

VORTEX FORMATION IN SHALLOW FLOWS

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M.Yavuz Y. Yang

Lehigh University

Sponsored by National Science Foundation

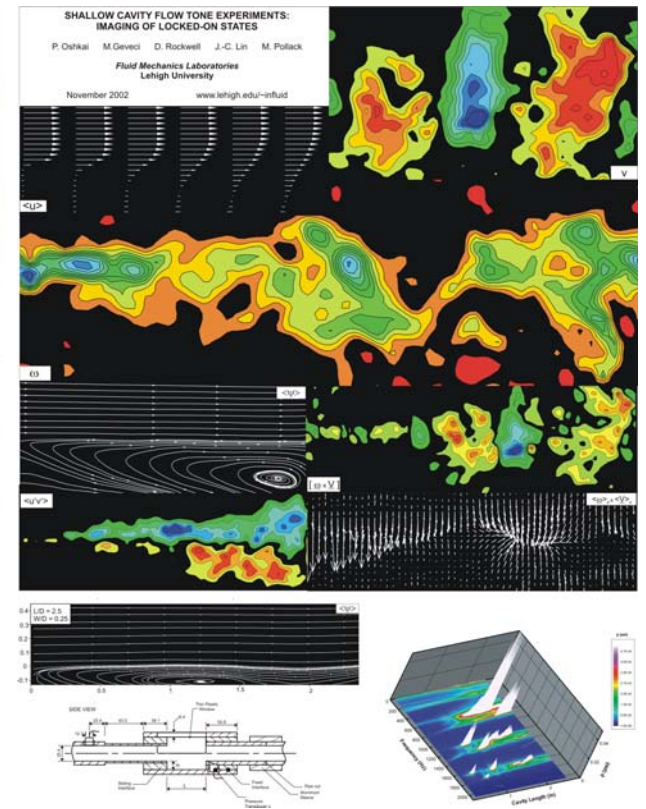
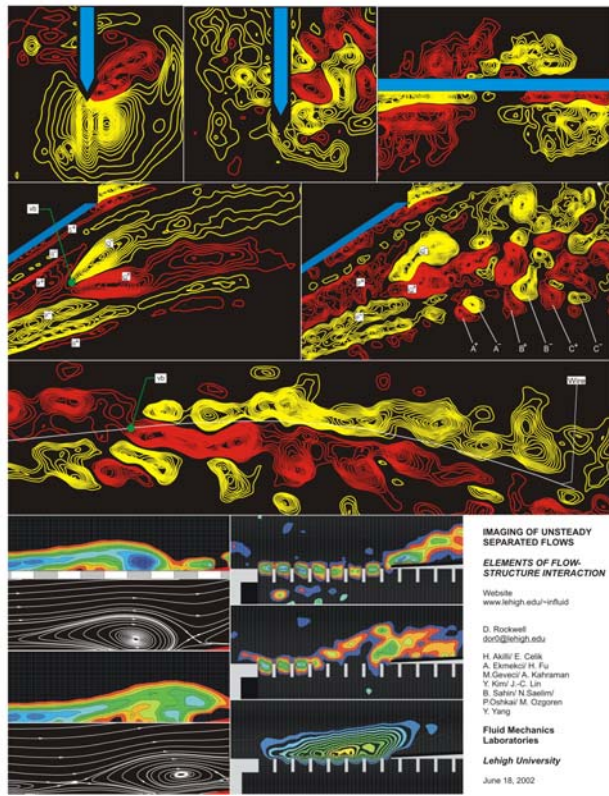
APS DFD November, 2006

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FLUID MECHANICS LABORATORIES

LEHIGH UNIVERSITY

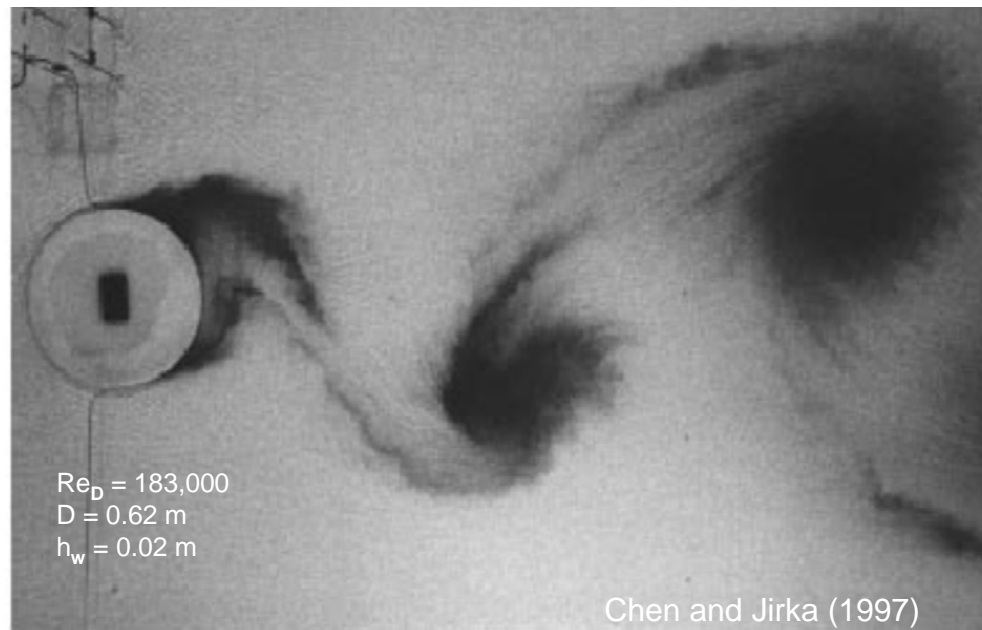
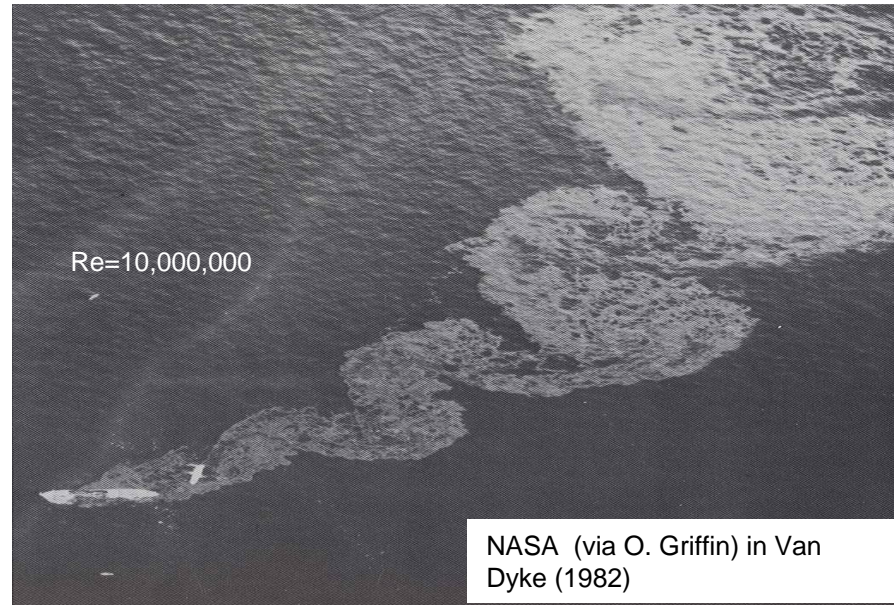
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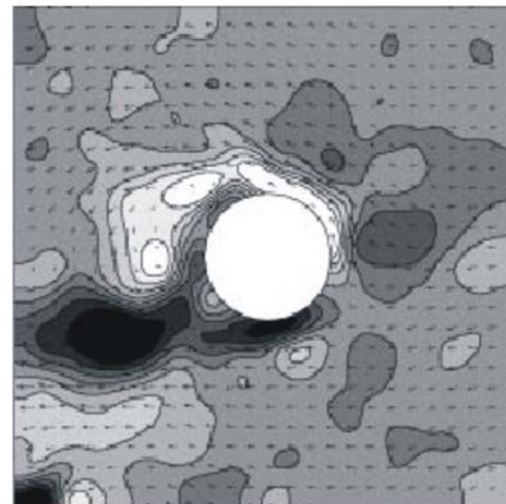
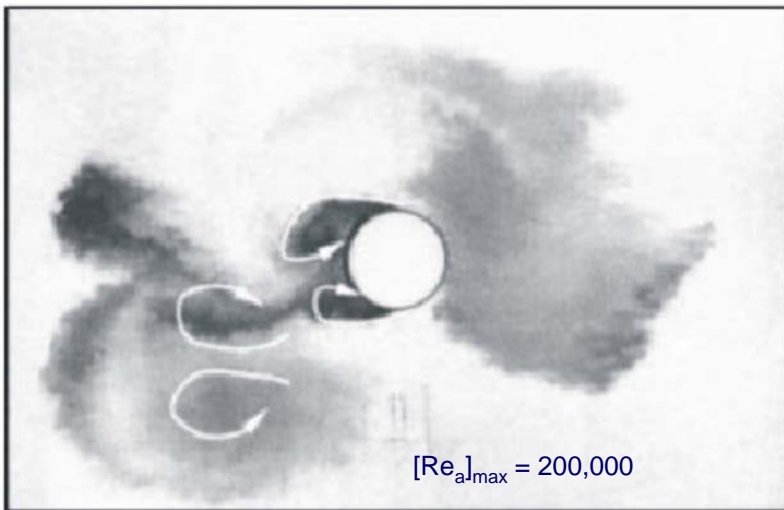
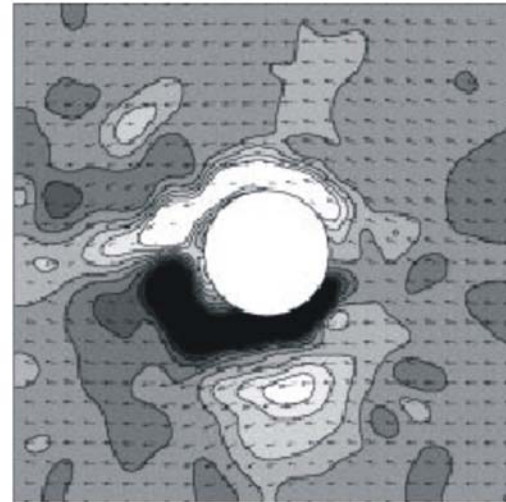
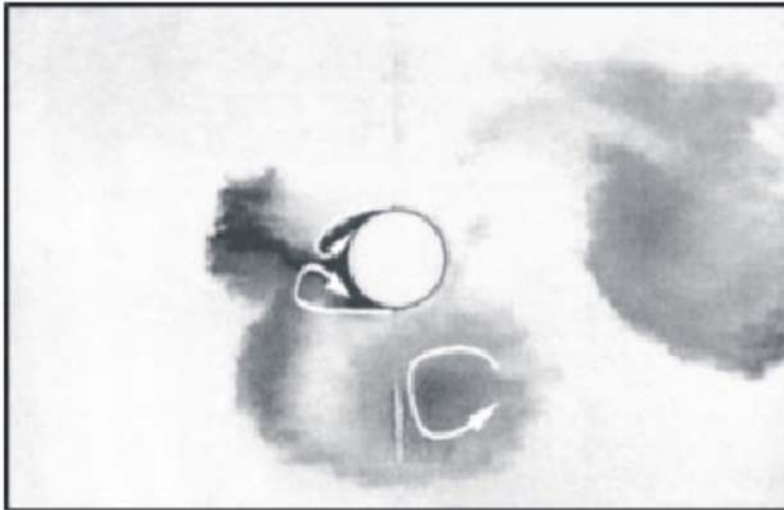


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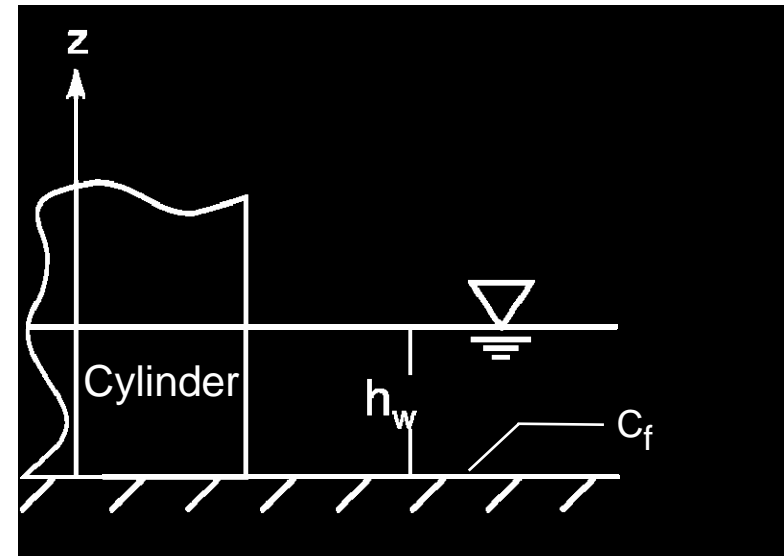
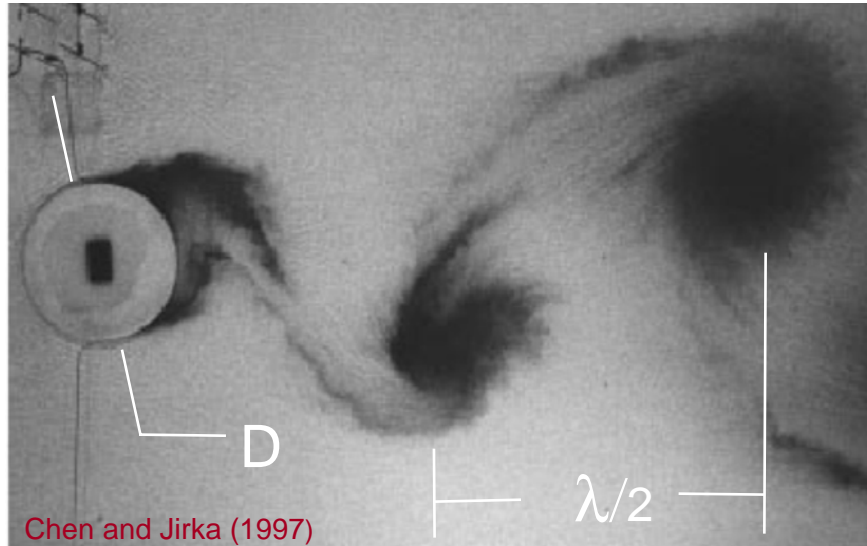


NASA (via O. Griffin) in Van Dyke (1982)





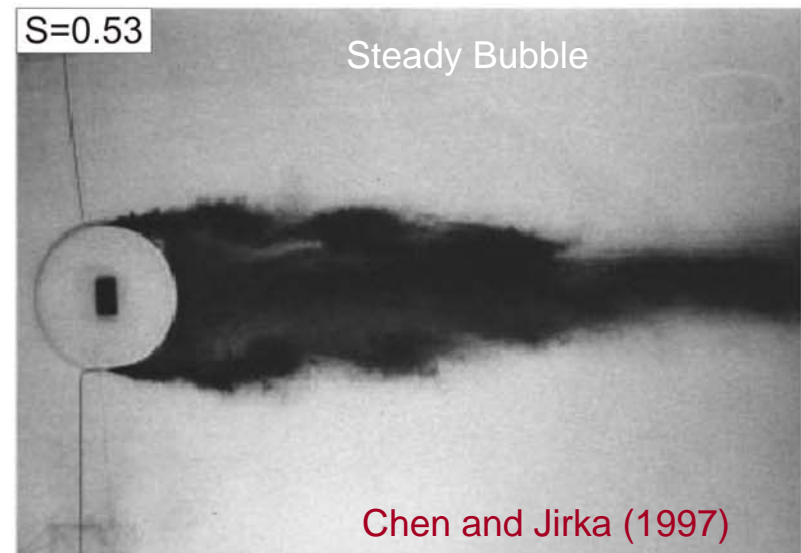
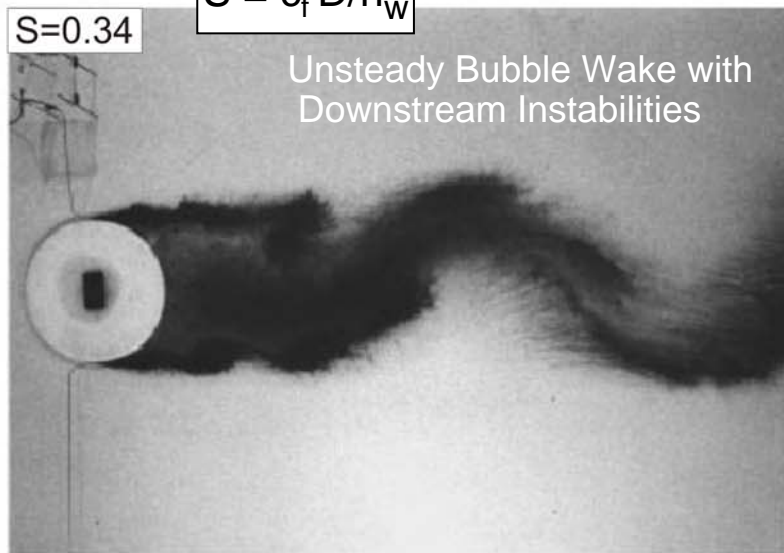
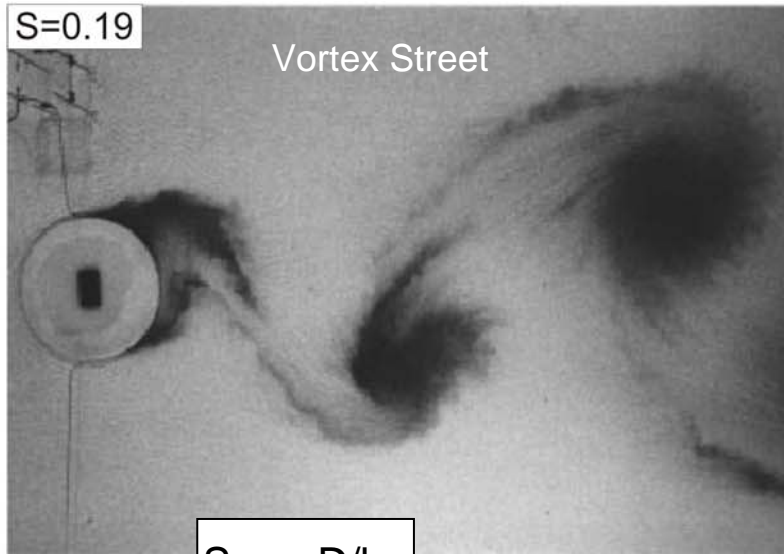
Lloyd, Stansby and Chen (2001)



Shallow Flow Criterion $\lambda/h_w \gg 1$

Reynolds Numbers Uh_w/ν and UD/ν

Shallow Wake Parameter $c_f D/h_w$



$$S = c_f D/h_w$$

Chen and Jirka (1997)

SHEAR FLOW INSTABILITIES IN SHALLOW FLOWS

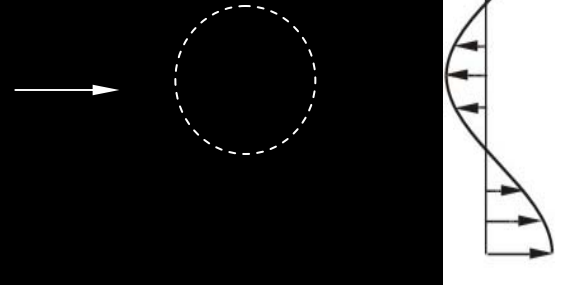
ANALYSES/ COMPUTATIONS

- Chu, Wu and Khayat (1983)
- Schar and Smith (1993)
- Grubisic, Smith and Schar (1995)
- Chen and Jirka (1997)
- Van Prooijen and Uijttewaal (2002)
- Kolyshin and Ghidaoui (2003)
- Socolofsky and Jirka (2004)
- Ghidaoui, Kolyshkin, Liang, Chan, Li, and Xu (2006)
- Chan, Ghidaoui and Kolyshkin (2006)

SHEAR FLOW INSTABILITIES IN SHALLOW FLOWS

CLASSES OF INSTABILITY

- *Absolutely Unstable*
- *Convectively Unstable*
- *Stable*



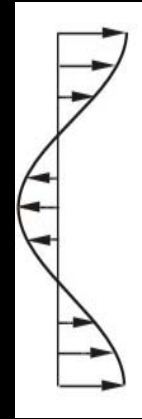
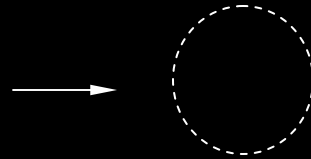
PHYSICAL CONSEQUENCE OF INSTABILITY (OF A WAKE)

- *Large-Scale Vortex Street*
- *Unsteady Bubble Wake*
- *Unsteady Bubble Wake with Downstream Instabilities*
- *Steady Bubble Wake*

SHEAR FLOW INSTABILITIES IN SHALLOW FLOWS

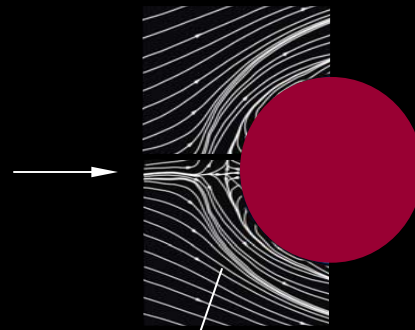
INSTABILITY IN ABSENCE OF CYLINDER

- Absolutely Unstable
- Convectively Unstable
- Stable



Instability based on representative velocity distribution

INSTABILITY IN PRESENCE OF CYLINDER



Instability may be influenced by, or coupled with, upstream region of flow

Region of distortion/
separation/ amplification

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VORTEX FORMATION IN SHALLOW FLOWS

VORTEX FORMATION

- *IN UNSTABLE SHEAR FLOW*
- *VIA CONTROLLED GENERATION*
- *COUPLED WITH WAVE SYSTEM*

SYSTEMS AND APPROACHES

FLOW SYSTEMS

Flow (water) systems with three-D optical access

QUANTITATIVE IMAGING

- Techniques of high-image-density particle image velocimetry (PIV)
- Whole field representations of quantitative, instantaneous and averaged flow structure.

POST-PROCESSING OF QUANTITATIVE IMAGES

Cinema sequences of images: space-time representations of flow structure.

