The Role of Turbulence on Wind Energy: From Single Blade to Wind Array

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OUTLINE

- Motivation
- Airfoil Studies (S809) & Turbulence
  - Roughness Effects on Blades
  - Effects of Free-Stream Turbulence at Various Angle of Attacks
  - Combine Effects
  - VGs versus No VGs
- A Scaled Down Wind Array: 3x5
  - Energy entrainment
  - Fluxes & Energy balance
  - Importance of Turbulence
- Conclusions

Main Objectives

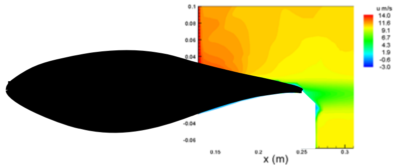
1. To **quantify aerodynamic performance (lift and drag)** of an S809 wind turbine blade with and without additional levels of free stream turbulence (FST) including the combine effect of surface roughness with FST

2. To **acquire the mean flow** over the blade in order to **gain insight into turbulent flow scale mixing on stall behavior** and its effect on aerodynamic performance.

3. To investigate the effect of aerodynamic enhancing vortex generators on **post-stall performance** of wind turbine blades.

4. Measure profiles **of horizontally averaged momentum fluxes & Mean K.E.** Compare turbulent shear stress with canopy (dispersive stress) mean velocity shear stress.

5. **Understand the role of the fluxes of kinetic energy in the vertical direction.**



Motivation: Effects of Free-Stream Turbulence On Wind Turbine Blade

- Many investigations have studied the **aerodynamics** of a wind turbine airfoil subject to high levels of free-stream turbulence.
  However, no studies have analyzed the effect of this condition on the mean flow when surface roughness is present.

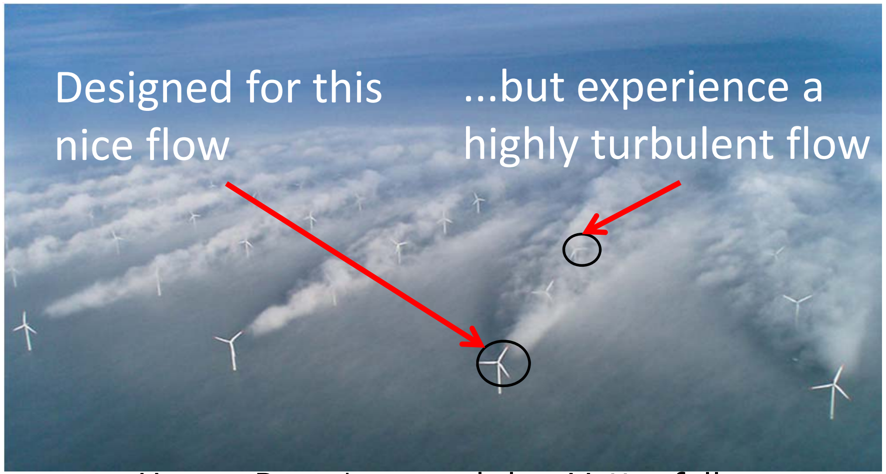
- Wind turbines operate in turbulent flow conditions including **wake induced turbulence** in wind farms.

- The effect of the **length and time scales** of this turbulence on blade loads must be understood to **improve aerodynamic performance and prevent premature turbine breakdown**.

- Aerodynamic studies have shown that the addition of free-stream turbulence (passive grid) to the flow over wind turbine blades delays flow separation.

- The aim of this study is to **analyze the influence of high levels of FST on the flow around a smooth and rough surface airfoil**.
  - Examine how wind turbine airfoils are affected by highly turbulent flow under stall conditions.
  - Analyze interaction of turbulent length scales with wind turbine blades, particularly at high angles of attack.

Motivation:



Horns Rev 1 owned by Vattenfall.
Photographer: Christian Steiness

Leading edge contamination due to insect debris causes production losses of 25%

Corten and Veldkamp (2001)

Wind turbine blade under icing conditions

- Wind power has become one of the most promising alternatives of renewable energy.
- Unanswered Questions:
  - How are wind turbine farms interacting with the highly turbulent atmospheric boundary layer?
  - How is the highly intermittent, turbulent free-stream influencing the performance, power extraction and control of wind turbine rotors?
  - How to improve Capacity Factor and thus the Profit?
  - How to model and mitigate the uncertainties in wind plant performance?

Research Motivation: Turbulence Affects Important Aspects of Wind Power Extraction

Efficiency

Blade pitch is difficult to control in a highly turbulent environment. Therefore, efficiency is not always at its highest.

Power loss due to wakes of upstream turbines of about 15%.

Cost

Wind turbines are designed to last 20 years; however, breakdowns appear as early as 7 years (cracked blades, broken gearboxes and generators).

Costly repairs that increase pay-back time and cost of energy (COE).

Environment

Wake extends for miles.

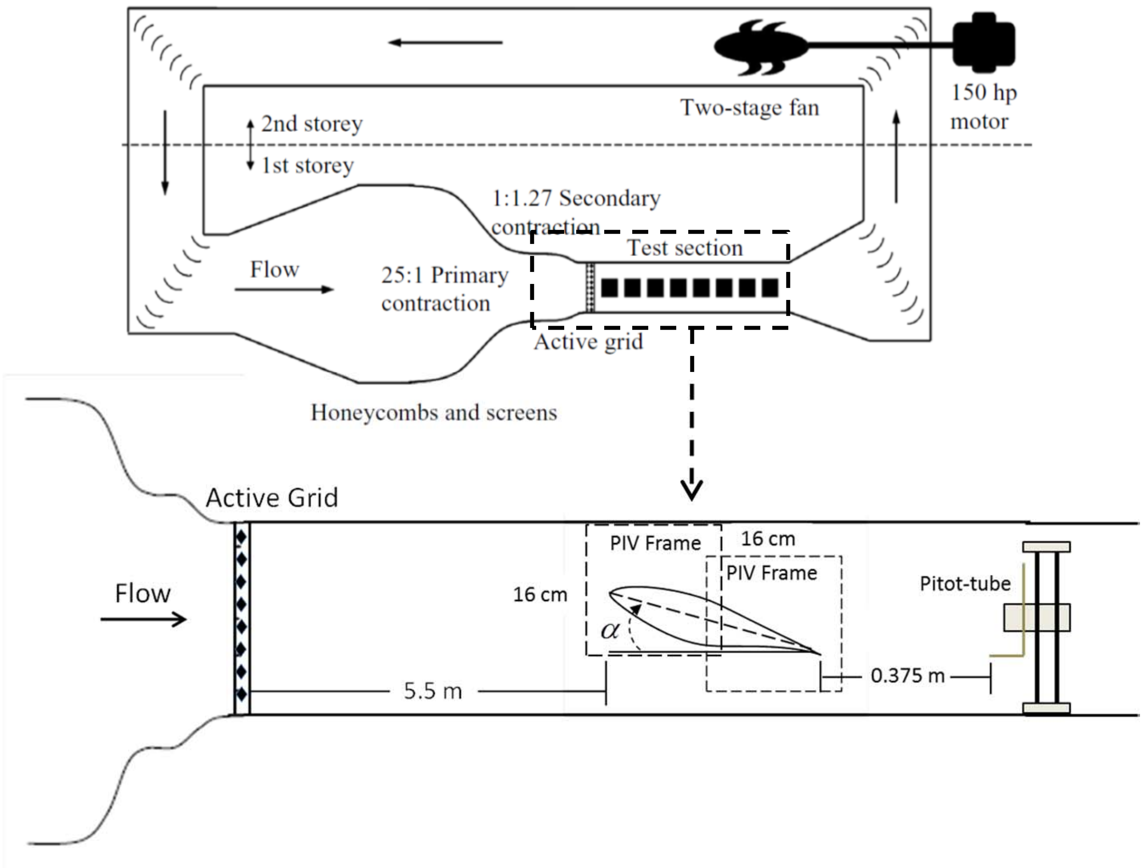
Christiansen & Hasager: “Wake effects of large wind farms identified from satellite synthetic aperture radar (SAR)” (2005)

Effect on humidity, pollination and local weather is unknown. *Wakes are highly turbulent.*

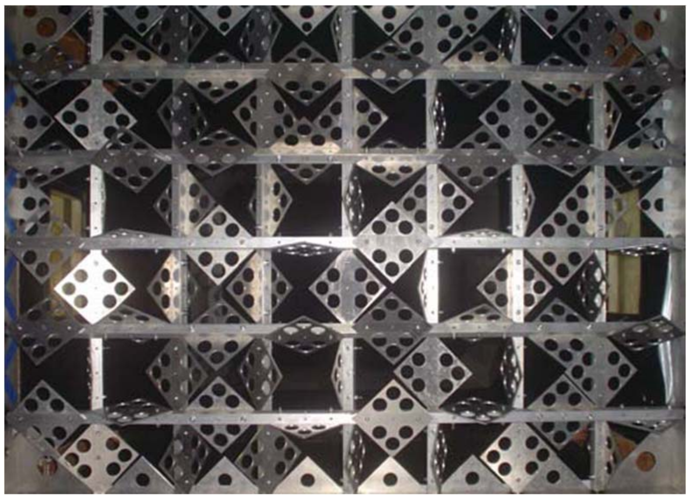
Experimental Setup

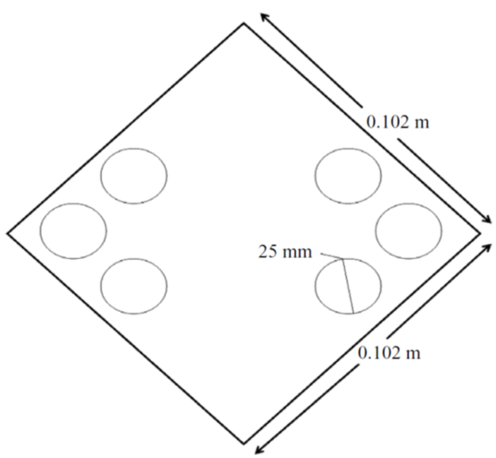
The Corrsin Wind Tunnel Facility

- Test section: 1.22 (*m*) width x 0.91 (*m*) height x 10 (*m*) length
- Background turbulence intensity < 0.1%



Experimental Setup: Active Grid





As proposed by *Mydlarski and Warhaft (1996)*

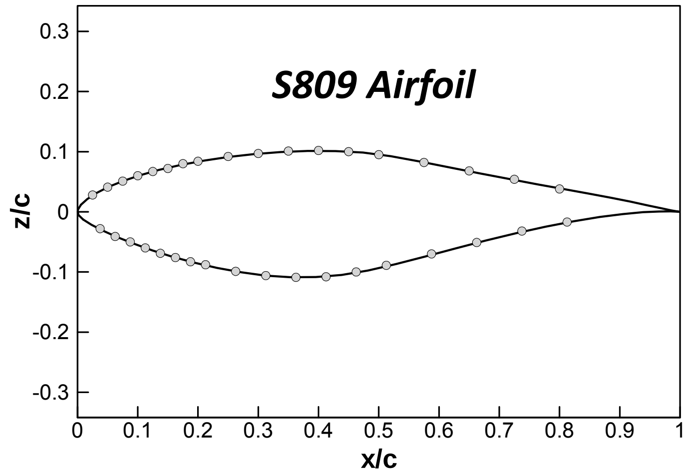
- Produces freestream turbulence, $T_u \leq 6\%$
- Each shaft independently controlled
- Random rotational speed of "winglets"
- Located 5.5 m upstream of the blade

Flow Parameters	
Reynolds Number, Re_c	$1.82x10^5$
Active Grid FST Intensity, T_u	6.14%
Integral Length Scale, L_∞	0.321m

Measurements by *Kang et al. 2003*

Experimental Setup: Wind Turbine Blade

- S809 Wind Turbine Blade Model
  - Based on the NREL S809 airfoil
  - Manufactured using a rib and spar technique
  - 2D blade, b = 1.22 m, c = 0.25 m
  - 21% chord thickness
  - 36 static pressure ports at y/b = 0.5
  - Trip wire (D =1.6 mm) 4 mm from leading edge



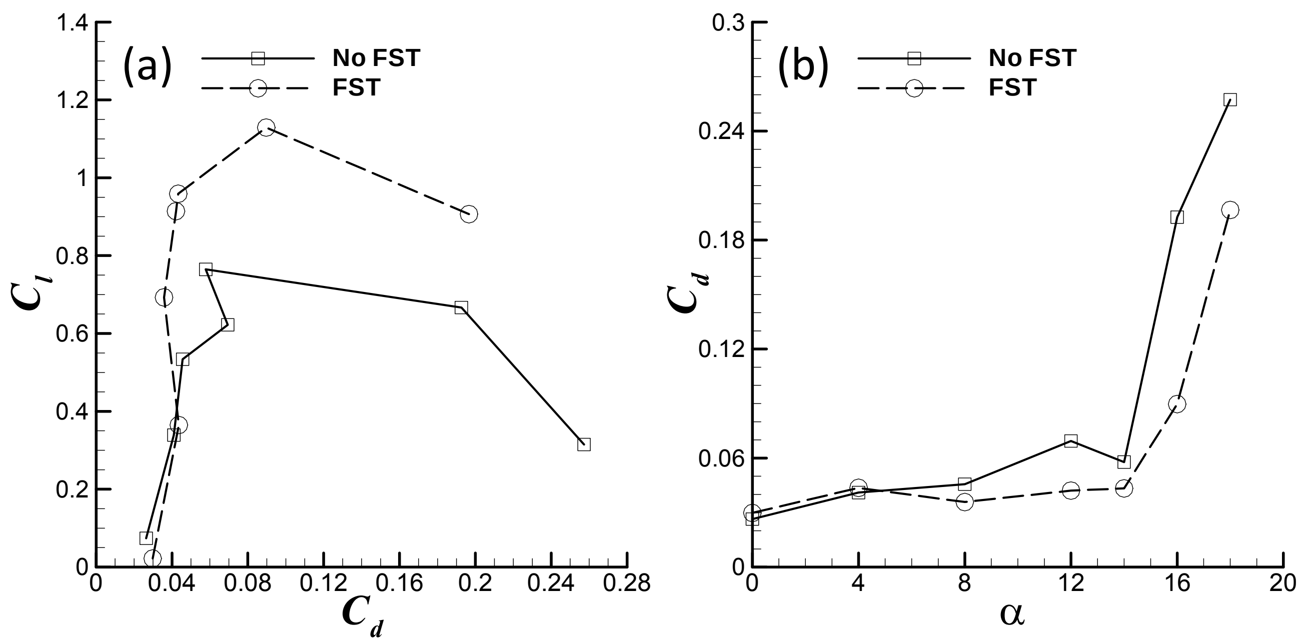
Wind Turbine Blade Mounted in the Corrsin Wind Tunnel

Results: Aerodynamic Performance

The pressure distributions and velocity deficit of the wake was measured with a pitot-tube in order to compute the lift coefficient and total drag of the blade.

Test Conditions: $Re_c \sim 1.82 \times 10^5$ ($U_\infty = 10$ m/s) , $T_u = 6.14\%$, $L_\infty = 0.321$ m

Importance of Free Stream Turbulence (FST)

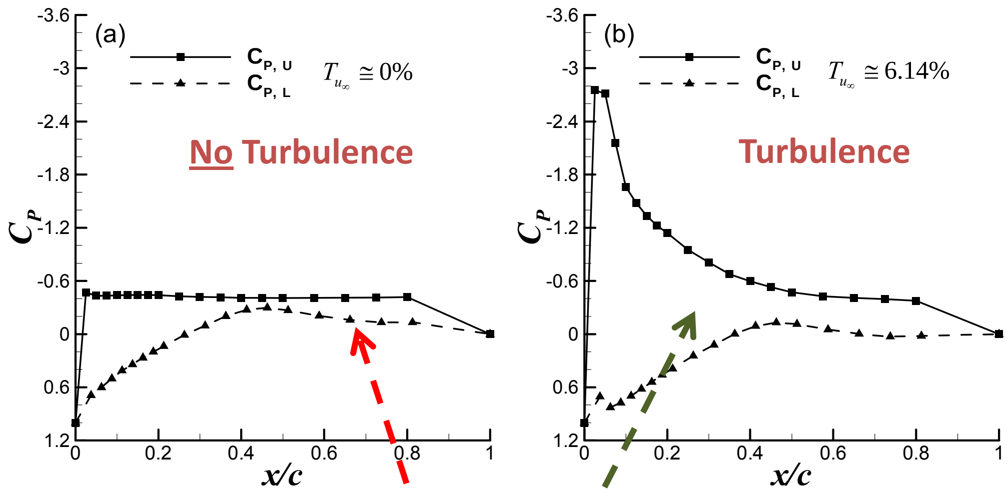


Free stream turbulence results in a **lower drag coefficient for a given lift coefficient**, particularly **at moderate to high (post-stall) angles of attack**.

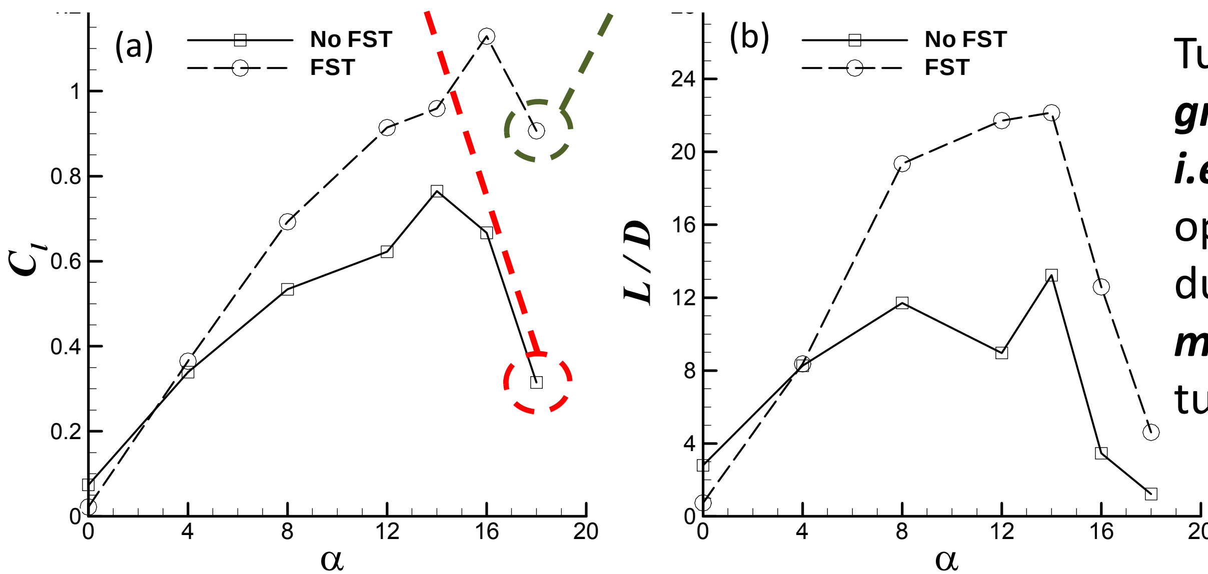
Results: Aerodynamic Performance

Test Conditions: $Re_c \sim 1.82\text{x}10^5$ ($U_\infty = 10$ m/s), $T_u = 6.14\%$, $L_\infty = 0.321$ m

Pressure Distributions, C_P



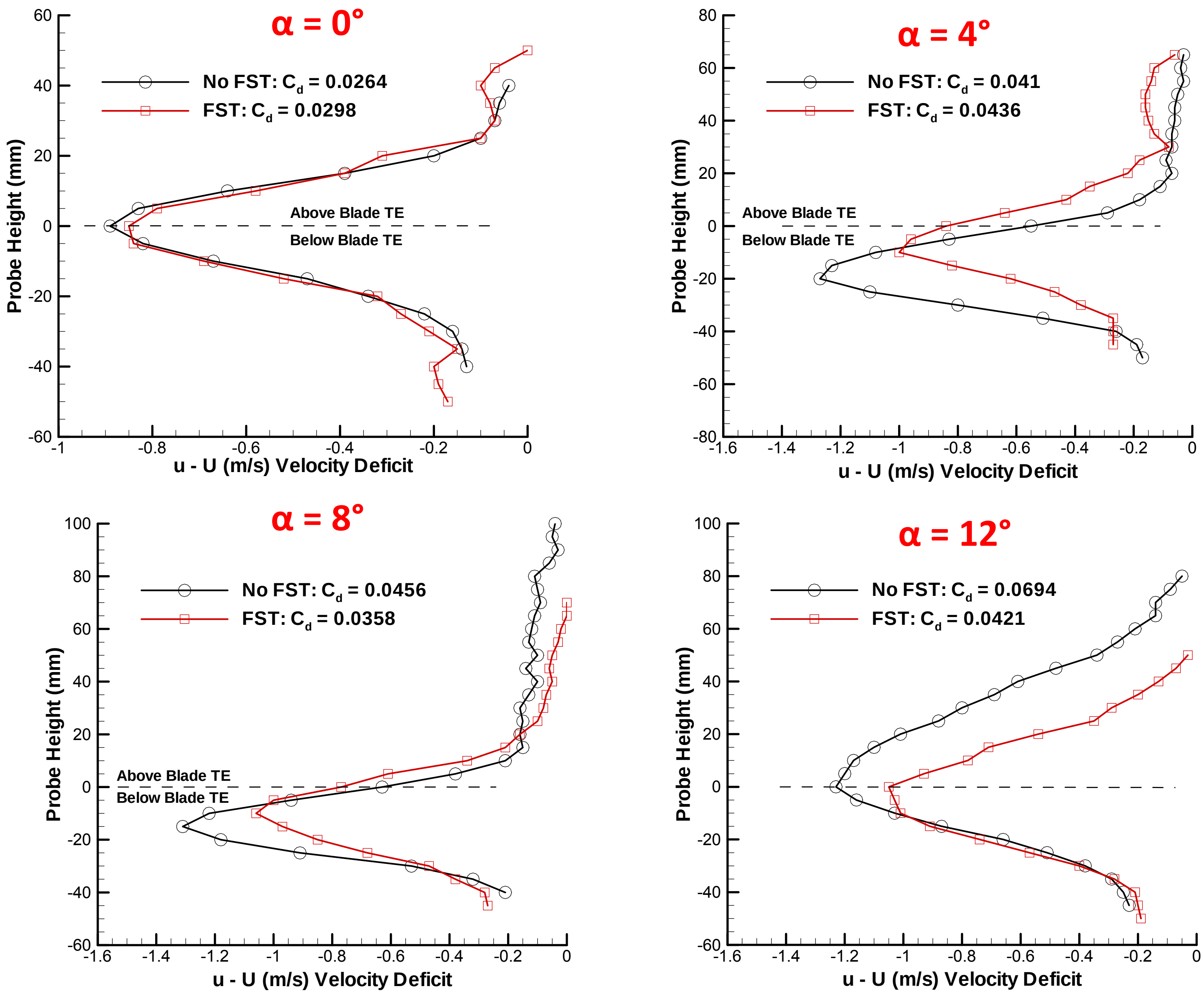
The pressure distributions indicate that ***the flow has completely separated for the case without turbulence at α = 18°***, however ***with turbulence, flow separation is delayed*** – still producing significant lift as shown in the plot of C_l vs α below.



