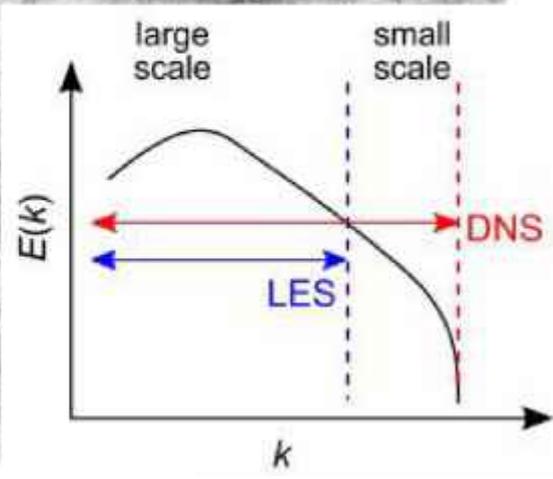
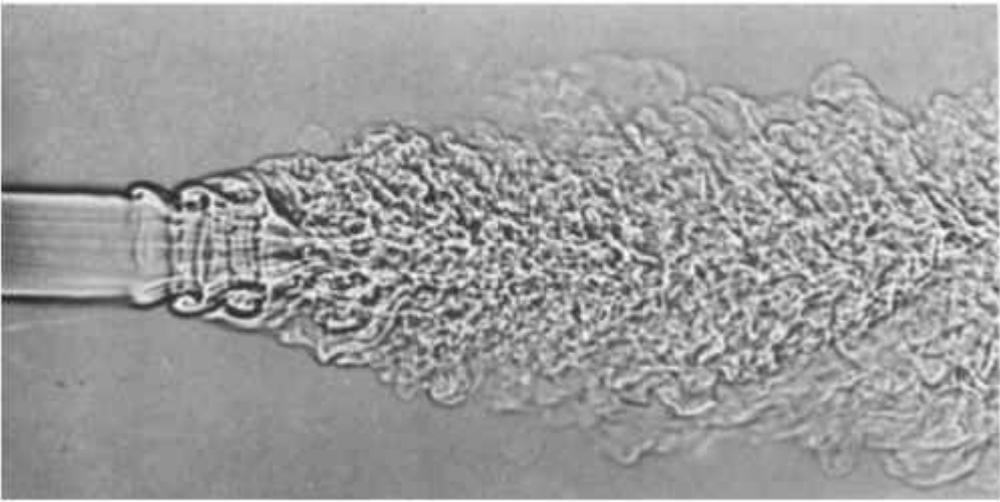


	cont.	U	V	W	$\delta P$	T					
# 1	2.503E-02	6.068E-02	6.127E-02	7.276E-02	2.951E-05	6.144E-02	4	4	4	41	4
# 2	1.130E-02	1.255E-02	1.260E-02	1.521E-02	2.209E-05	1.690E-02	3	3	3	41	3
# 3	9.510E-03	2.641E-03	2.693E-03	3.209E-03	1.214E-05	3.405E-03	3	3	3	41	3
# 4	4.425E-03	5.609E-04	5.720E-04	6.851E-04	5.140E-06	7.284E-04	2	2	2	41	2
# 5	4.260E-03	1.206E-04	1.231E-04	1.486E-04	2.013E-06	1.537E-04	2	2	2	15	2
# 6	3.013E-03	2.682E-05	2.741E-05	3.344E-05	1.060E-06	3.290E-05	1	1	1	6	1
# 7	2.118E-03	6.865E-06	7.052E-06	8.360E-06	1.668E-06	7.127E-06	1	1	1	0	1
250565	1.253E+03	4.382E-02	1.286E-03	1.078E+00	-3.347E-02	1.000E+00					
# [1]							2.117E+01	0.000E+00	6.817E-01	1.762E+03	

# План презентации

1. О вычислительных кодах
- 2. Введение**
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# Турбулентные потоки



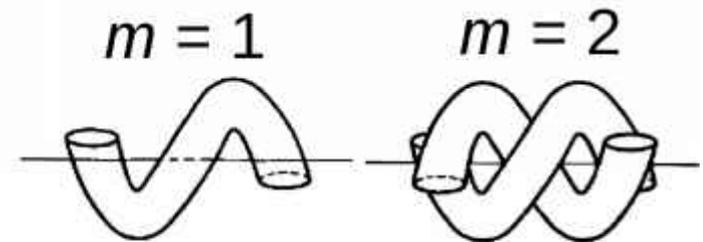
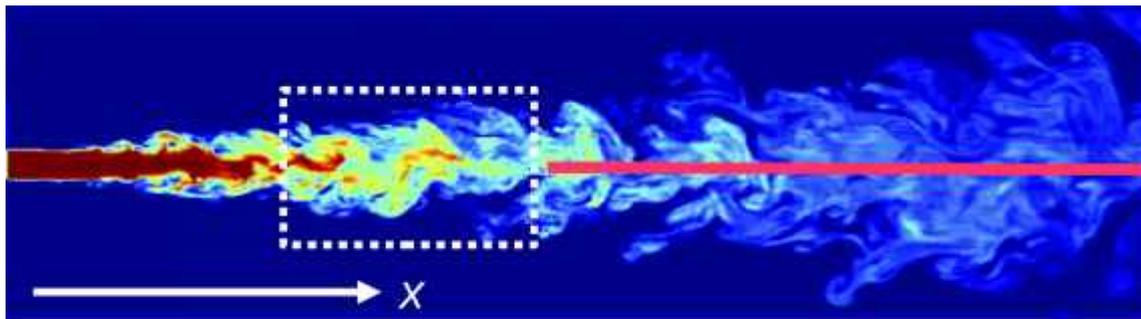
# План презентации

1. О вычислительных кодах
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# Незакрученная струя. Идеи

$7 \cdot 10^3$ ).

( $Re \sim 5 \cdot 10^3$ ).



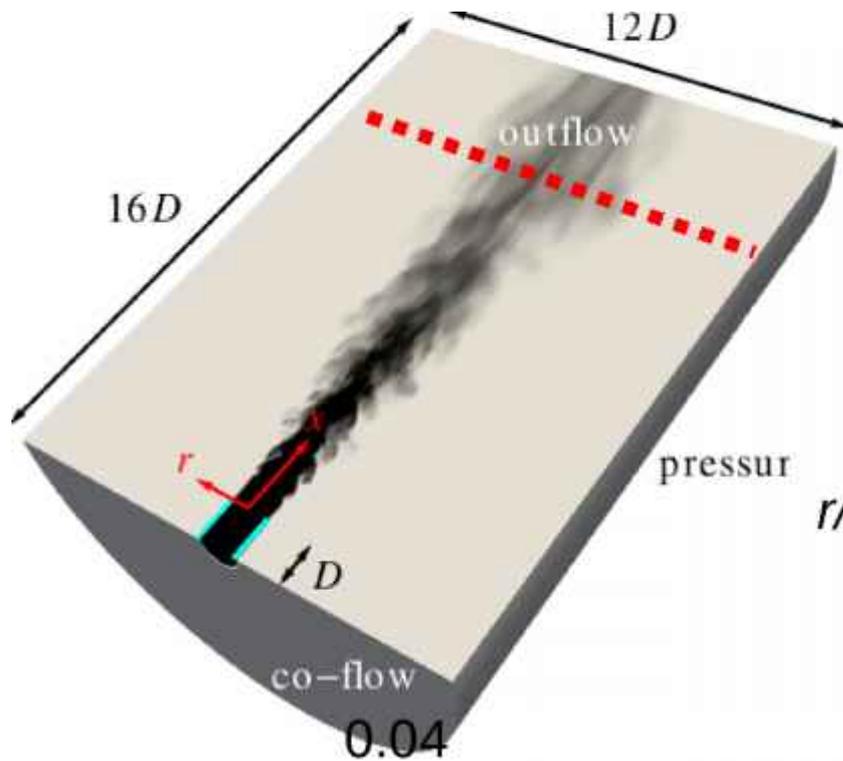
Tso, Hussain JFM 1989

Yoda et al. JFM 1993

<https://tasc.llnl.gov/galleries/image-gallery>

(2 )