VORTEX FORMATION IN SHALLOW FLOWS

VORTEX FORMATION

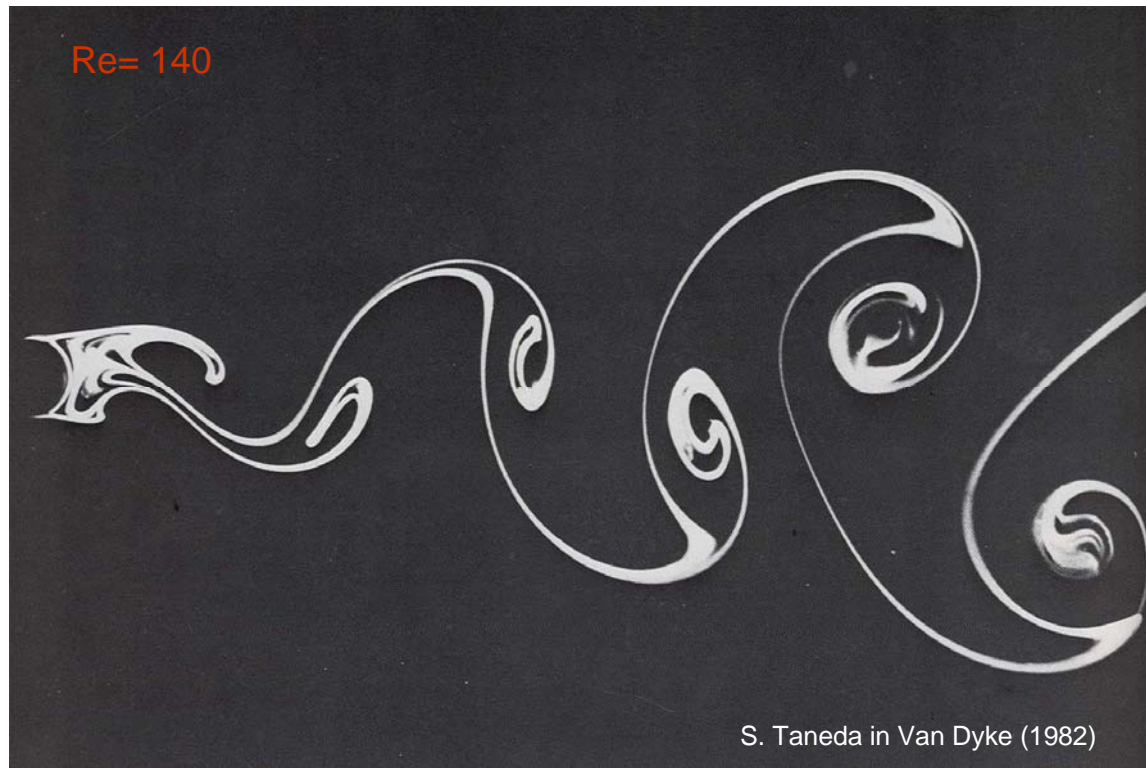
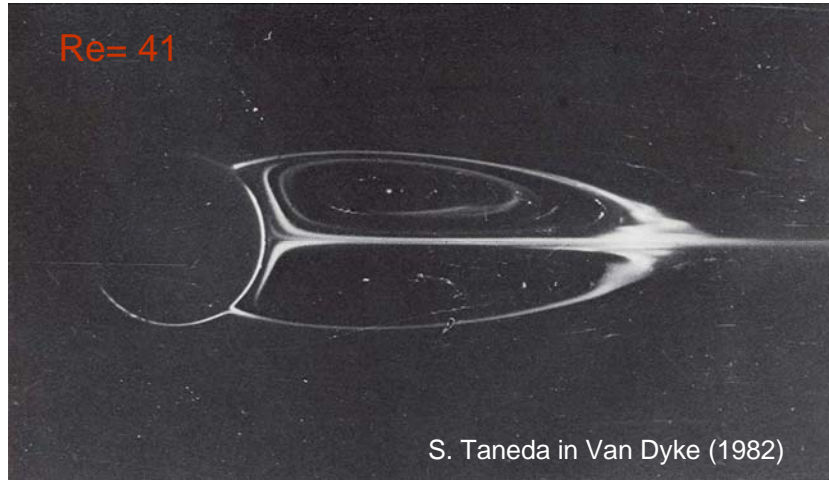
- *IN UNSTABLE SHEAR FLOW*
- *VIA CONTROLLED GENERATION*
- *COUPLED WITH WAVE SYSTEM*

VORTEX FORMATION IN SHALLOW FLOWS

VORTEX FORMATION IN UNSTABLE SHEAR FLOW

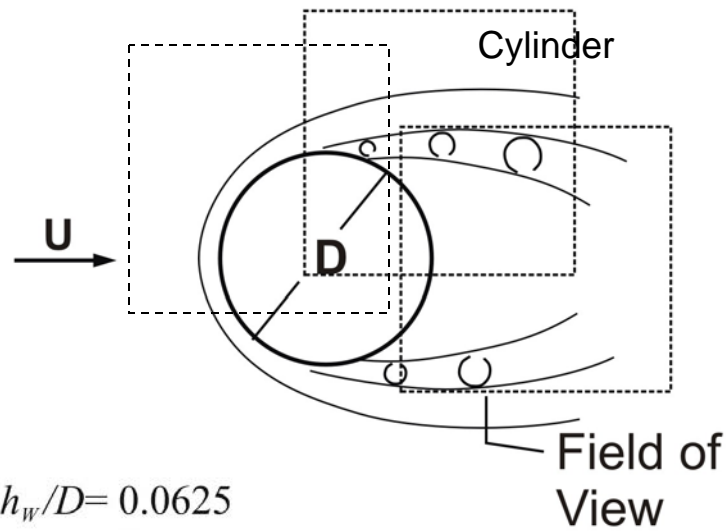
- LAMINAR INFLOW

- TURBULENT INFLOW



SHALLOW WAKE OF A CYLINDER: LAMINAR APPROACH FLOW

PLAN VIEW

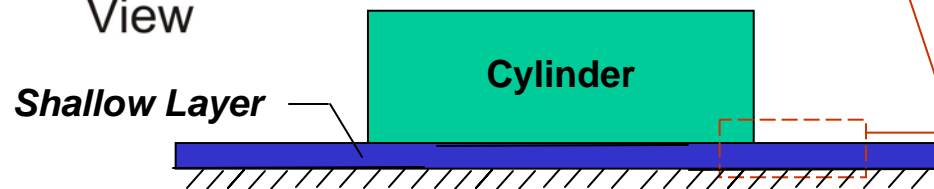
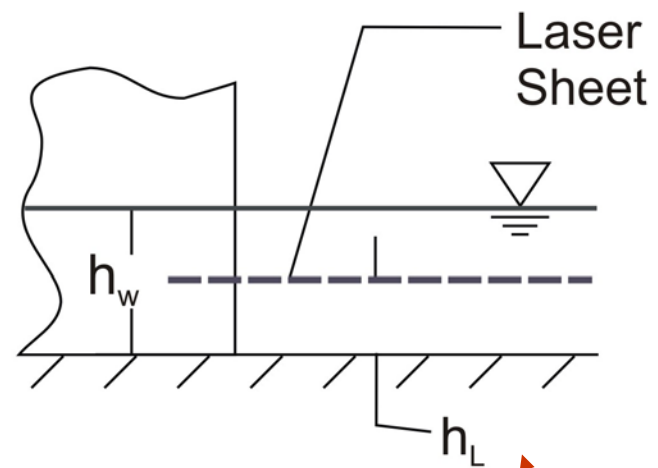


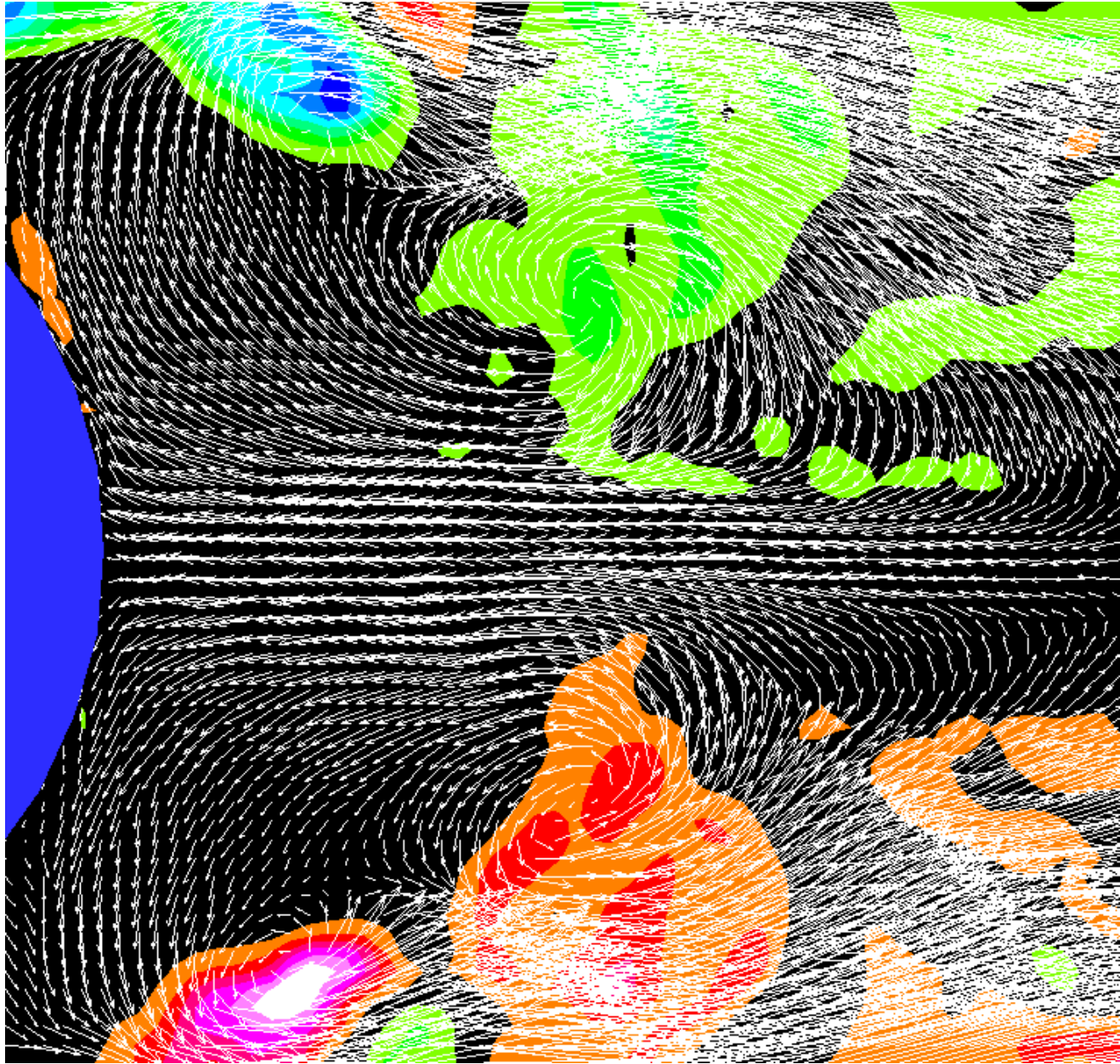
$$h_w/D = 0.0625$$

$$Re_h = 260 \sim 360$$

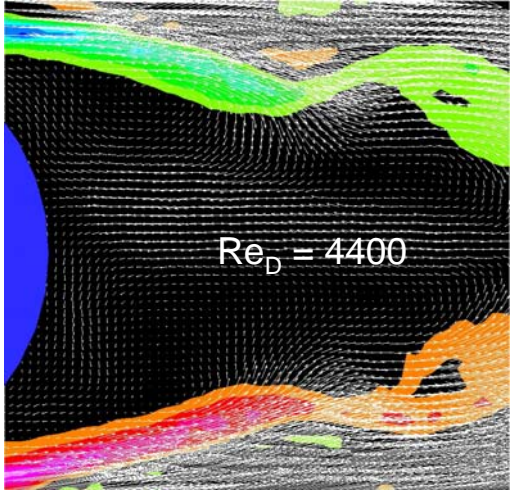
$$Re_D = 4,000 \sim 6,000$$

SIDE VIEW

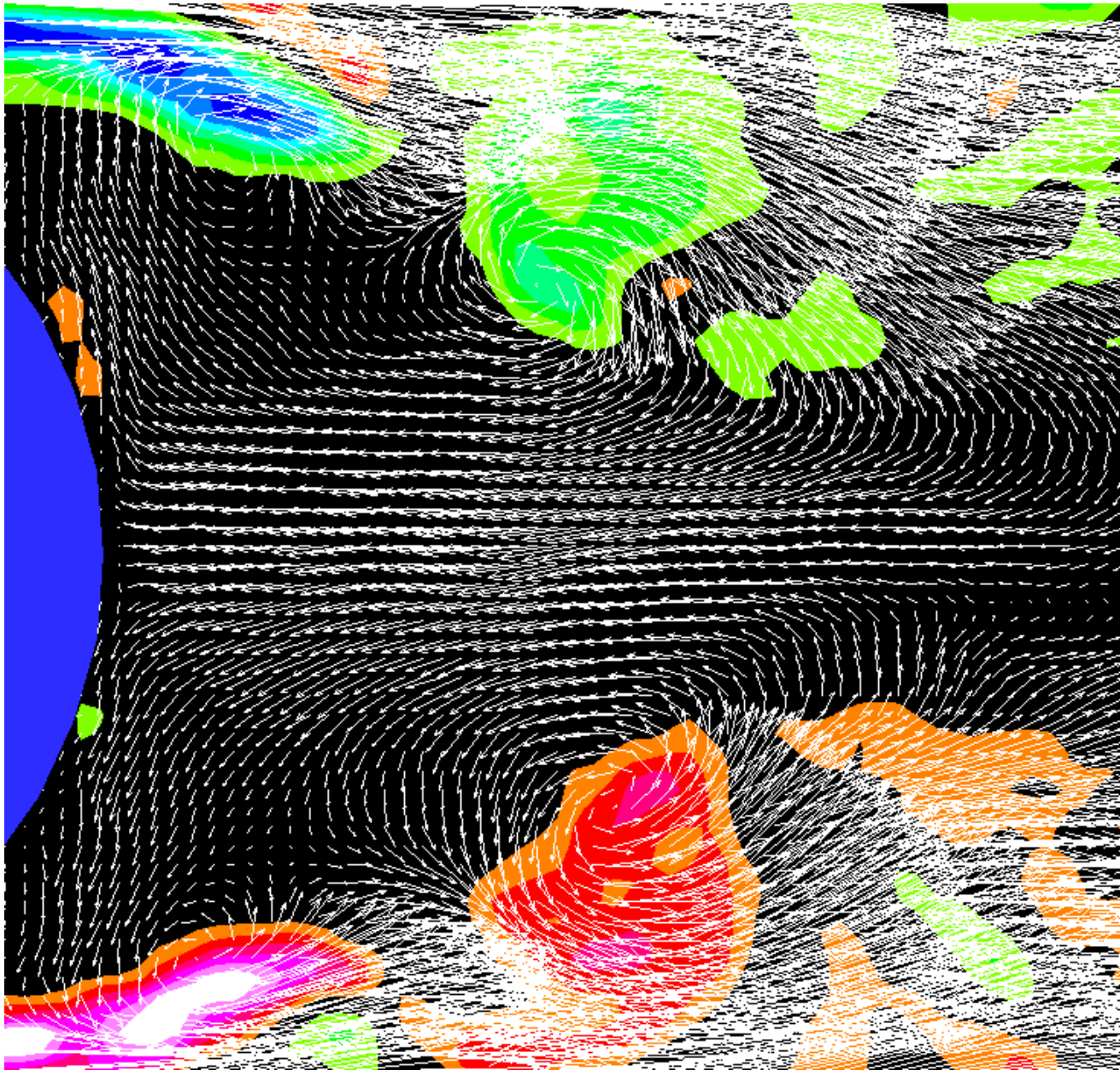




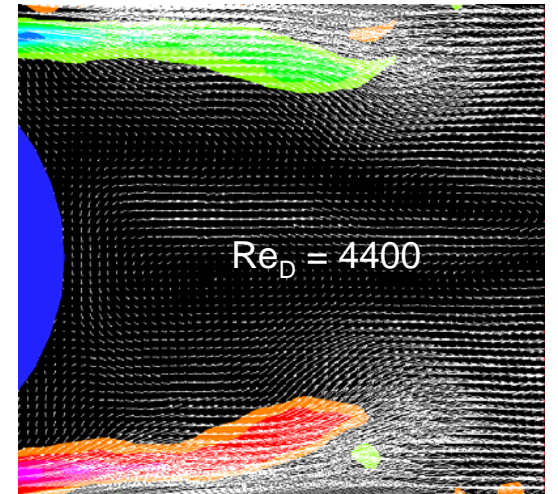
$Re_D = 5800$



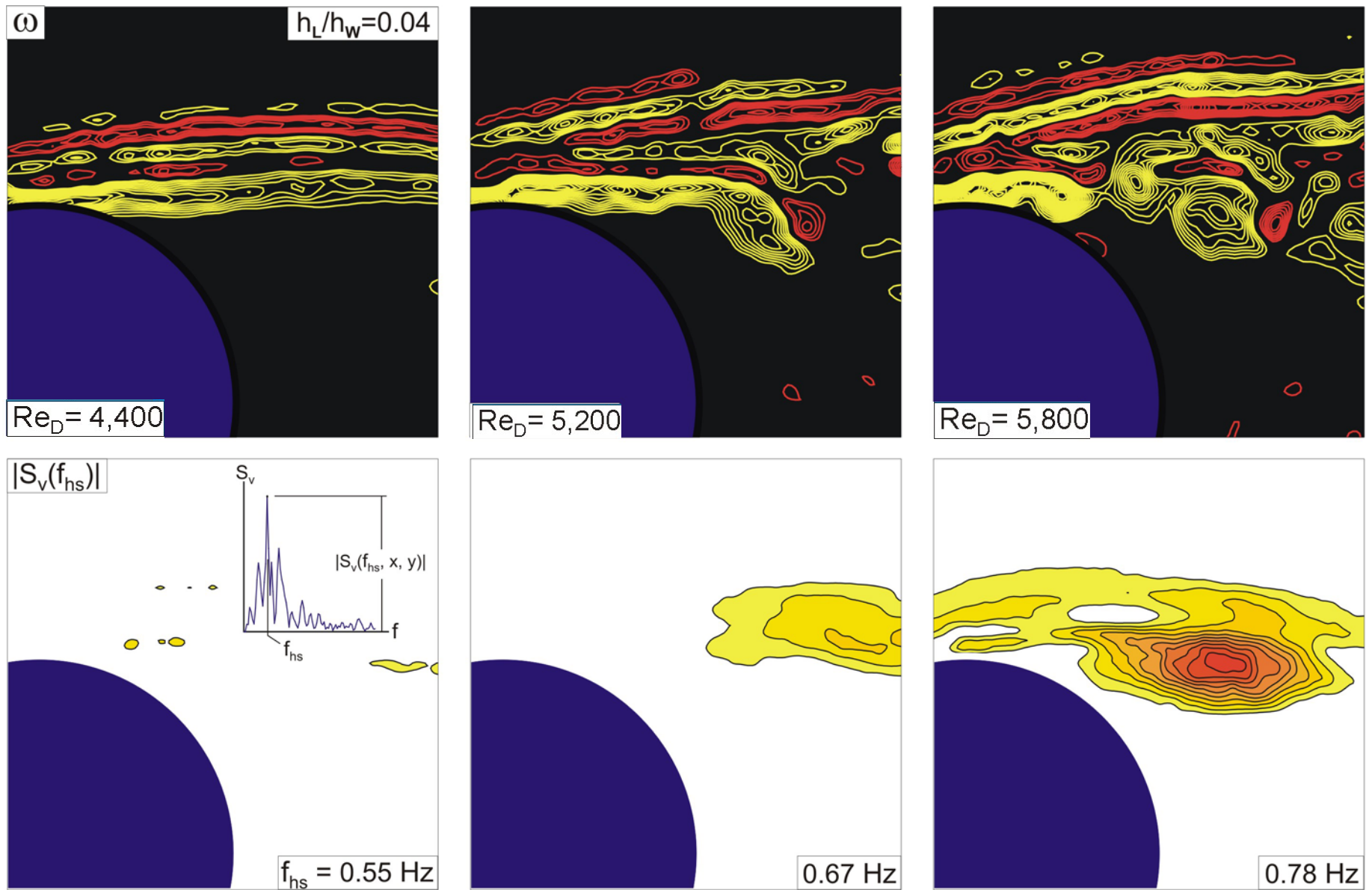
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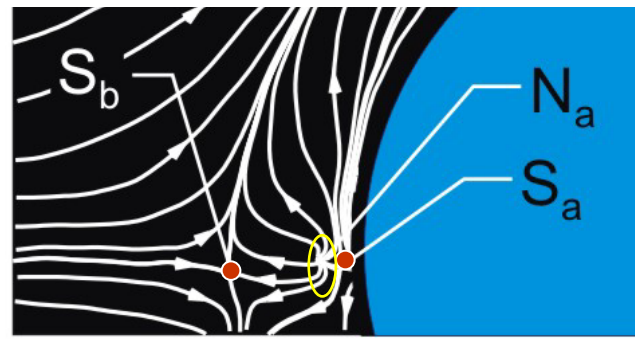
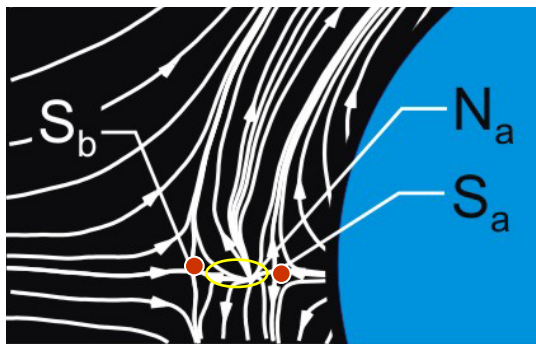
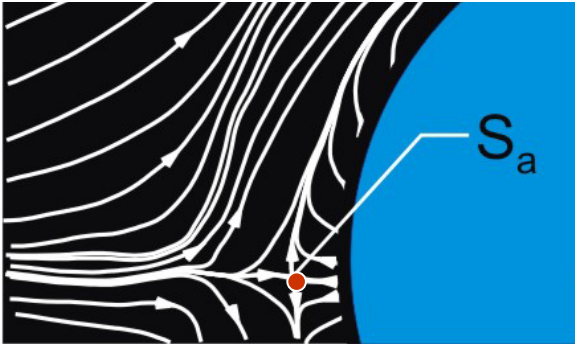
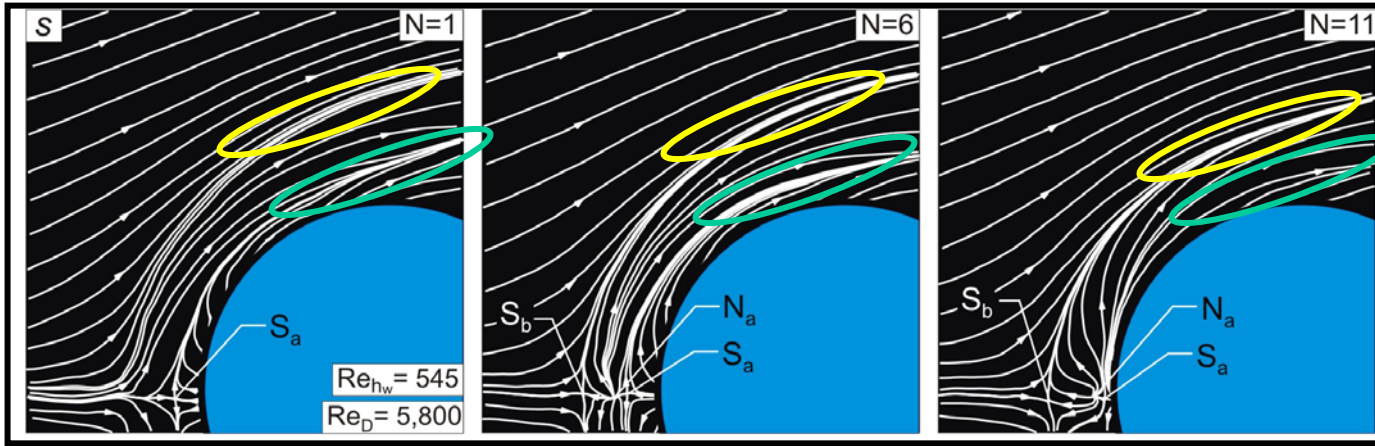
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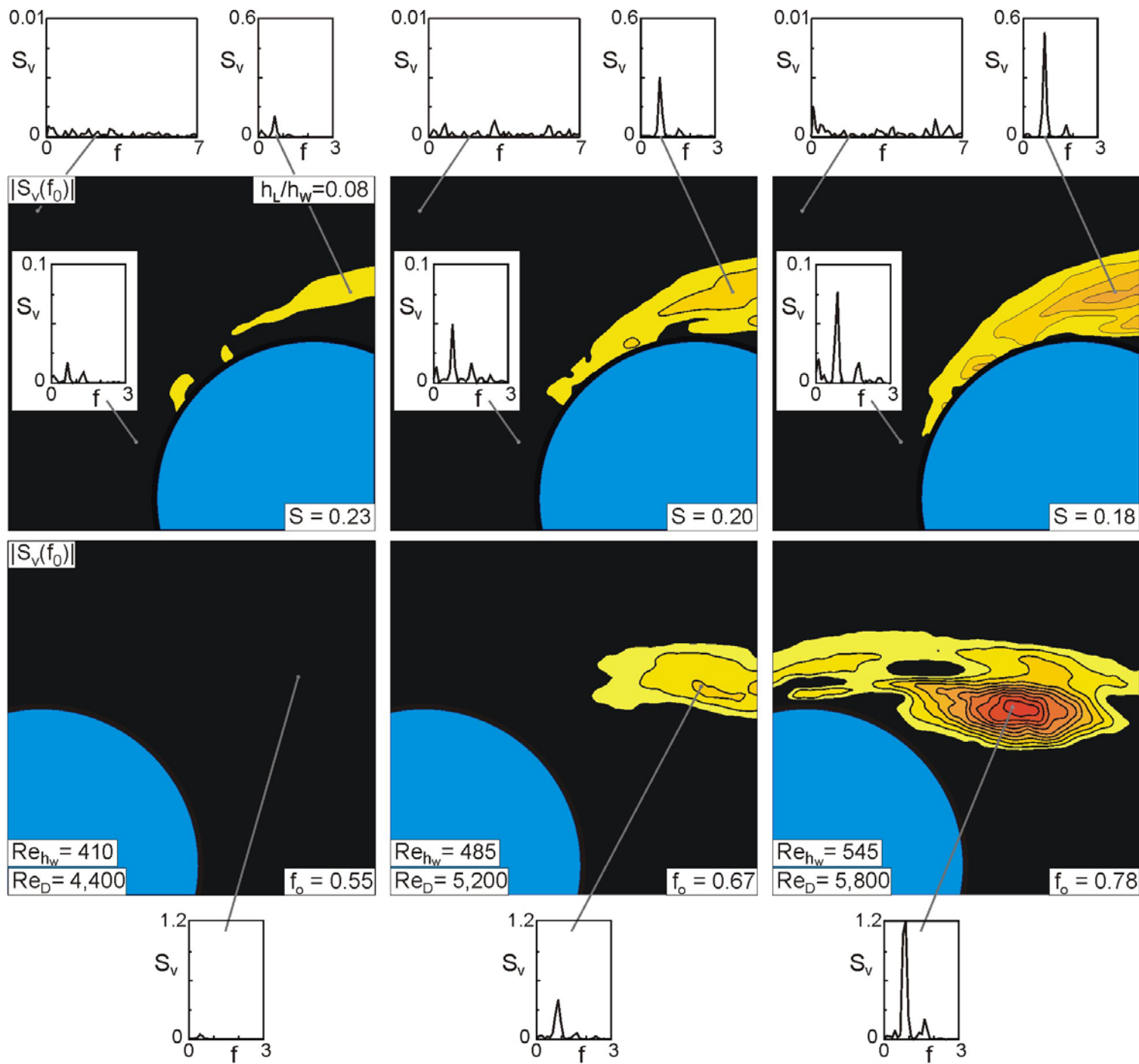