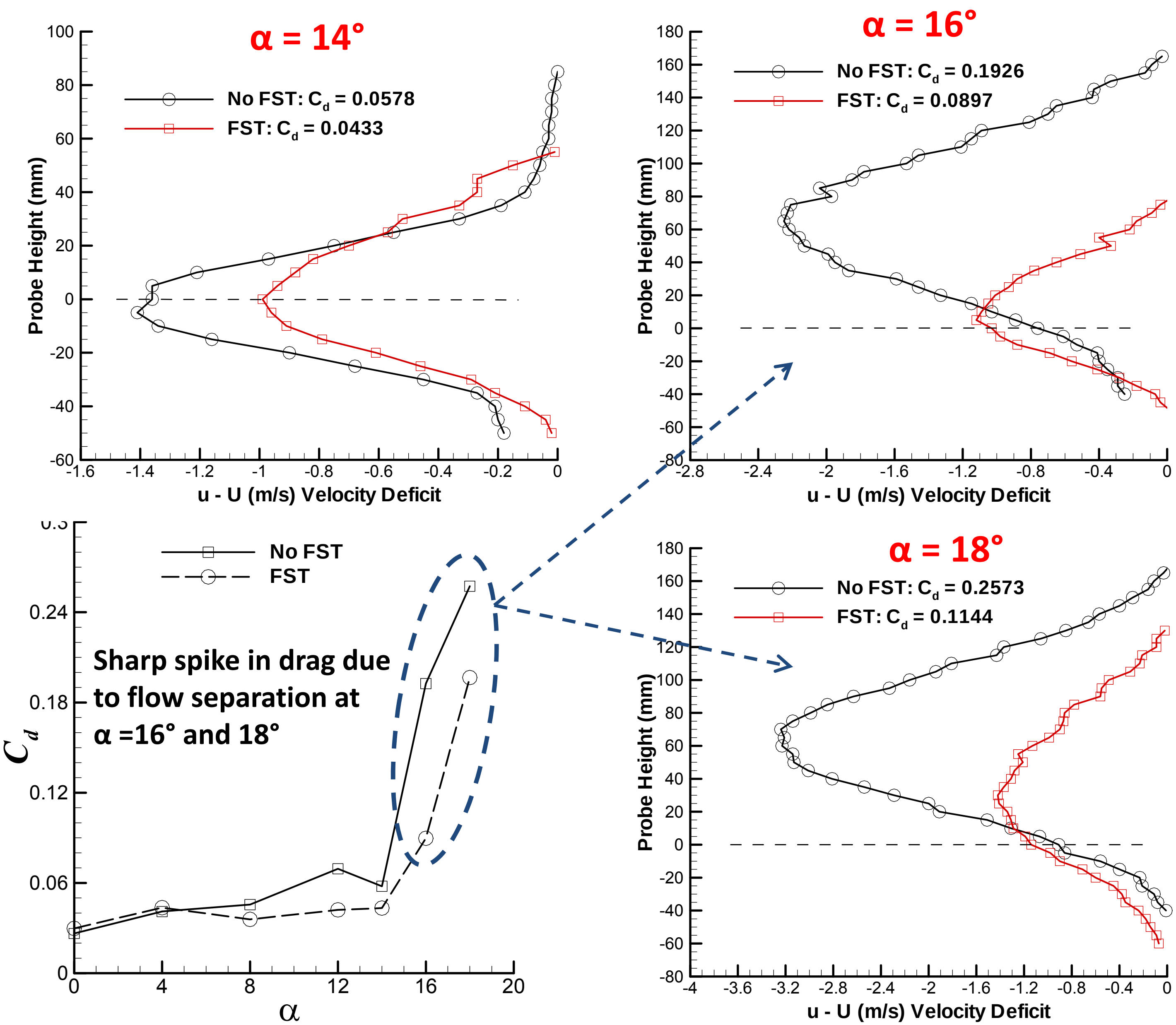
Turbulence results in a ***significantly greater aerodynamic efficiency, i.e. lift to drag ratio (L/D)*** for most operating angles of attack. This is due to the ***mixing and higher momentum of eddies*** in the turbulent boundary layer.

Results: Wake Velocity Deficit

(Results were measured with a pitot-tube, also measured with a hot-wire probe – similar results obtained)

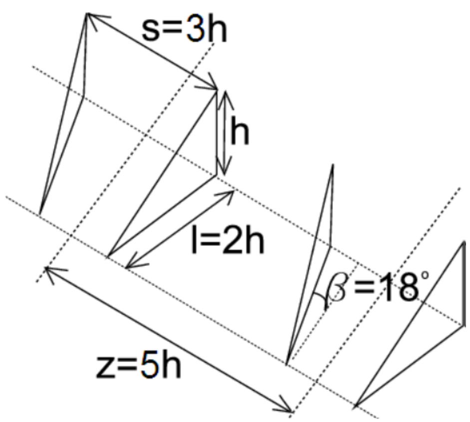


Results: Wake Velocity Deficit



Vortex Generators Study

Vortex generators were utilized ***to investigate their role on improving post-stall aerodynamic performance*** on the S809 wind turbine blade. This study has ***implications on the* power production of wind turbines** in the post-stall flow regime



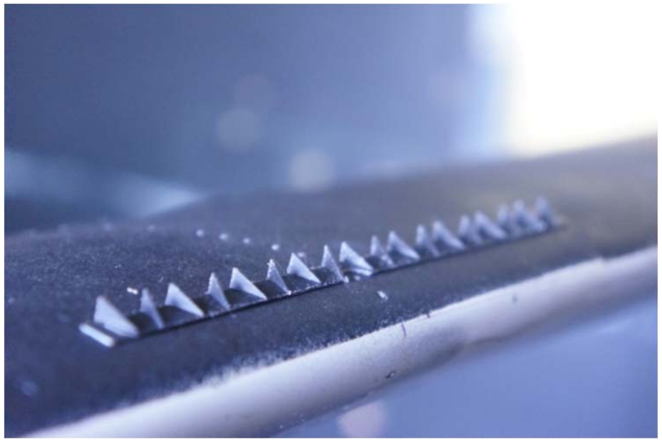
Vortex generator geometry (Velte et al.)

Dimensions

$h = 2.5$ mm

$l = 5$ mm

$z = 12.5$ mm



Vortex generators mounted on the blade

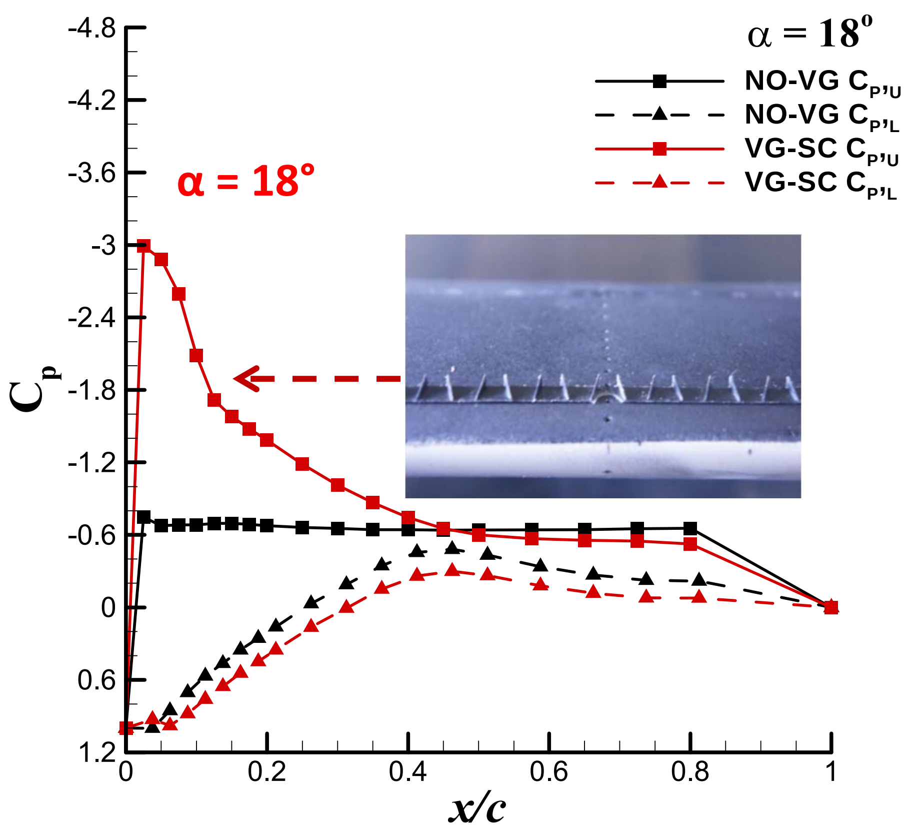
Experiments

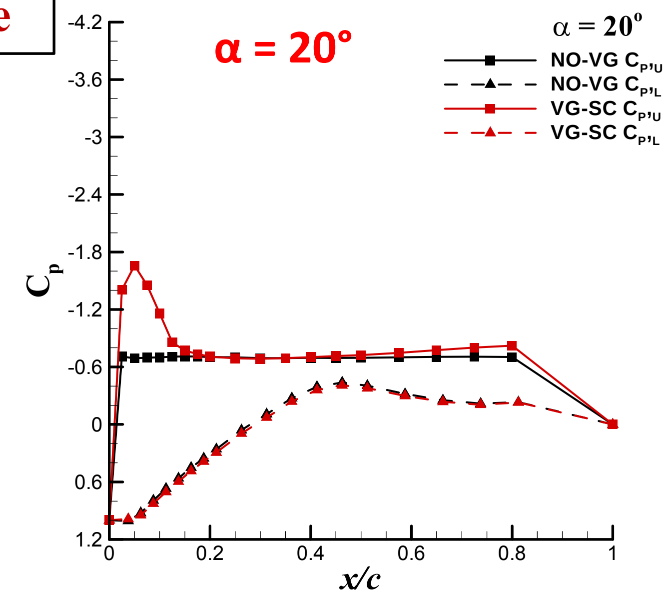
1. The blade pressure distributions were acquired for angles of attack of 18°, 20°, and 22° without free stream turbulence at a velocity, U_∞ of 10 m/s (Re = 182,000).

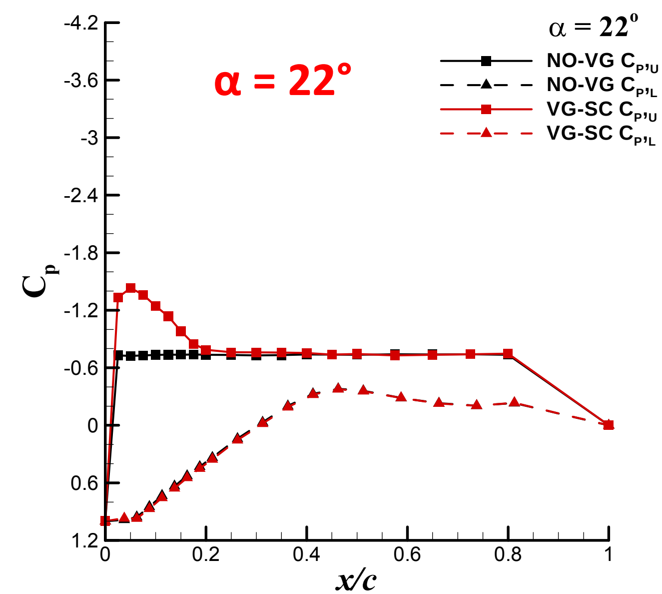
2. The mean velocity fields over the blade surface was acquired utilizing 2-D PIV to capture the flow physics related to flow separation and behavior of the wake for the same conditions.

Results: Pressure Distributions

All Cases: $Re_c \sim 1.82 \times 10^5$ ($U_\infty = 10$ m/s) without turbulence







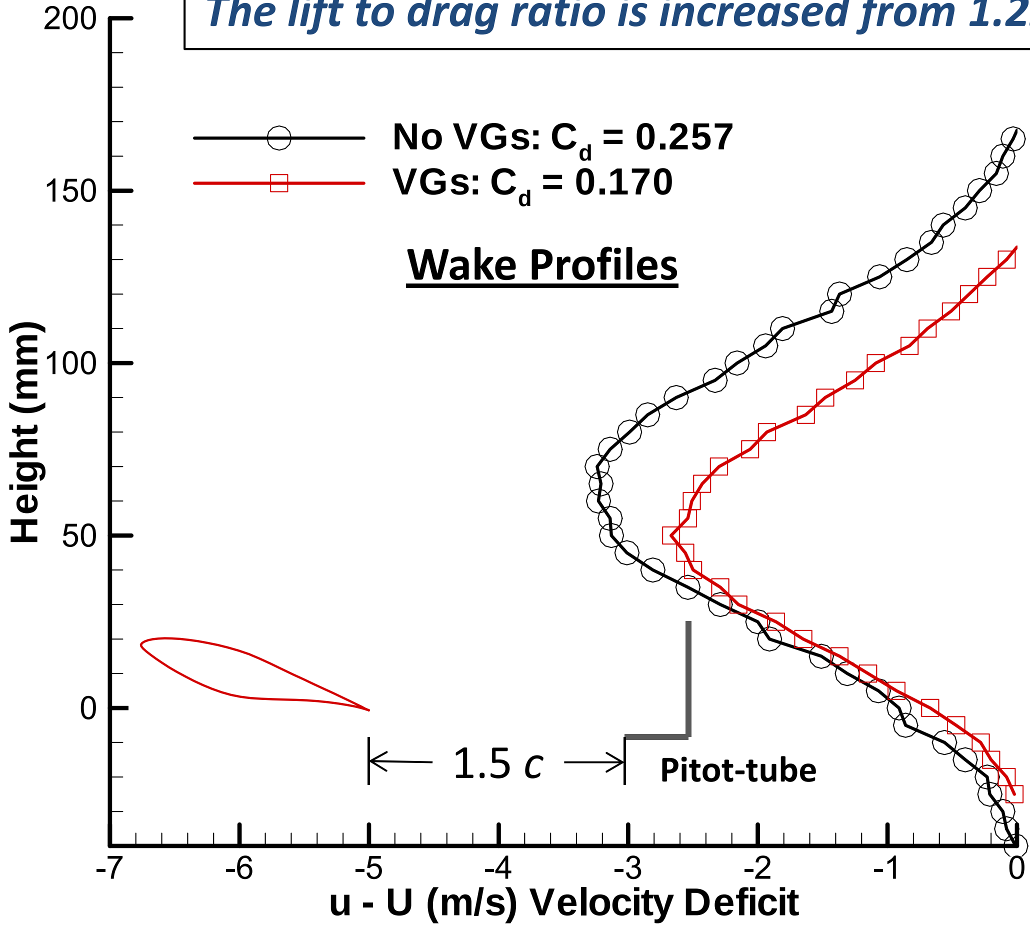
With Vortex generators, the blade leading edge suction peak is ***significantly increased***, indicating more lift generation. This effect ***decreases*** with higher post-stall angles of attack of 20° and 22°.

Results: Wake Velocity Deficit and Drag

The wake was measured with a pitot-tube 1.5*c* behind the blade with and without vortex generators at 18 degrees angle of attack.

Conditions: U_∞ = 10 m/s (Re = 182,000) and α = 18° Without turbulence

The lift to drag ratio is increased from 1.22 to 6.14 using VGs!



Aerodynamics Results

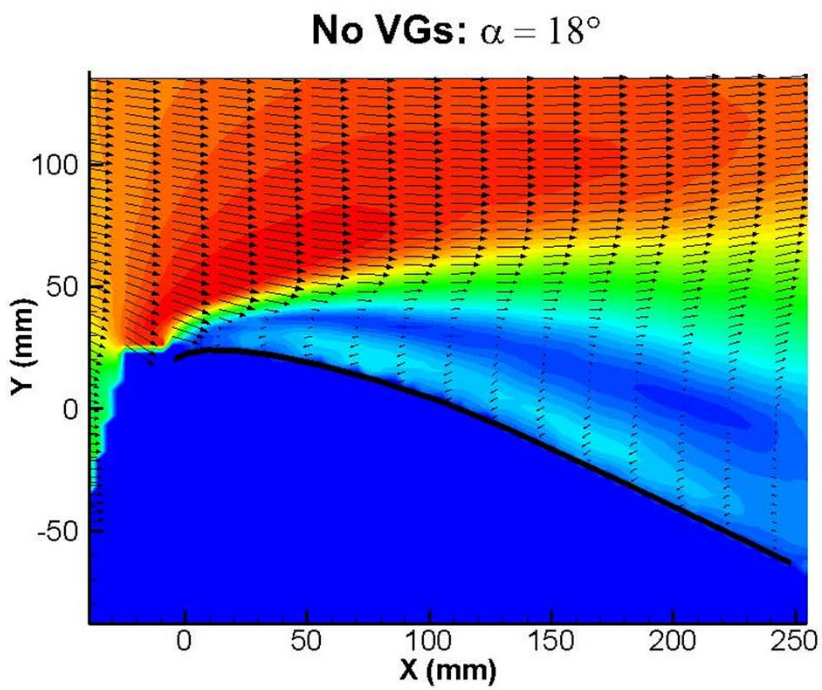
	No VGs	VGs
C_l	0.315	1.045
C_d	0.257	0.17
L/D	1.224	6.145

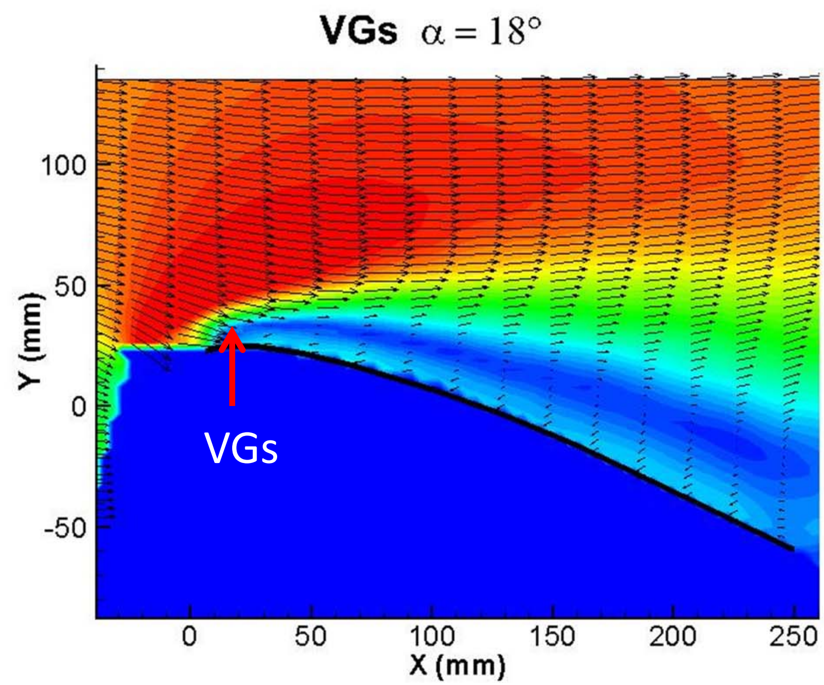
Results: 2-D PIV Mean Velocity Fields

The mean flow of the suction surface of the blade was acquired with 2-D PIV for the same conditions without and with vortex generators at 18 degrees angle of attack .