LES (T-FlowS)

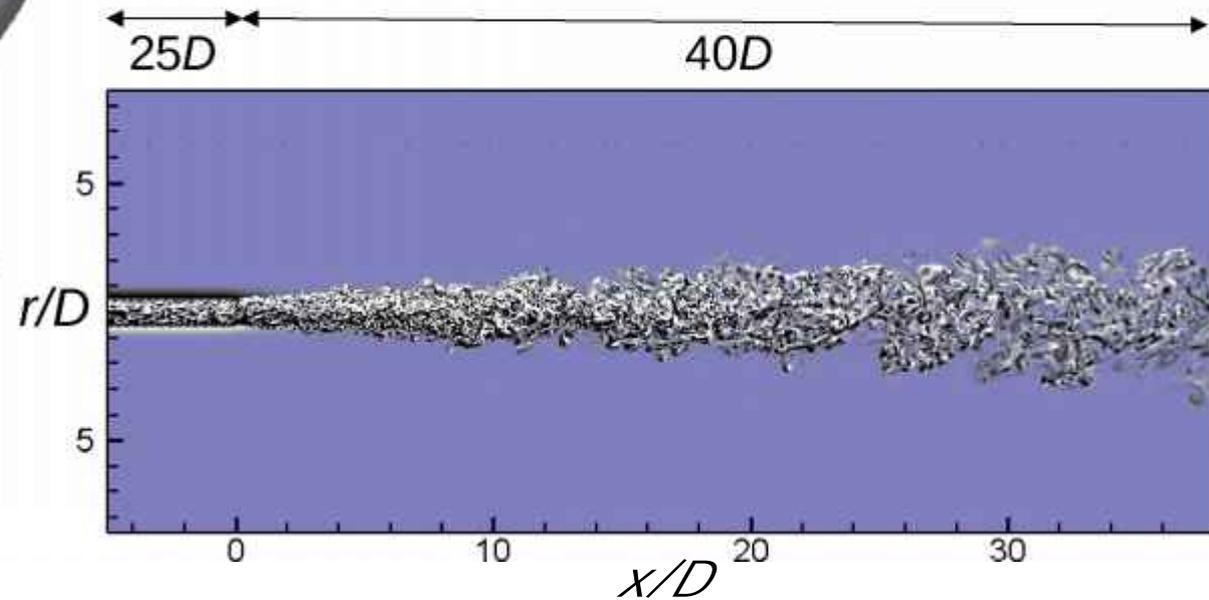


252 x 282 x 264 ~ 16.7 mln

video!

DNS (HiPSTAR)

R.D.Sandberg



918 x 3432 x 130 ~ 408.2 mln

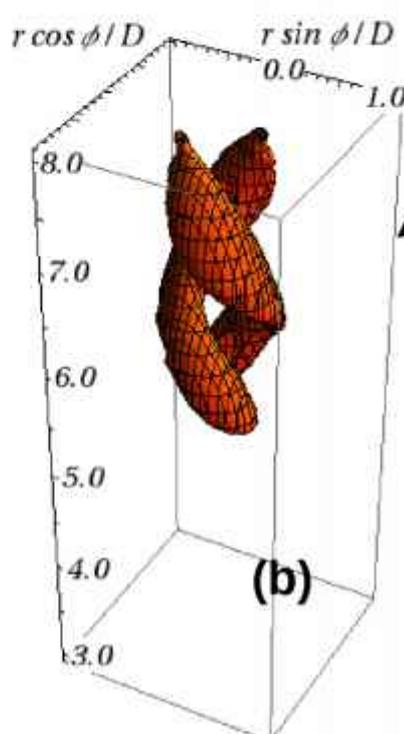
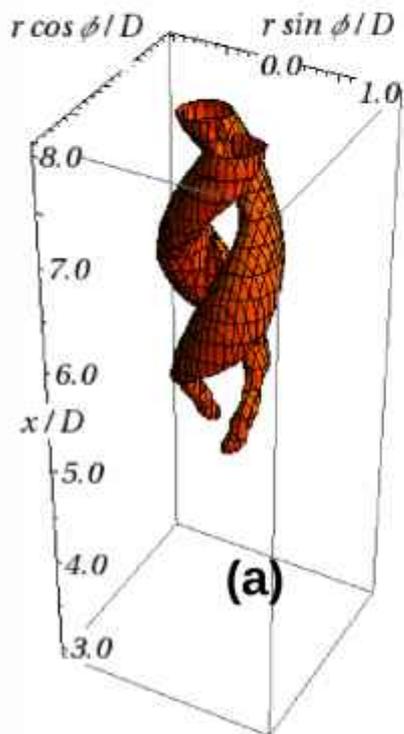
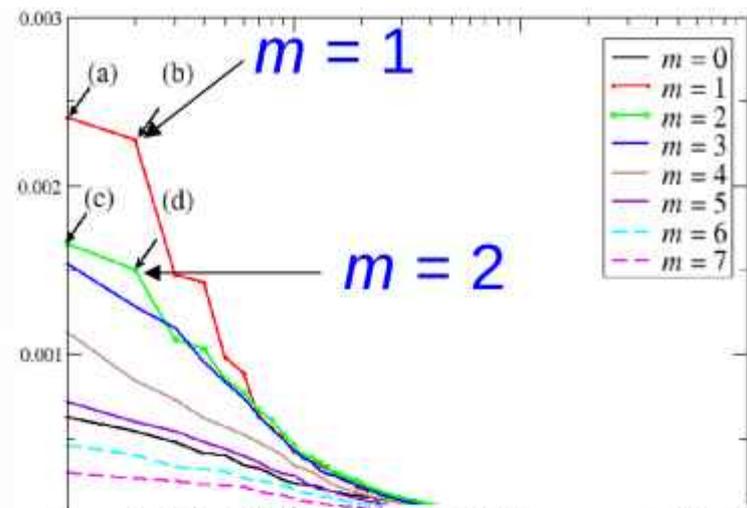
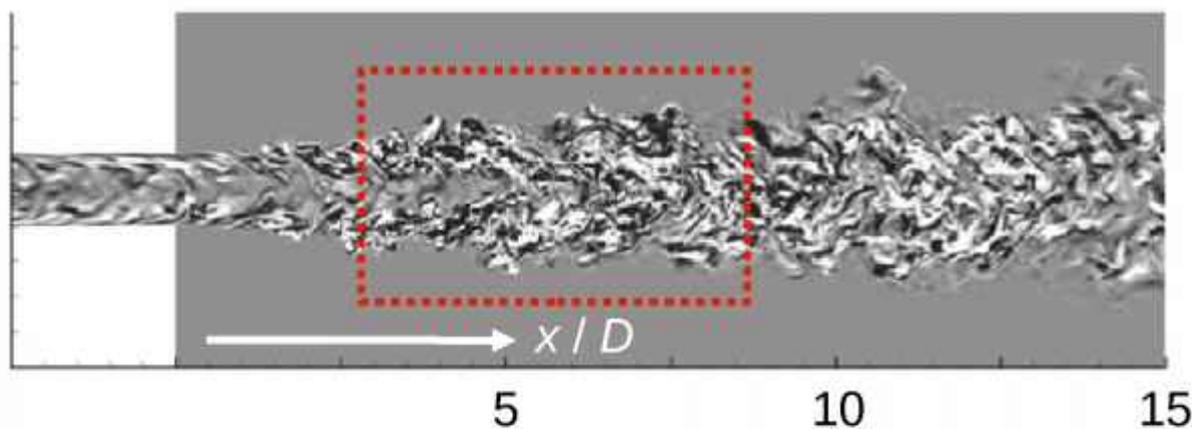
# Proper Orthogonal Decomposition