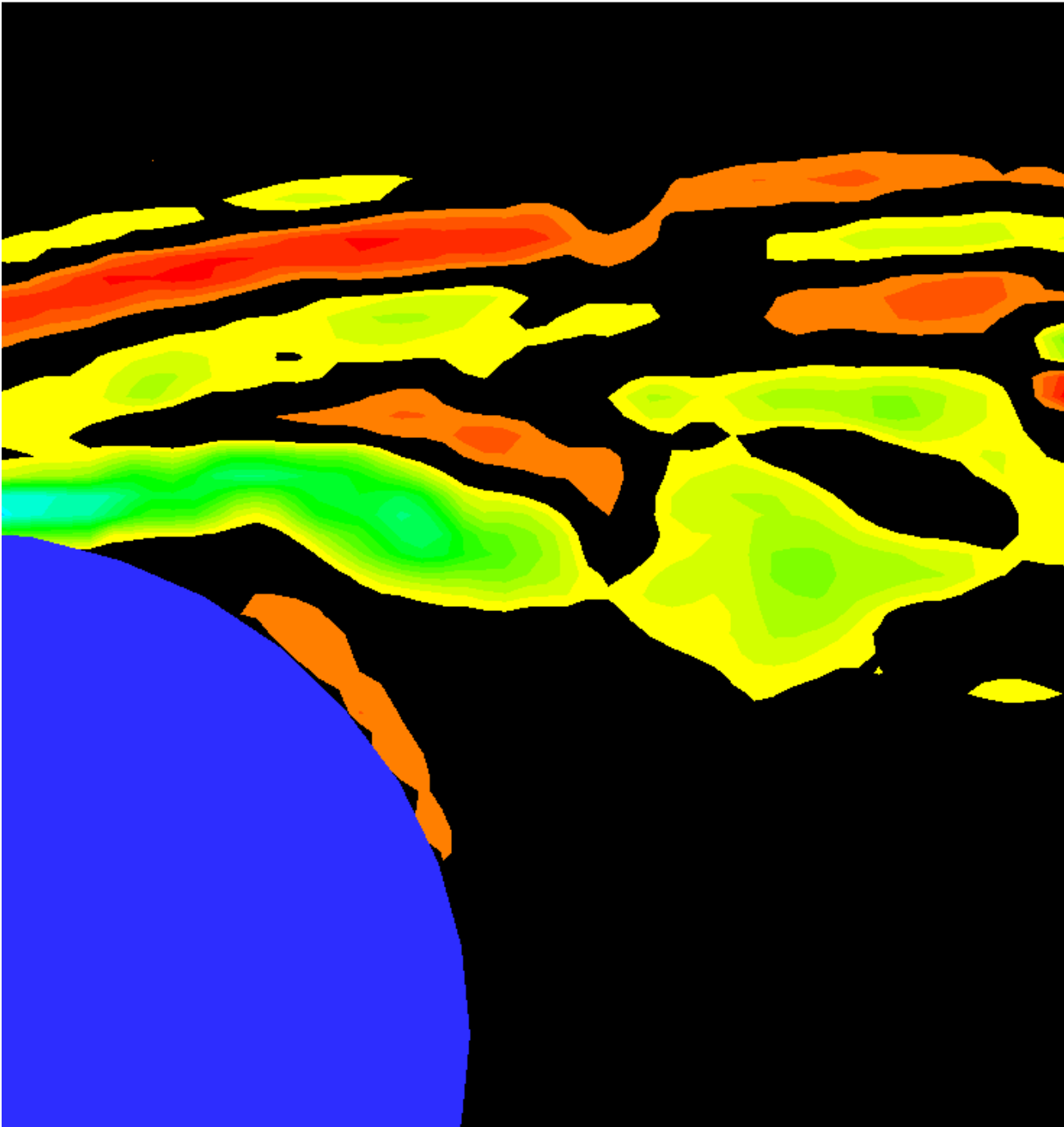
$Re_D = 4400$

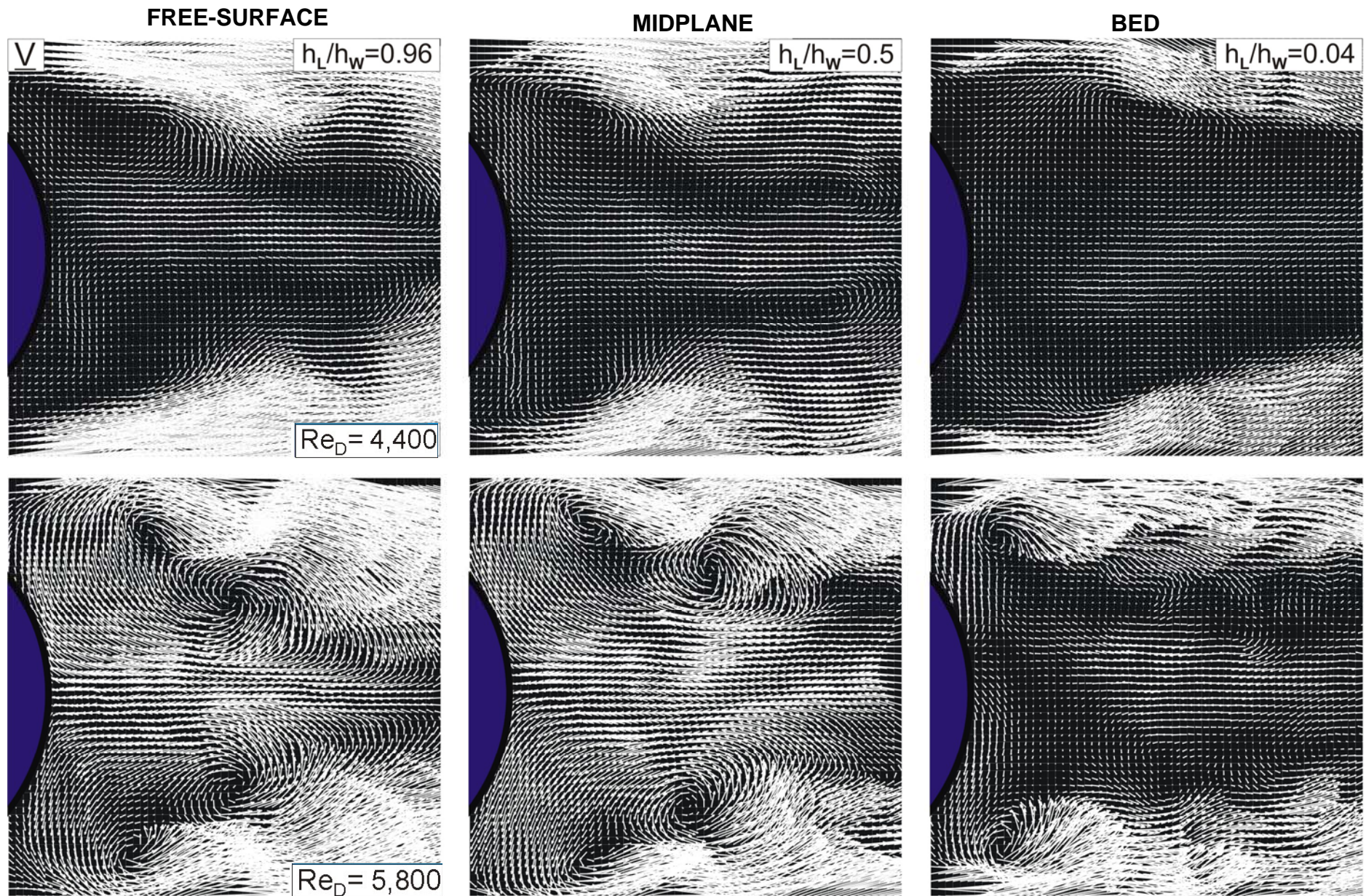


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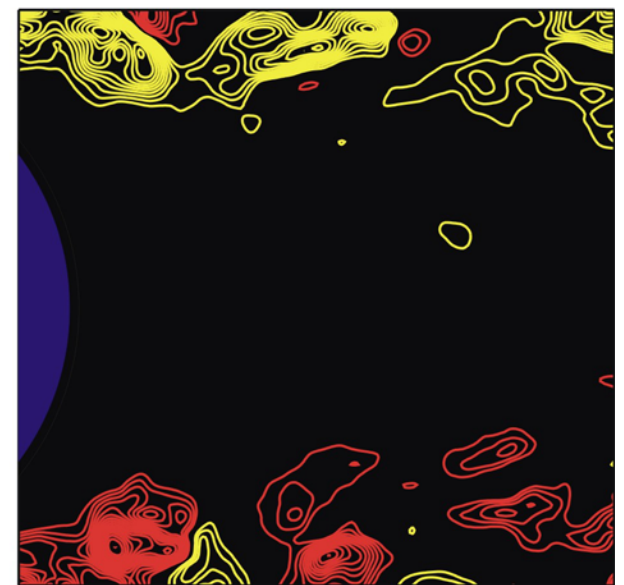
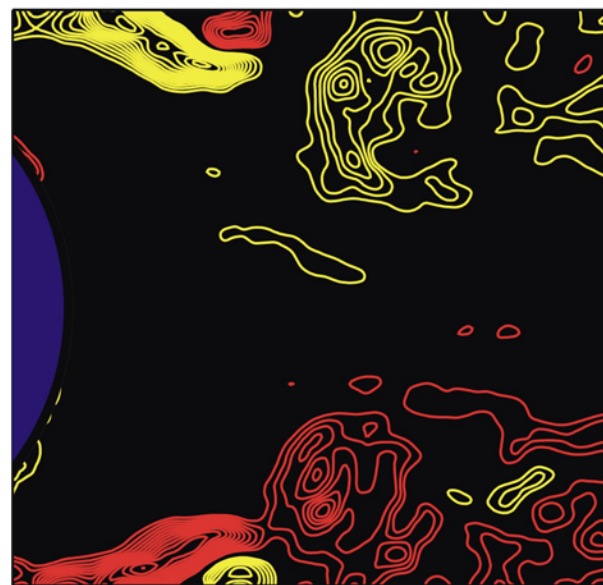
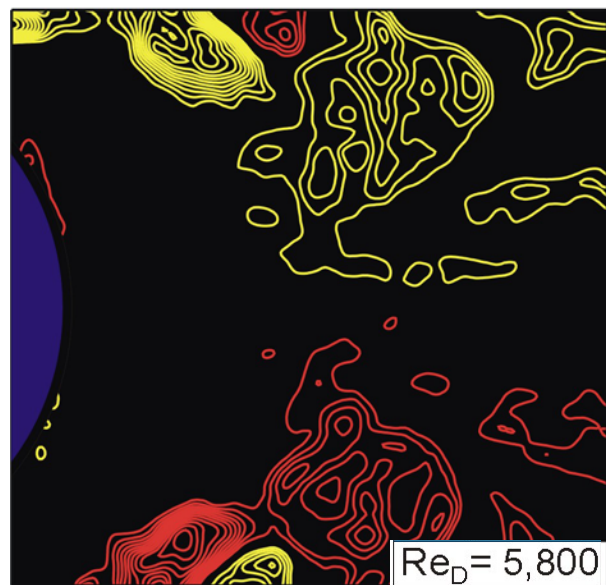
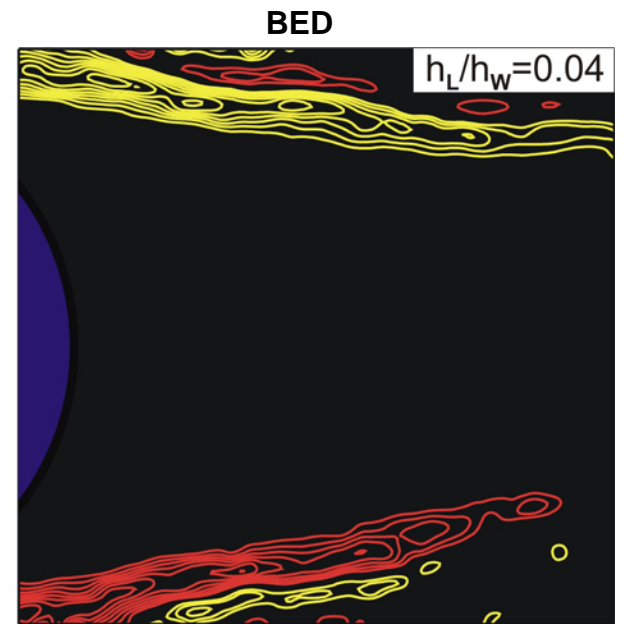
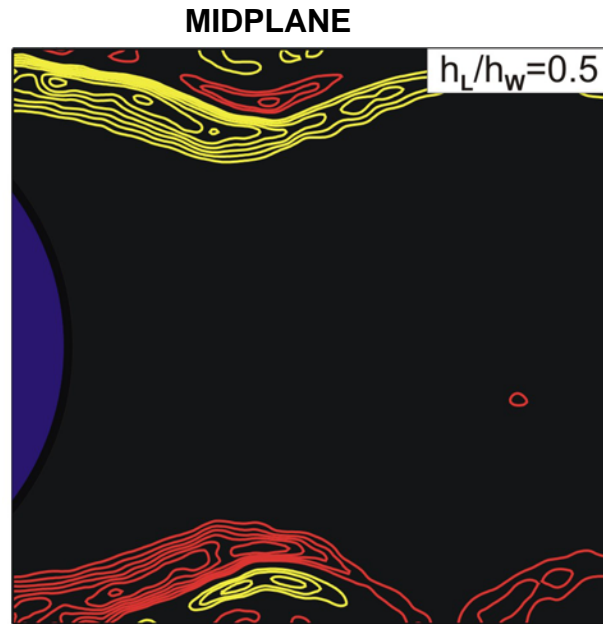
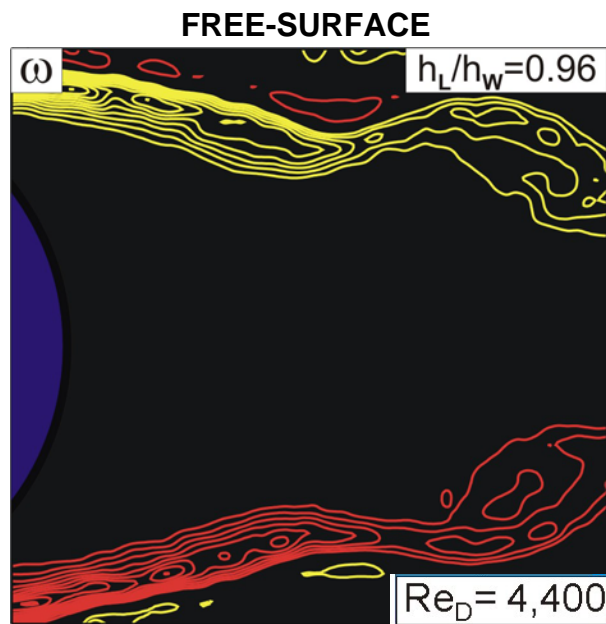




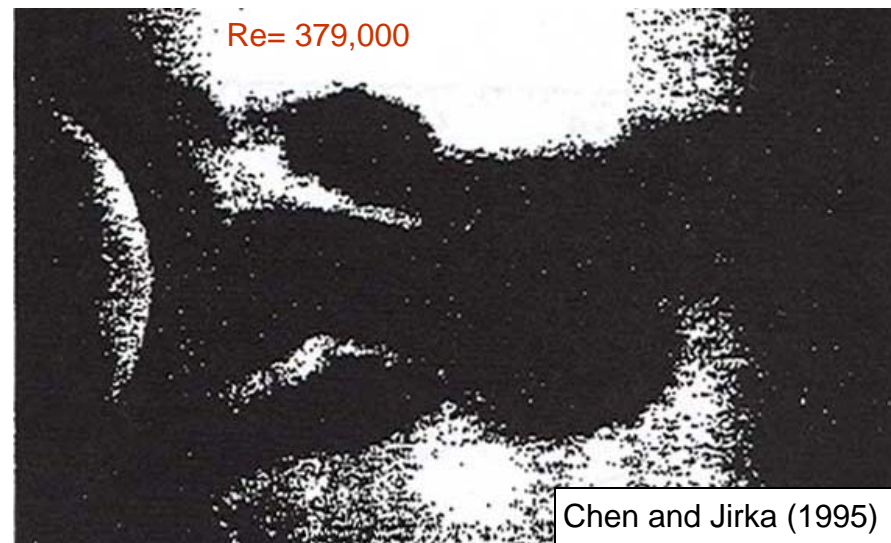
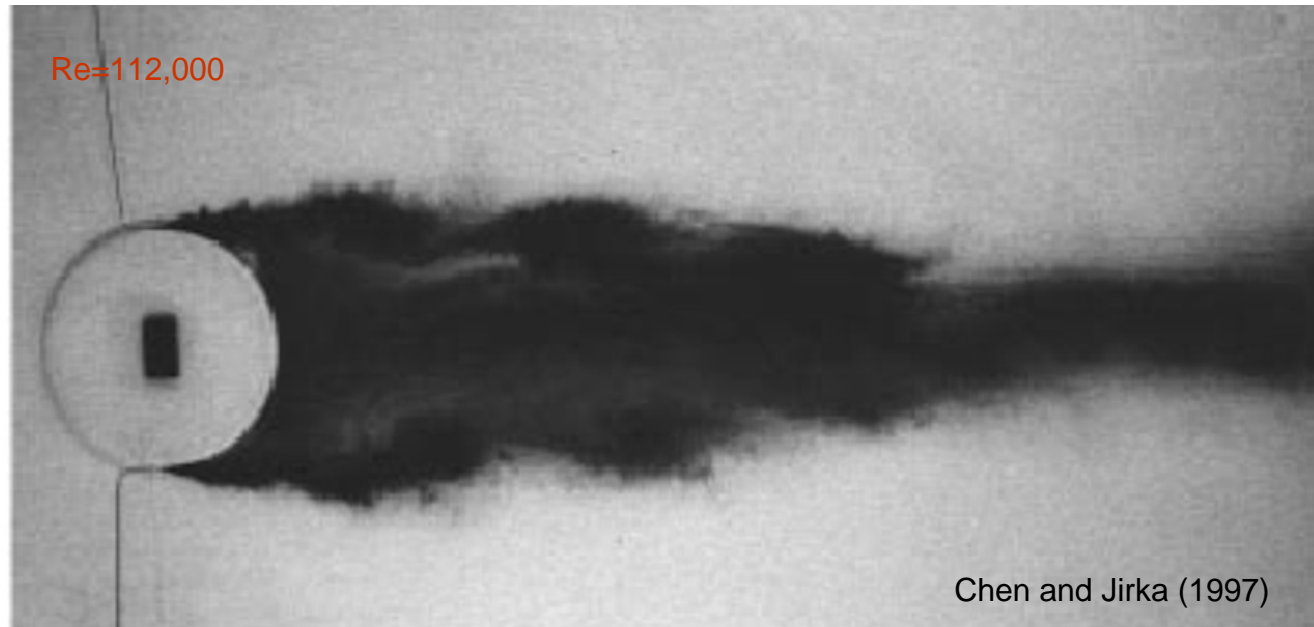




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VORTEX FORMATION IN SHALLOW FLOWS

VORTEX FORMATION IN UNSTABLE SHEAR FLOW

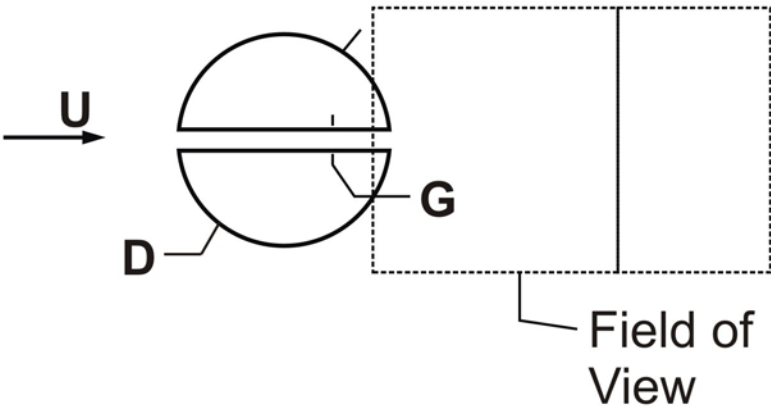
- *LAMINAR INFLOW*

- *TURBULENT INFLOW*

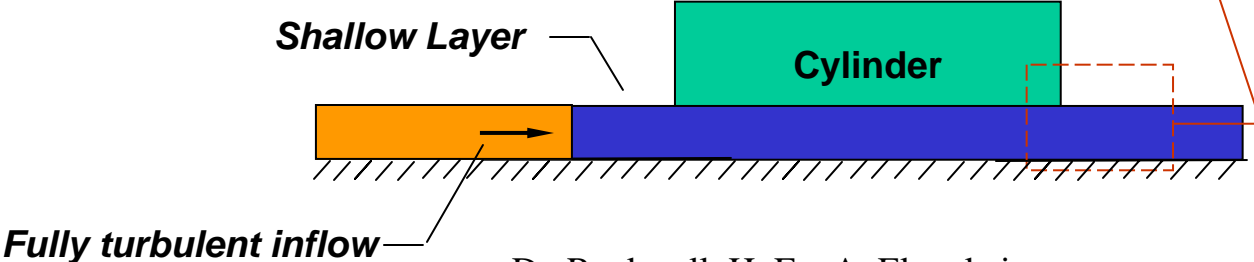
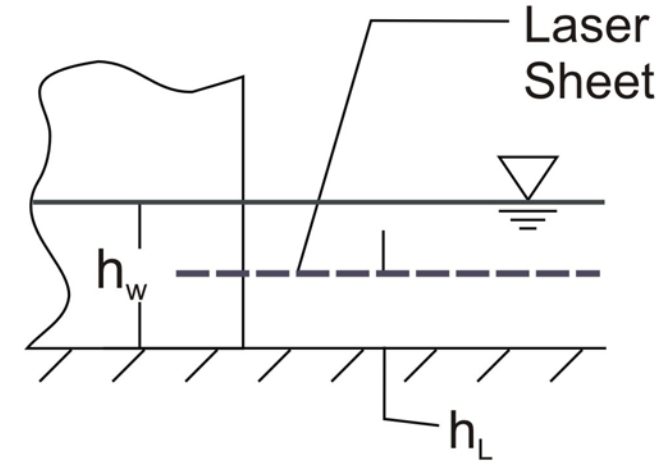
SHALLOW WAKE OF A CYLINDER: TURBULENT APPROACH FLOW