Conditions: U_∞ = 10 m/s (Re = 182,000) and α = 18° Without FST

Boundary layer separation is ***mitigated with VGs***, resulting in a ***lower velocity deficit and wake thickness***. This translates to higher lift and lower drag, ***increasing the lift to drag ratio***.



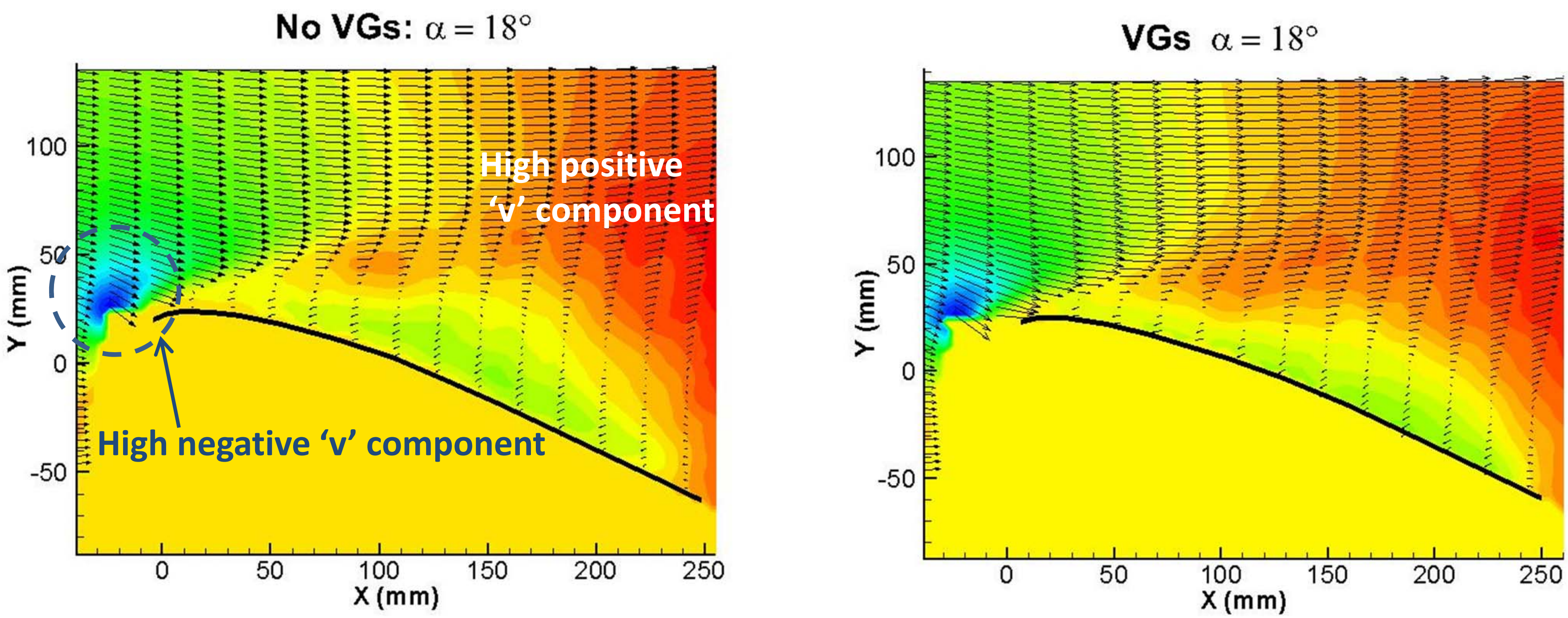


Results: 2-D PIV Mean ‘v’ Velocity

The mean flow of the suction surface of the blade was acquired with 2-D PIV for the same conditions without and with vortex generators at 18 degrees angle of attack .

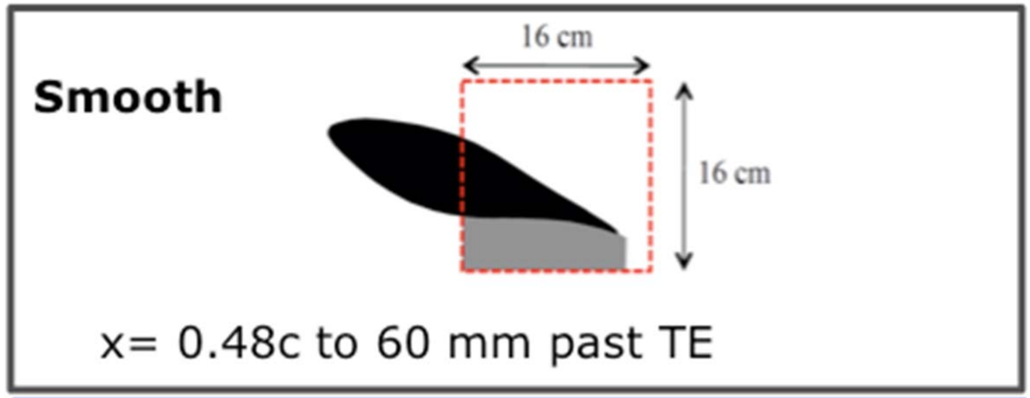
Conditions: U_∞ = 10 m/s (Re = 182,000) and α = 18° Without FST

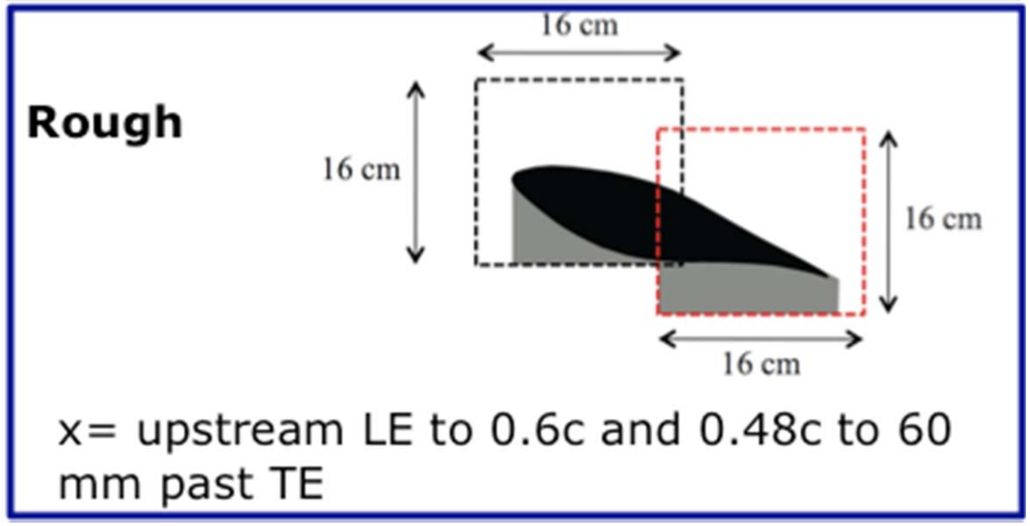
There is a ***region of low negative ‘v’ mean velocity*** near the blade surface as the boundary layer separates – this region is ***slightly reduced*** with VGs.



PIV Measurements: Smooth, Rough & FST

- **2-D Particle Image Velocimetry**
  - Double pulse Nd:YAG laser (120 mJ/pulse)
  - time between pulses of 100 μs
  - FOV: 16 cm x 16 cm
  - Measurements captured entire airfoil (upstream leading edge to 0.6c; 0.48c to 60 mm past trailing edge)
  - 3,000 samples at 7.25 Hz





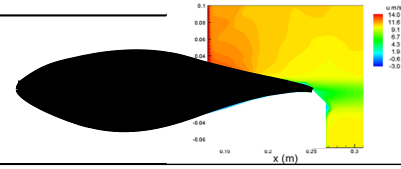
- **Experimental Parameters**

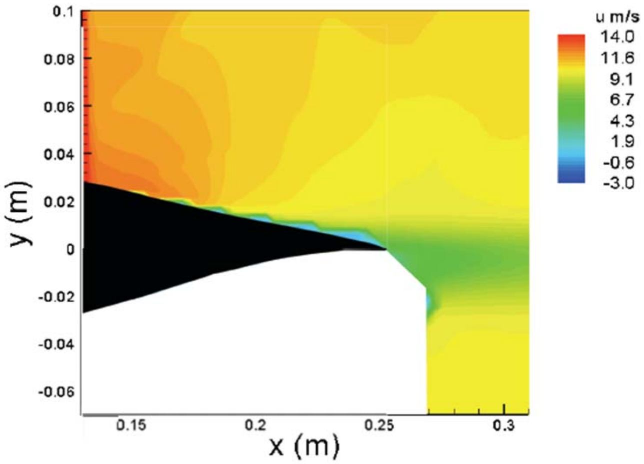
x/c	α	Re_c	Tu_∞ (%)	L_∞ (m)	k (mm)
0.48 - 1	16°	182,000	6.15	0.321	1.522

L_∞ approximation using measurements by *Kang et al. 2003*

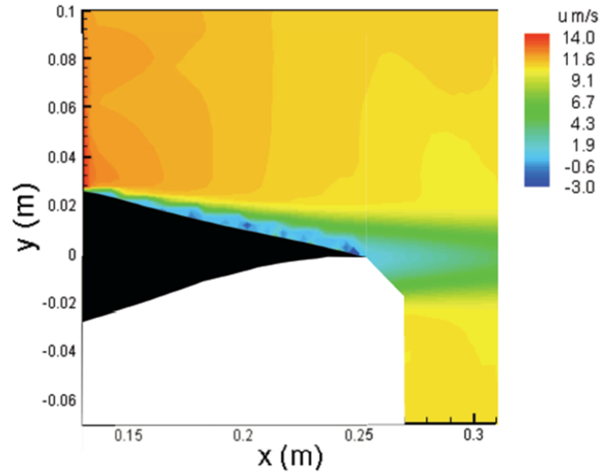
$c = 0.25$ m

Streamwise Mean Velocity Contours: $\alpha = 0°$
Smooth and Rough Surface

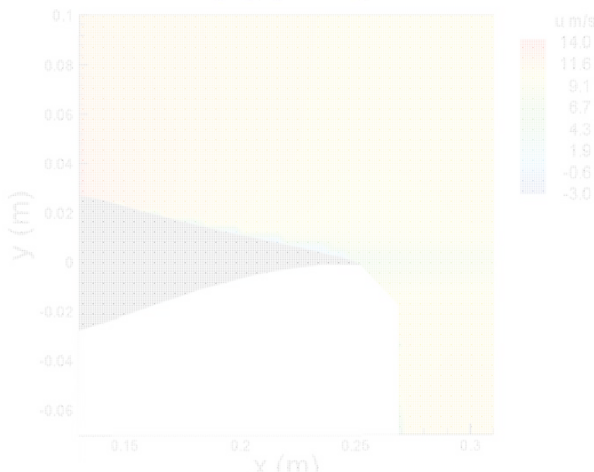




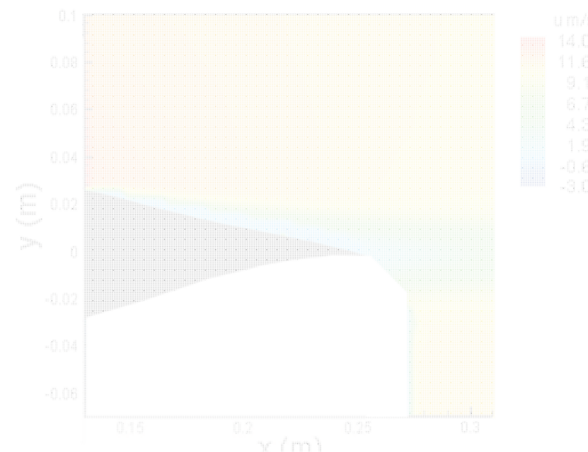
Baseline



Surface Roughness



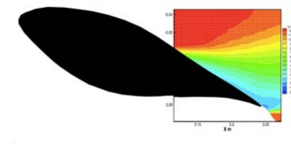
Free-stream Turbulence

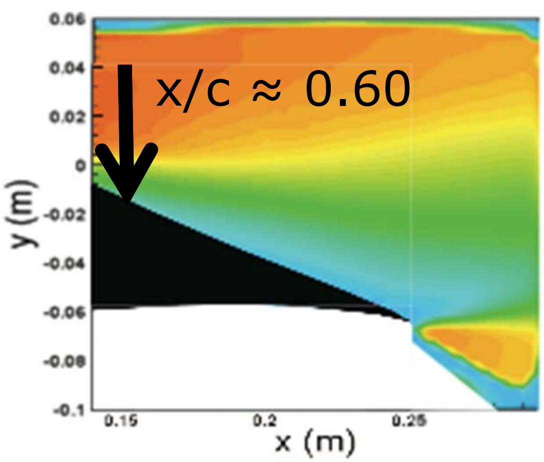


Roughness + FST

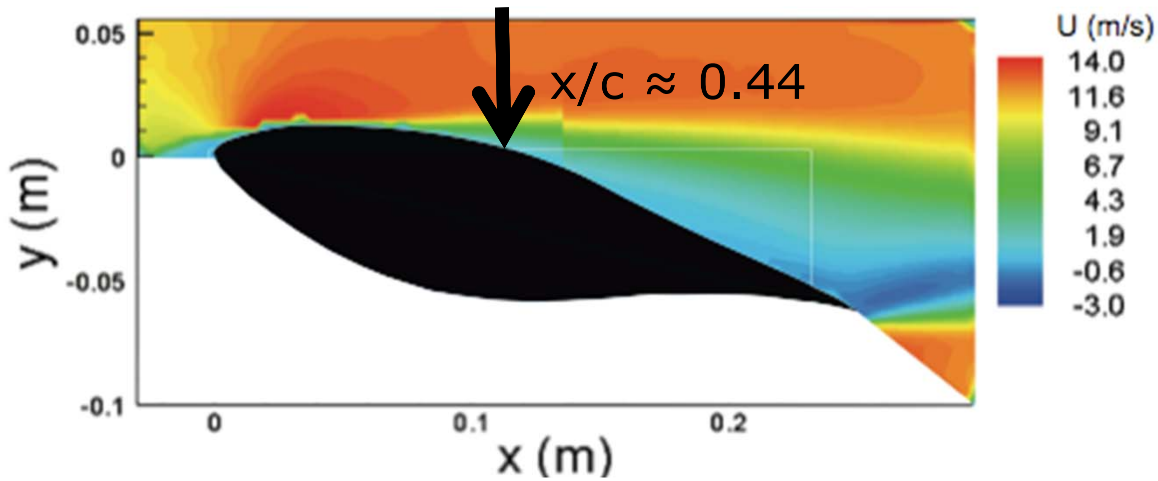
Low-speed region appears when roughness is present at the wall.
Free-stream turbulence weakens the wake.
Combined effect of free-stream turbulence and surface roughness further increases the wake--
Dominant effect of surface roughness.

Streamwise Mean Velocity Contours: α= 16°
Smooth and Rough Surface

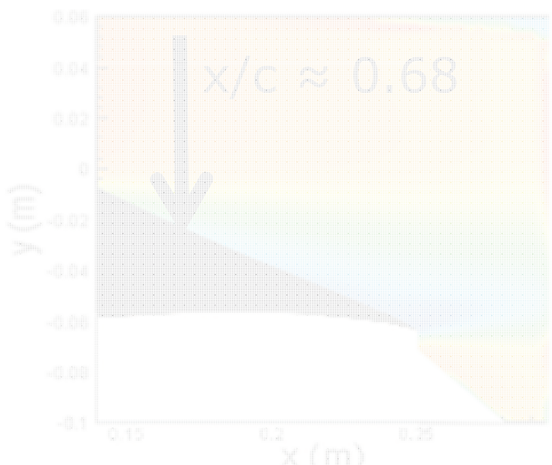




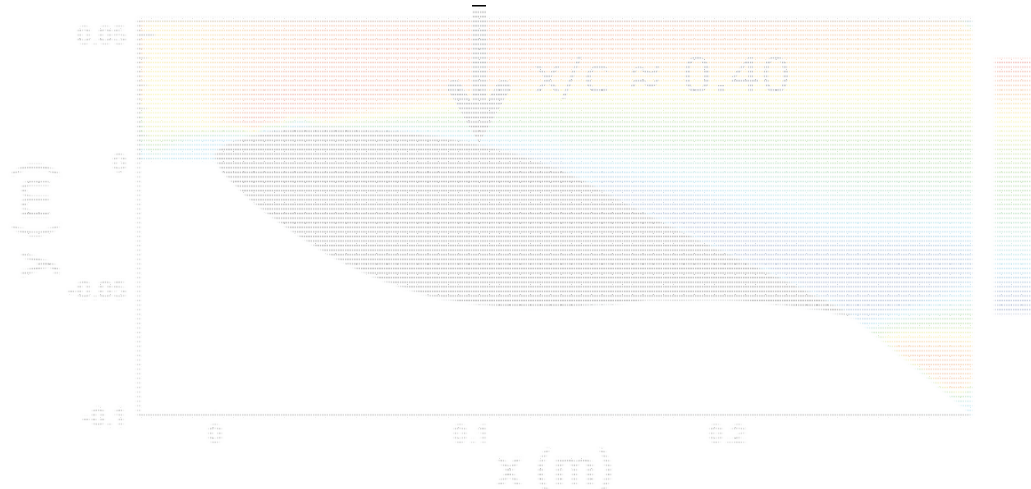
Baseline



Surface Roughness



Free-stream Turbulence

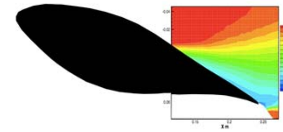


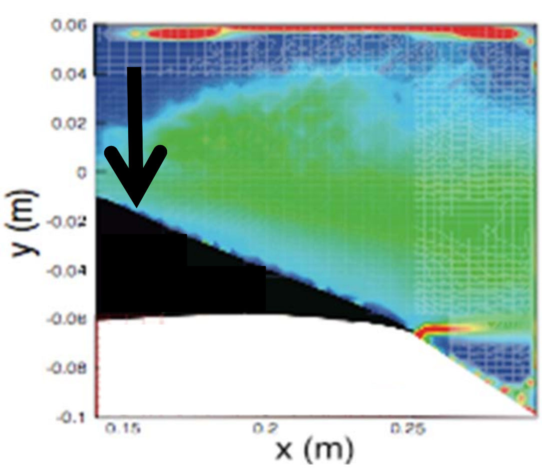
Roughness + FST

Combination of surface roughness and free-stream turbulence is advancing separation.