$$\mathbf{u}(x, r, m, t) = \frac{1}{2\pi} \int_0^{2\pi} \mathbf{u}(x, r, \phi, t) e^{im\phi} d\phi,$$

$$\mathbf{u}_i^m(x, r) = \mathbf{u}(x, r, m, t_i) = \sum_{q=1}^N a_q^m(t_i) \lambda_q^{(m)} \mathbf{v}_q^m(x, r),$$

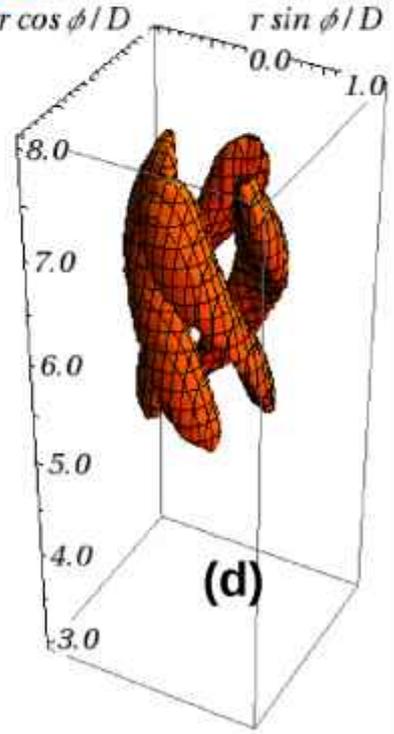
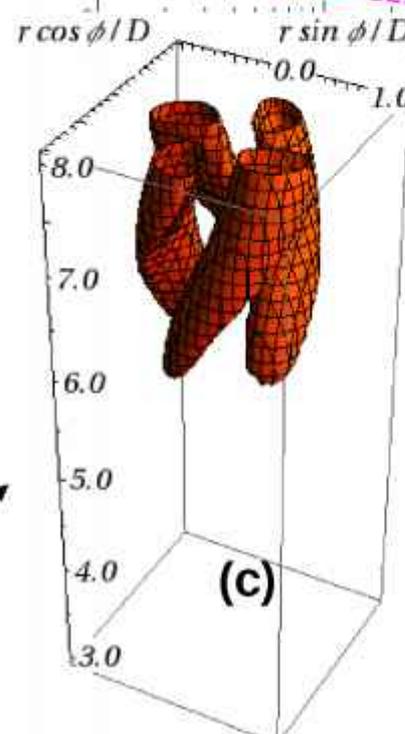
$$\int \mathbf{v}_i^m \mathbf{v}_j^m r dr dx = \delta_{ij}, \quad \frac{1}{N} \sum_{n=1}^N a_i^m(t_n) a_j^m(t_n) = \delta_{ij},$$

# Незакрученная струя

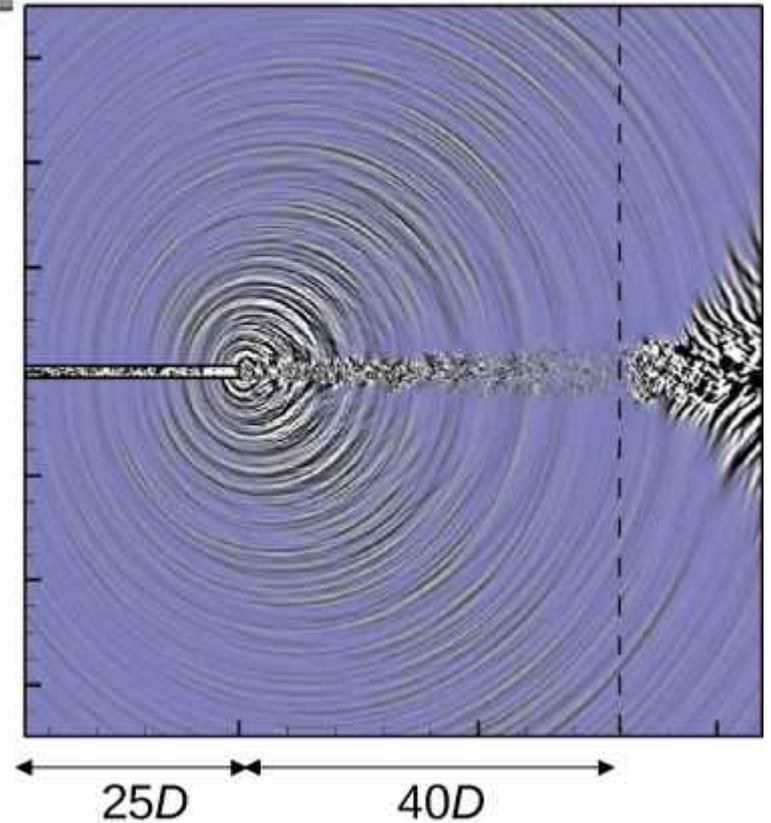
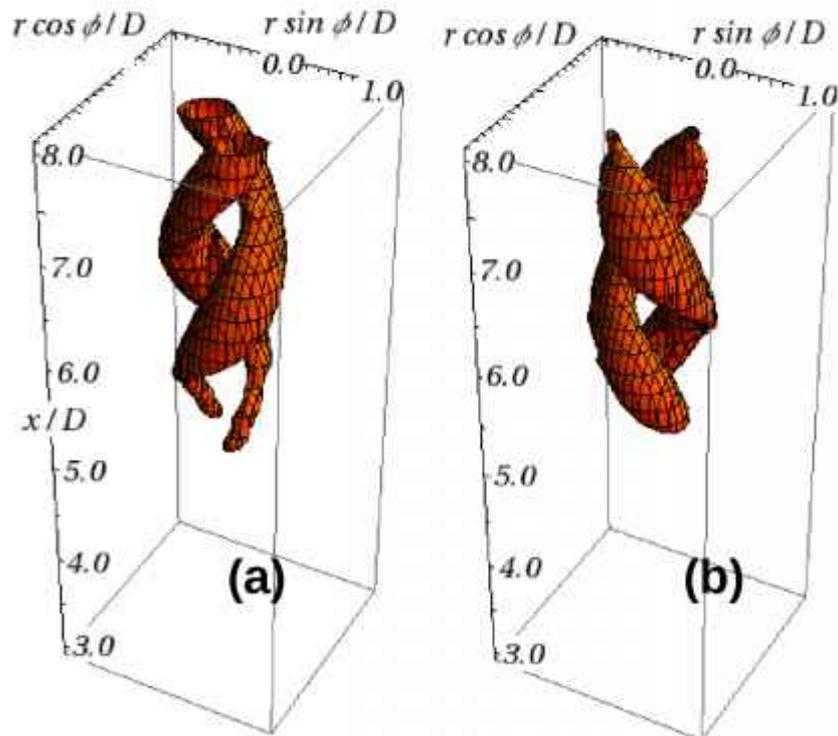
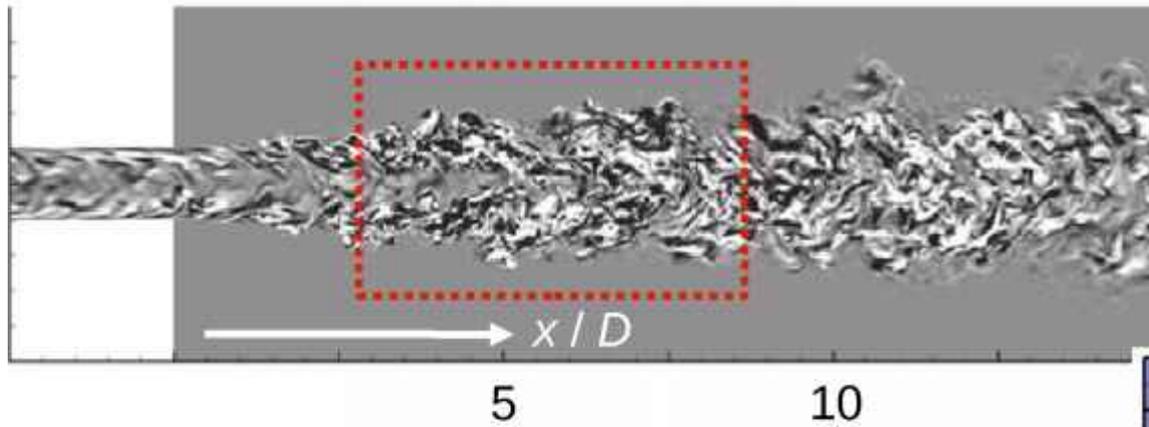