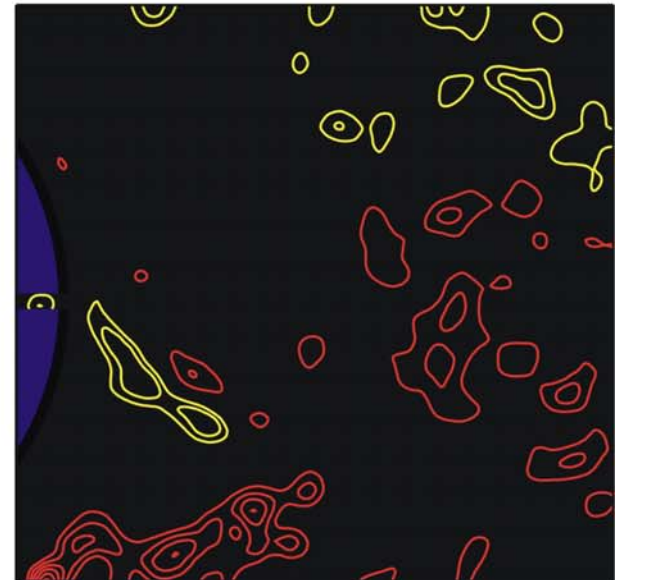
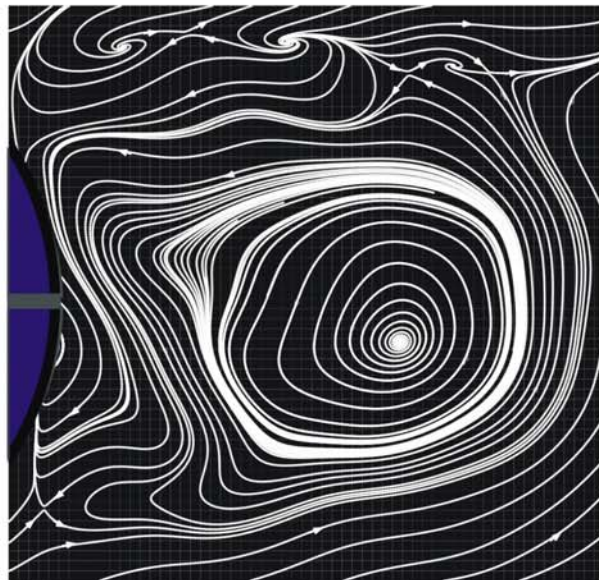
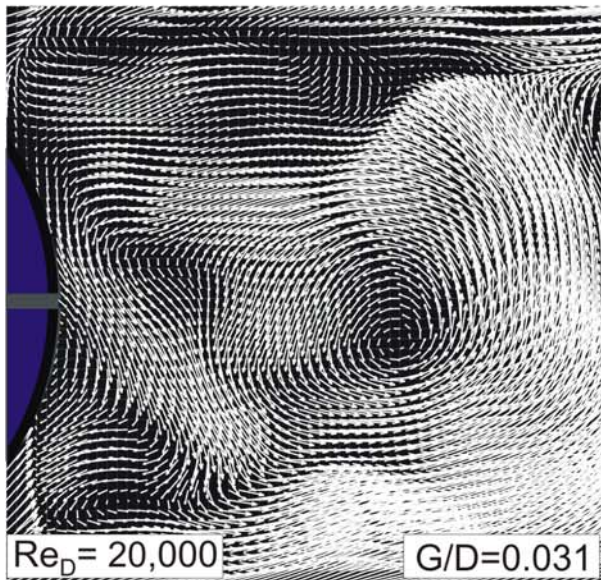
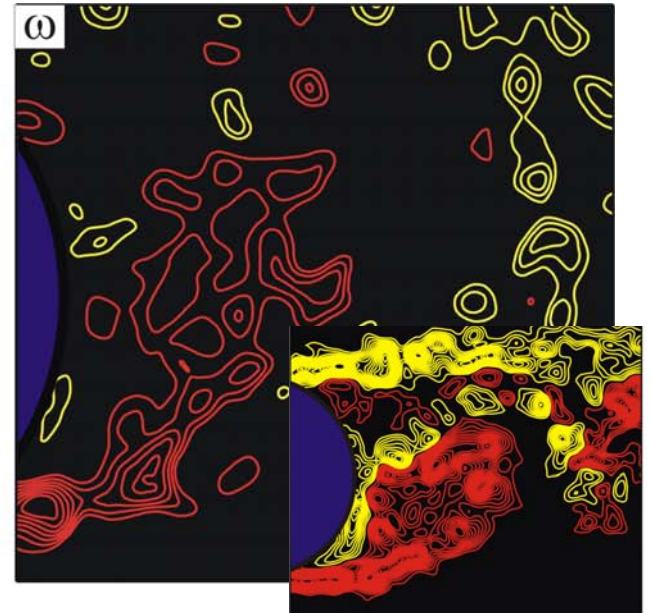
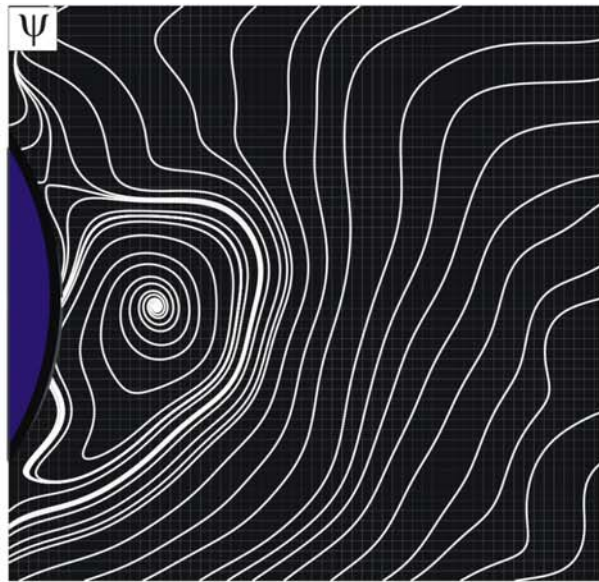
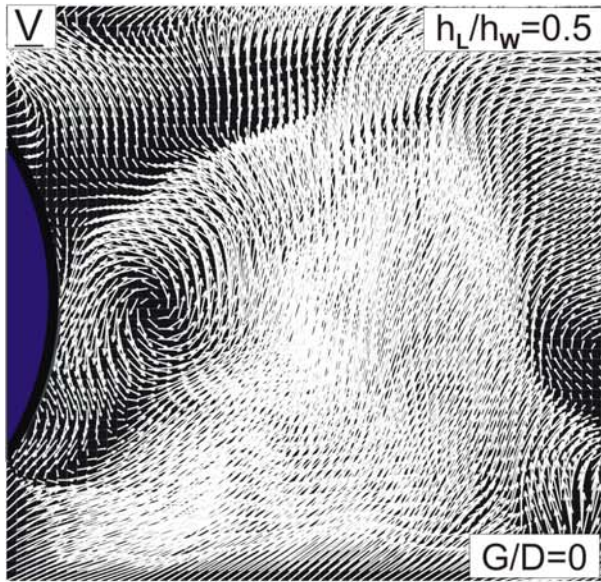
PASSIVE BASE BLEED CONTROL

PLAN VIEW

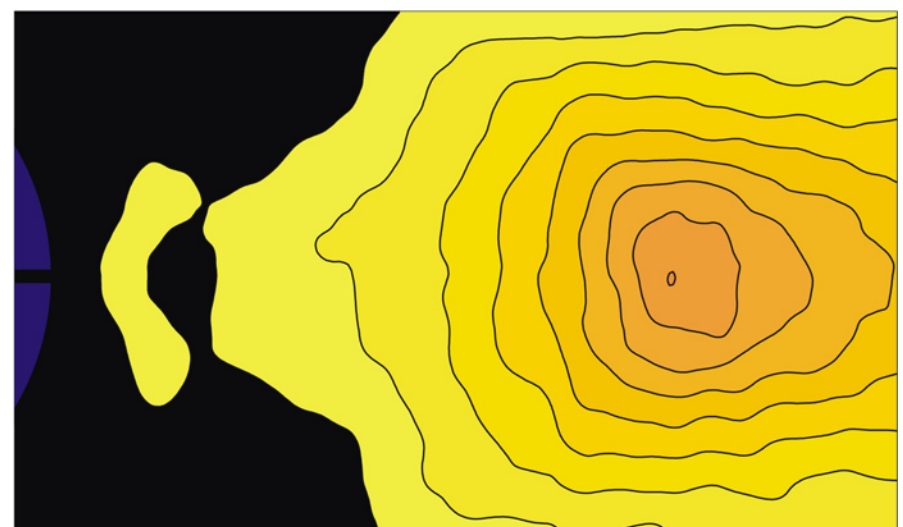
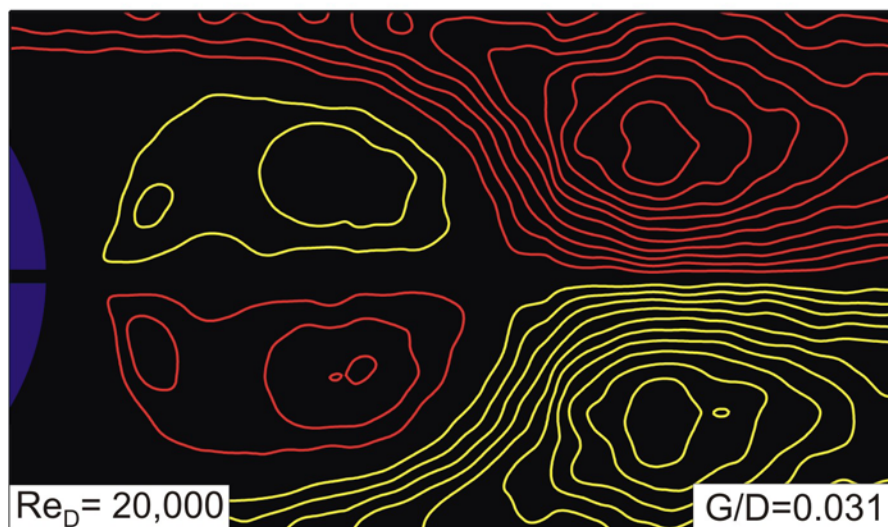
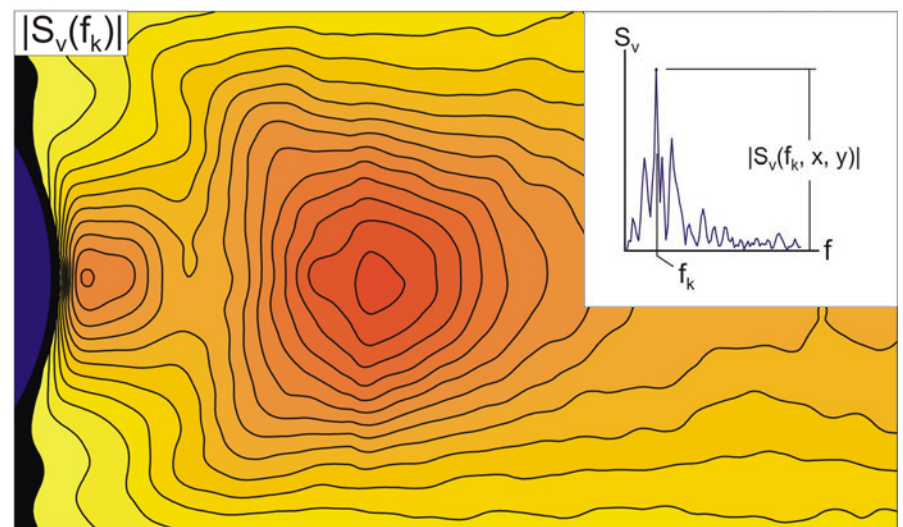


SIDE VIEW



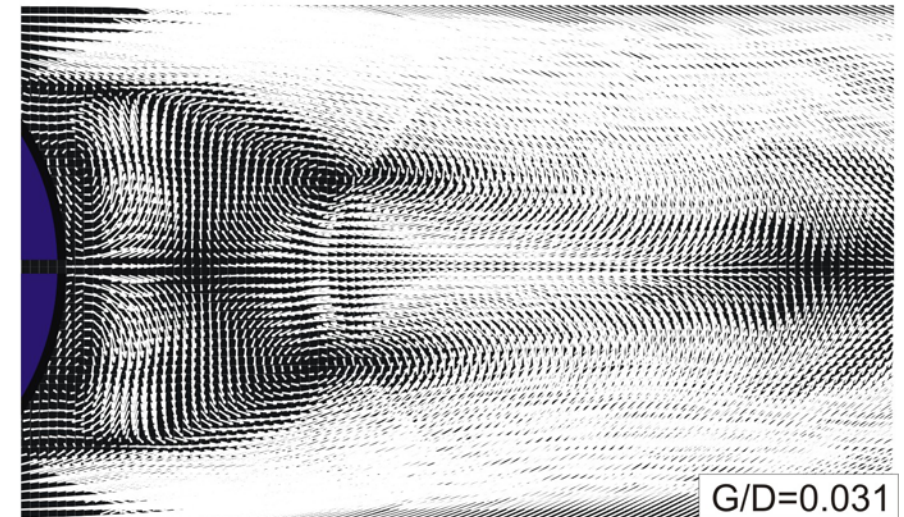
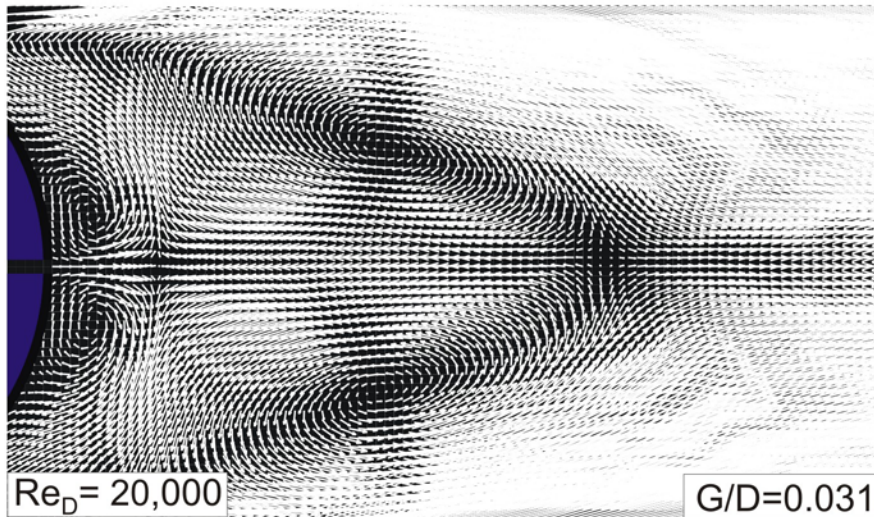
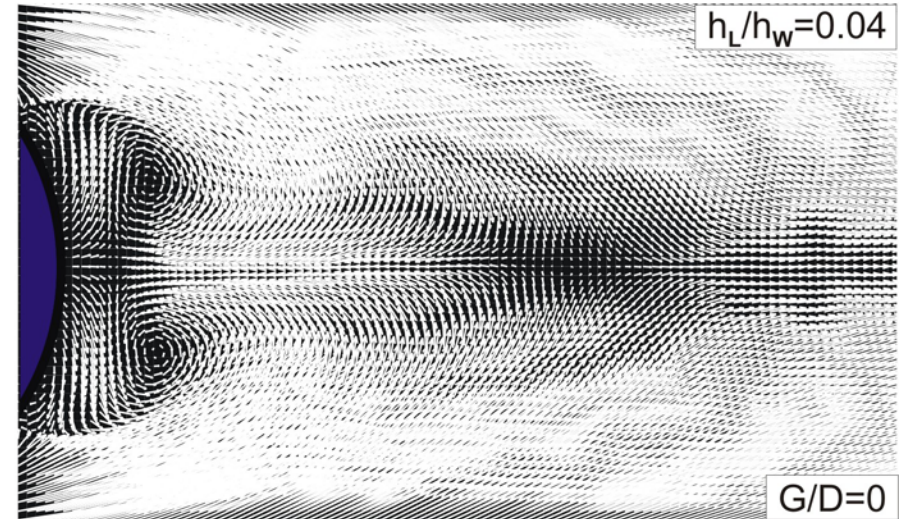
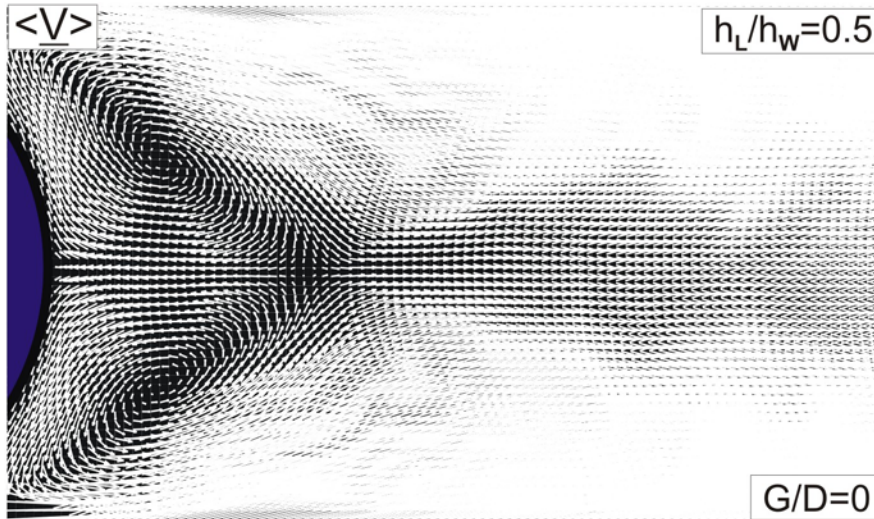


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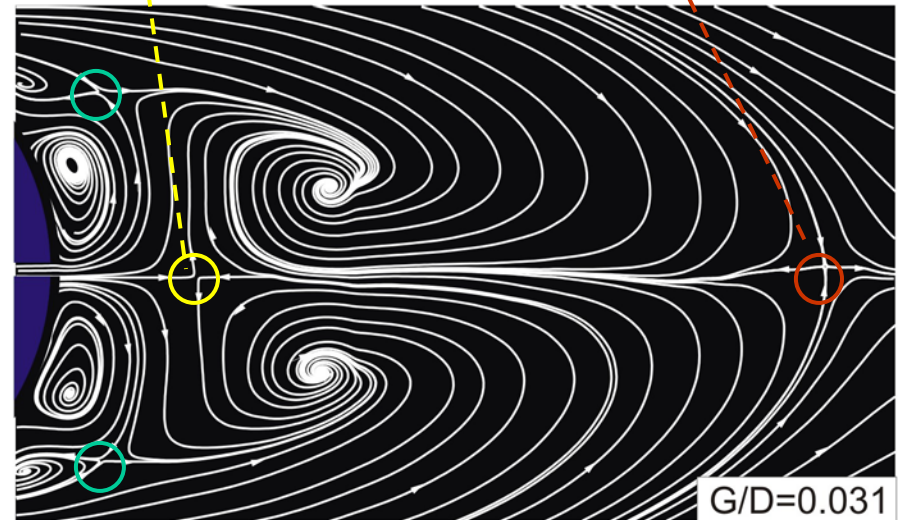
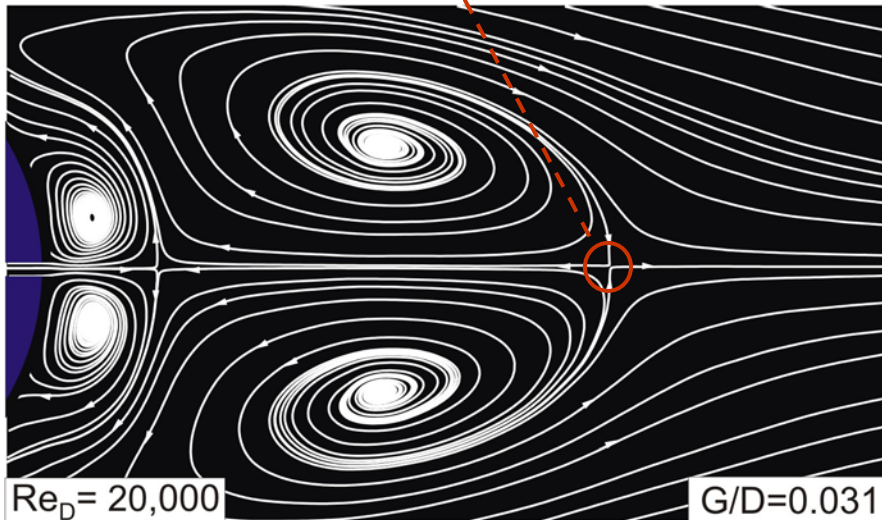
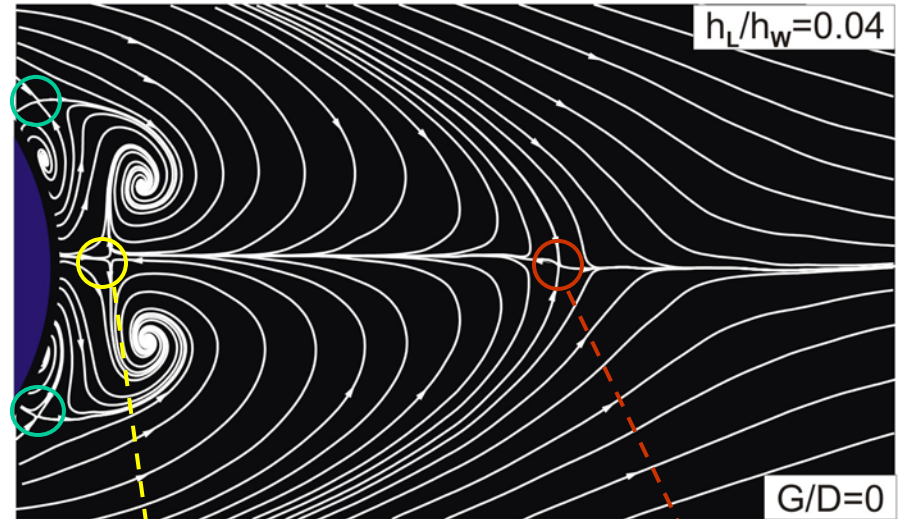
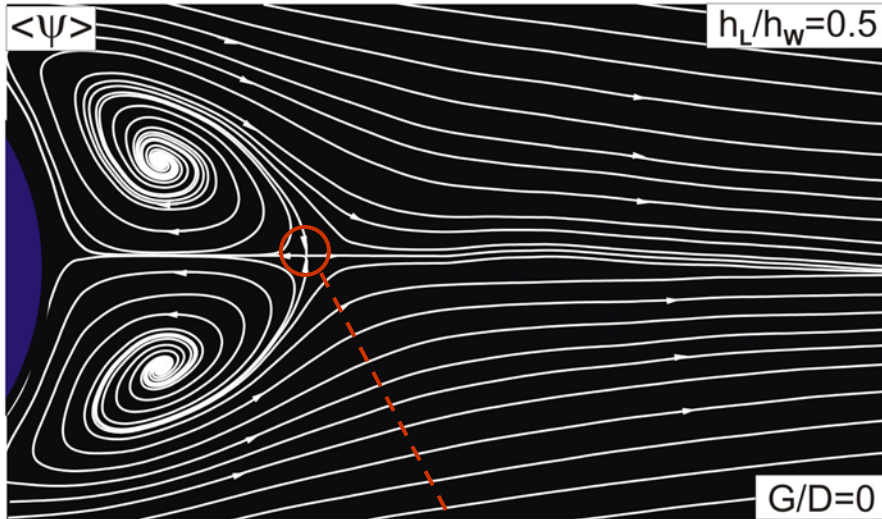
MIDPLANE