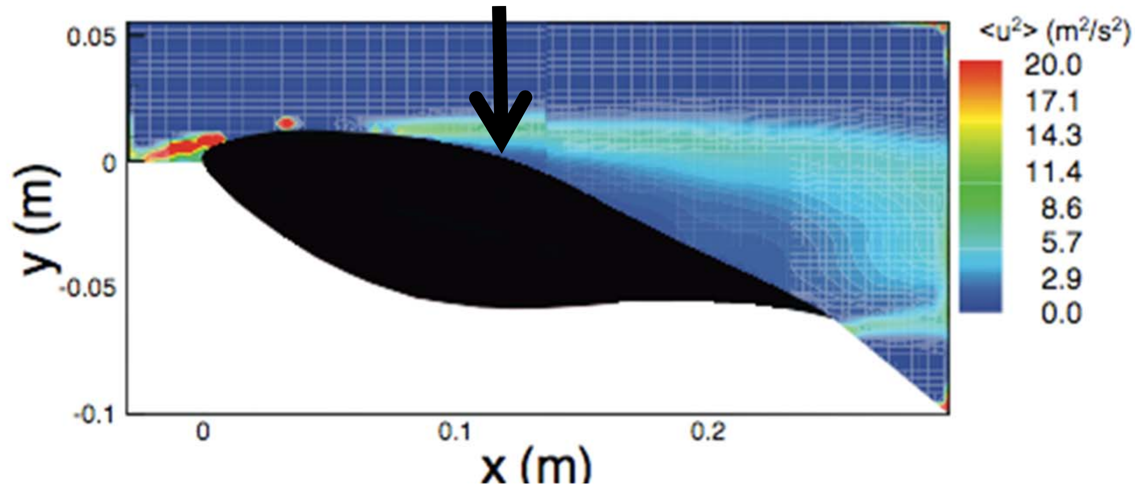
Effect of surface roughness is dominant.

Streamwise Reynolds Stress Contours: α= 16°
Smooth and Rough Surface

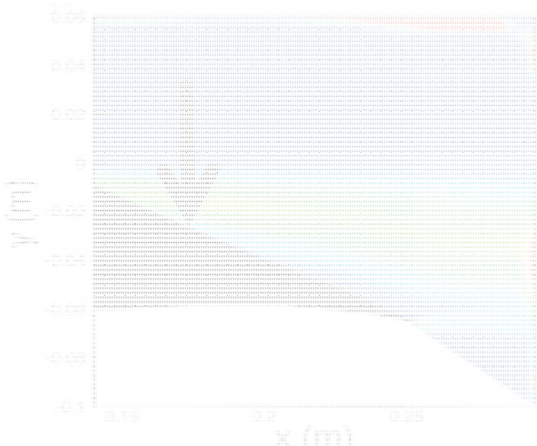




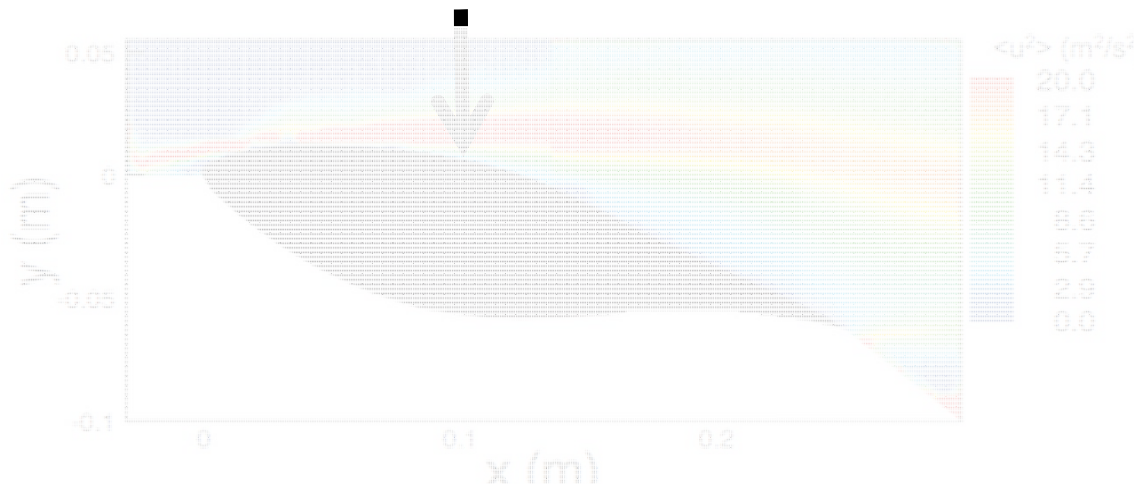
Baseline



Surface Roughness



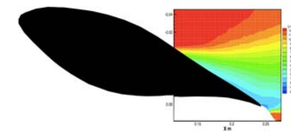
Free-stream Turbulence

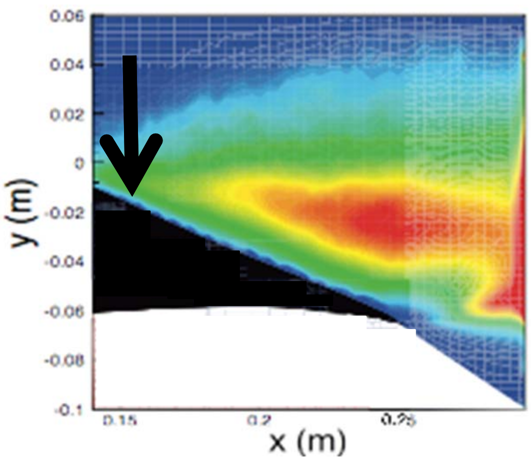


Roughness + FST

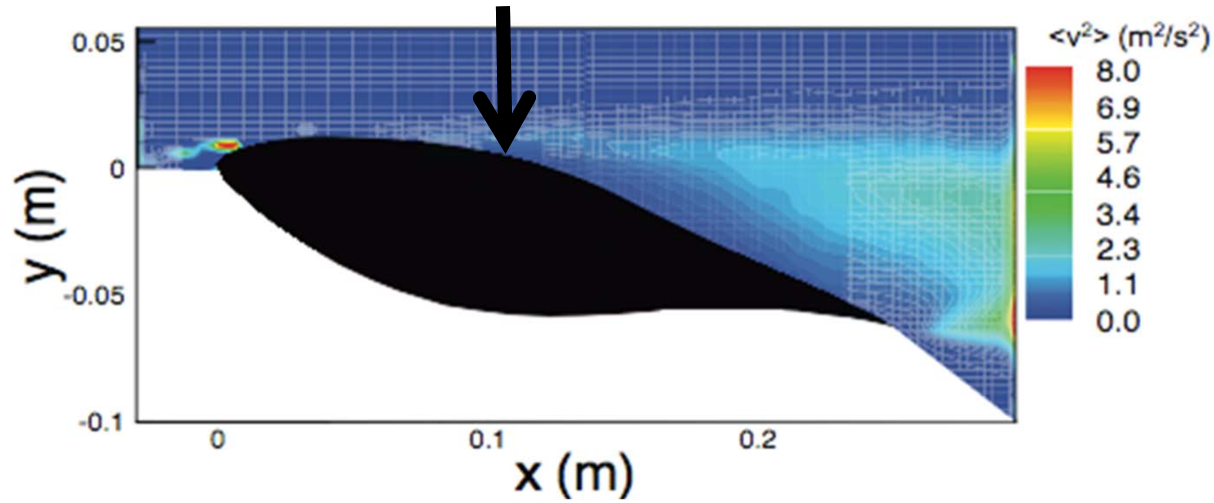
Dominant effect of surface roughness on separation.

Wall-normal Reynolds Stress Contours: α= 16°
Smooth and Rough Surface

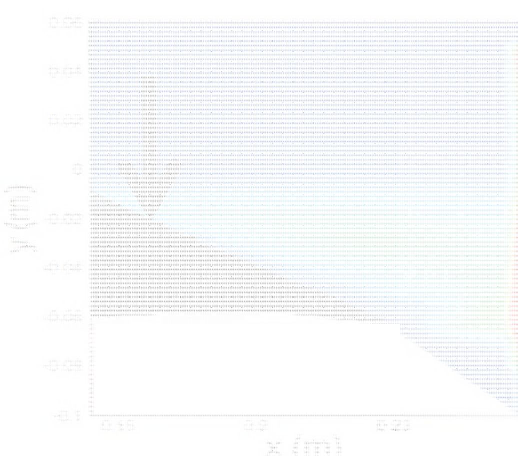


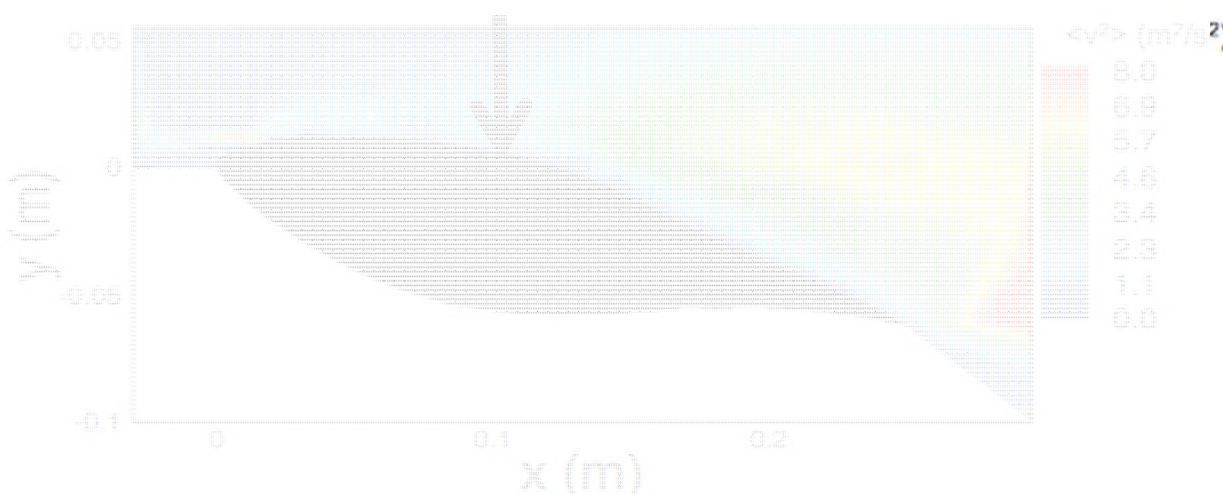


Baseline



Surface Roughness



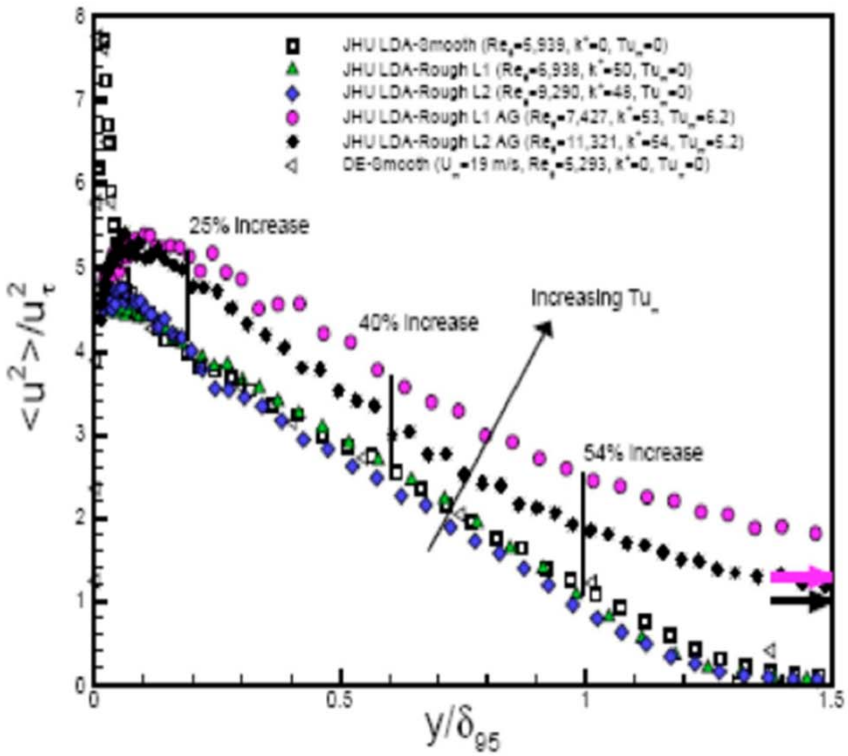


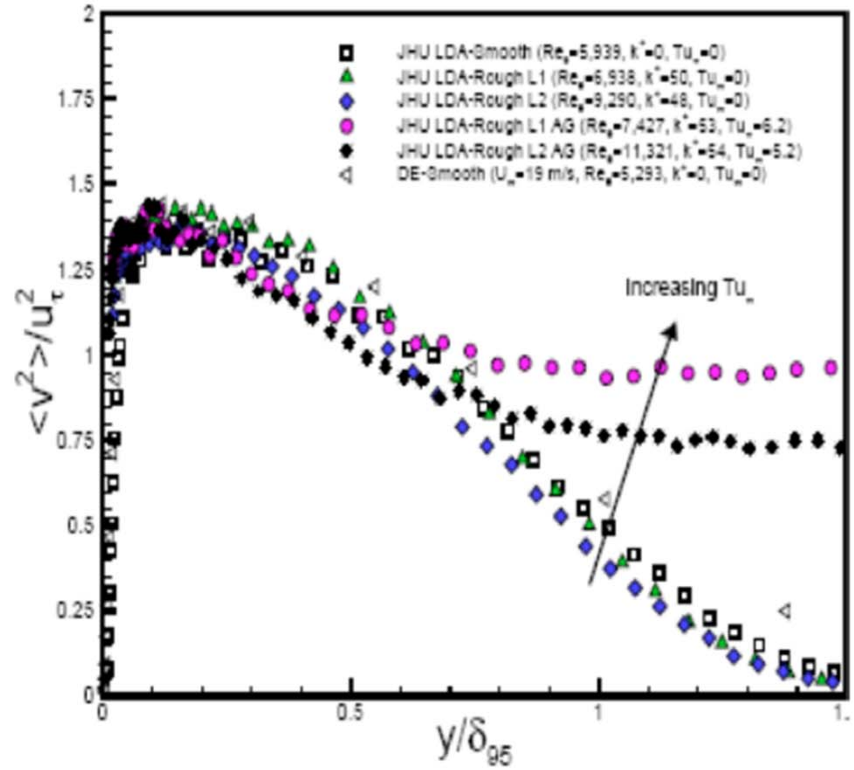
Free-stream Turbulence

Roughness + FST

Dominant effect of surface roughness on separation.

Reynolds Stresses: ZPG

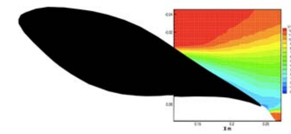


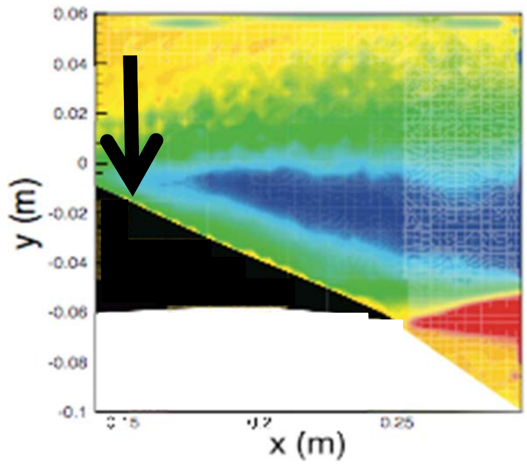


B. Brzek, S. Torres-Nieves, J. Lebron, R.B. Cal, C. Meneveau, and L. Castillo, "Effects of free-stream turbulence on rough surface turbulent boundary layers", *J. Fluid Mech.*, *635*, *207-243*, *2009.*

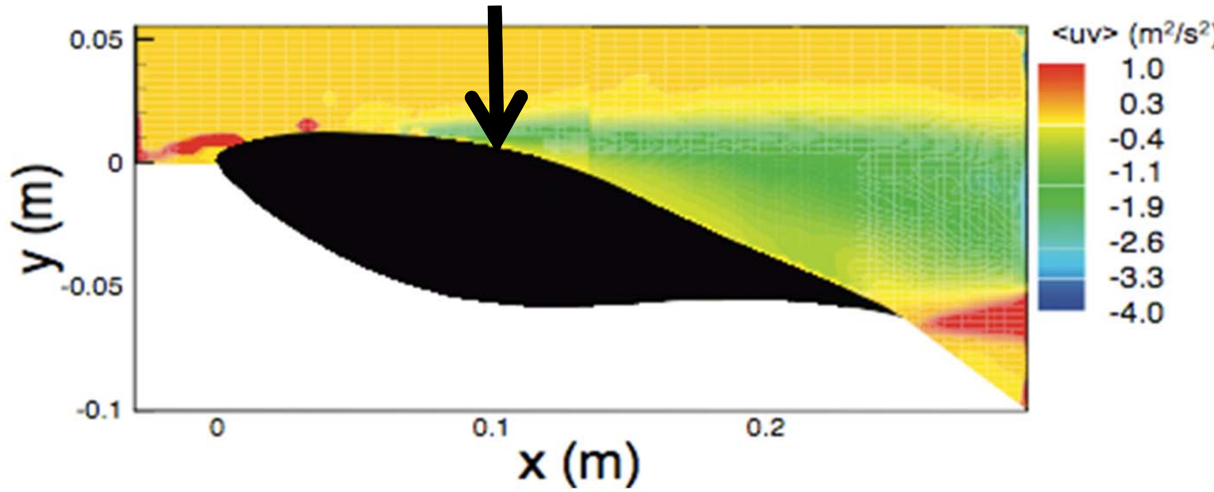
Reynolds Shear Stress Contours: α= 16°

Smooth and Rough Surface

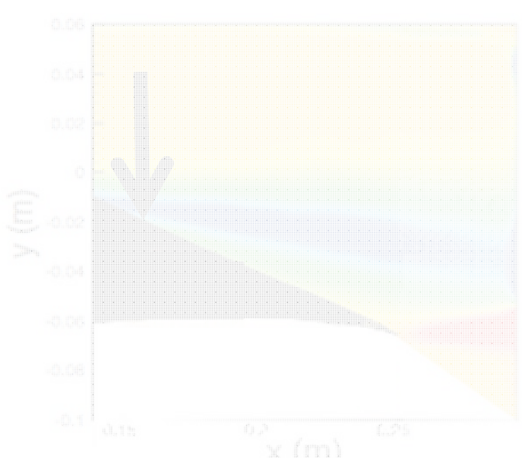




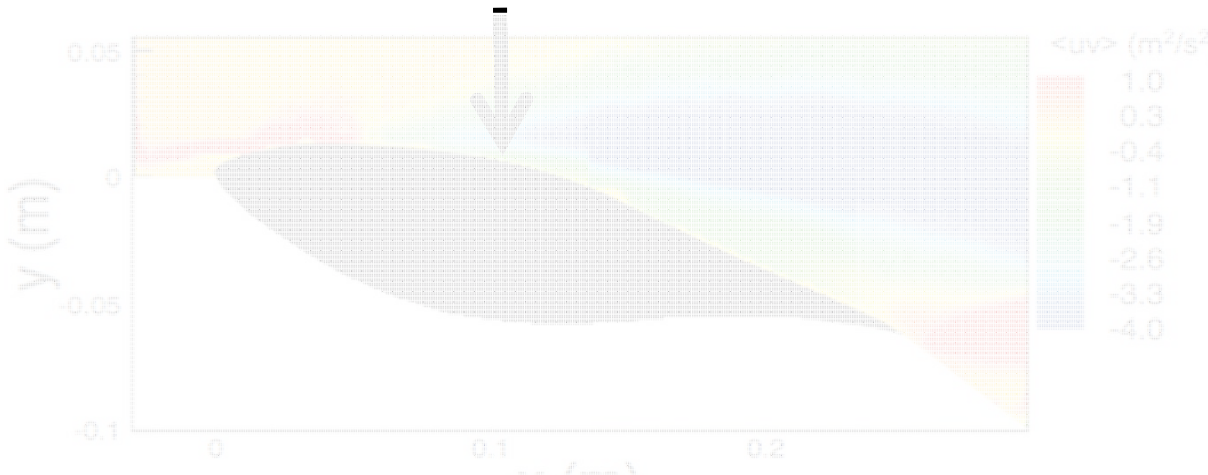
Baseline



Surface Roughness



Free-stream Turbulence



Roughness + FST

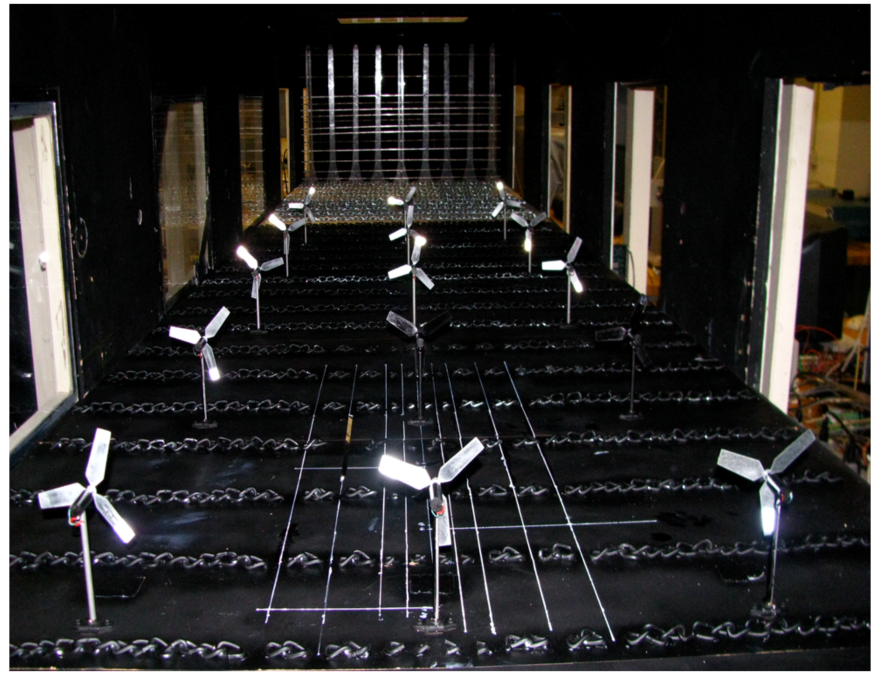
Concluding Remarks

- **Individual effect of free-stream turbulence is to delay separation.**
- ***Surface roughness results in earlier separation.***
- Combination of free-stream turbulence and surface roughness is advancing separation.
- When the flow over the wind turbine blade is mostly stalled (i.e., α= 16°), the non-trivial interactions among the different length scales result in complex flow dynamics.
    - Highly non-linear interactions were observed in Reynolds shear stress.