$m = 1$

$m = 2$



# Незакрученная струя



# План презентации

1.

2.

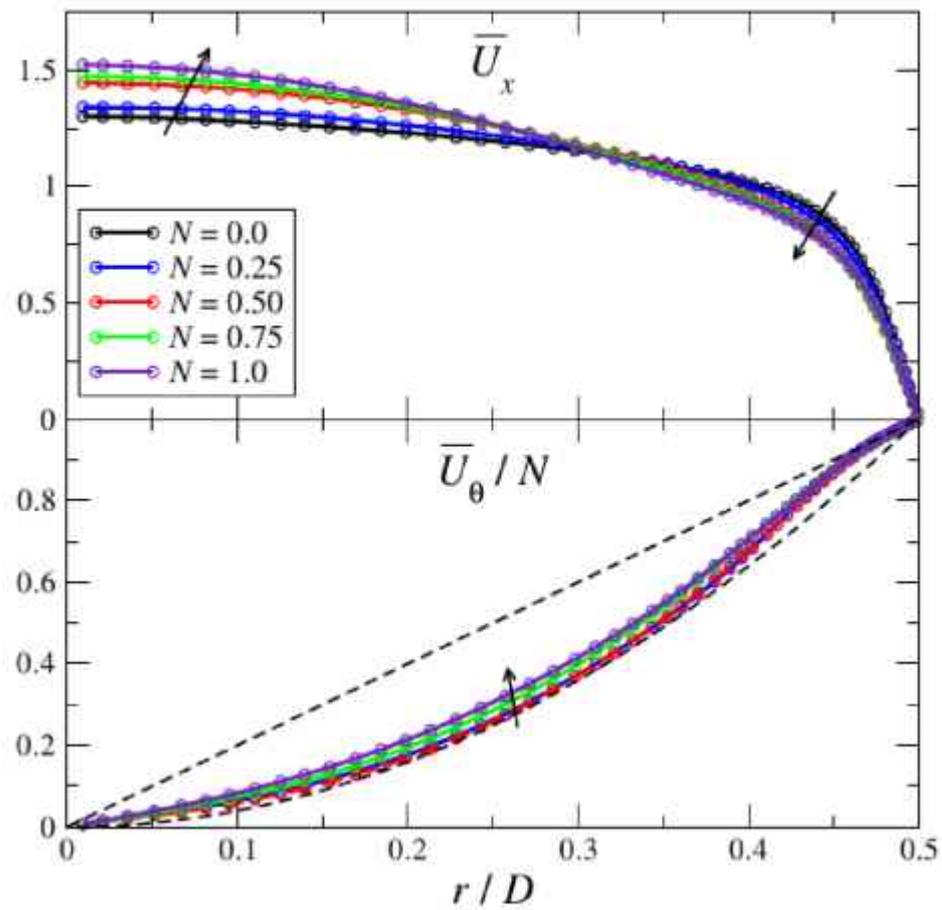
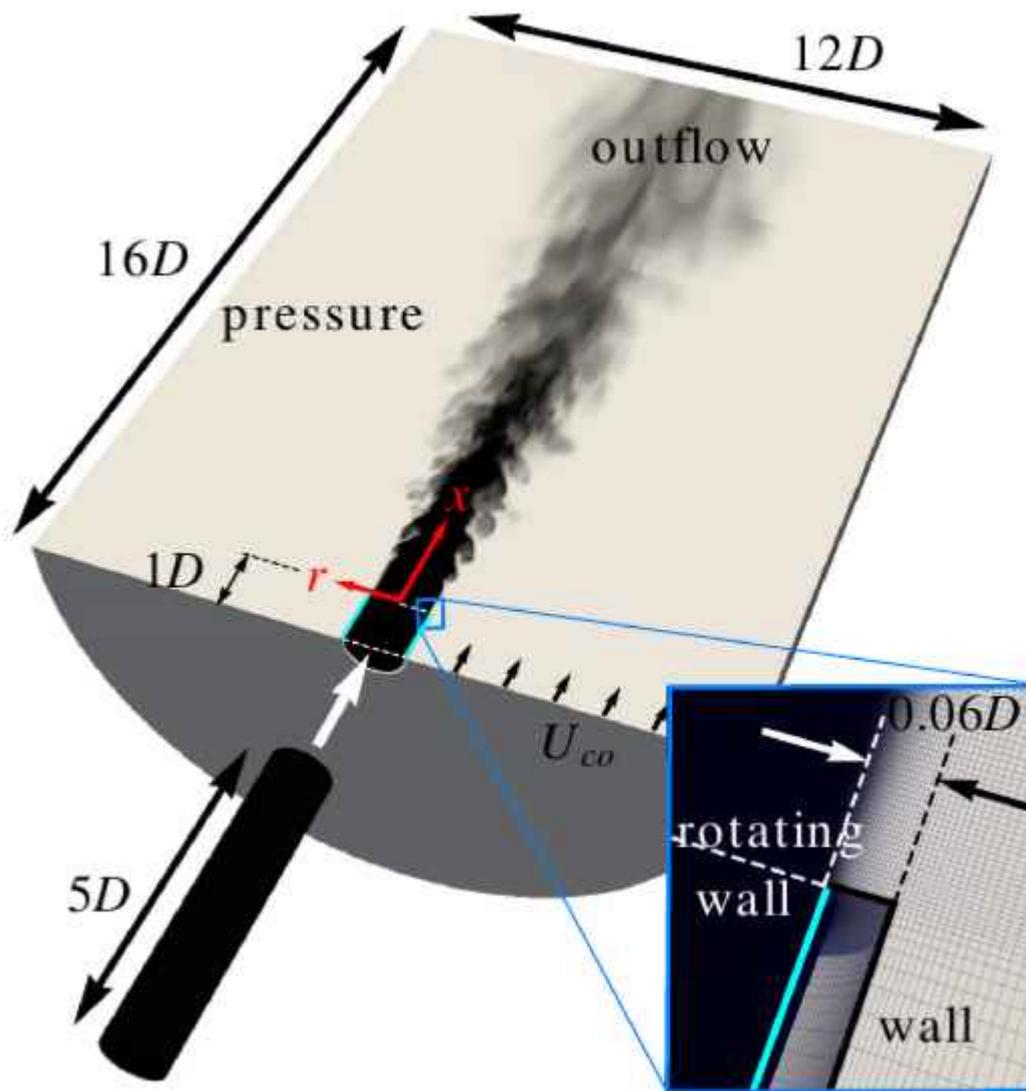
3.