BED



MIDPLANE

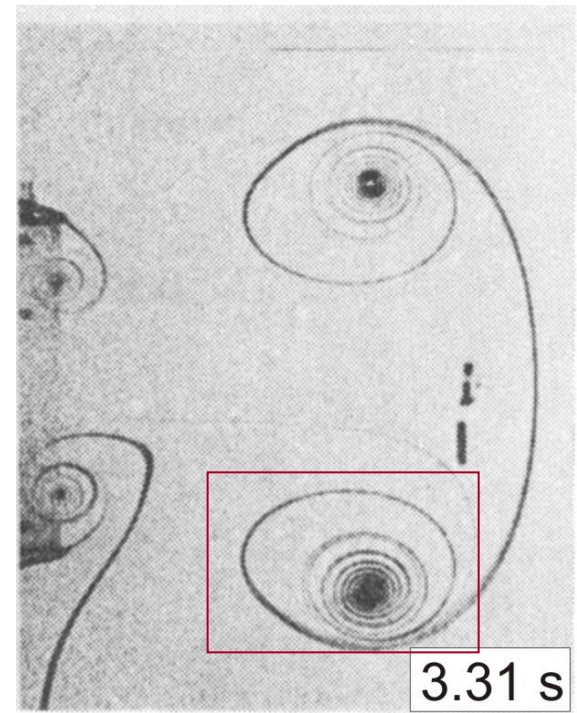
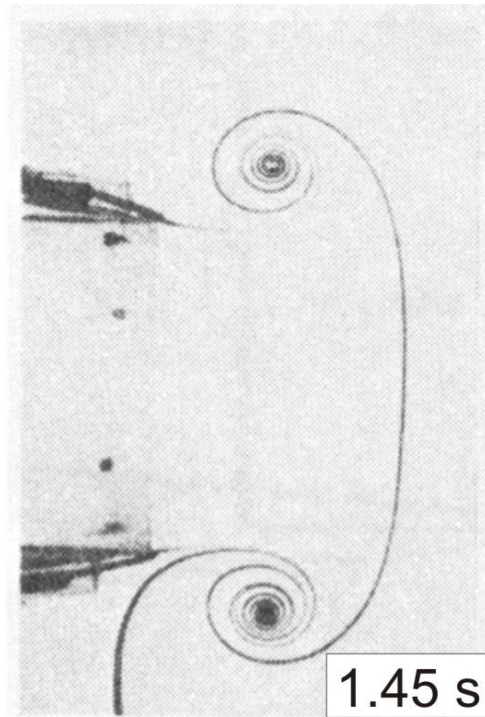
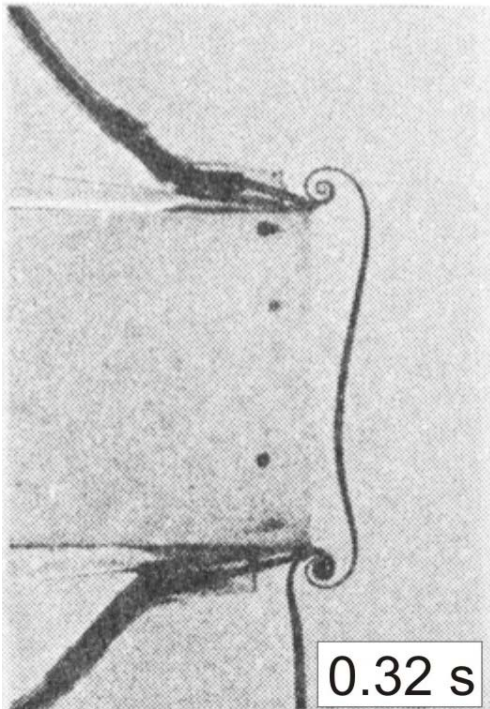
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VORTEX FORMATION IN SHALLOW FLOWS

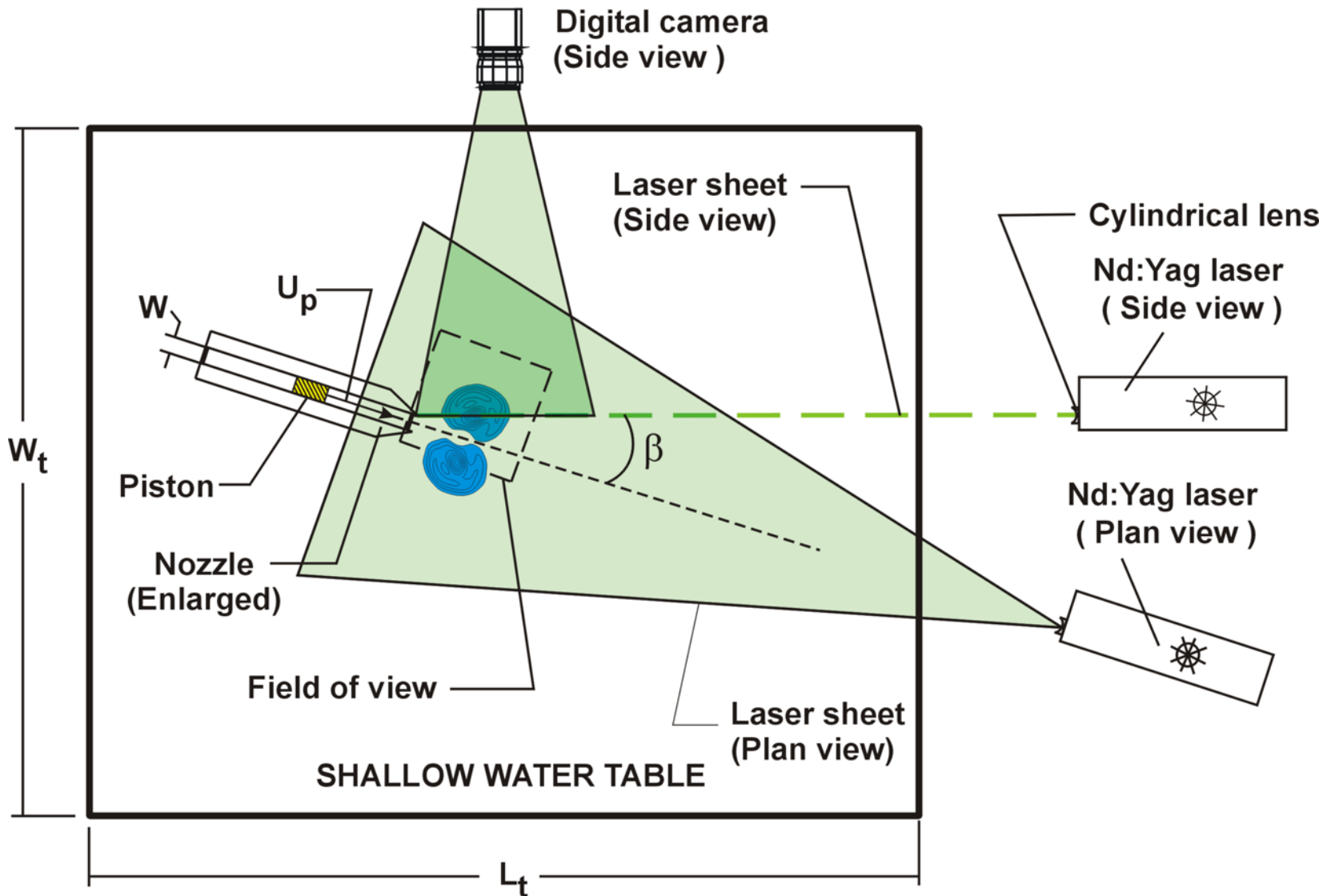
VORTEX FORMATION

- *IN UNSTABLE SHEAR FLOW*
- *VIA CONTROLLED GENERATION*
- *COUPLED WITH WAVE SYSTEM*



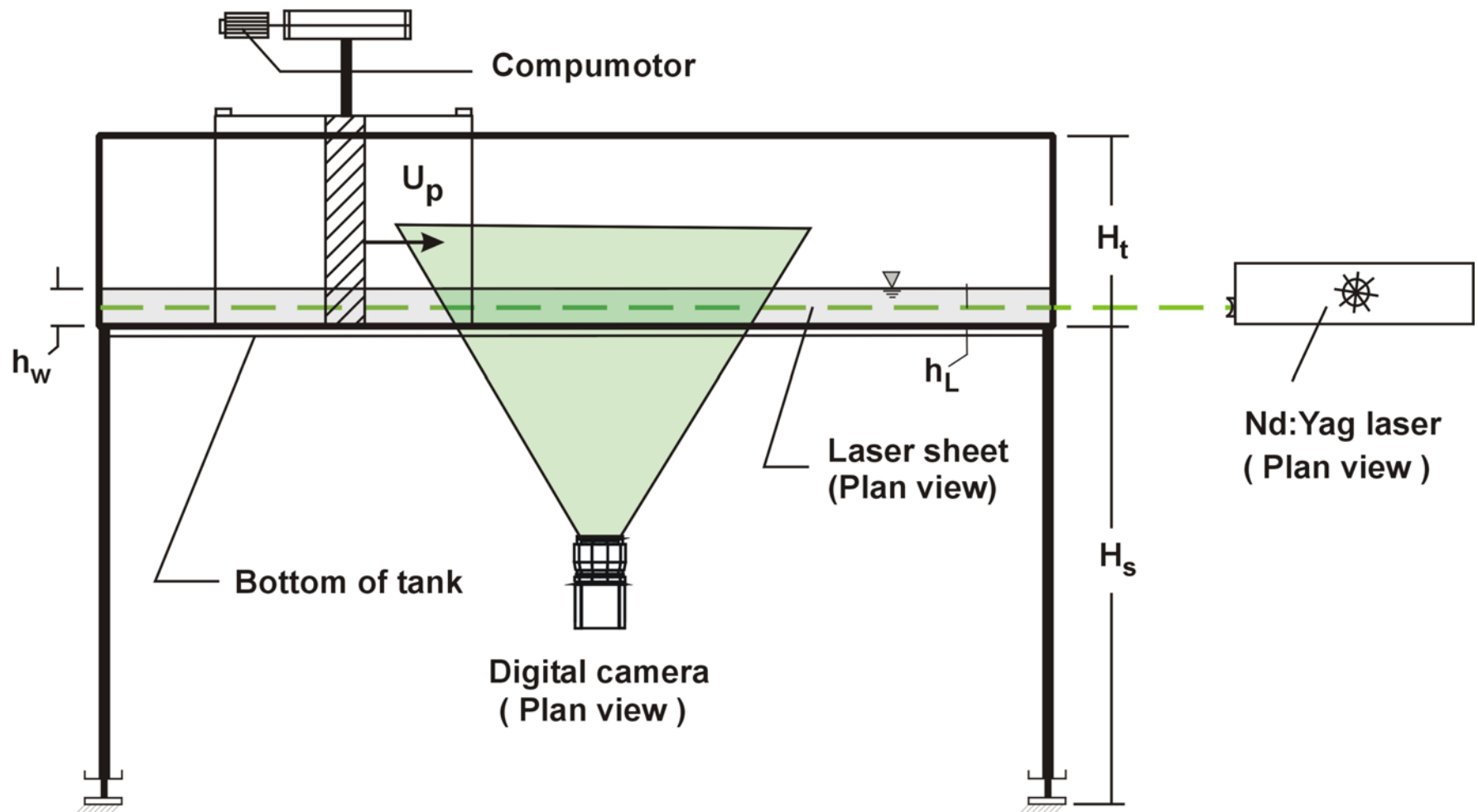
Didden (1979)

PLAN VIEW

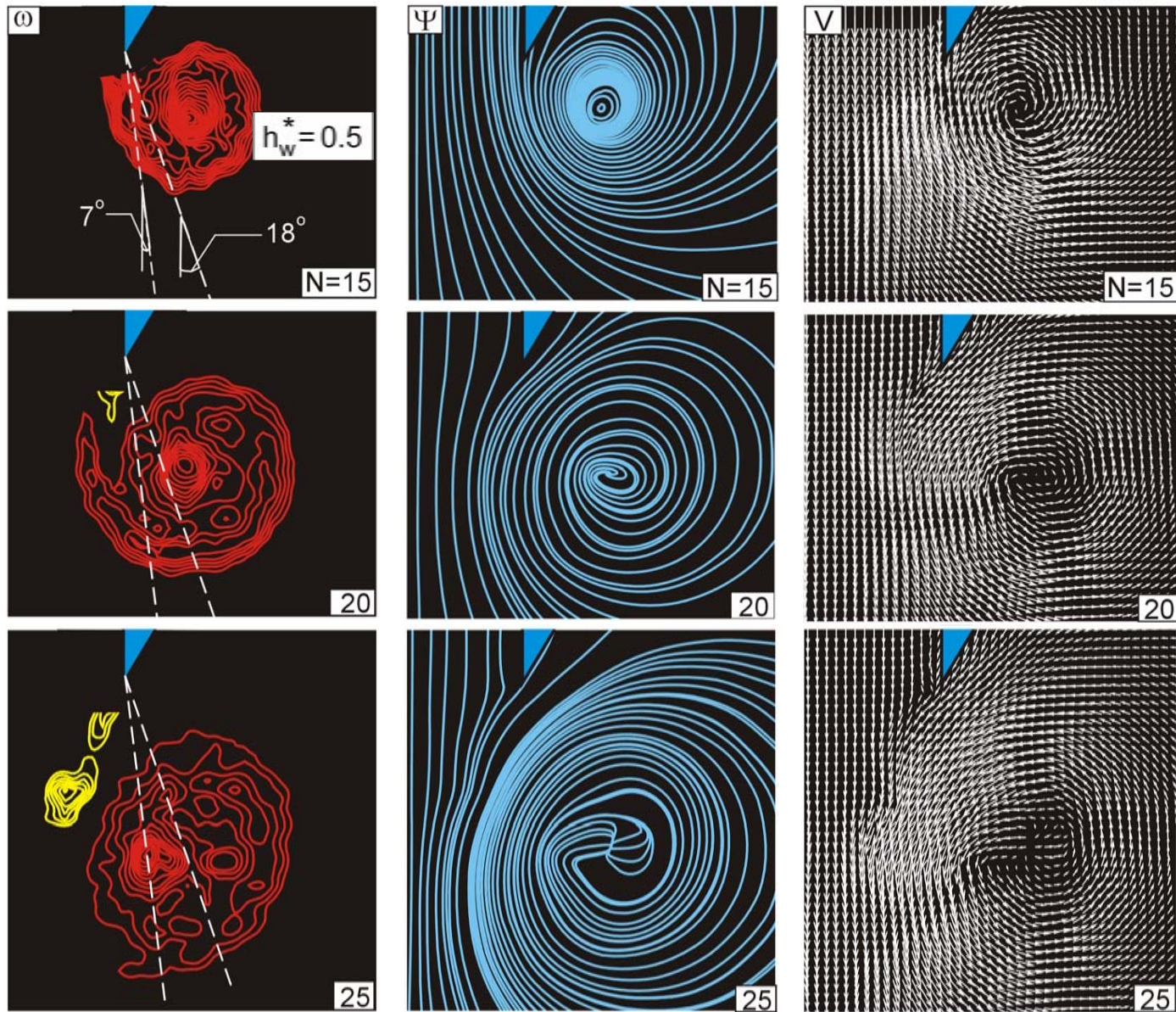


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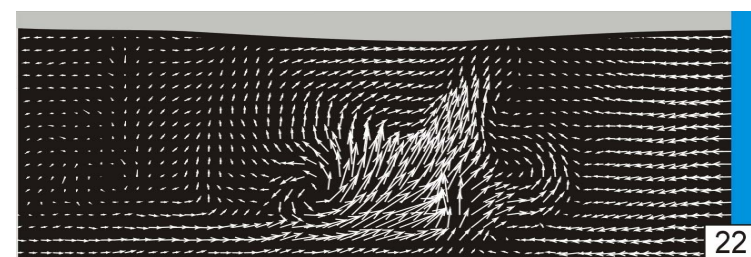
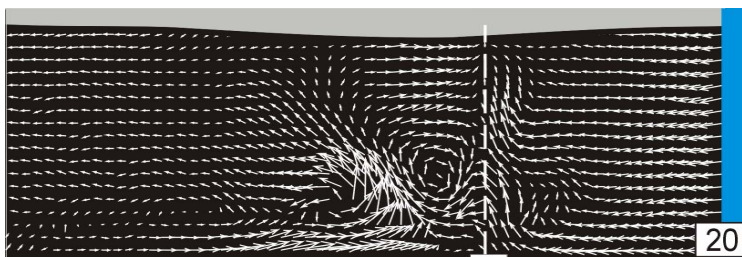
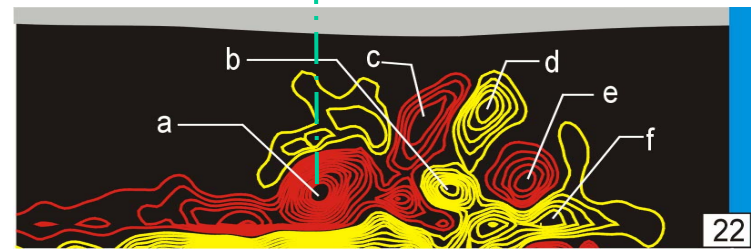
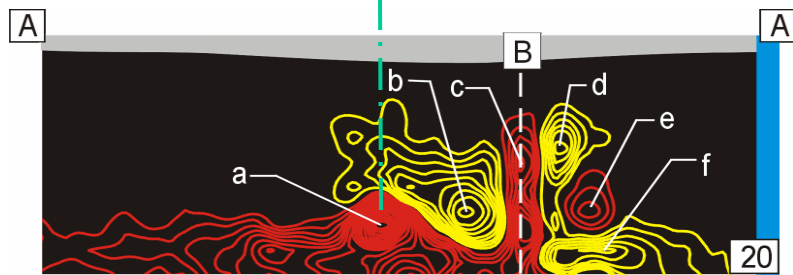
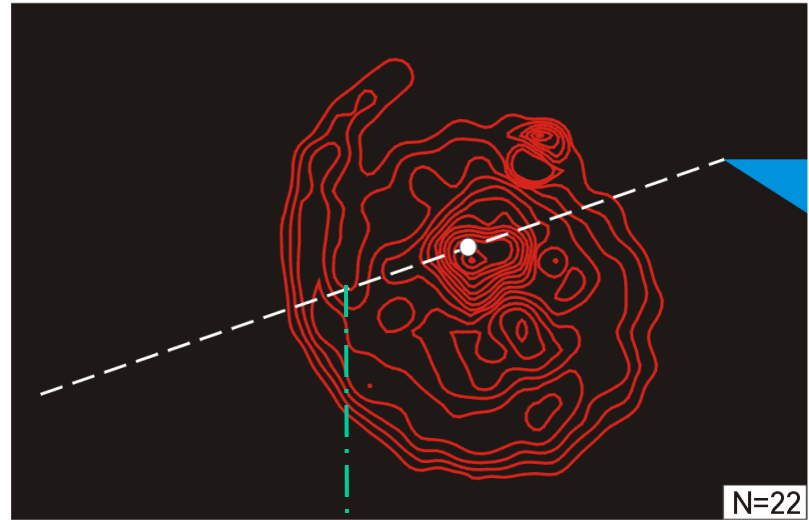
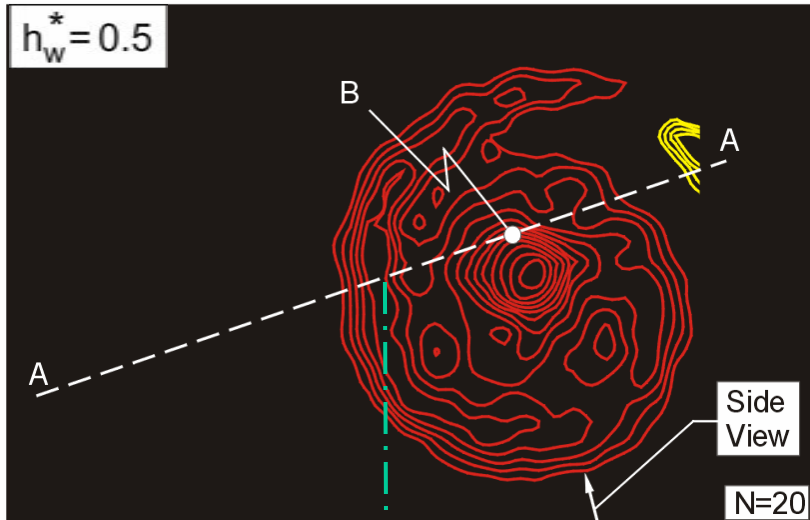
SIDE VIEW



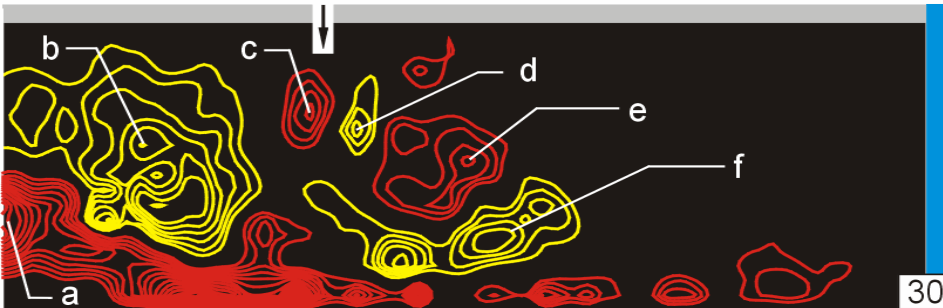
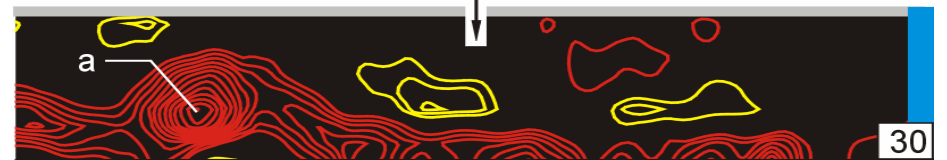
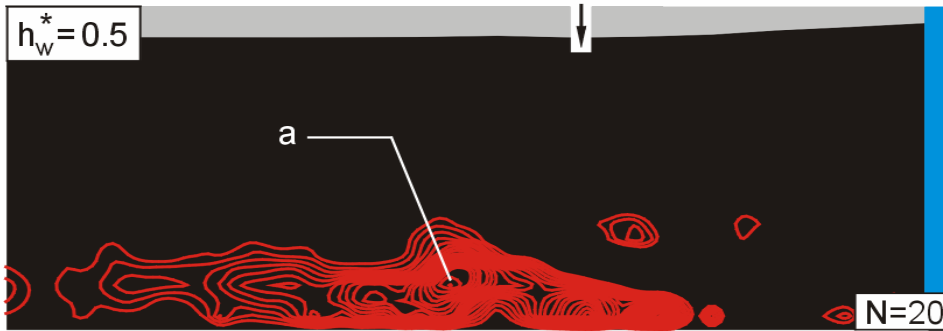
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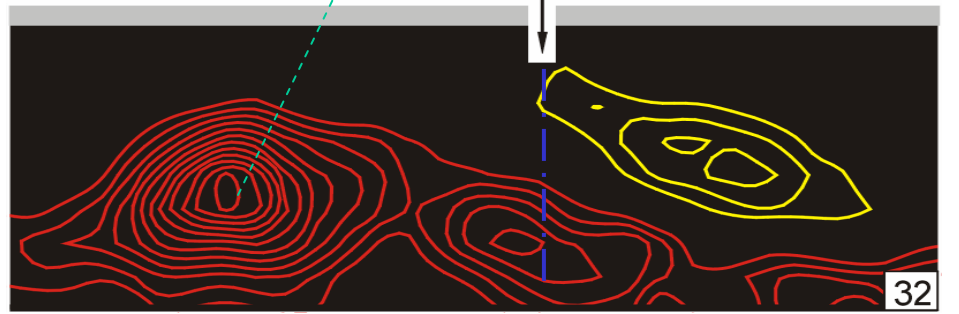
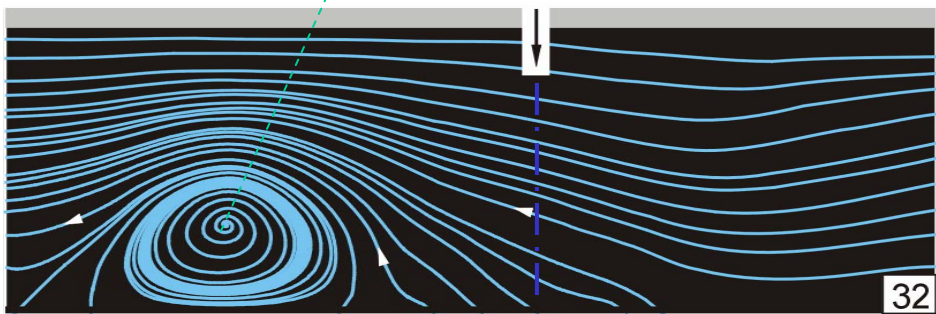
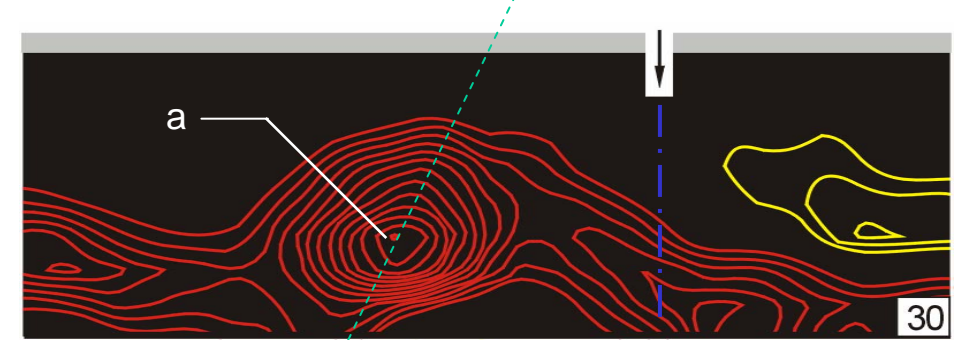
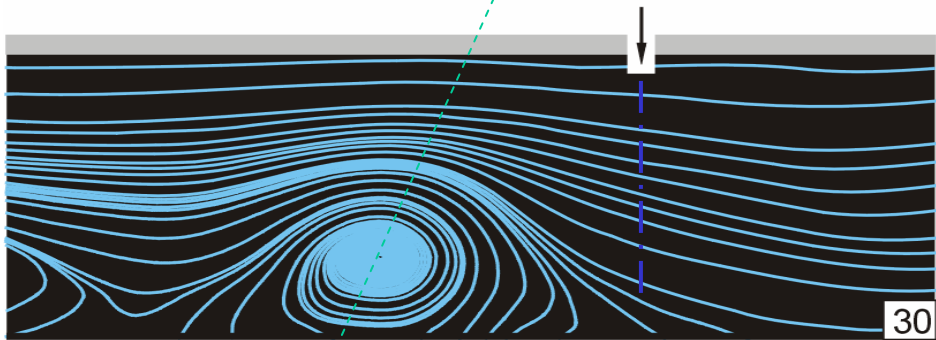
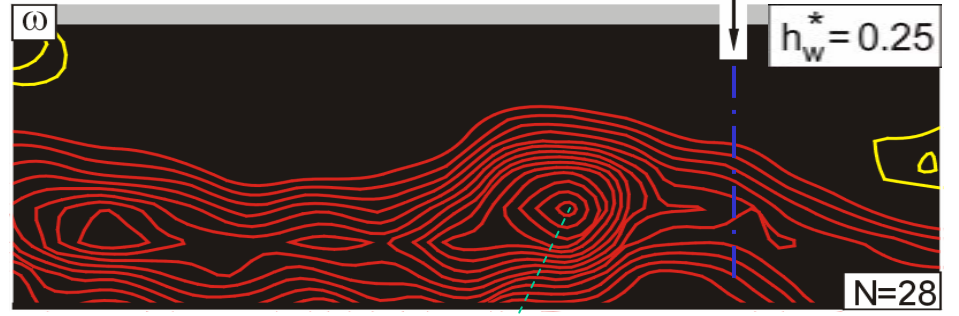
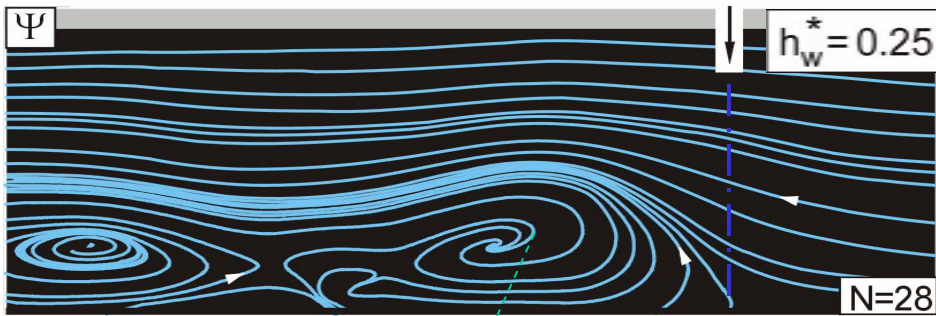