Unresolved questions

- How energy is entrained in an array?
- What is the importance of turbulence in arrays and wake-wake interaction?

Wind Array: Scaled down experiments and Role of Turbulence

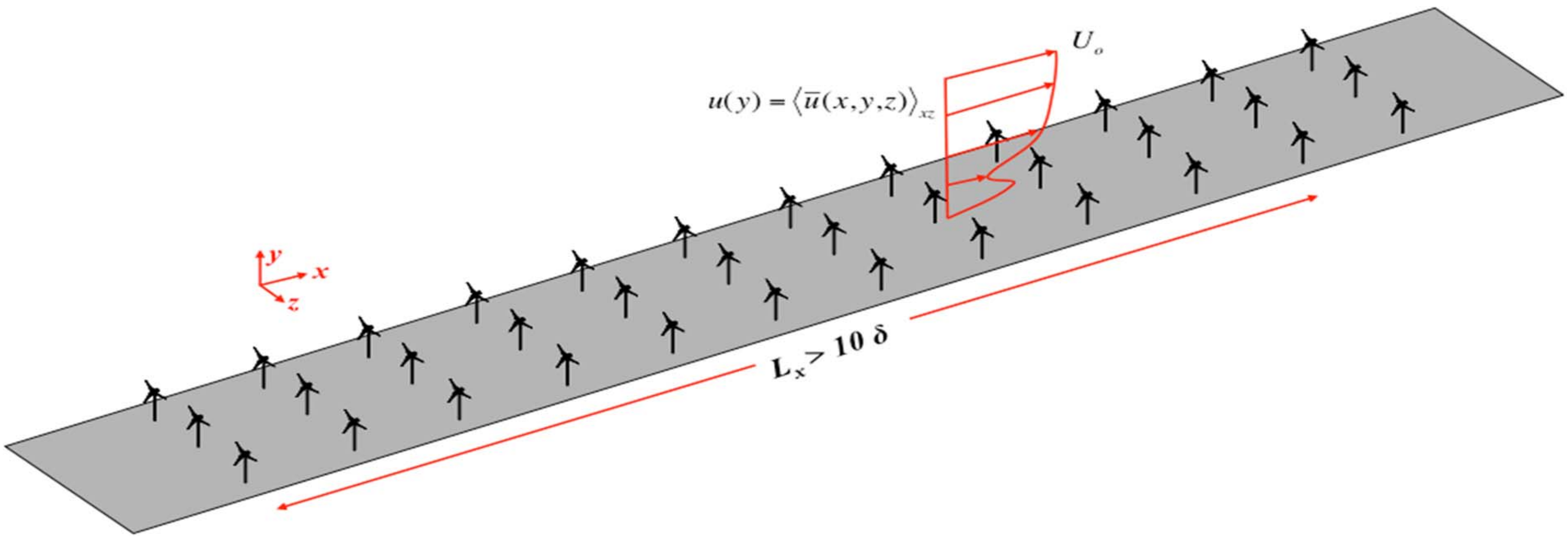


Lebrón, J Meneveau, C., and Castillo, L., "Experimental study of the horizontally averaged flow structure in loaded turbines array", to be submitted at the Journal of Wind Energy, (2012).

Objectives

- **Show studies in a wind array of 3x5** scaled 850 times from full-scale turbine.
  - Measure profiles **of horizontally averaged momentum fluxes & Mean K.E.**
  - Compare turbulent shear stress with canopy (dispersive stress) mean velocity shear stress.
  - **Understand the role of the fluxes of kinetic energy in the vertical direction.**
- To show that we must use a system of systems approach in dealing with wind farm underperformance issue.

The WTABL and the Momentum Theory Eqn.



- Momentum theory (time averaged + "dispersive stress"):

averaged thrust force

$$\langle \overline{u} \rangle_{xz} \frac{\partial \langle \overline{u} \rangle_{xz}}{\partial x} + \langle \overline{v} \rangle_{xz} \frac{\partial \langle \overline{u} \rangle_{xz}}{\partial x} = -\frac{1}{\rho}\frac{dp_\infty}{dx} + \frac{d}{dy}\left(-\langle \overline{u'v'} \rangle_{xz} - \langle \overline{u}''\overline{v}'' \rangle_{xz} \right) + \langle \overline{f_x} \rangle_{xz}$$

$$\overline{u}'' = \overline{u} - \langle \overline{u} \rangle_{xz}$$

Horizontal average of turbulent shear Reynolds stress

Correlations between mean velocity deviations from their spatial mean "dispersive stress"
(Raupach et al. Appl Mech Rev 44, 1991)

The WTABL and the Mean Kinetic Energy Eqn.

•Multiplying the momentum by the mean velocity leads to the mechanical energy describing the kinetic energy.

$$\langle\overline{u}\rangle\frac{\partial\frac{1}{2}\langle\overline{u}\rangle^2}{\partial x}+\langle\overline{v}\rangle\frac{\partial\frac{1}{2}\langle\overline{u}\rangle^2}{\partial y}=$$

$$-\frac{1}{\rho}\langle\overline{u}\rangle\frac{dp_\infty}{dx}-\frac{\partial}{\partial y}\left(\langle\overline{u'v'}\rangle\langle\overline{u}\rangle+\langle\overline{u}''\overline{v}''\rangle\langle\overline{u}\rangle\right)+\langle\overline{u'v'}\rangle\frac{\partial\langle\overline{u}\rangle}{\partial y}+\langle\overline{u}''\overline{v}''\rangle\frac{\partial\langle\overline{u}\rangle}{\partial y}-\mathcal{P}(y),$$

• In the inner region, the following terms are dominant:

$$-\frac{\partial}{\partial y}\left(\langle\overline{u'v'}\rangle\langle\overline{u}\rangle+\langle\overline{u}''\overline{v}''\rangle\langle\overline{u}\rangle\right)+\langle\overline{u'v'}\rangle\frac{\partial\langle\overline{u}\rangle}{\partial y}+\langle\overline{u}''\overline{v}''\rangle\frac{\partial\langle\overline{u}\rangle}{\partial y}-\mathcal{P}(y)\approx 0$$

Kinetic energy flux

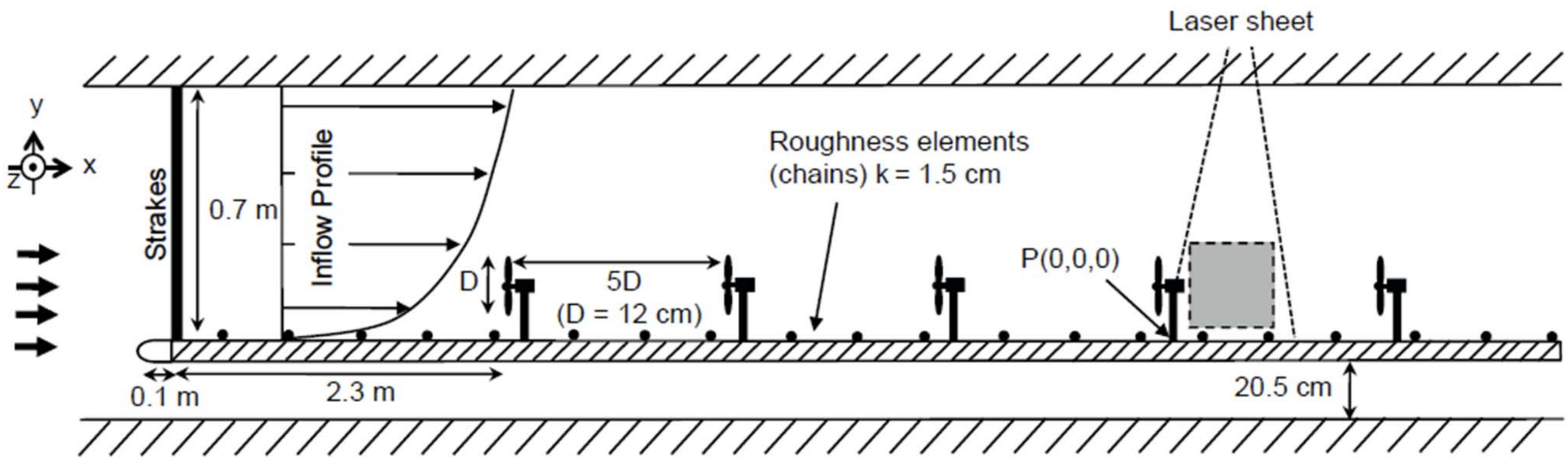
Dispersive flux due to spatial average

Turbulent dissipation dispersive dissipations

Product of the spatially averaged velocity and the averaged thrust force

What is the role of turbulent momentum & KE flux in energy?

Experimental set up: Overview

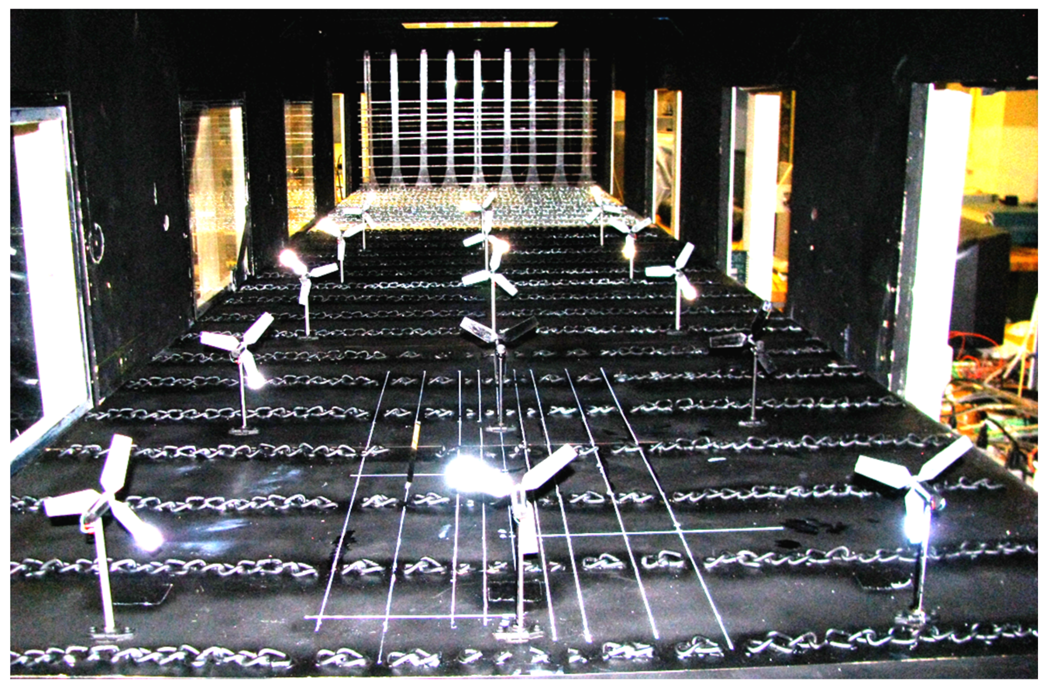


Wind turbine models

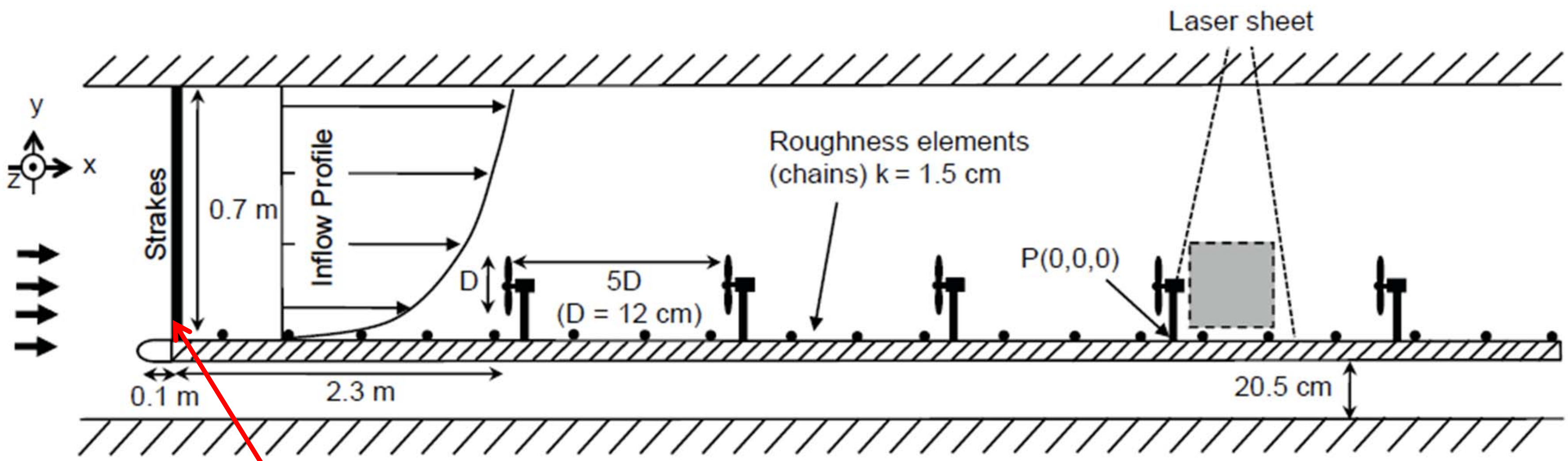
- Rotors - water jet cut + 3D print mold
- DC motor
- Improved proportions
- Higher thrust
- 3 by 5 Array
- s_x = 5D and s_z = 3D
- Tip-speed ratio = 4

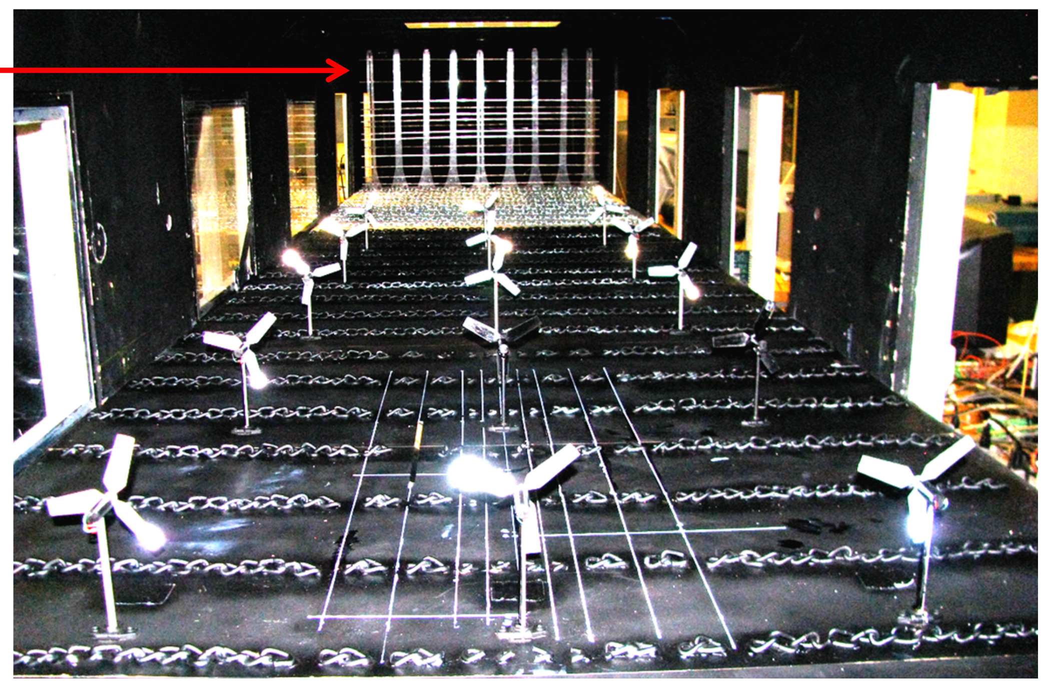
Rough plate

- Emulate a rough flat terrain
- Roughness made of steel chains
- Separated 1.5 D (18 cm)
- k = 1.5 cm