**4.**

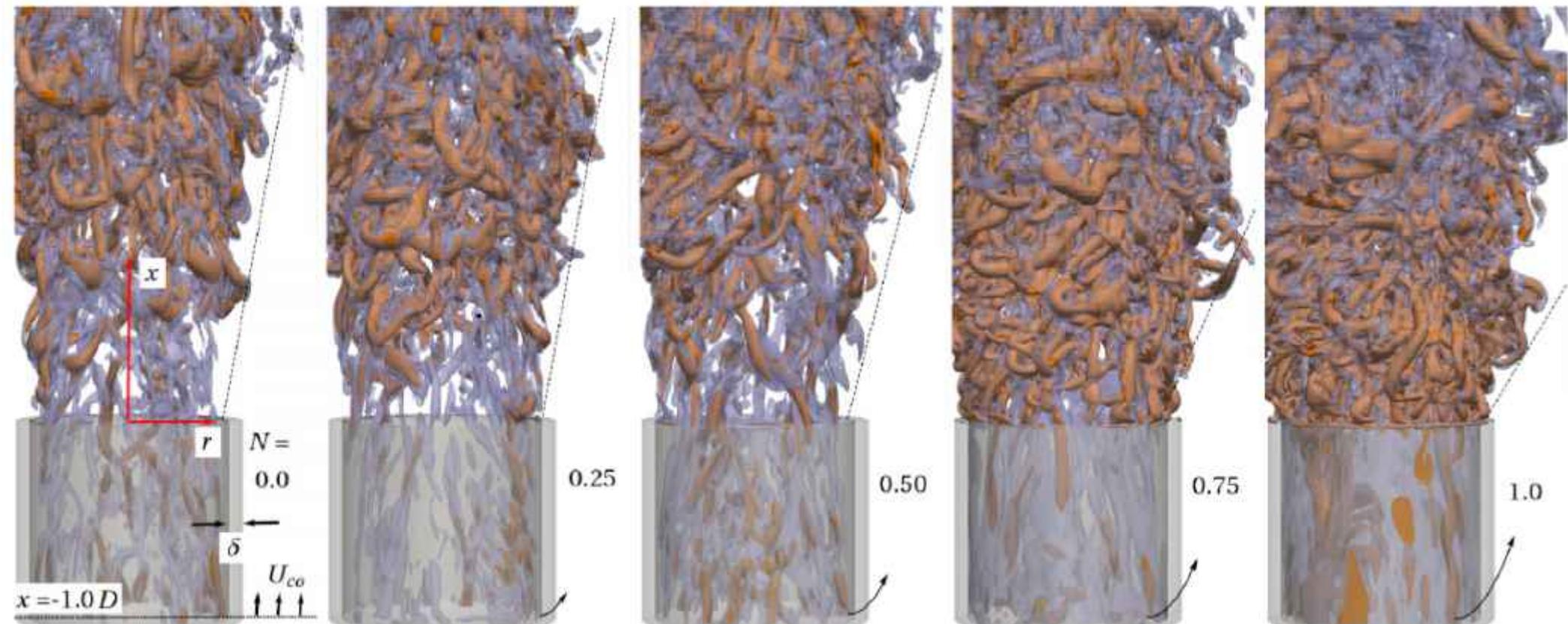
5.

6.