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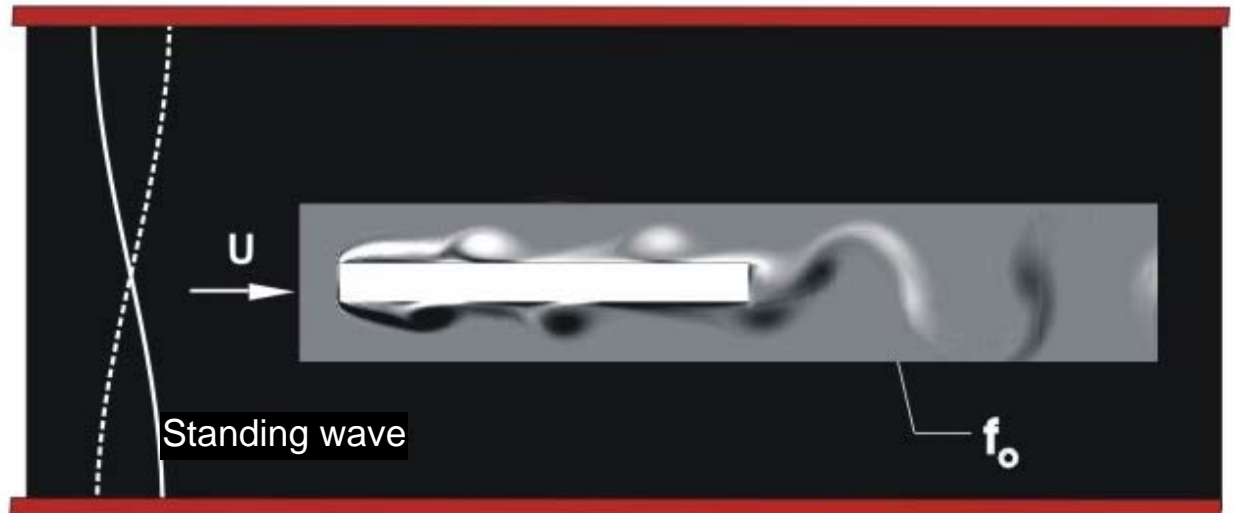
VORTEX FORMATION IN SHALLOW FLOWS

VORTEX FORMATION

- *IN UNSTABLE SHEAR FLOW*
- *VIA CONTROLLED GENERATION*
- *COUPLED WITH WAVE SYSTEM*

**AN ANALOGY TO A
SHALLOW FLOW SYSTEM**

**VORTEX FORMATION
COUPLED WITH ACOUSTIC
RESONANCE (AIR FLOW)**



Tan, Hourigan and Thompson (2003)

Instantaneous acoustic power

$$-\rho_0 \boldsymbol{\omega} \cdot (\mathbf{u} \times \mathbf{v})$$



Averaged acoustic power

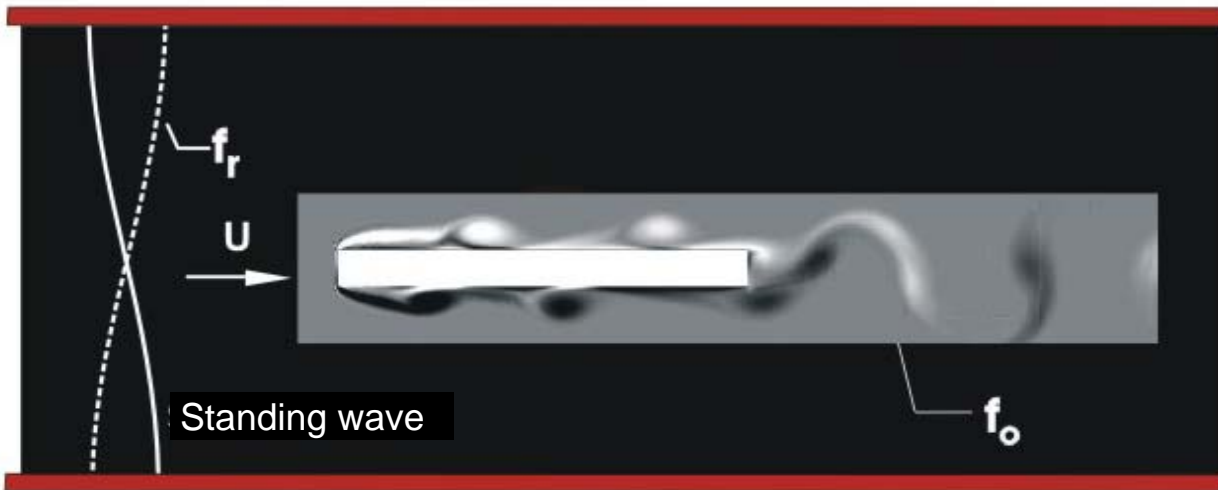
$$P = -\rho_0 \int \boldsymbol{\omega} \cdot (\mathbf{u} \times \mathbf{v}) dV$$

Vorticity

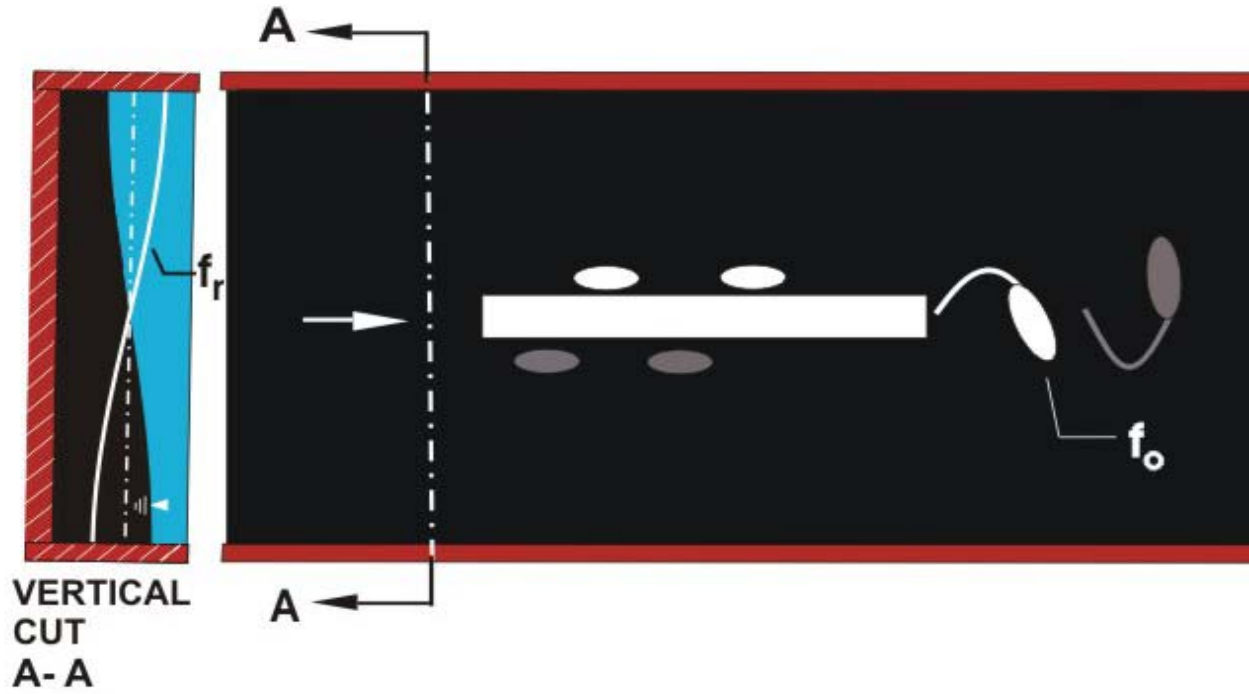
Hydrodynamic velocity

Acoustic particle velocity

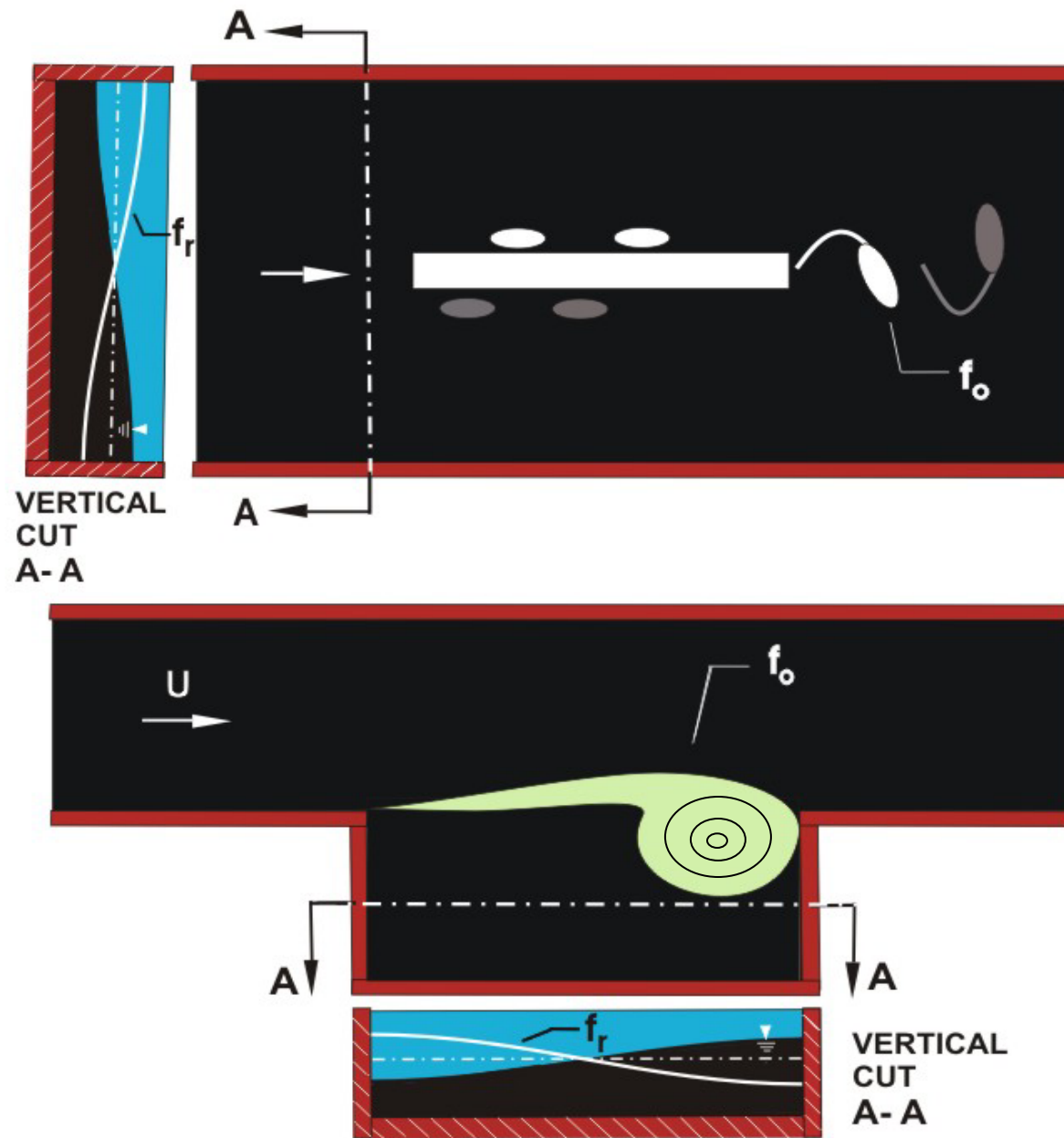




Tan, Hourigan and Thompson (2003)



VORTEX FORMATION: INFLUENCE OF GRAVITY STANDING-WAVE





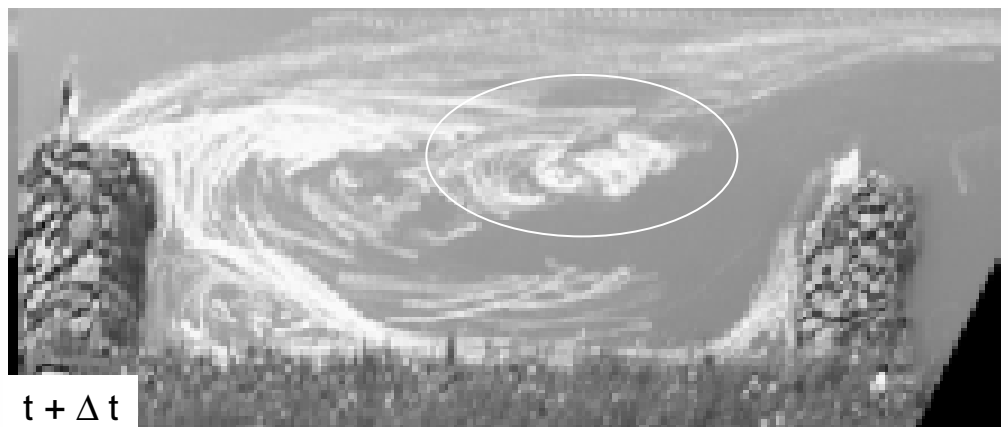
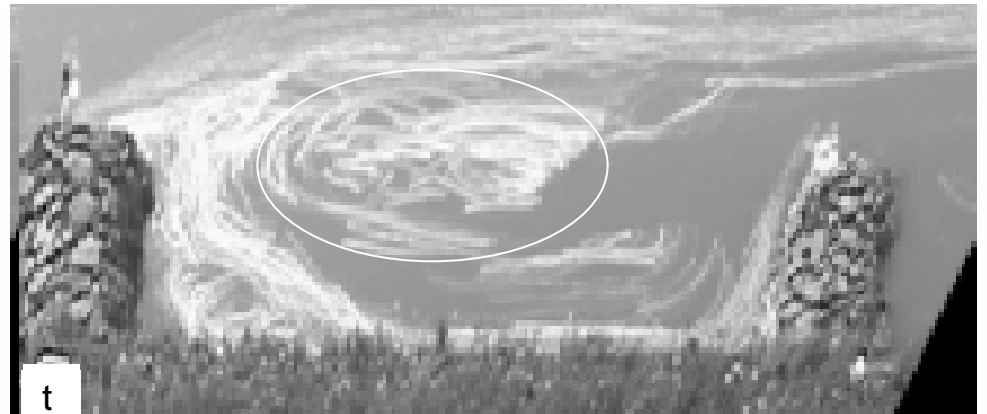
Waal River (Major branch of the Rhine in the Netherlands)

(Yossef, 2005)

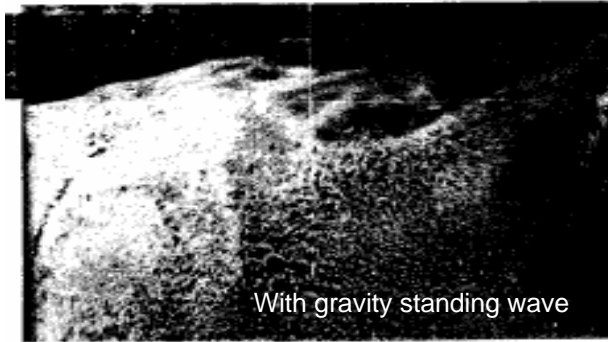


Yodo River (Central Japan)

Yasunori, Yasuyuki and Shiro (2002)



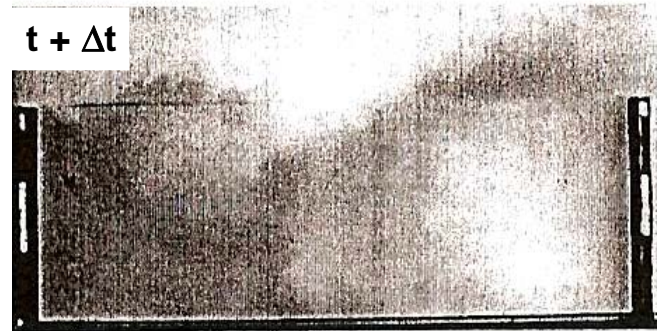
CAVITY OSCILLATION IN PRESENCE OF GRAVITY STANDING WAVE



Kimura and Hosoda (1997)