Experimental set up: Inflow

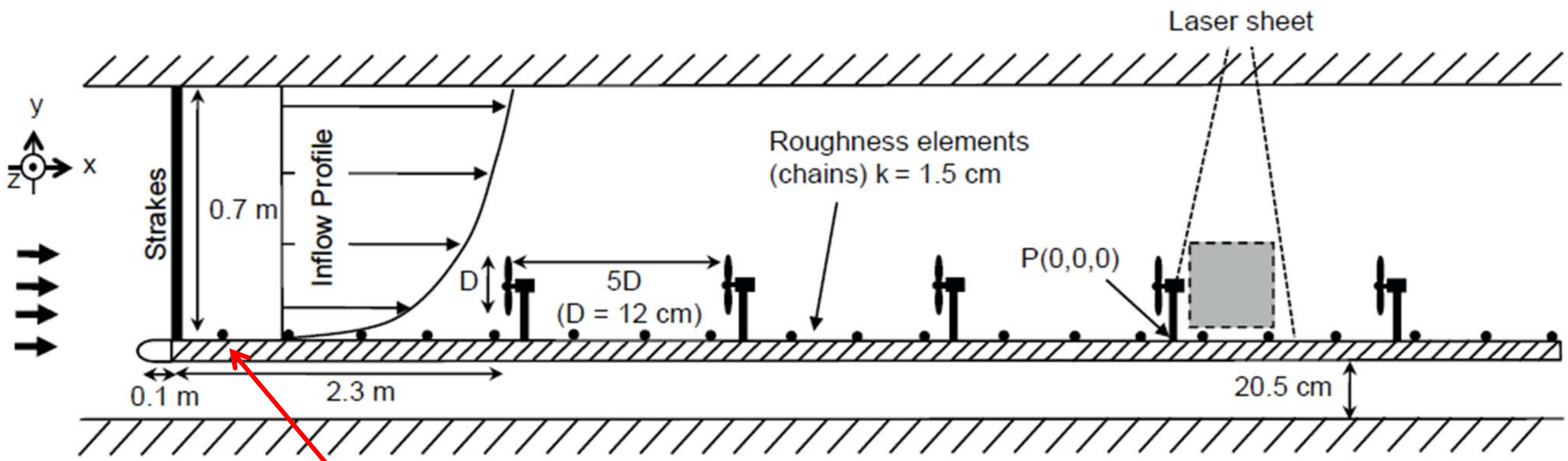


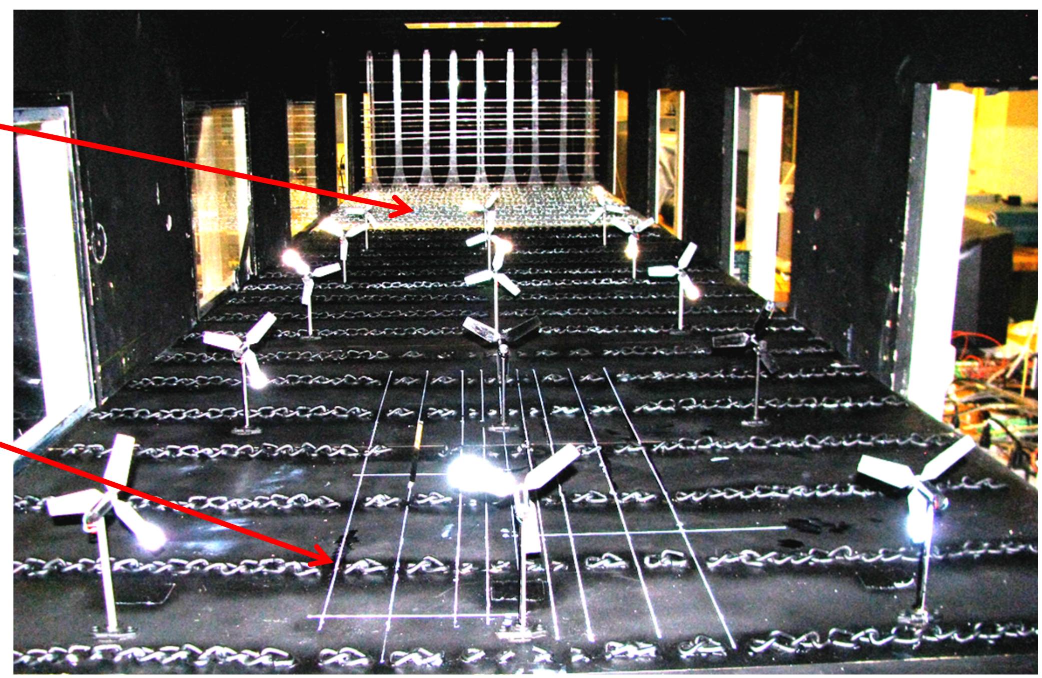


Strakes

- Generate shear and turbulence
- Iterative design
- Laser Cutter

Experimental set up: Rough plate





Rough plate

- Emulate a rough flat terrain
- Roughness made of steel chains
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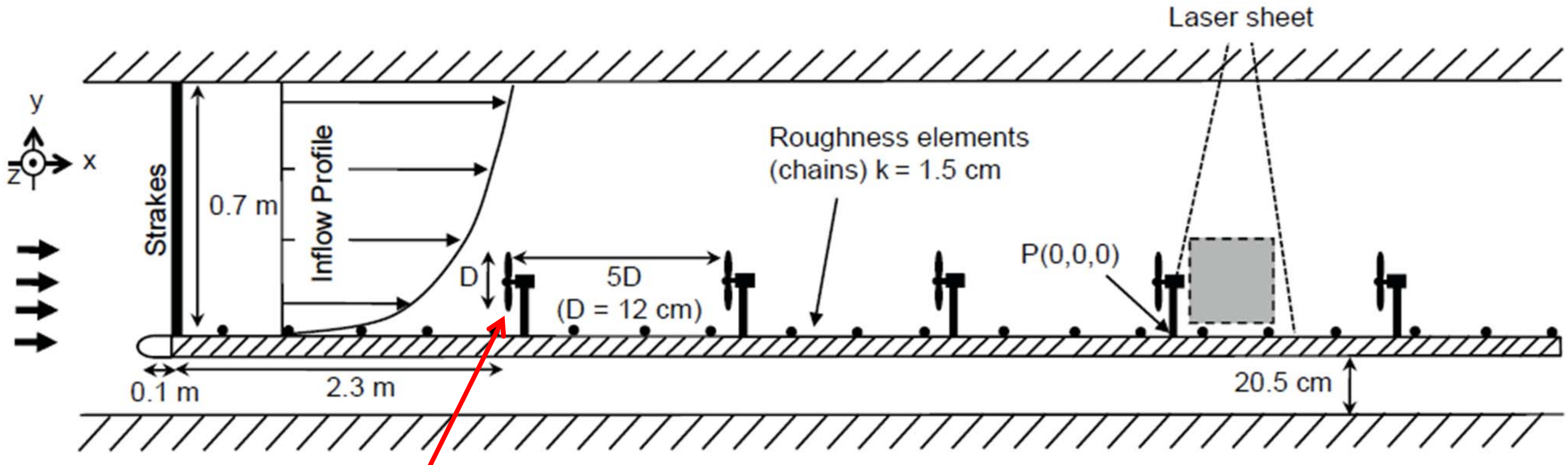
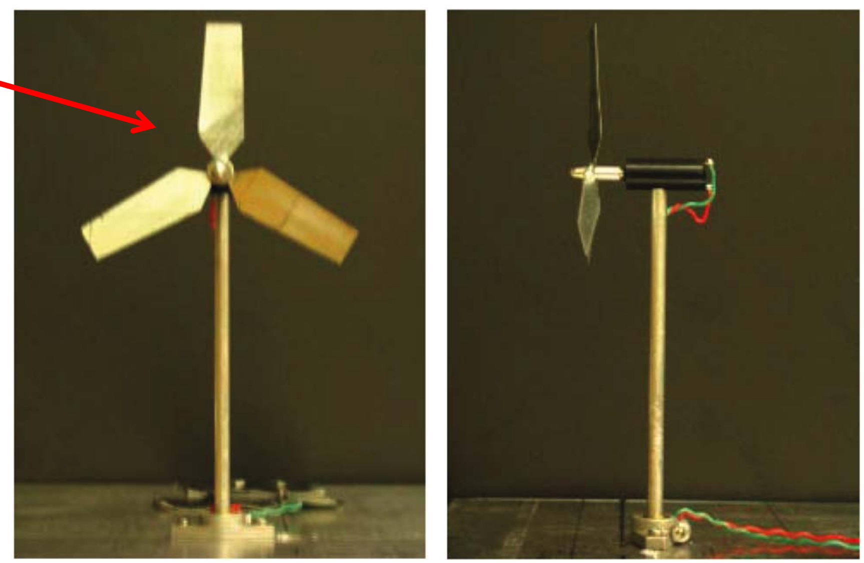
Experimental set up: Wind turbine models

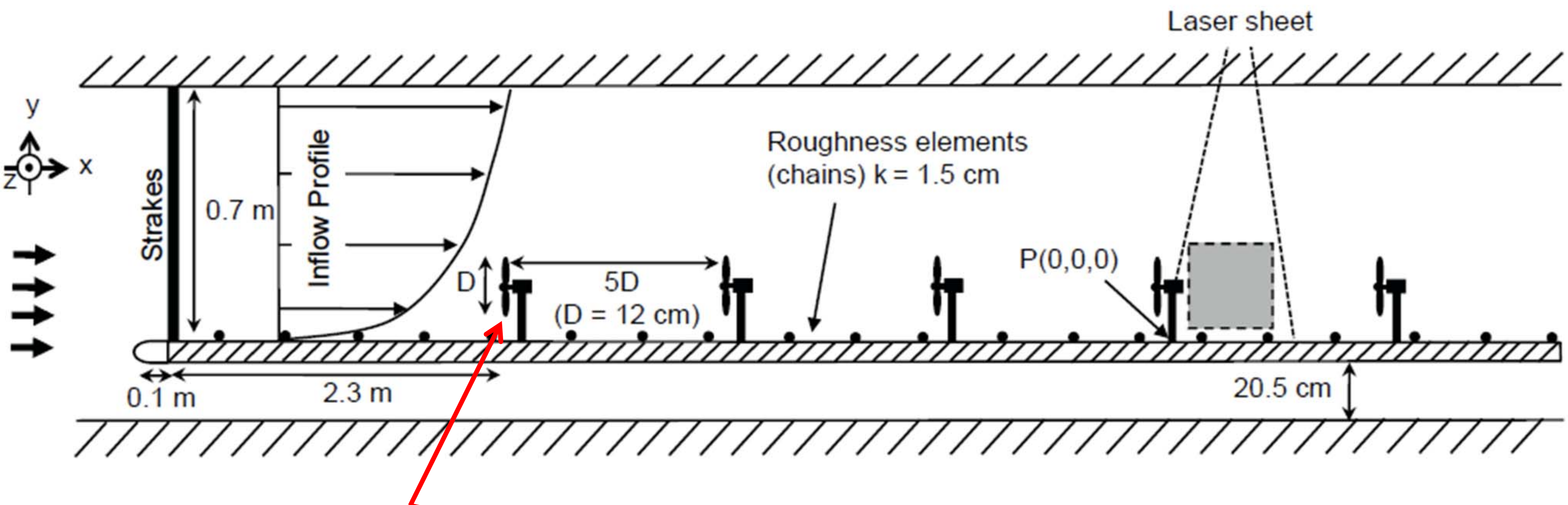




Wind turbine models

- Rotors - water jet cut + 3D print mold
- DC motor
- Improved proportions
- Higher thrust
- 3 by 5 Array
- s_x = 5D and s_z = 3D
- Tip-speed ratio = 4

Experimental set up: PIV



Particle Image Velocimetry

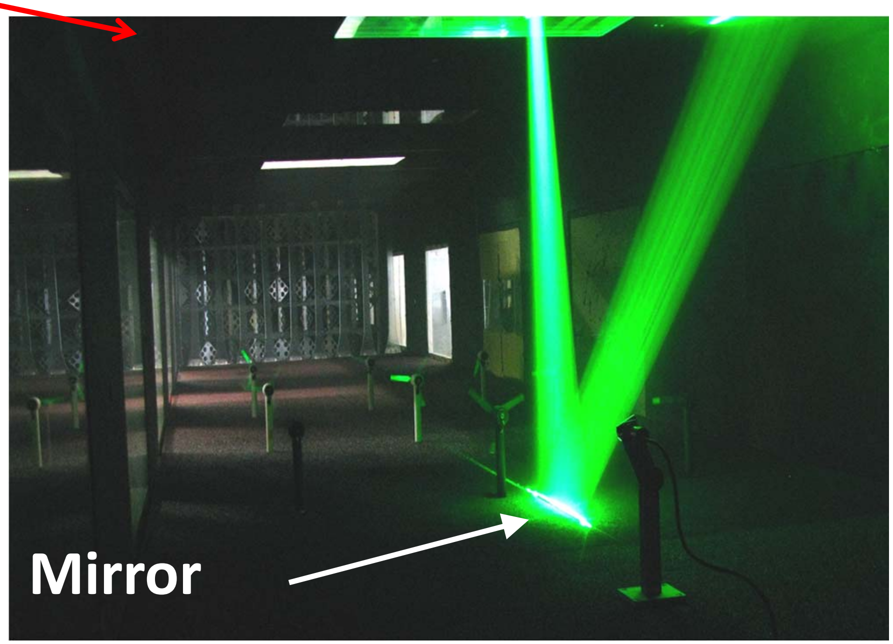
Δt setup to 80 μs to 100μs (faster in wake)

FOV 23 cm x 23 cm

Mirror

3,000 samples at 7 Hz

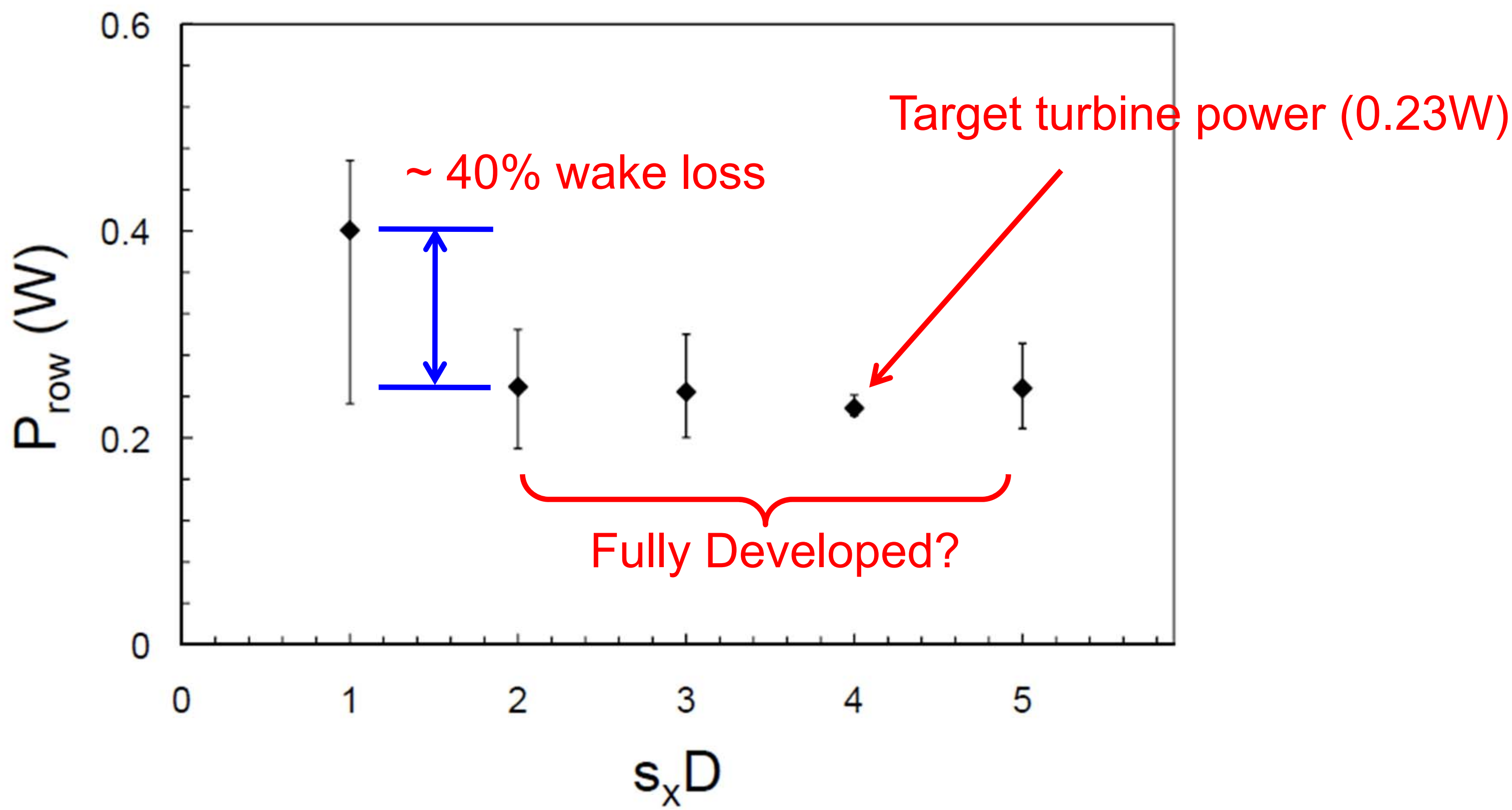
Laser sheet thickness 1.2 mm



Wind turbine array power

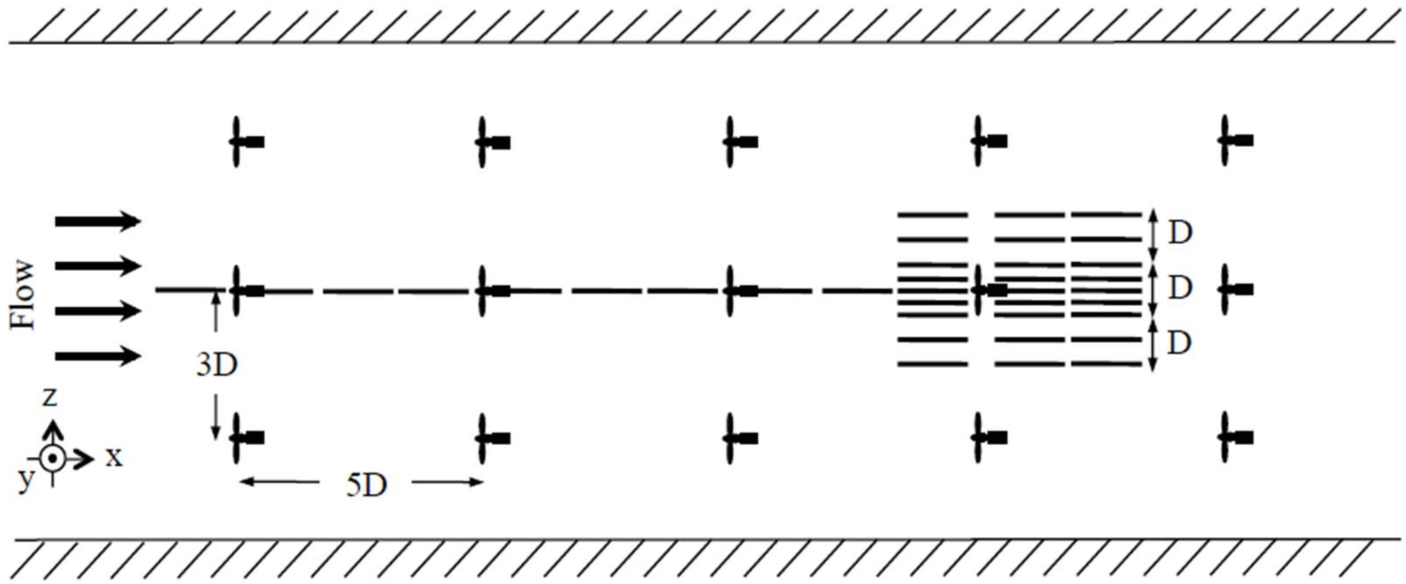
$$\overline{P}_{WT} = \overline{\omega}\overline{T}_{WT} = \overline{\omega}(0.00027063 + 0.005682\overline{I})$$

H.S. Kang, C. Meneveau, Meas Sci Technol 21, 105206, (2010)



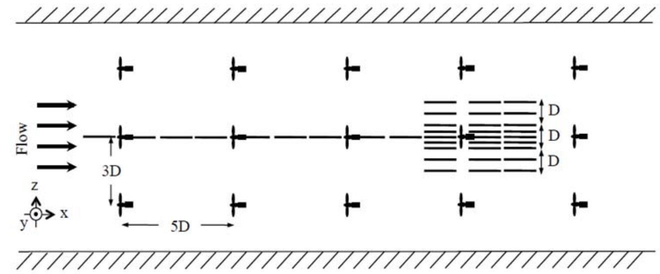
- Averaged over the duration of the experiments and over each of the 5 rows of turbines.
- Wake loss consistent with field experiments by Van Leuven (1992) and Barthelmie *et al.* (2007)

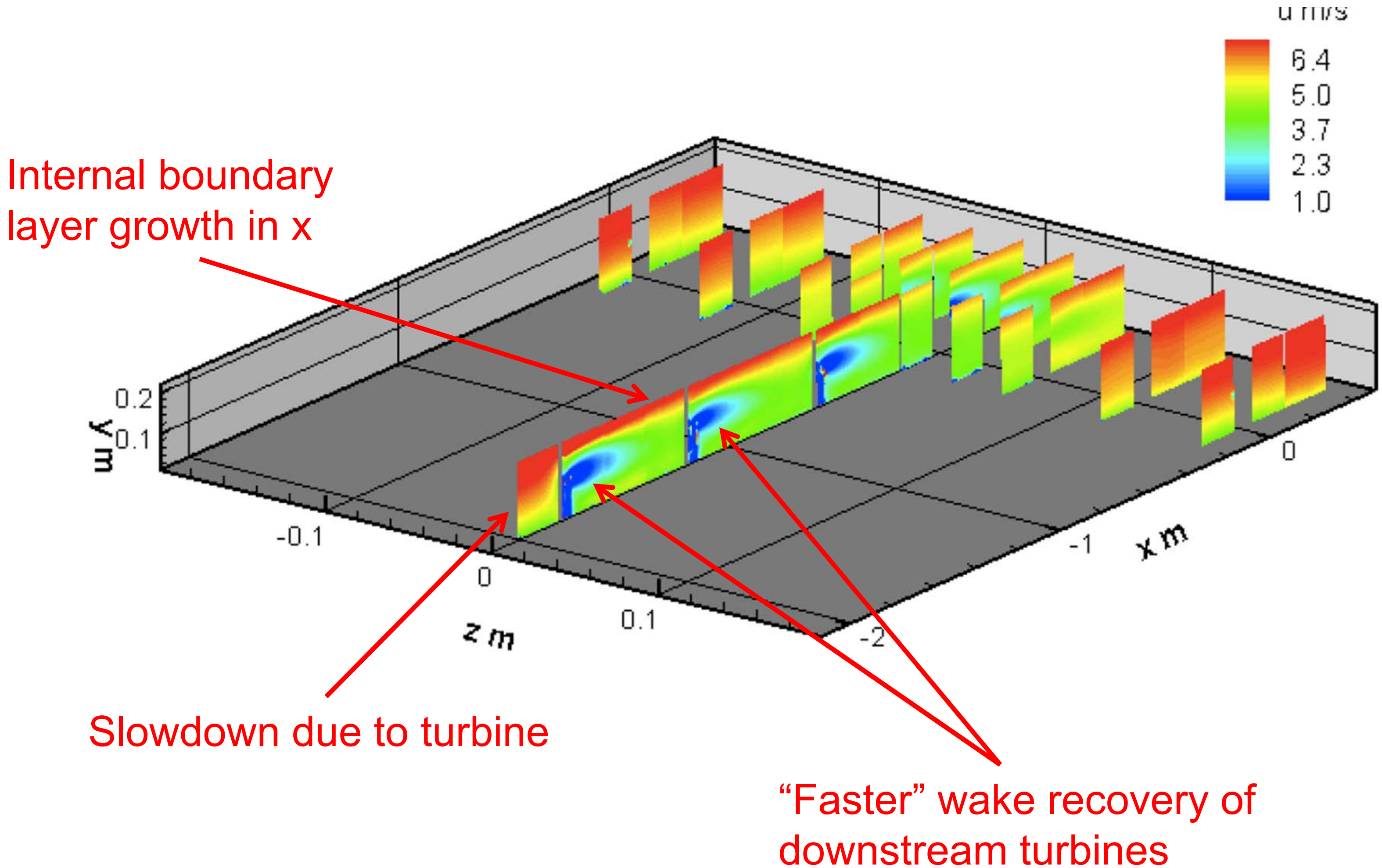
PIV measurements locations



- PIV fixed in x and y but traversed in z
- Set up slide in x
- Measurements w/o turbines along centerline
- Measurements with turbines elsewhere