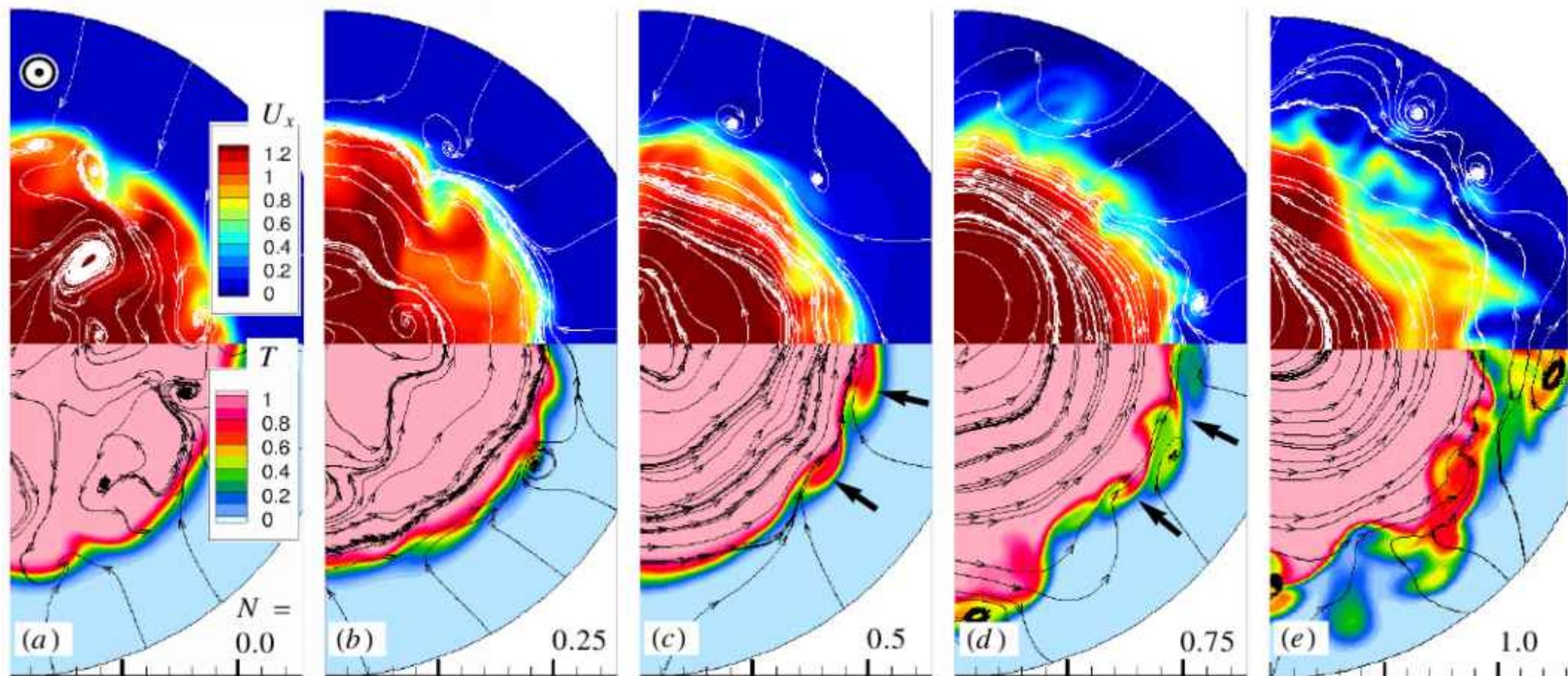
# Закрученная струя



# Закрученная струя

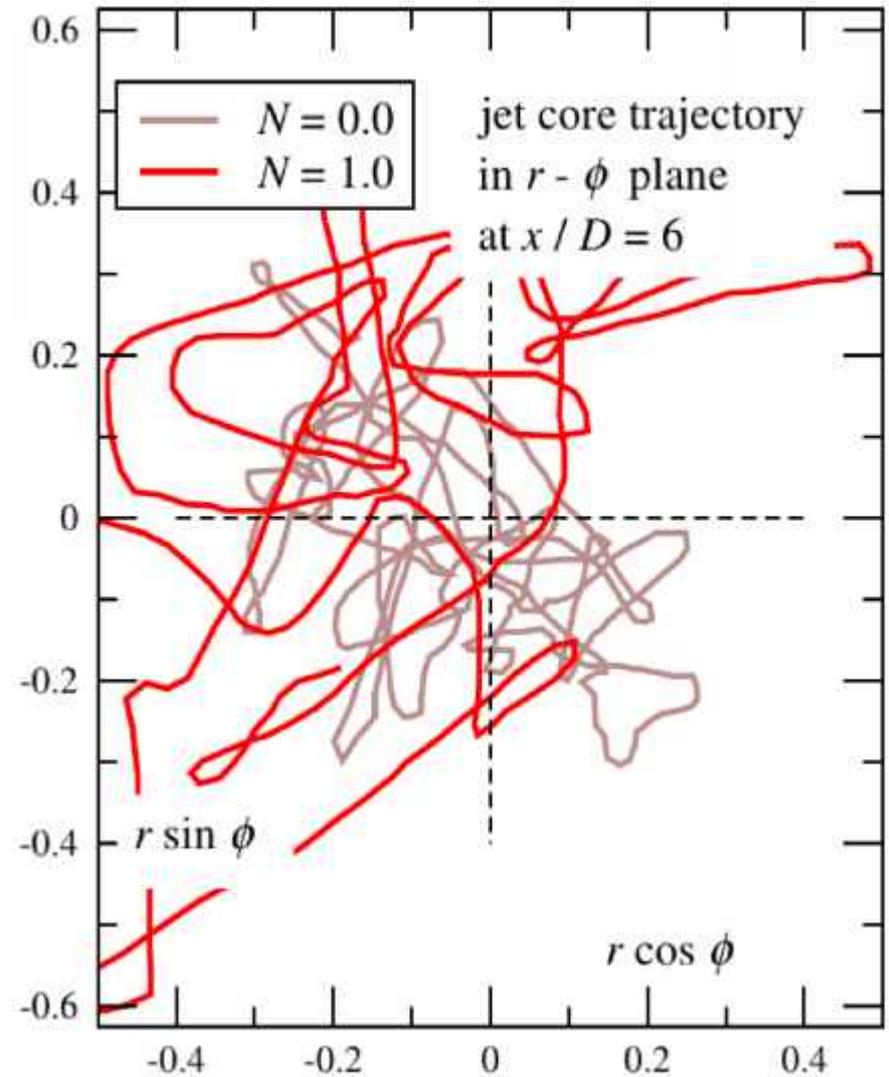
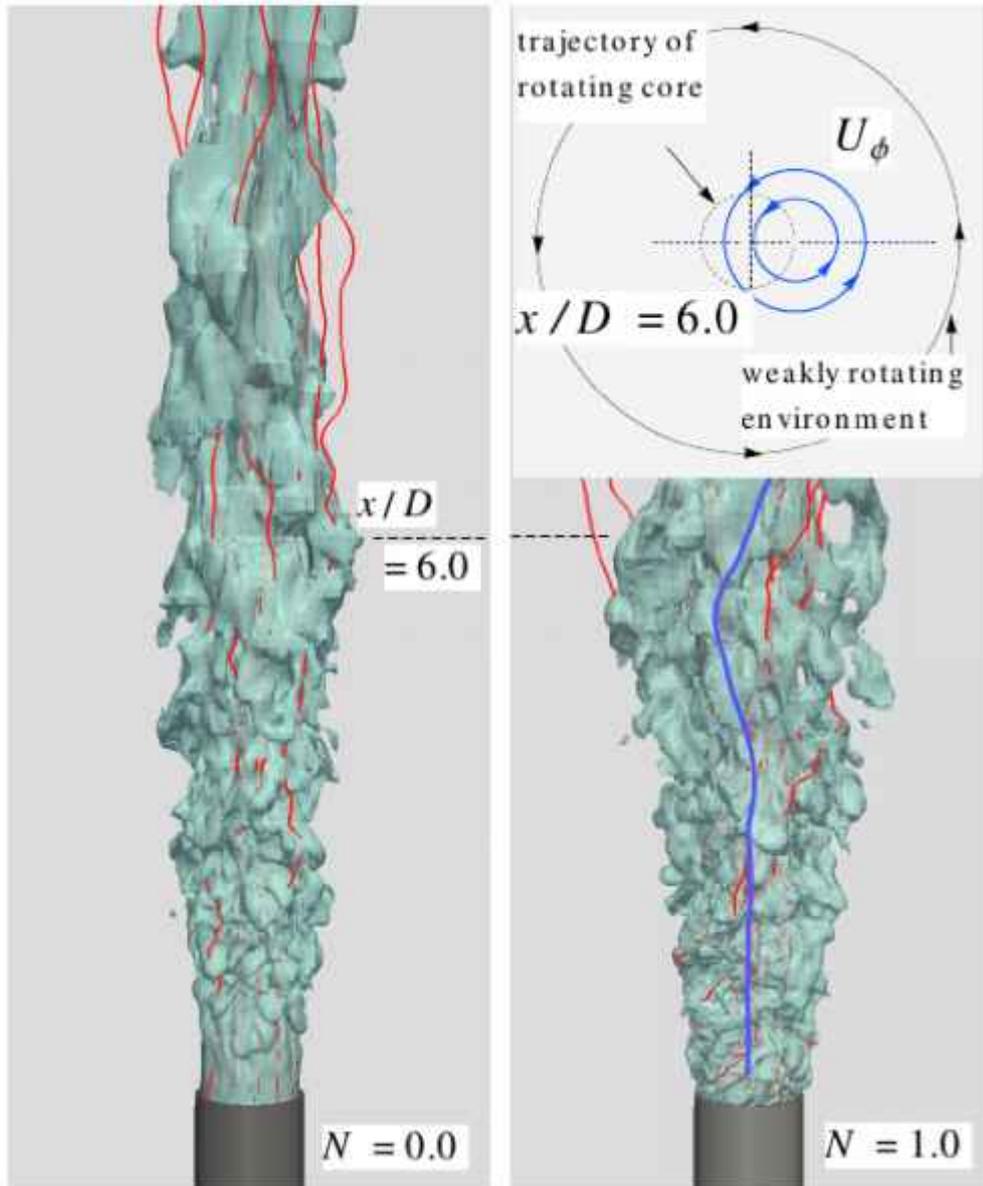


# Закрученная струя



$\ell/D = 0.5$

# Закрученная струя



# План презентации

1.