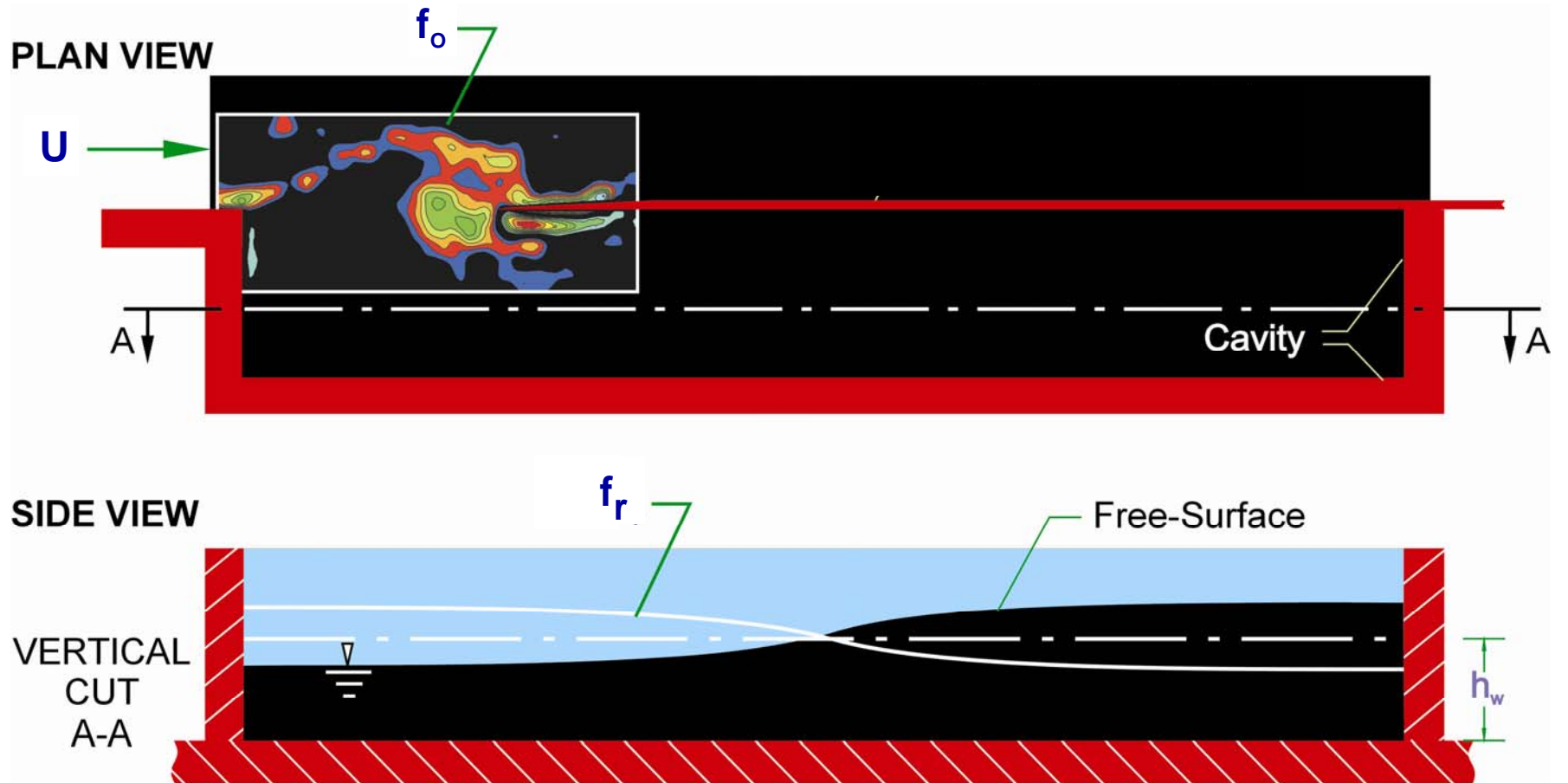
Kyoto

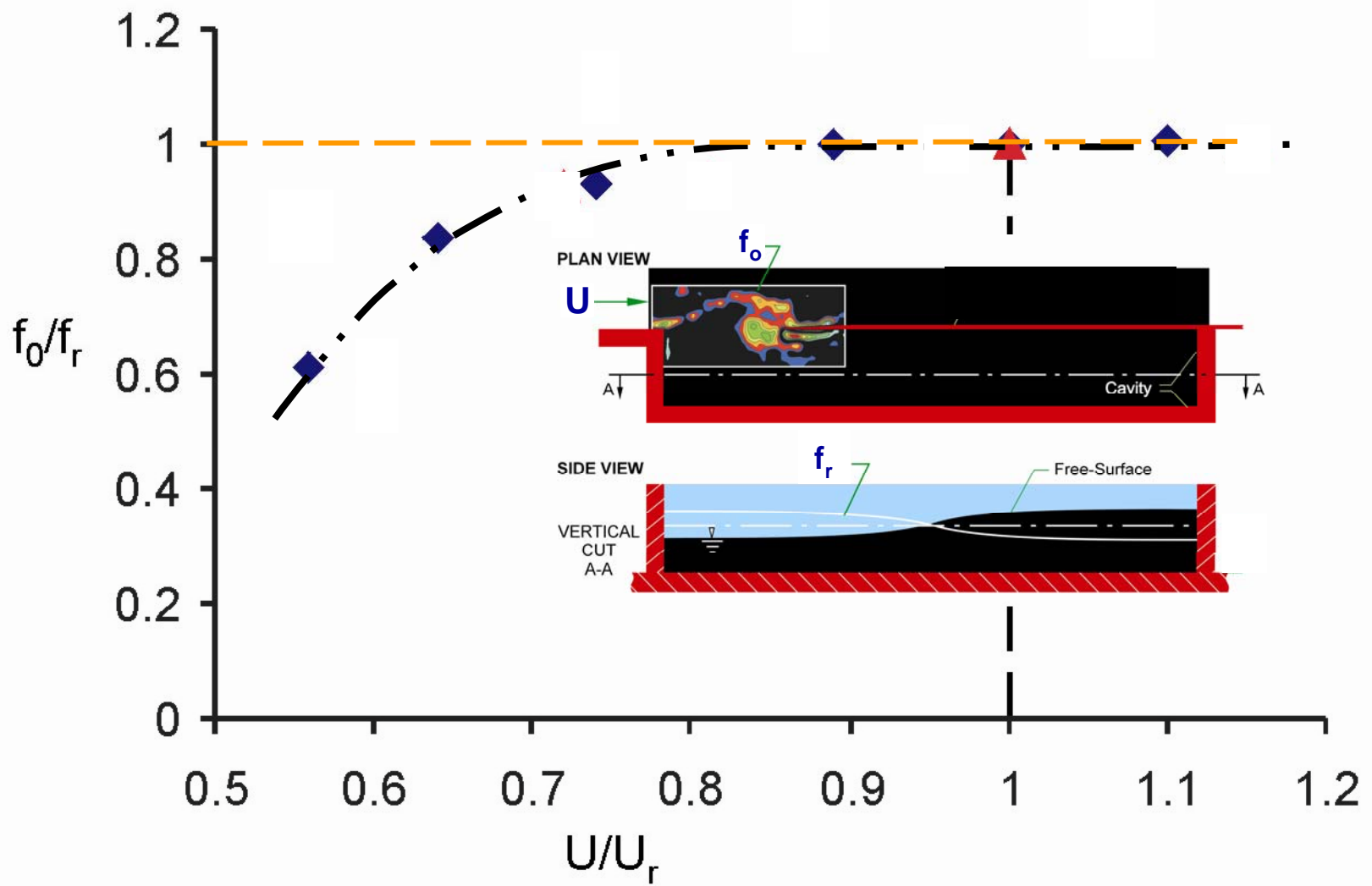
MASS EXCHANGE BETWEEN CAVITY AND FREESTREAM

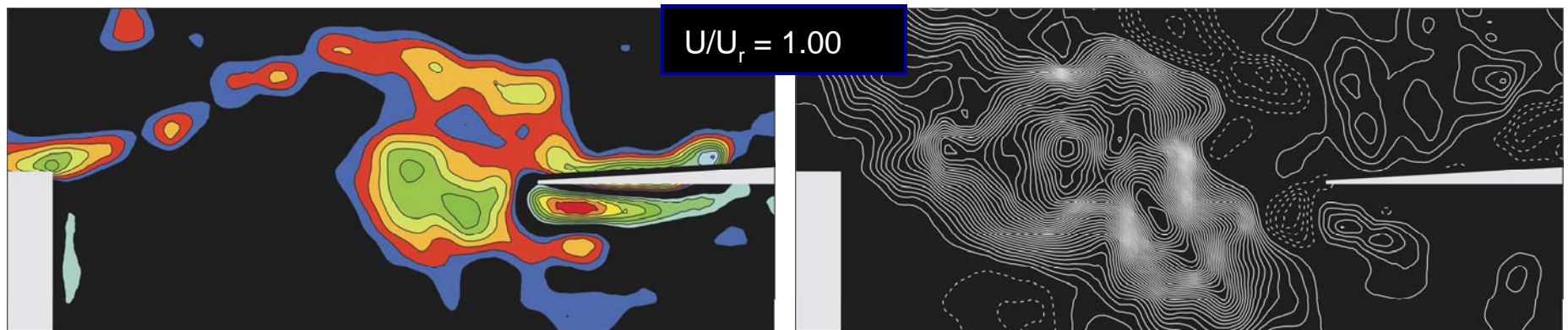
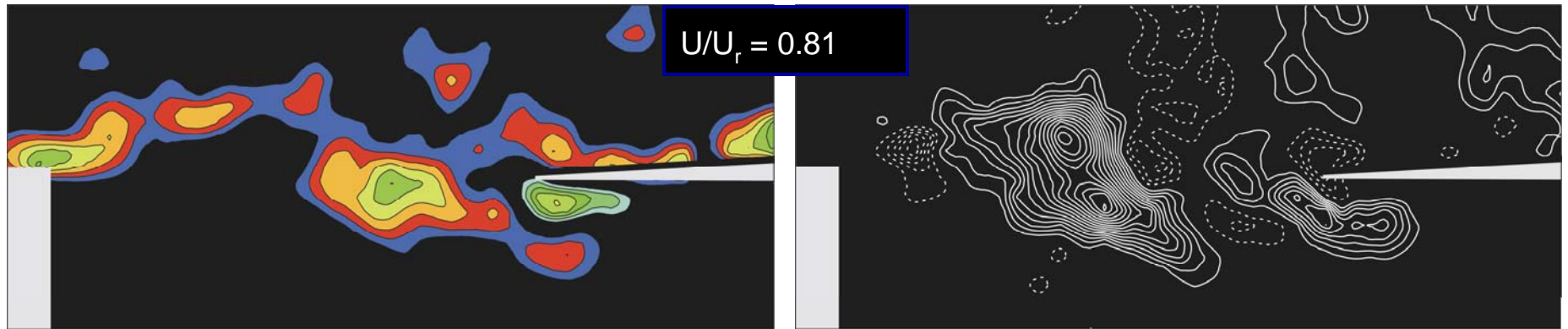
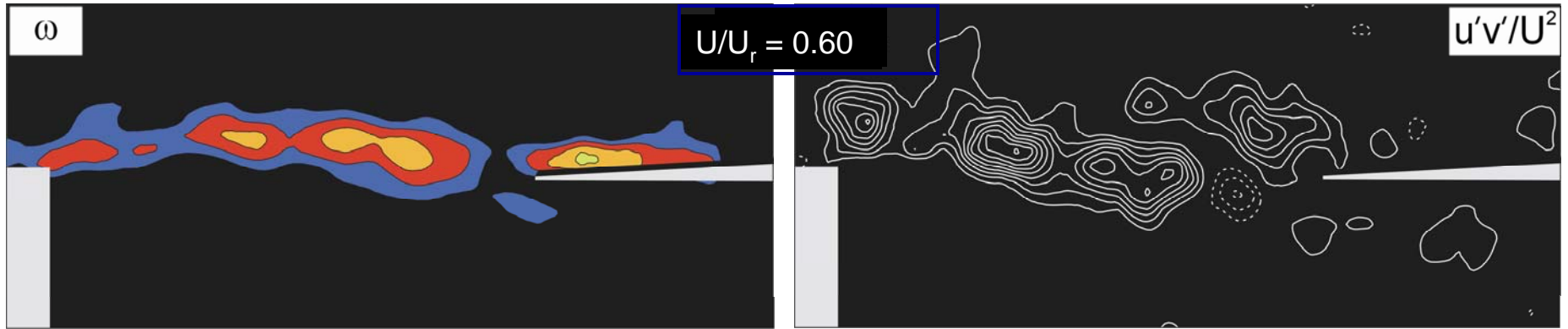


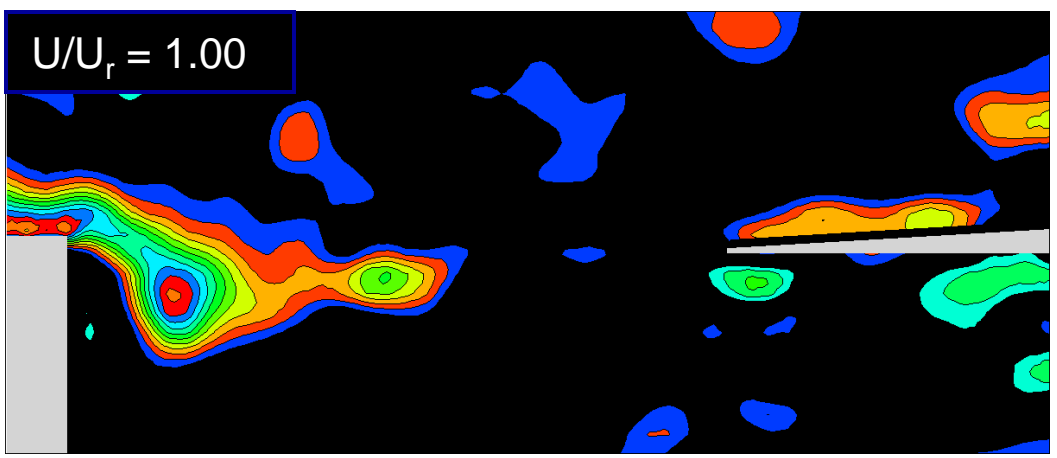
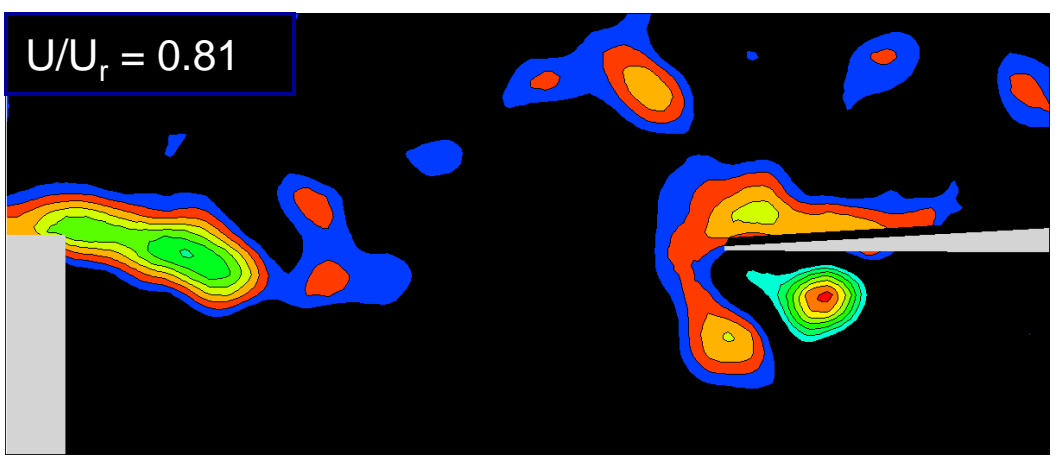
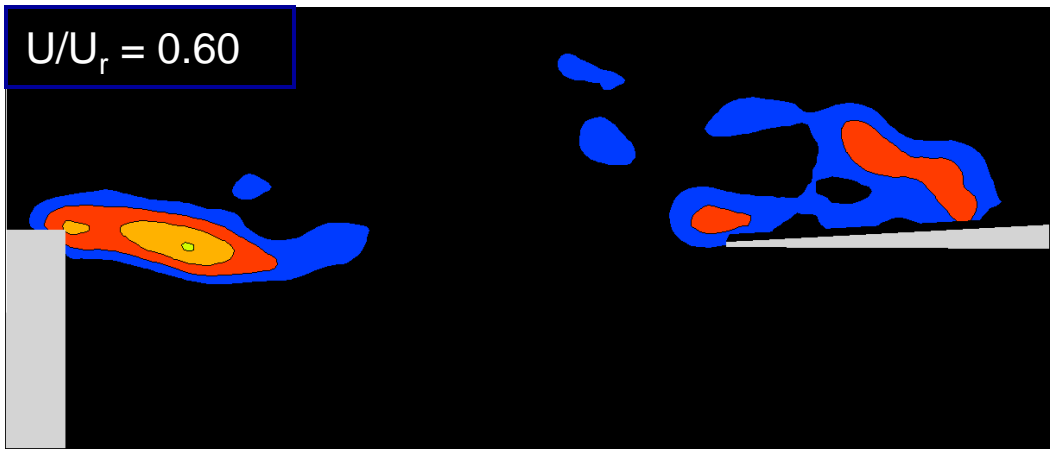
Uijtewaal, Lehman, and van Mazijk (2001)

Delft

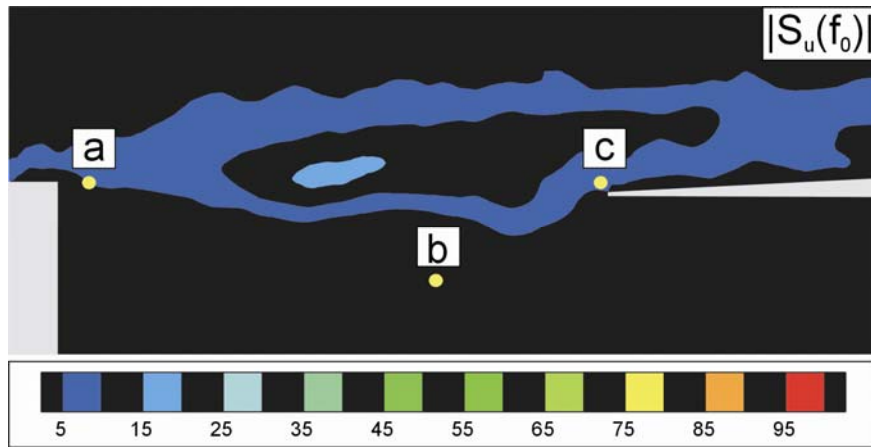




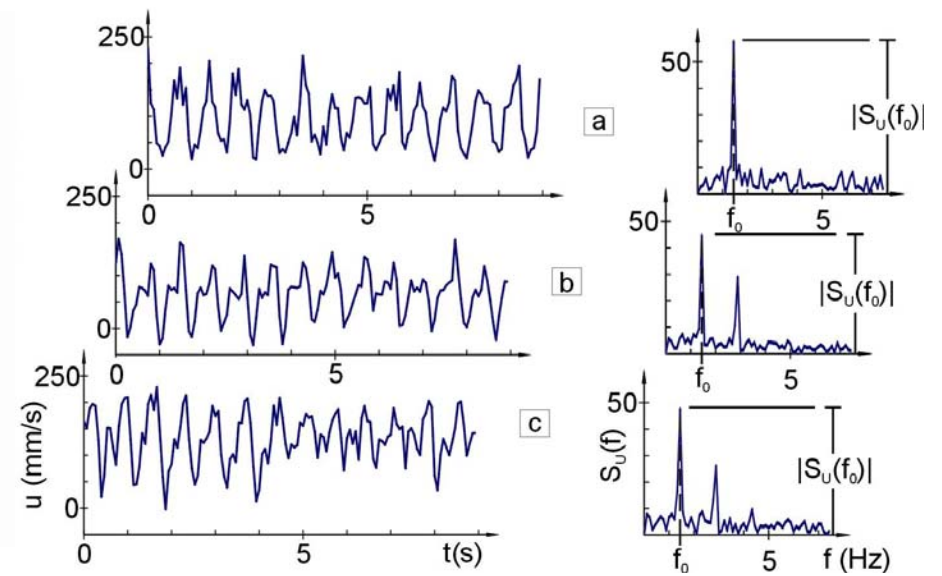
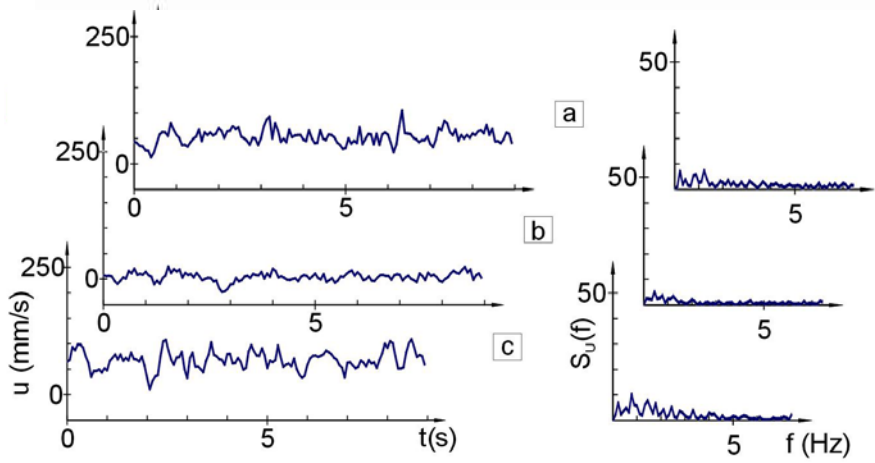
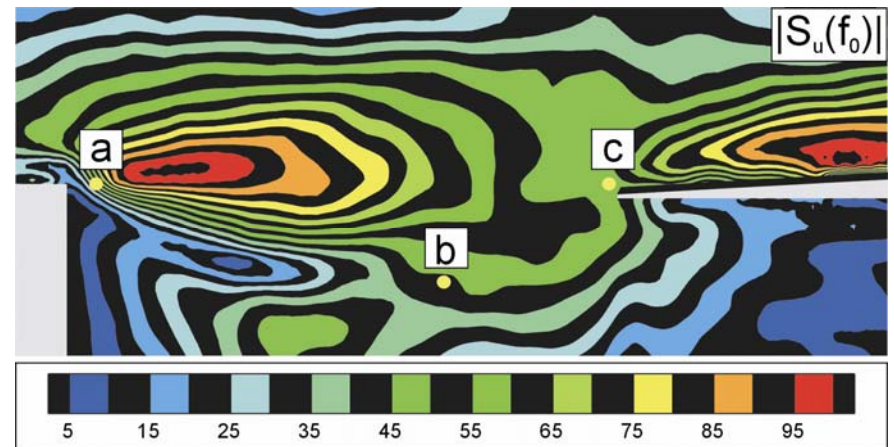




$U/U_r=0.60$



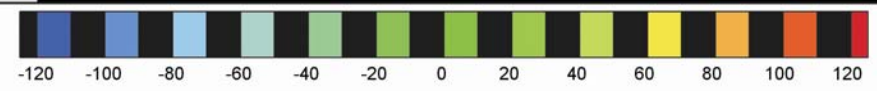
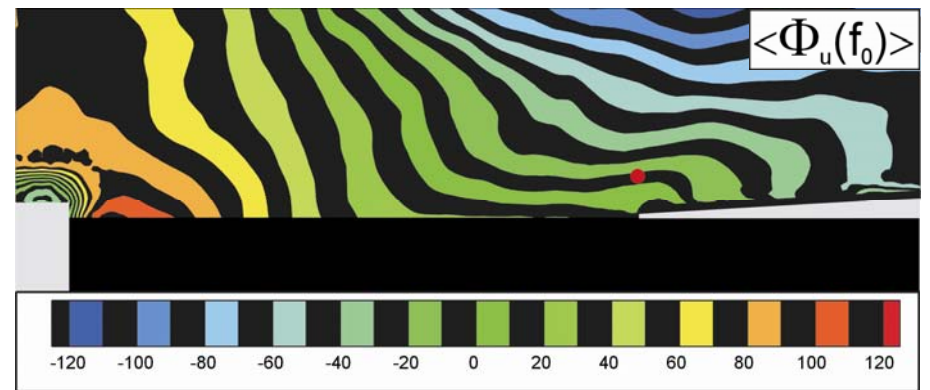
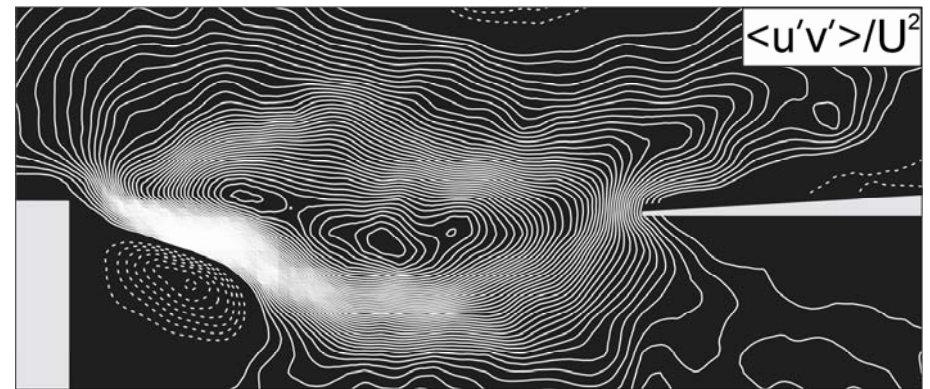
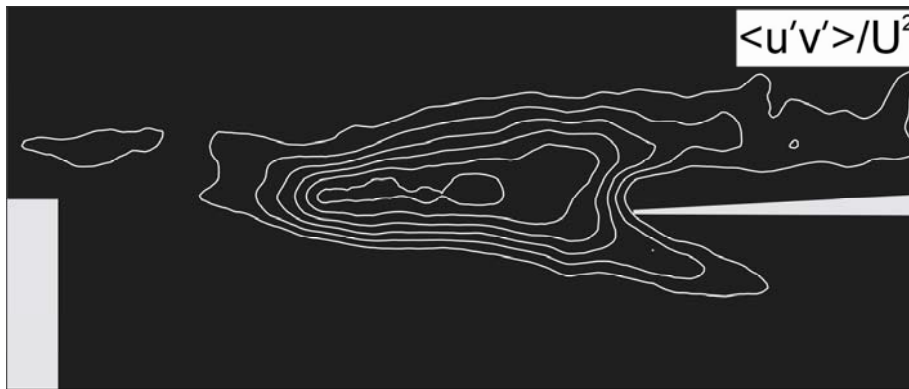
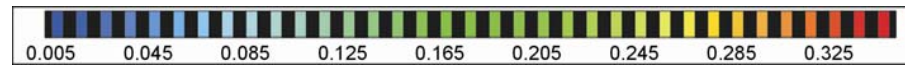
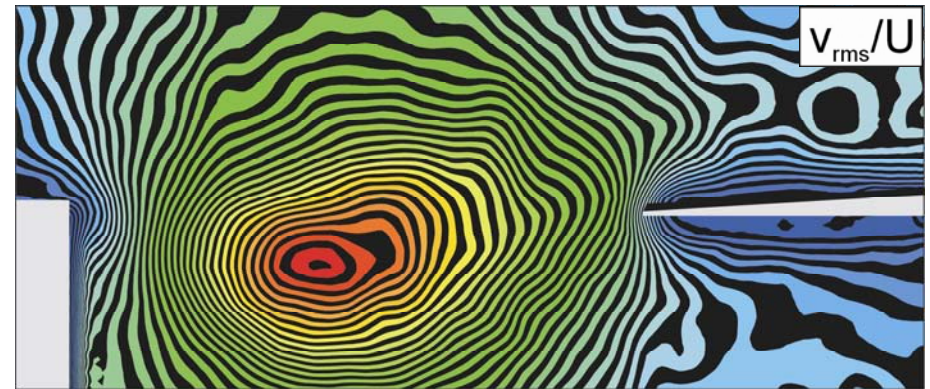
$U/U_r=1.00$



$U/U_r=0.60$



$U/U_r=1.00$



VORTEX FORMATION IN SHALLOW FLOWS

OVERVIEW

Highly coherent vortex formation in shallow flows due to:

- (i) Classical absolute instability of near-wake*
- (ii) Global instability of entire system of distorted flow about body and near wake*
- (iii) Convective instability triggered and reinforced by gravity wave resonance*
- (iv) Eruption of boundary layer from bed at leading-edge of nominally two-D vortex*

Viewed in isolation, formation of highly robust coherent vortical structures due to (ii) and (iii) mimics features of (i).