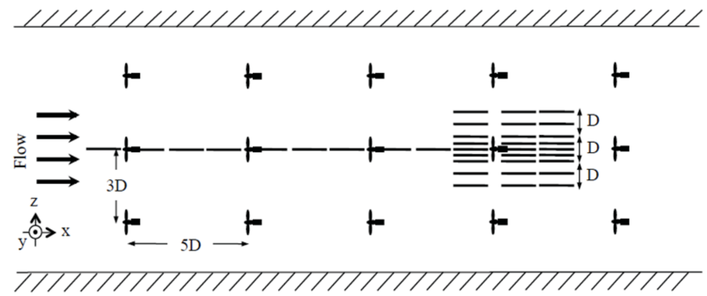
Distribution of mean streamwise velocity

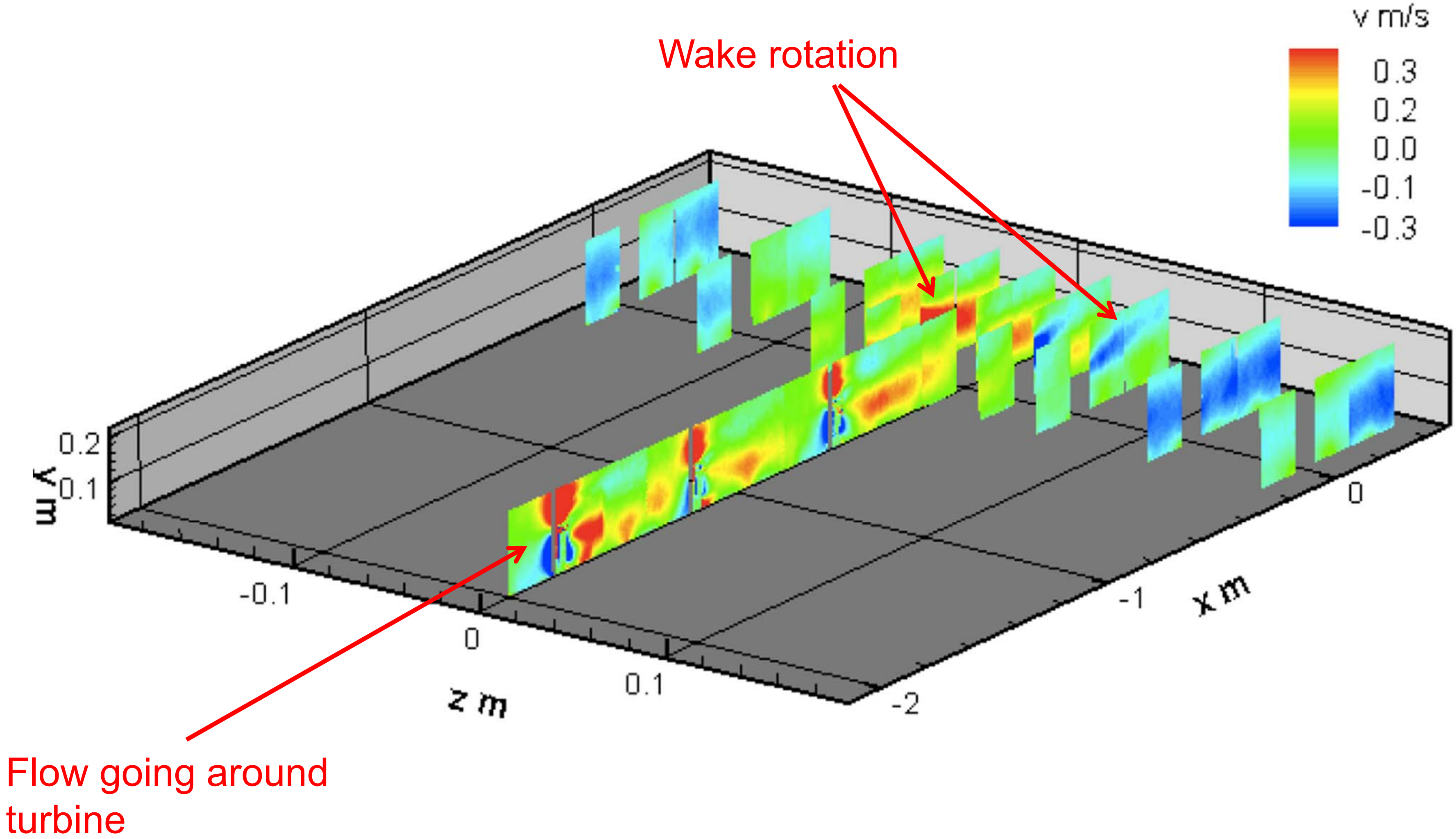




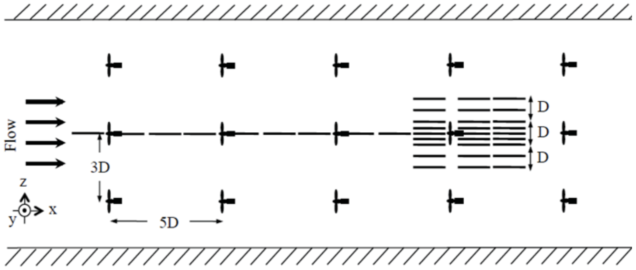
Contour stretched in the z-direction

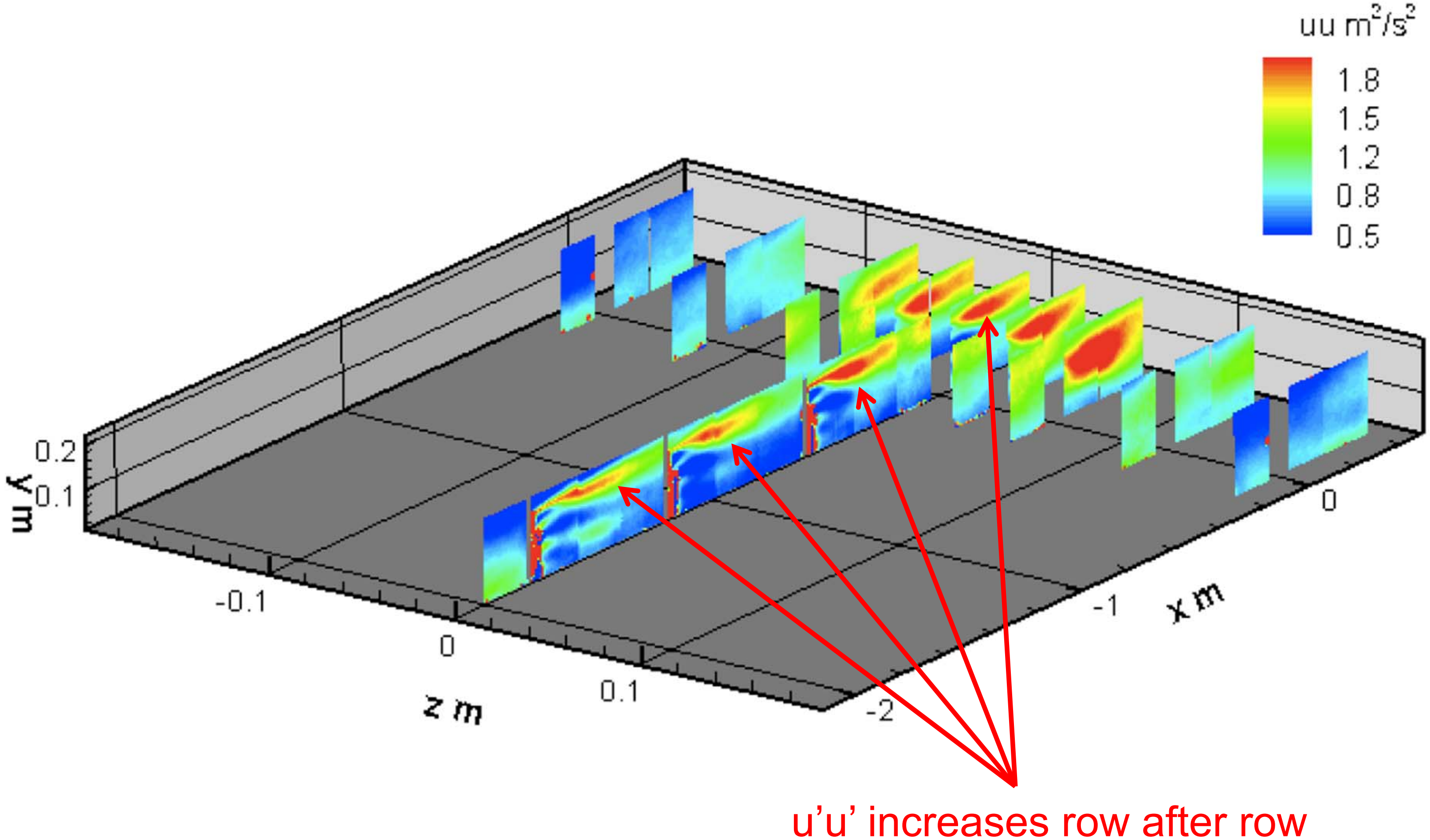
Distribution of vertical velocity



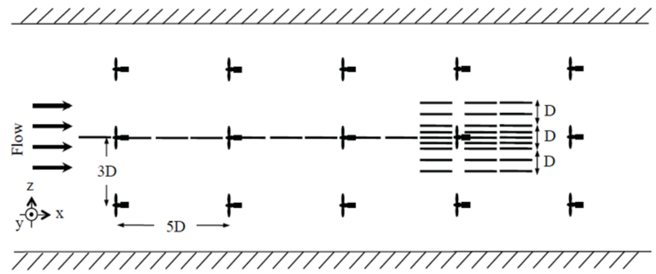


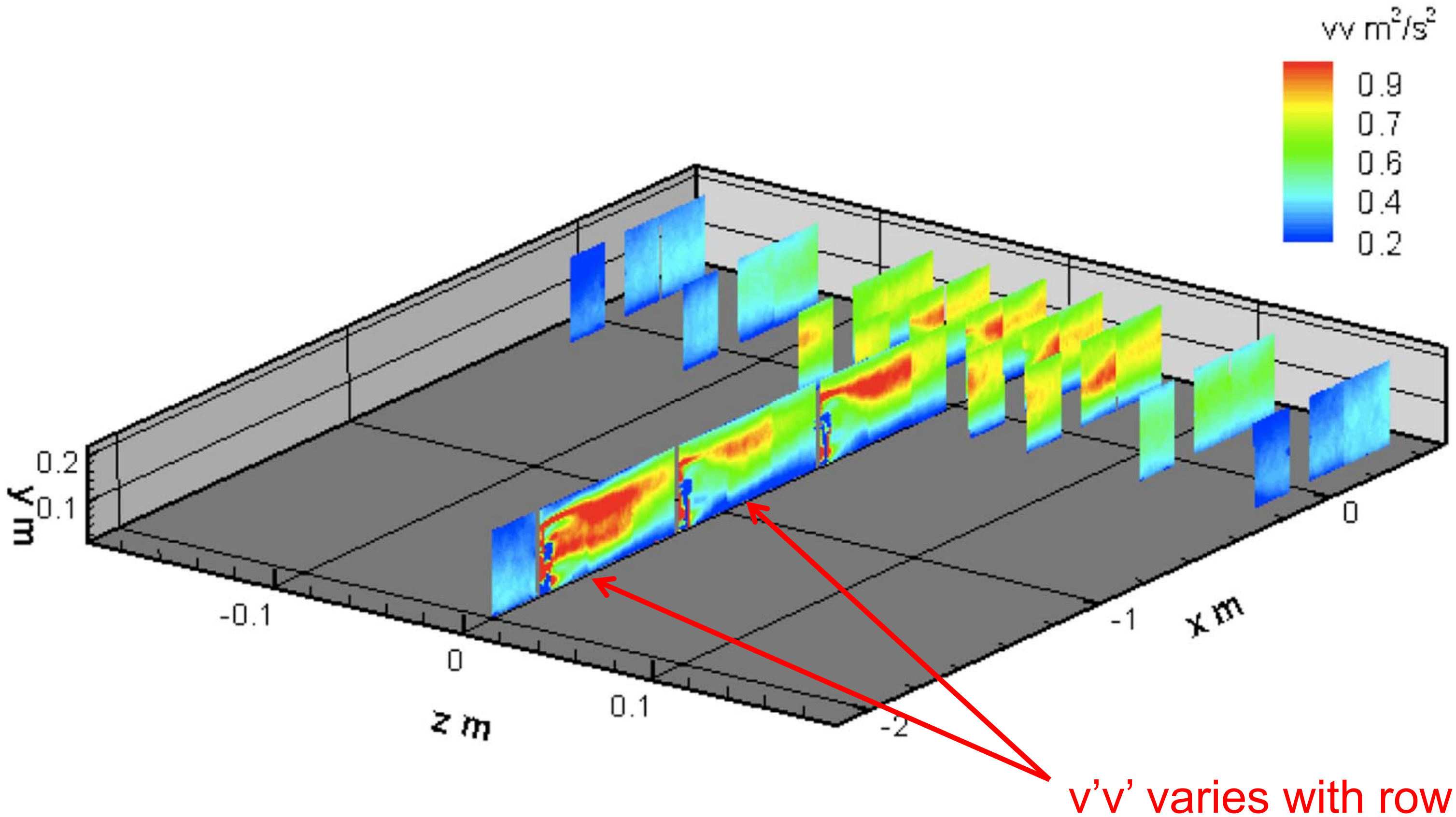
Distribution of streamwise Reynolds stress



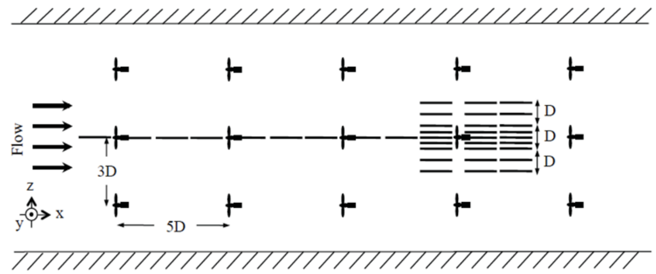


Distribution of vertical Reynolds stress

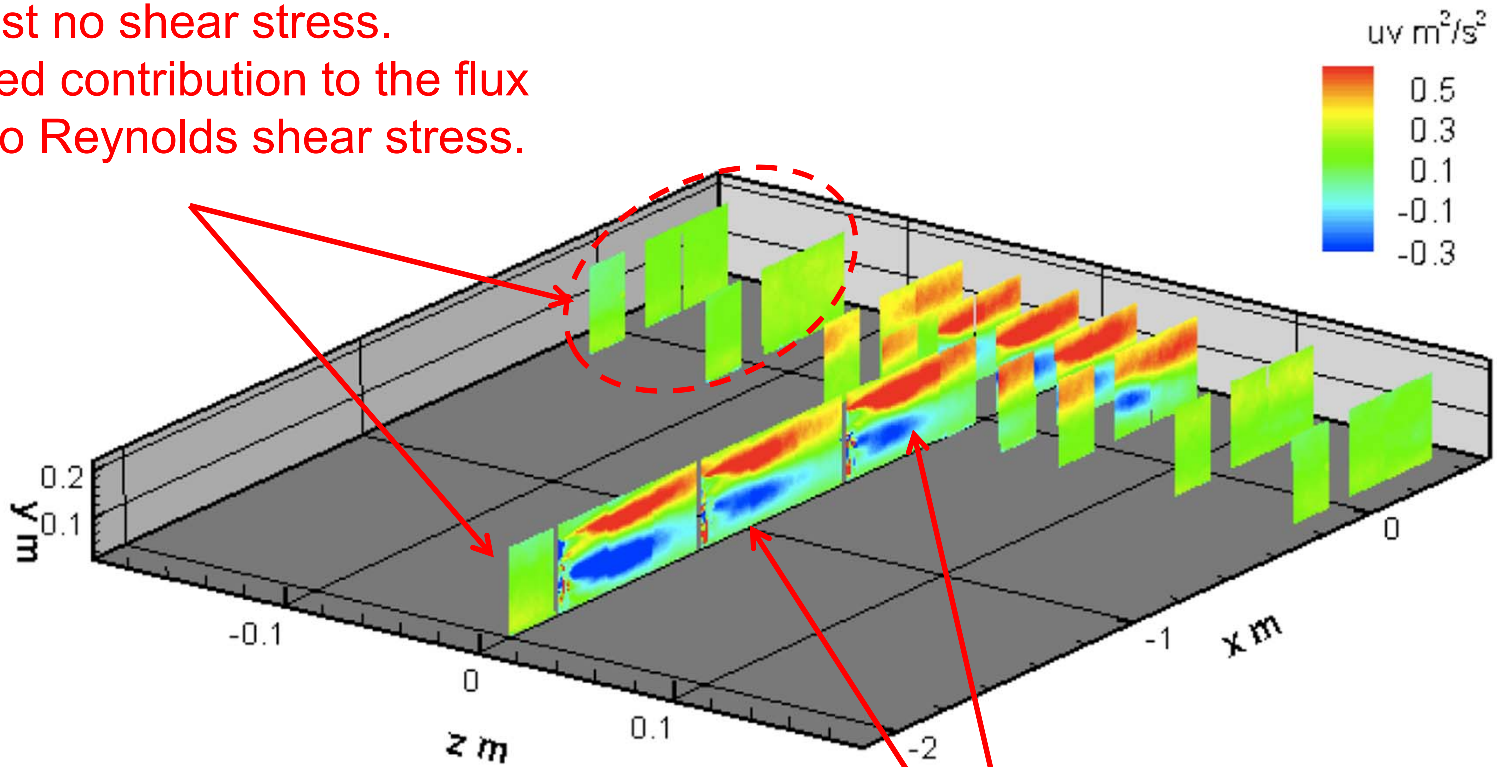




Distribution of Reynolds shear stress

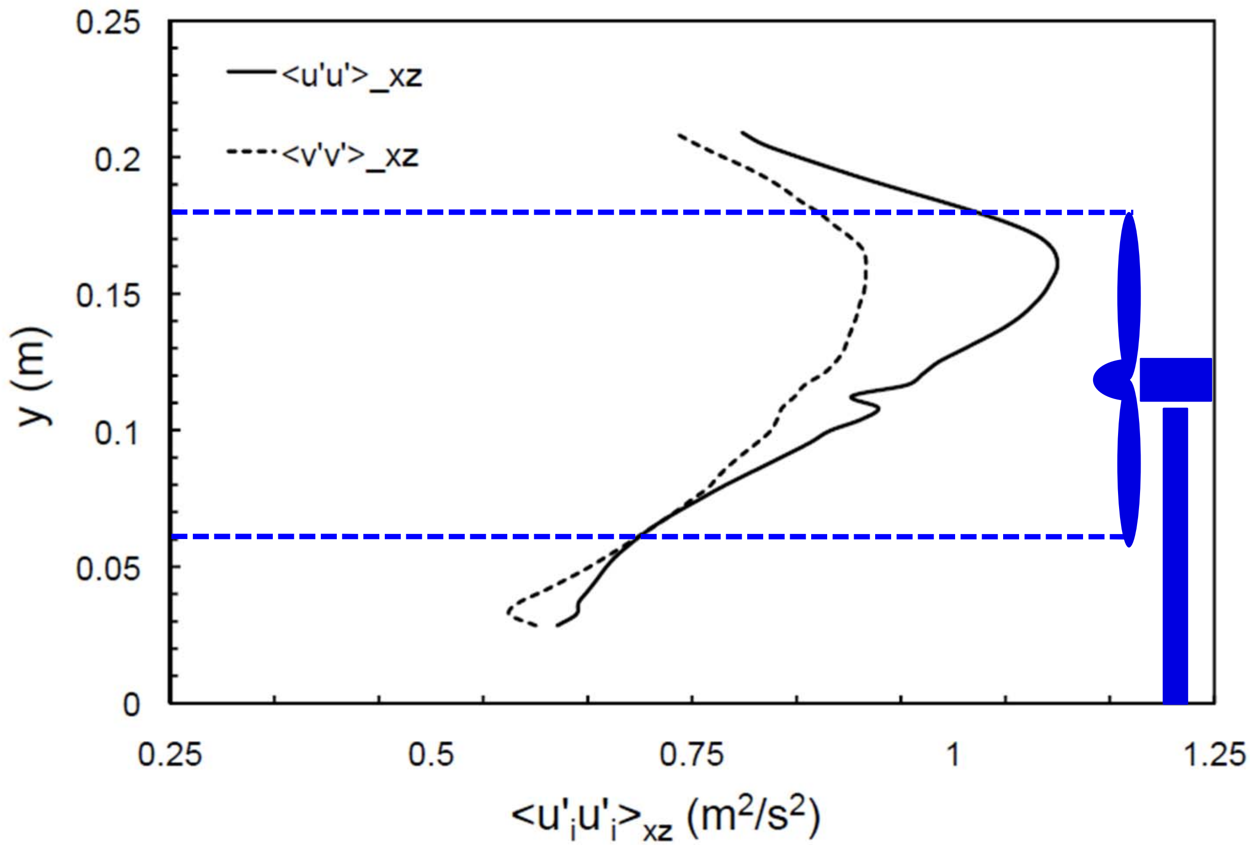


Almost no shear stress.
Limited contribution to the flux due to Reynolds shear stress.