2.

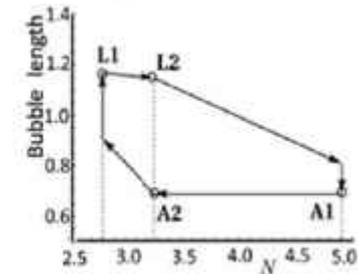
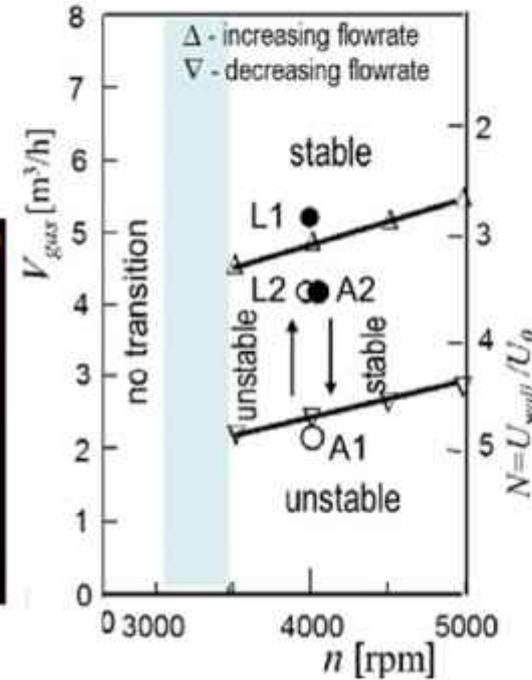
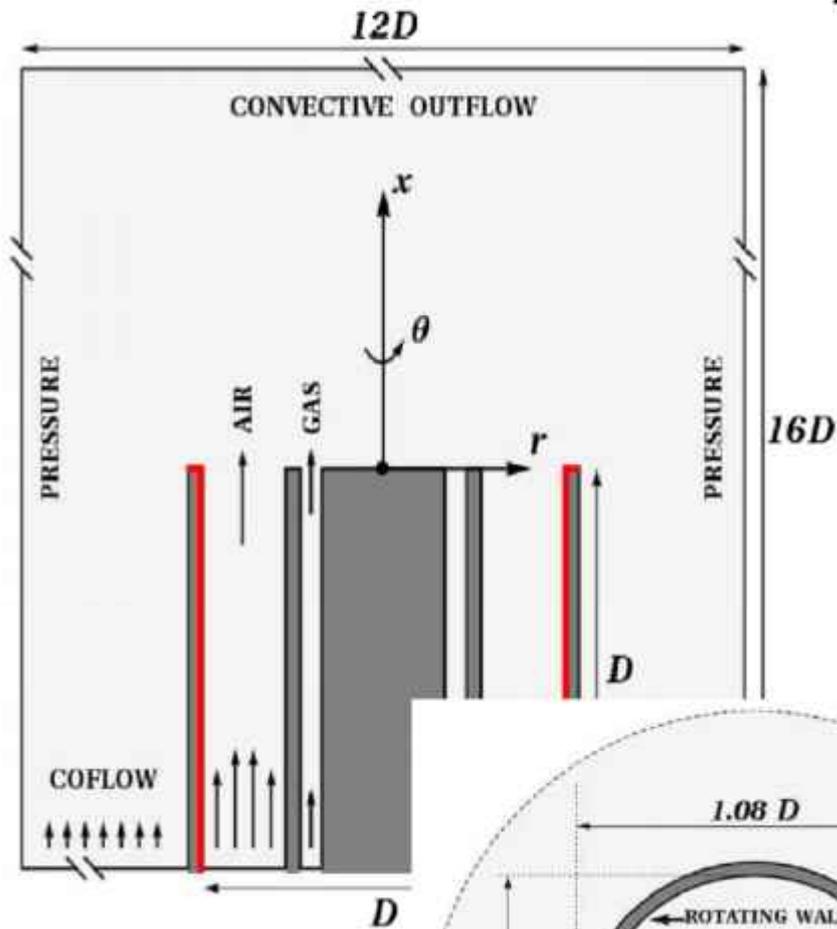
3.

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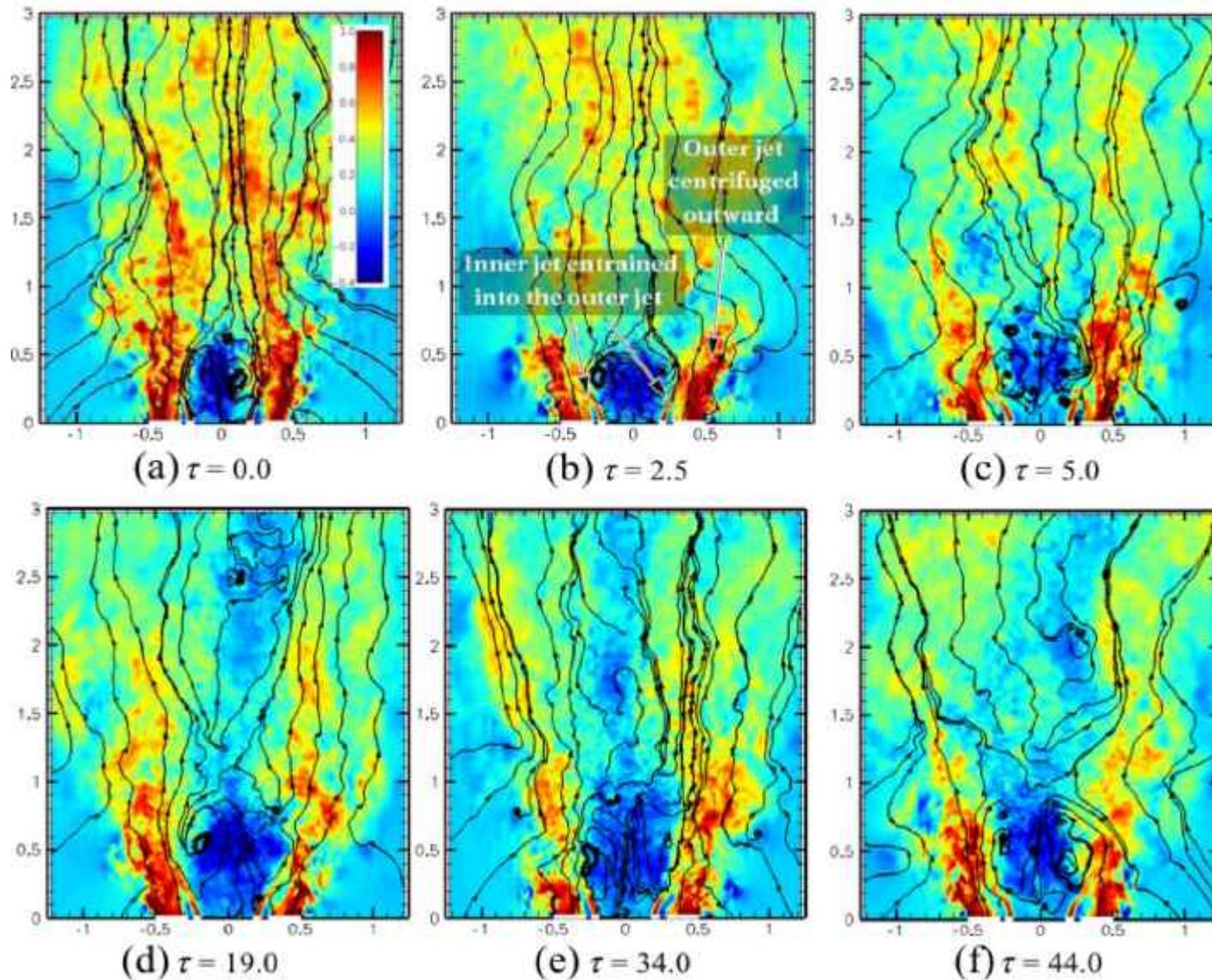
**5.**