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November 2006



Tan, Hourigan and Thompson (2003)

Instantaneous acoustic power

$$-\rho_0 \omega \cdot (\mathbf{u} \times \mathbf{v})$$



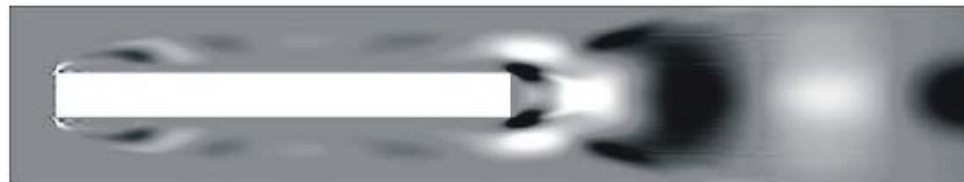
Averaged acoustic power

$$P = -\rho_0 \int \omega \cdot (\mathbf{u} \times \mathbf{v}) dV$$

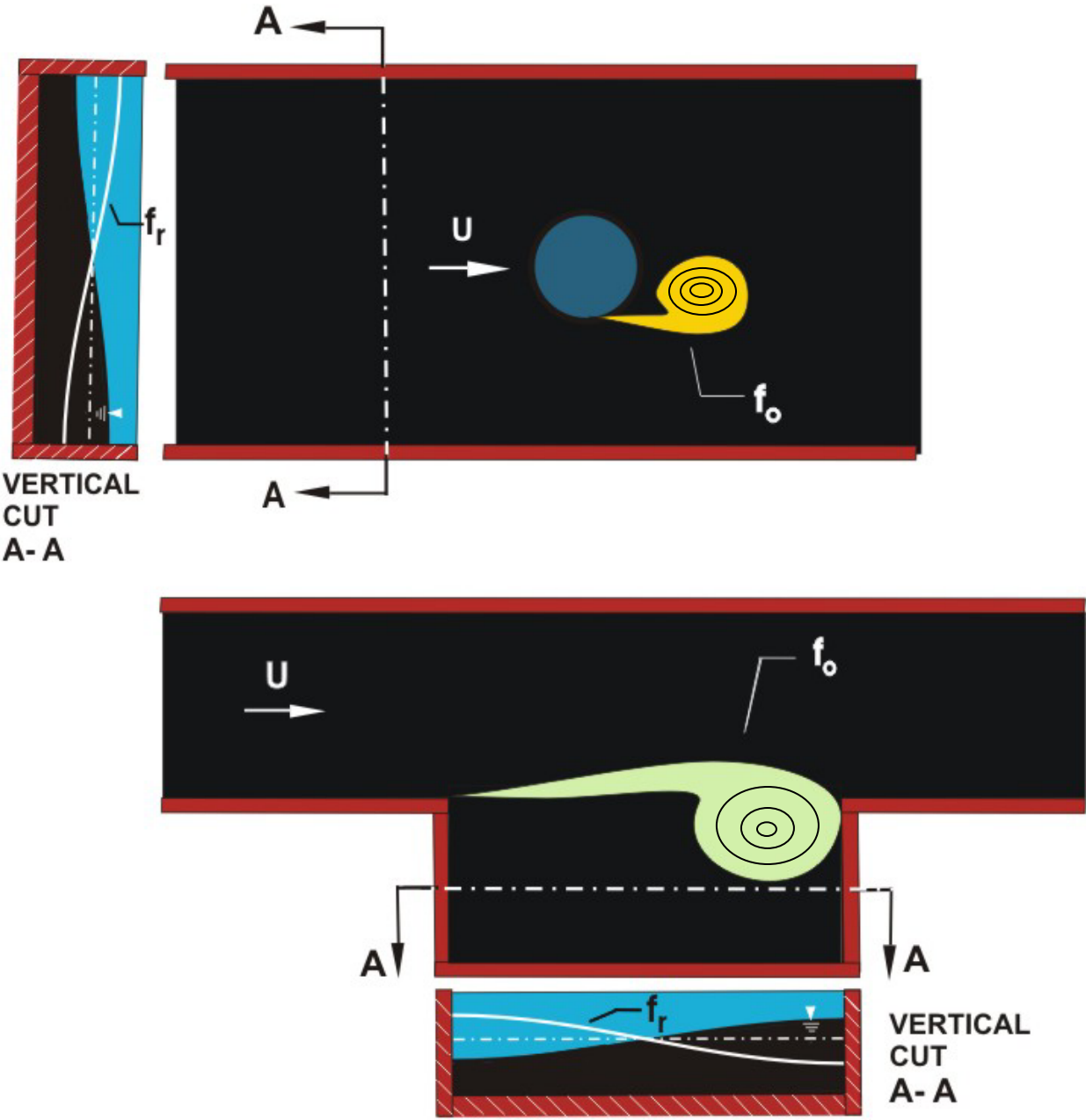
Vorticity

Hydrodynamic velocity

Acoustic particle velocity

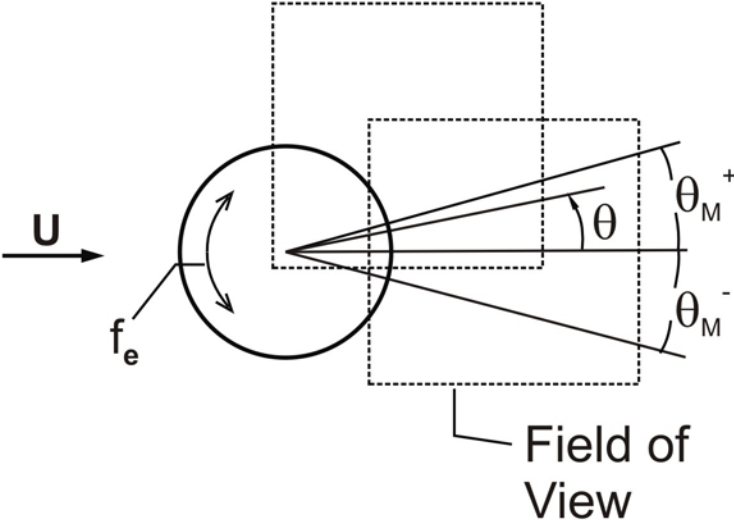


VORTEX FORMATION: INFLUENCE OF GRAVITY STANDING-WAVE

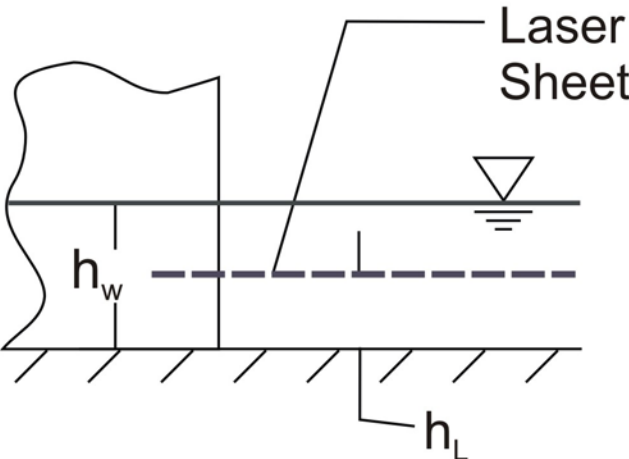


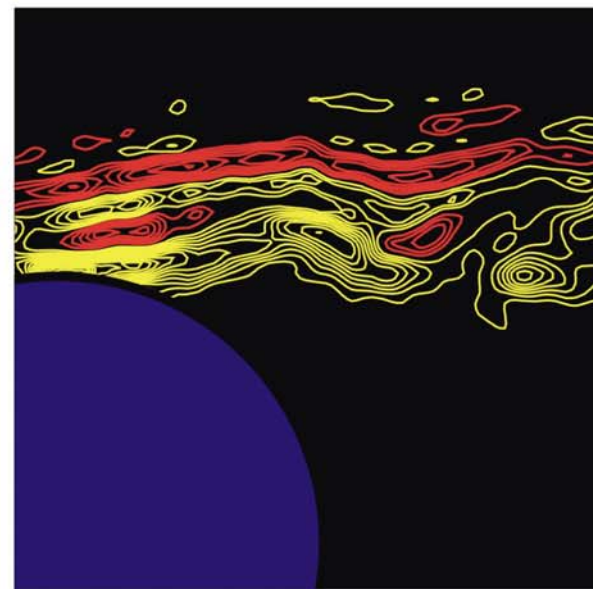
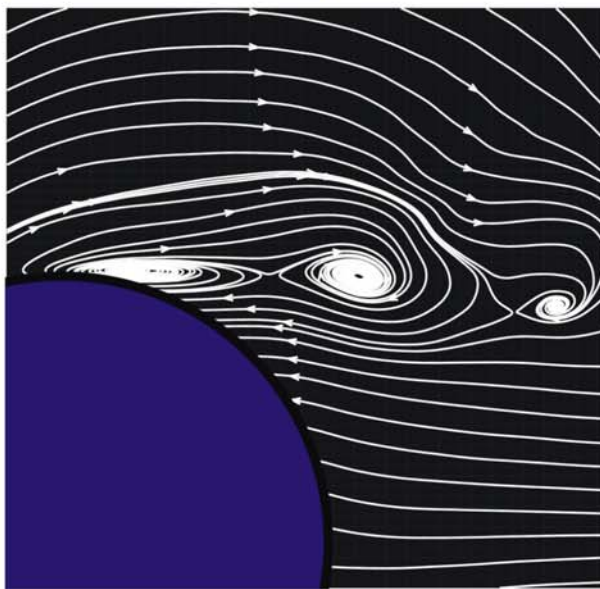
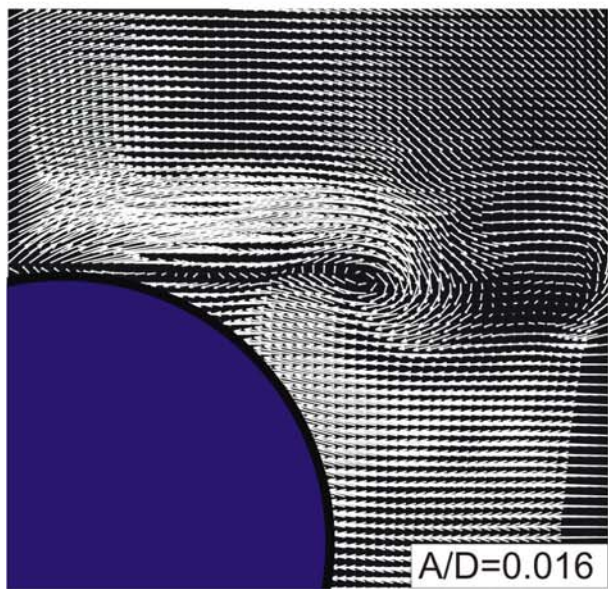
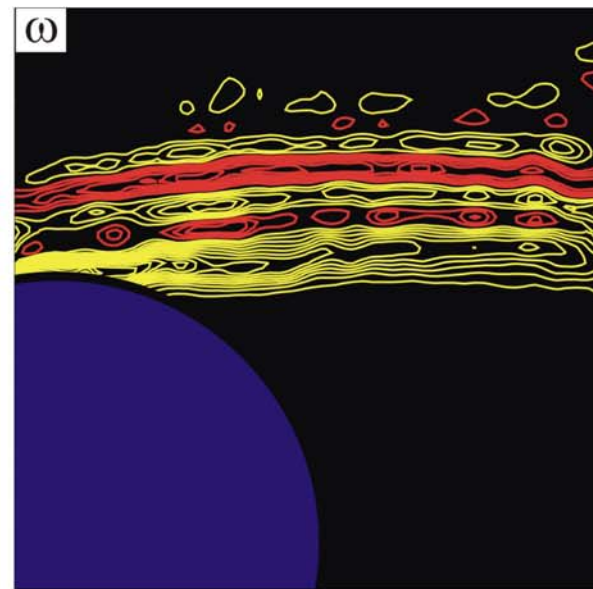
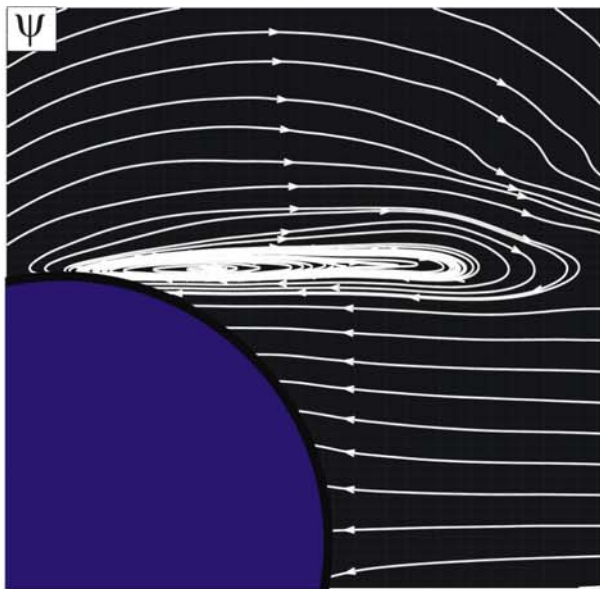
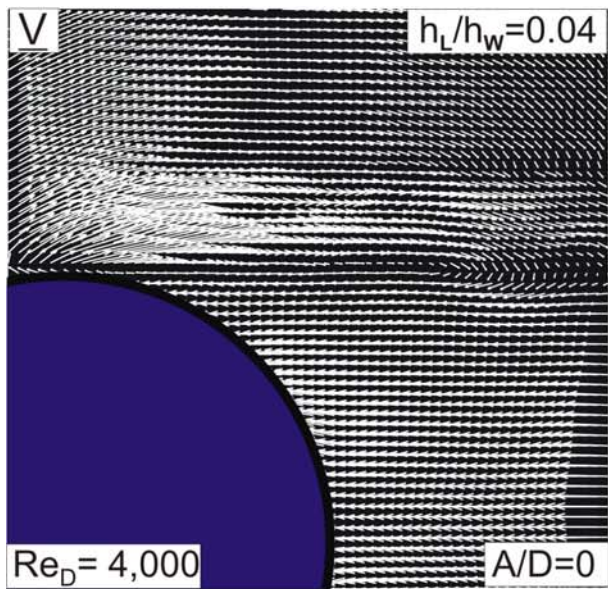
ROTATIONAL CONTROL OF CYLINDER IN LAMINAR APPROACH FLOW

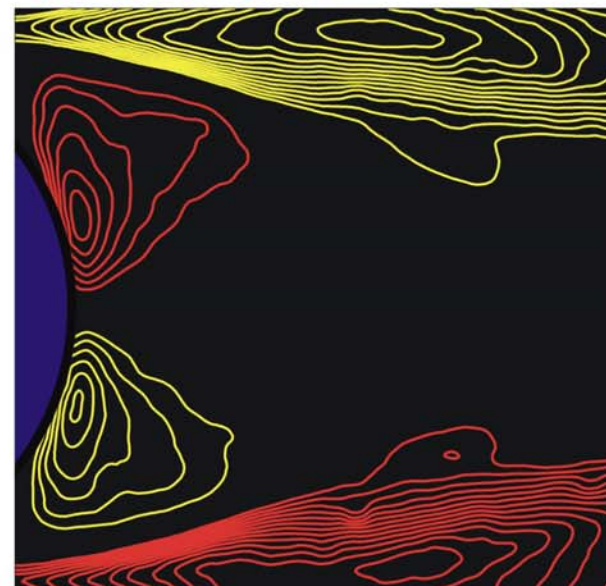
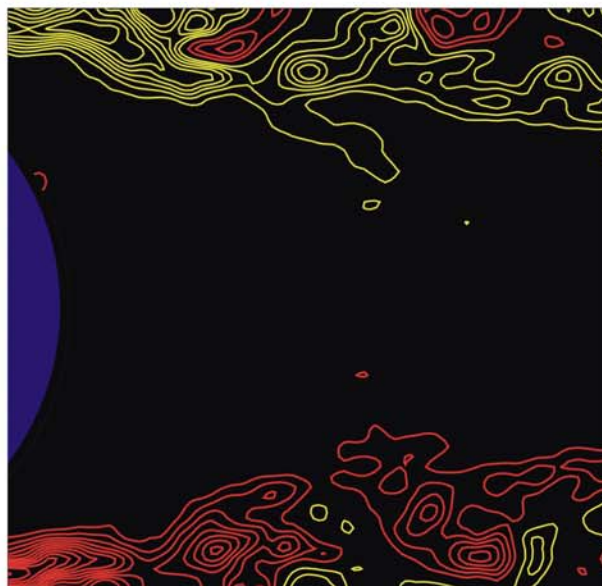
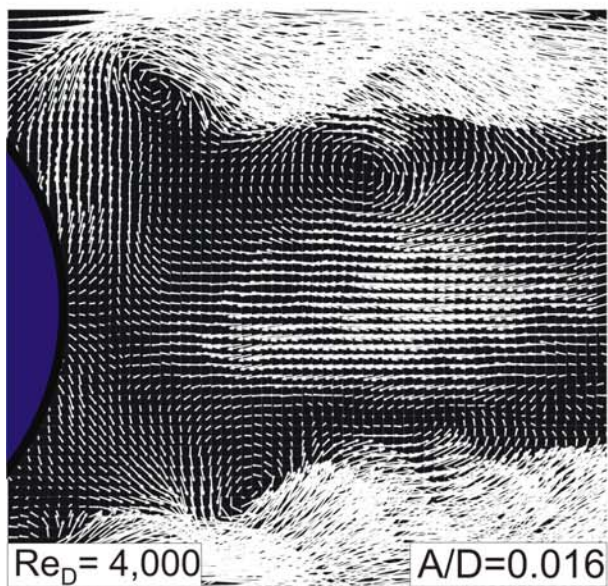
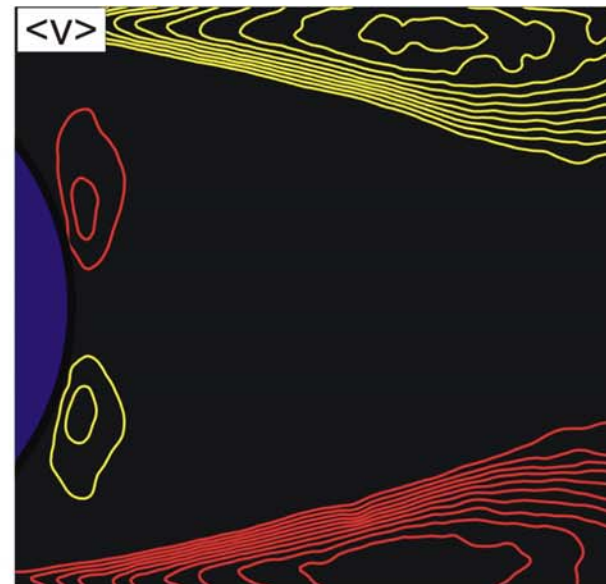
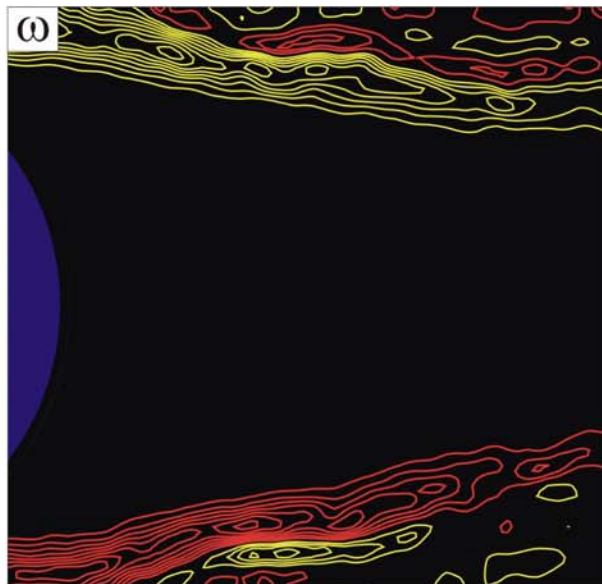
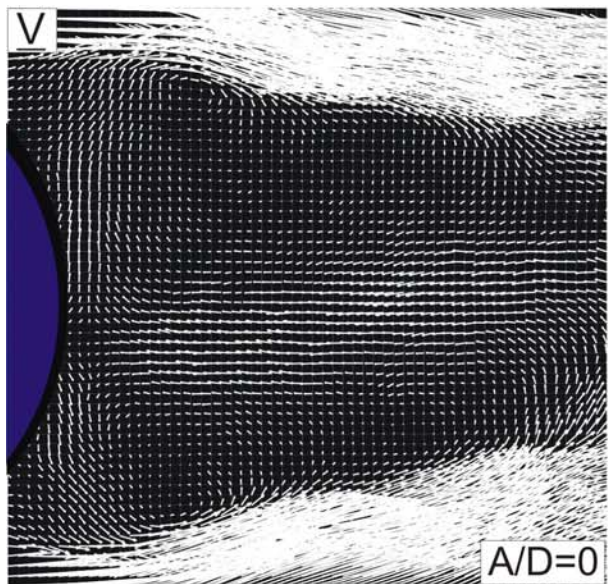
PLAN VIEW

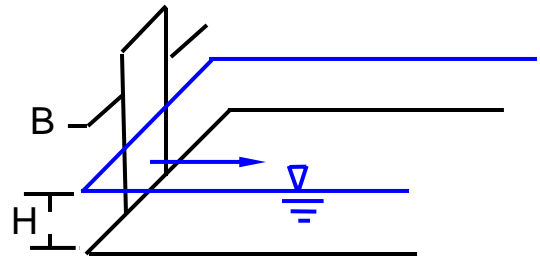
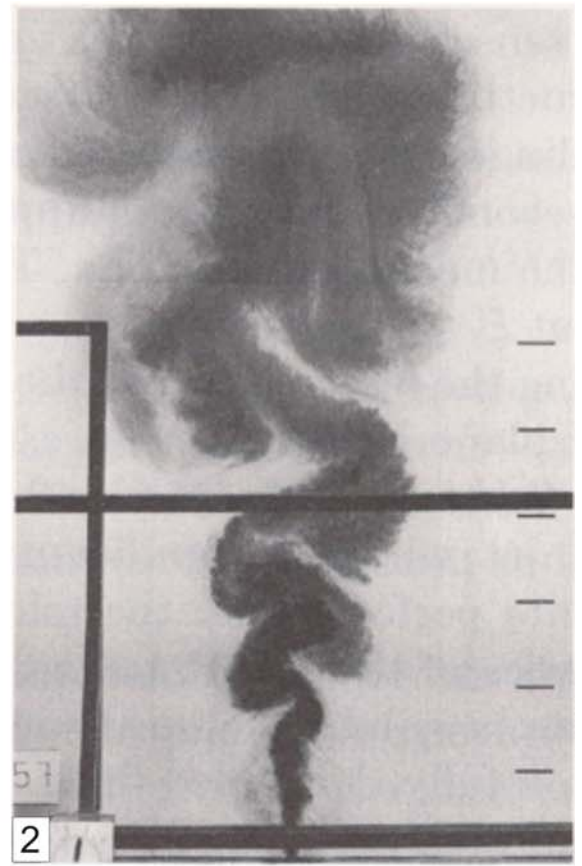
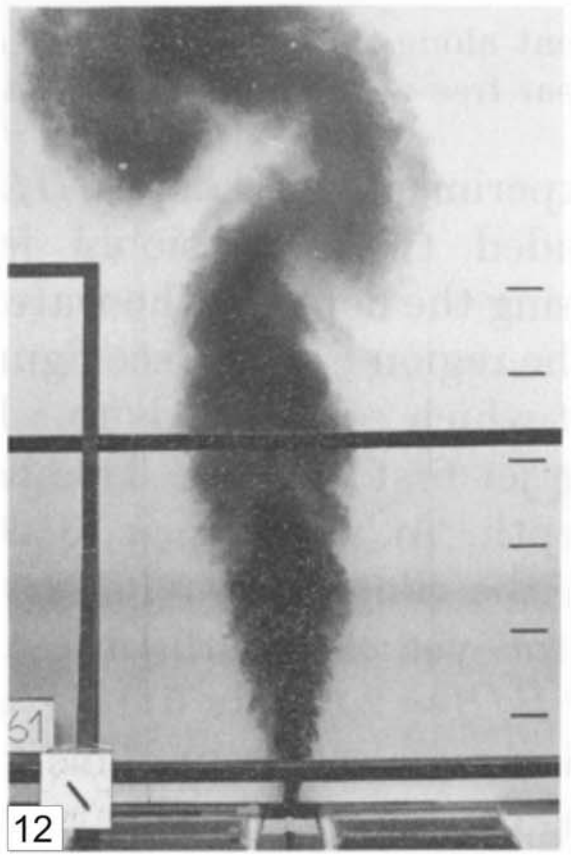
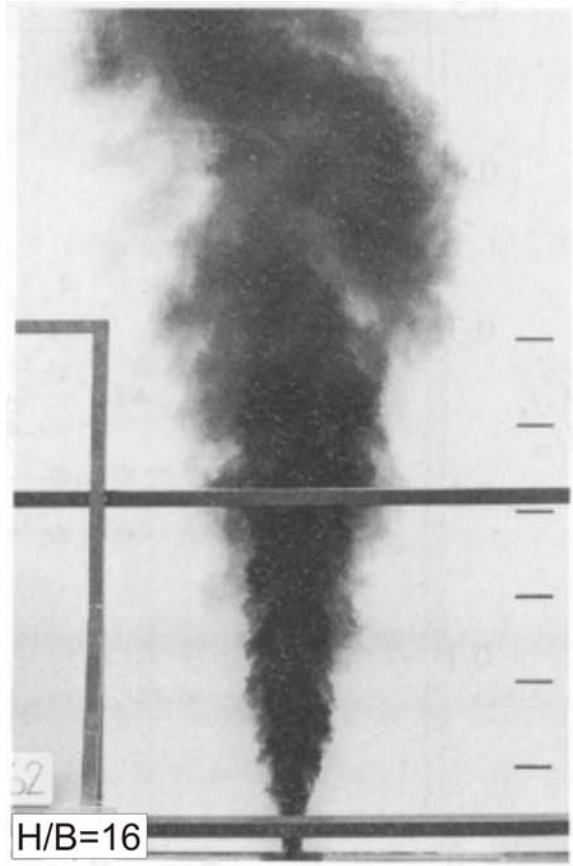


SIDE VIEW









Dracos, Geiger and Jirka (1992)



Prooijen & Uijtewaal (2002)

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