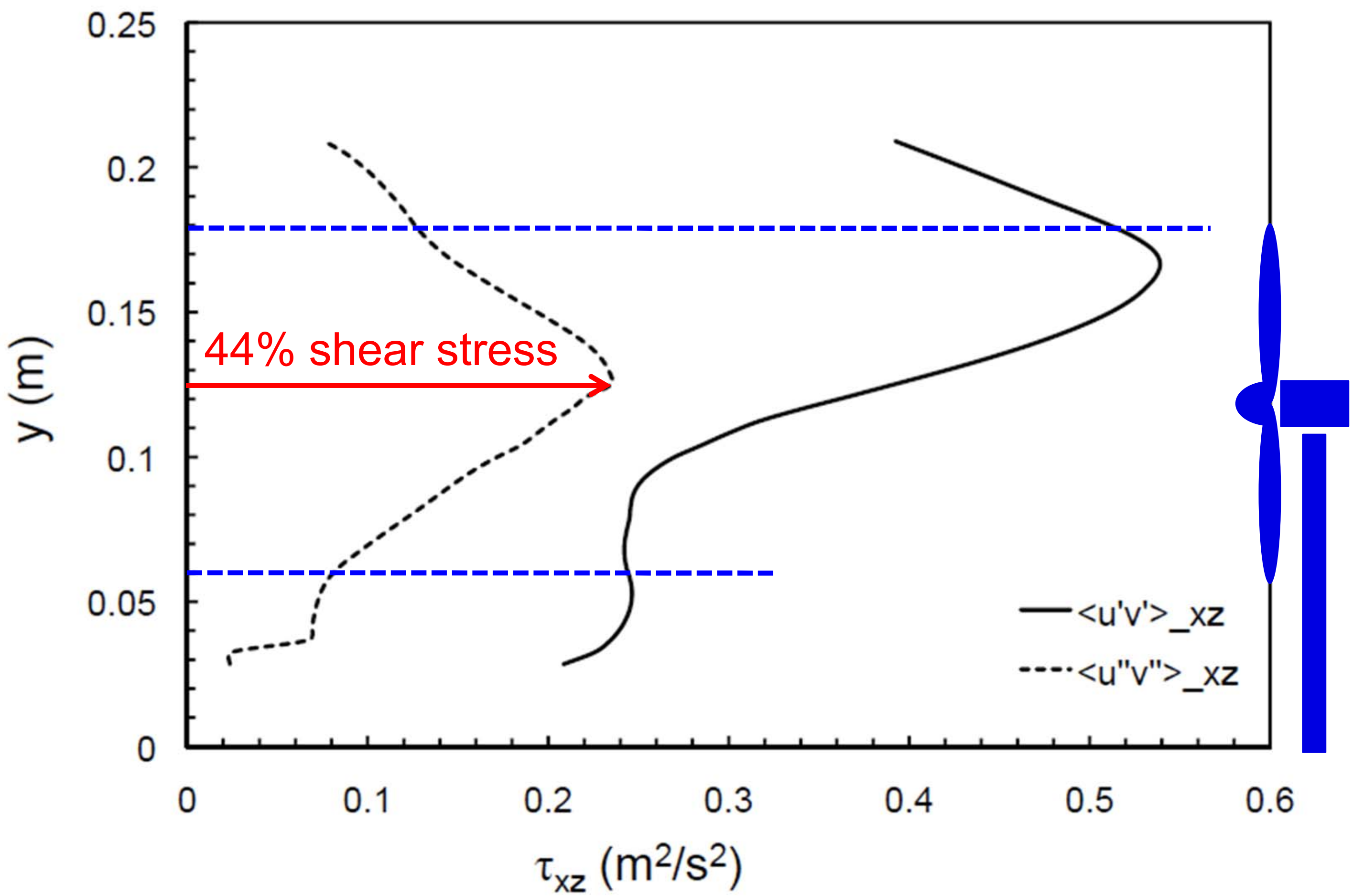
Little change between rows

Horizontally-averaged Reynolds normal stresses

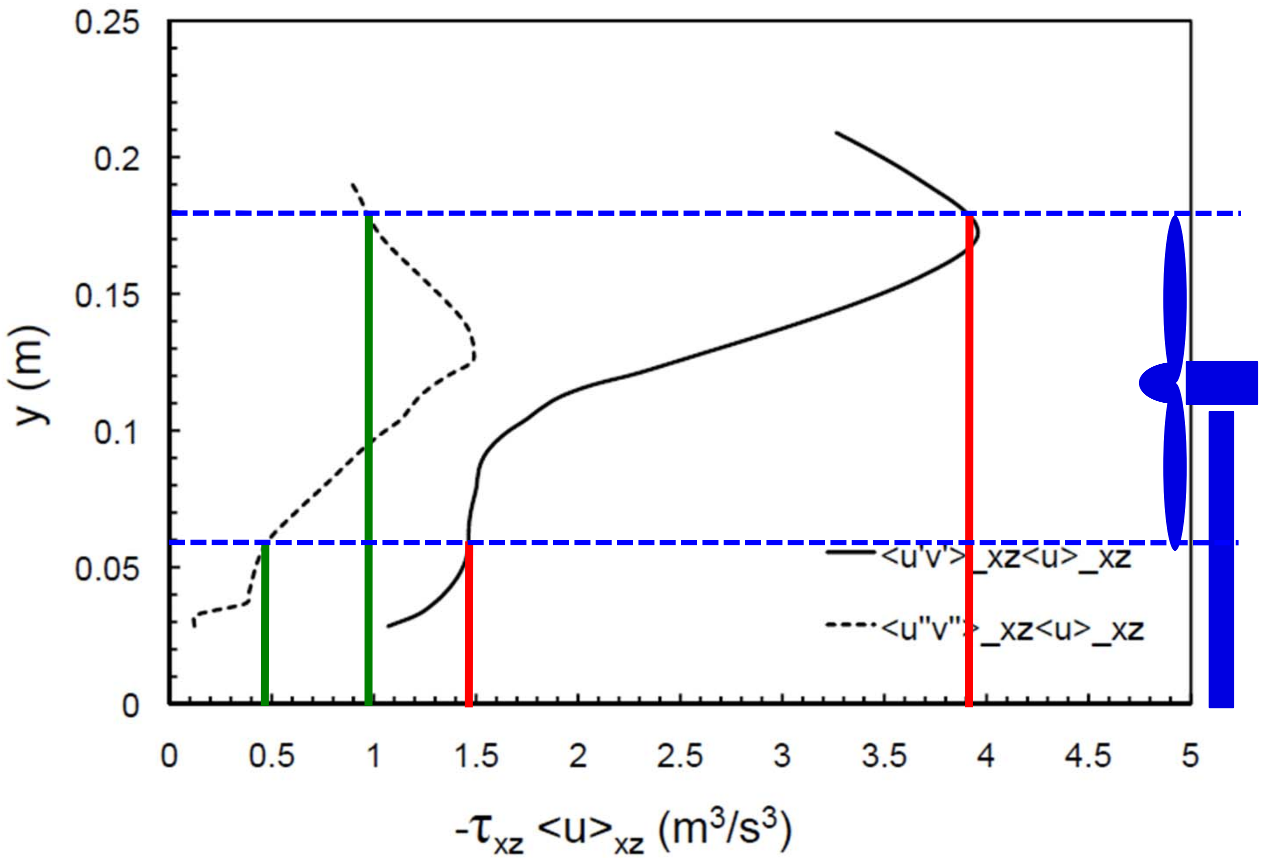


Higher $\langle v'v' \rangle_{xz}$ than that of Cal *et al.* JRSE (2010)

Horizontally-averaged Reynolds shear and dispersive stresses



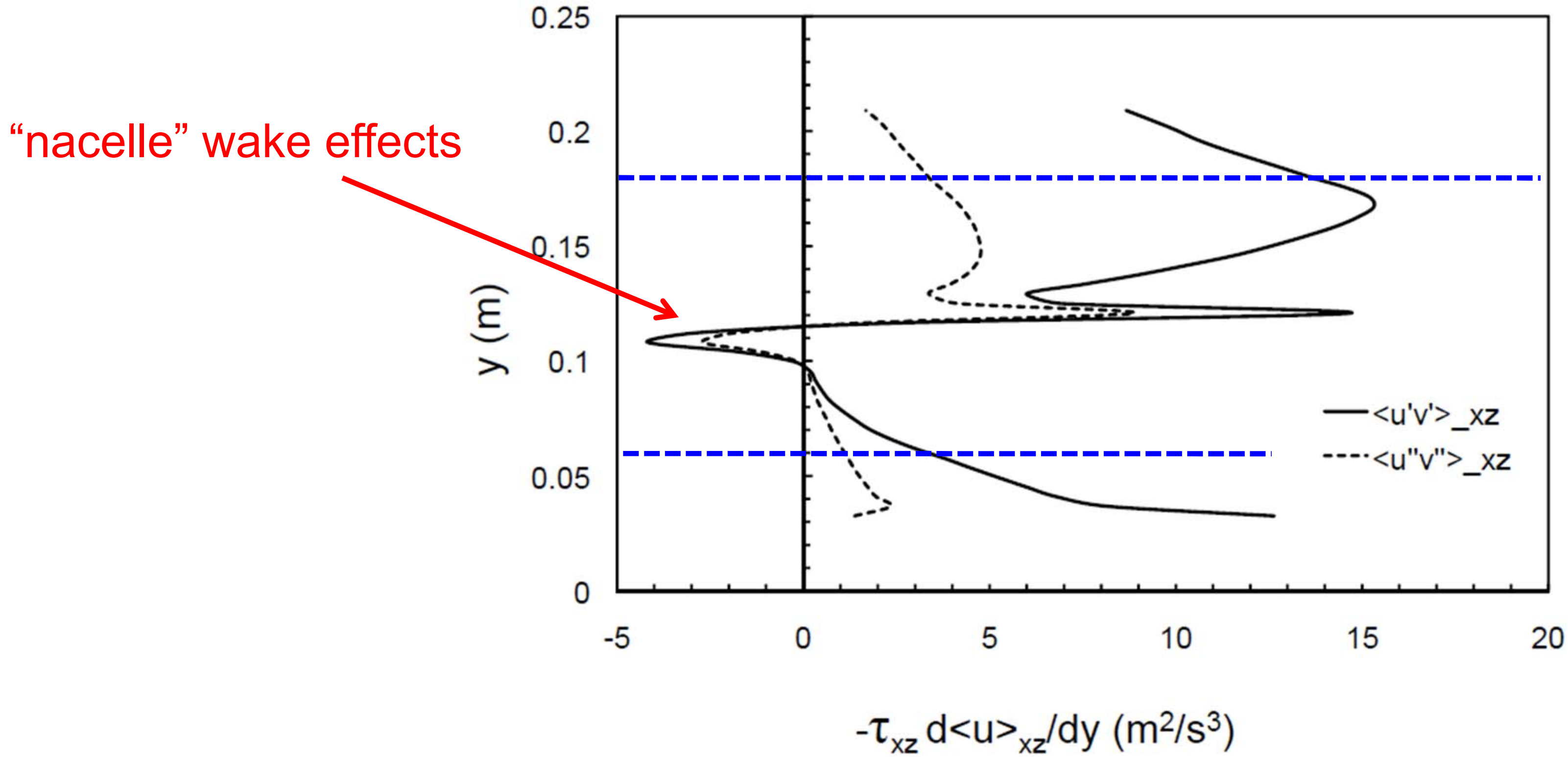
Fluxes of KE due to Reynolds shear and dispersive stresses



$$P_{flux-shear} = \rho \cdot (s_x s_z D^2) \left[\langle \overline{u'v'} \rangle_{xz} \langle \overline{u} \rangle_{xz} (y_{hi}) - \langle \overline{u'v'} \rangle_{xz} \langle \overline{u} \rangle_{xz} (y_{lo}) \right] = \underline{0.62 \text{ W}}$$

$$P_{flux-disp} = \rho \cdot (s_x s_z D^2) \left[\langle \overline{u''v''} \rangle_{xz} \langle \overline{u} \rangle_{xz} (y_{hi}) - \langle \overline{u''v''} \rangle_{xz} \langle \overline{u} \rangle_{xz} (y_{lo}) \right] = \underline{0.13 \text{ W}}$$

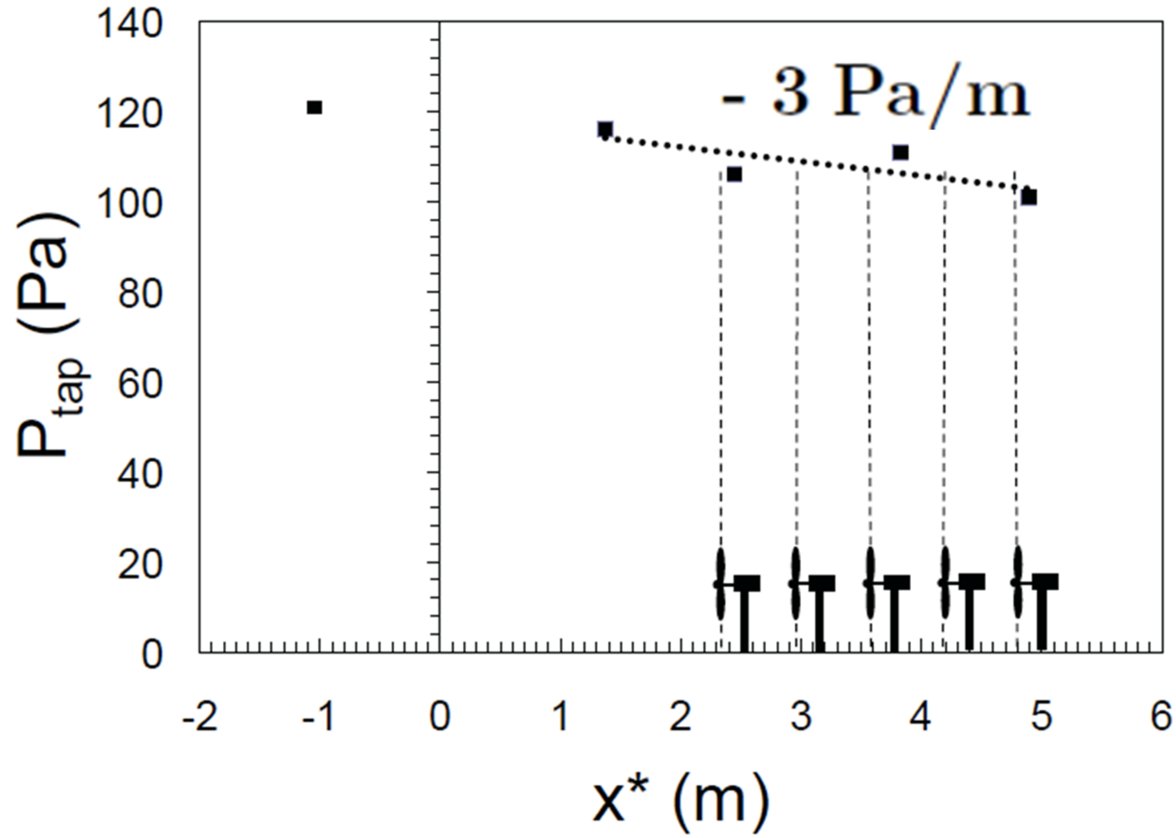
Dissipation of kinetic energy



$$P_{loss-dissip} = \rho s_x s_z D^2 \int_{y_h+D/2}^{y_h-D/2} -\langle\overline{u'v'}\rangle_{xz} \frac{\partial\langle\overline{u}\rangle_{xz}}{\partial y} \partial y \approx 0.12W$$

$$P_{loss-disp} = \rho s_x s_z D^2 \int_{y_h+D/2}^{y_h-D/2} -\langle\overline{u''v''}\rangle_{xz} \frac{\partial\langle\overline{u}\rangle_{xz}}{\partial y} \partial y \approx 0.06W$$

Contribution of the pressure gradient



$$P_{press} = \langle \overline{u} \rangle_{xz} \frac{-dp_\infty}{dx} s_x s_z D^3 \approx 0.54W,$$

Budget of KE Fluxes

	Flux due to	Power (W)
	$\overline{P}_{wt}$	-0.23
$P_{flux-shear}$	$< u'v' >_{xz} < u >_{xz}$	0.62
$P_{flux-disp}$	$< u''v'' >_{xz} < u >_{xz}$	0.13
$P_{loss-shear}$	$< u'v' >_{xz} \frac{d<u>_{xz}}{dx}$	-0.12
$P_{loss-disp}$	$< u''v'' >_{xz} \frac{d<u>_{xz}}{dx}$	-0.06
P_{press}	$< u >_{xz} \frac{dp_\infty}{dx}$	0.54

$$P_{wt} = P_{flux-shear} + P_{flux-disp} - P_{loss-shear} - P_{loss-disp} + P_{press}$$

- All terms considered are of importance, including those associated with the dispersive stress.
- Budget is not balanced. Array is too small to be fully developed
  - Significant contribution of advection terms is expected

Conclusions

Impact of the fluxes of mean kinetic energy due to dispersive stresses (i.e. transport and dissipation) on the overall budget is significant. This is consistent with LES simulations by Calaf, Meneveau and Meyer, Phys. Fluids (2010).

As in Cal *et al.* JRSE (2010), flux due to Reynolds stress is of the same order as the wind turbine power and larger than the flux due to mean vertical velocity.

Salient conclusion: The present study reveals that the vertical entrainment of mean kinetic energy (i.e., dominant mechanism of energy exchange between large WT arrays and the ABL), is dominated by both mean and turbulent quantities.

Residual of the budget of mean kinetic energy fluxes is not zero. *Array is too small to be fully developed*

Future research will include the calculation of the flux of mean kinetic energy due to mean streamwise velocity.