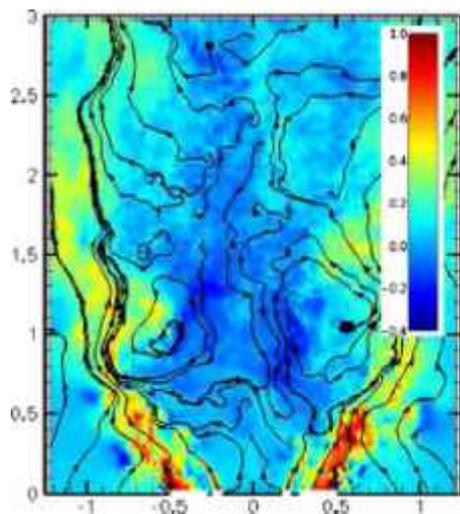
6.

# Импульсная струя

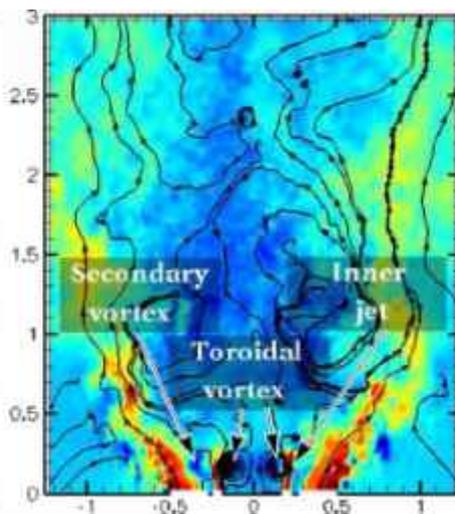


# Импульсная струя

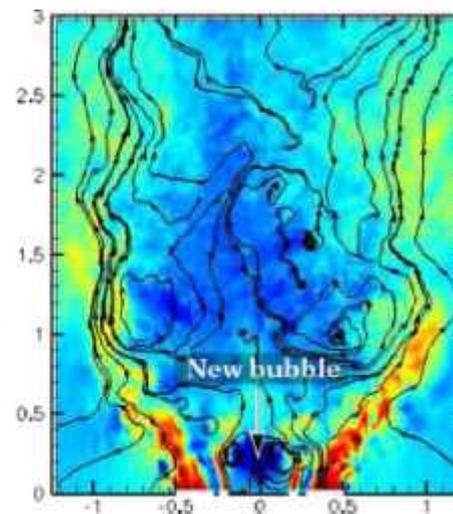




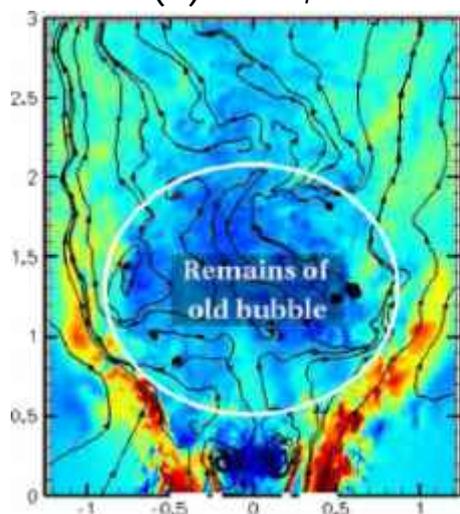
(a)  $\delta = 0.5$



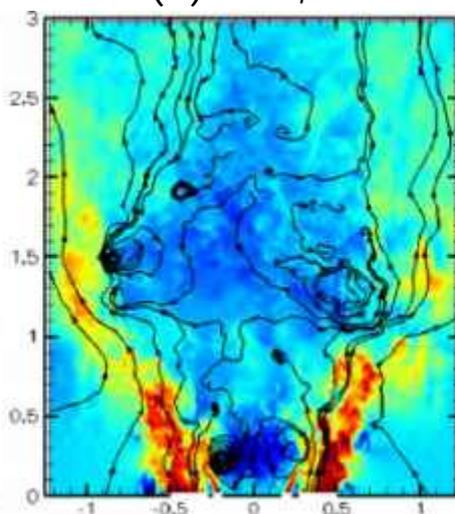
(b)  $\delta = 0.8$



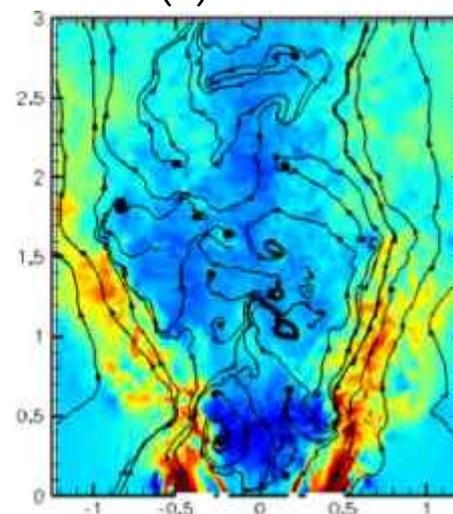
(c)  $\delta = 1.6$



(d)  $\delta = 2.5$



(e)  $\delta = 3.5$



(f)  $\delta = 5.0$

video!

A1 - A2

ССКЦ, 28 апреля 2016

# План презентации

1.

2.

3.

4.

5.

**6.**

# Заключение

1. T-FlowS

2. DNS/LES

3.

4.

# Список недавних публикаций

1. Mullyadzhanov R., Ilyushin B., Hanjalić K., On dynamics and secondary currents in meandering confined turbulent shallow jet, *Int. J. Heat Fluid Flow*, 2015
2. Hanjalić K., Mullyadzhanov R., On spatial segregation of vortices and pressure eddies in a confined slot jet, *Phys. Fluids*, 2015
3. Mullyadzhanov R., Hadžiabdić M., Hanjalić K., LES investigation of the hysteresis regime in the cold model of a rotating-pipe swirl burner, *Flow Turb. Comb.*, 2015
4. Hadžiabdić M., Hanjalić K., Mullyadzhanov R., LES of turbulent flow in a concentric annulus with rotating outer wall, *Int. J. Heat Fluid Flow*, 2013
0. Mullyadzhanov R., Abdurakipov S., Hanjalić K., On coherent structures and mixing characteristics in the near field of a rotating-pipe jet, *Int. J. Heat Fluid Flow*, 2016 (submitted after revision)
0. Mullyadzhanov R., Abdurakipov S., Hanjalić K., Helical Structures in the Near Field of a Turbulent Pipe Jet, *Flow Turb. Comb.*, 2016 (submitted after revision)

!

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