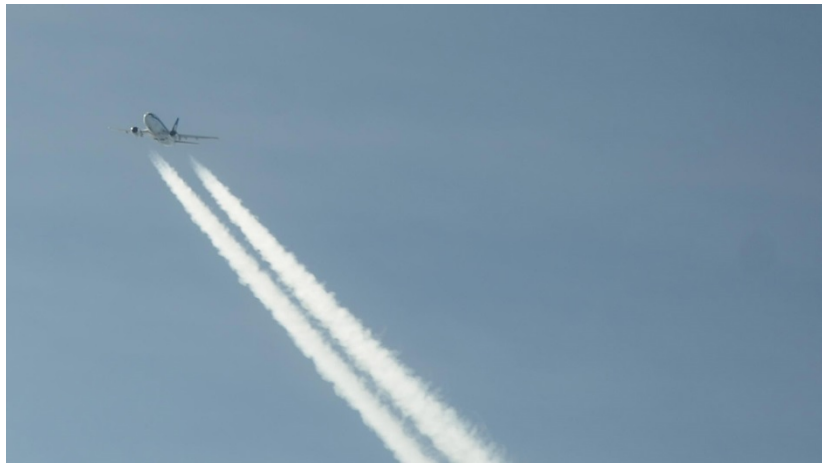
Influence of wind on receivers for solar power towers

OpenFOAM user conference 2014

Institute of Solar Research, German Aerospace Center
Robert Flesch

German Aerospace Center (DLR)



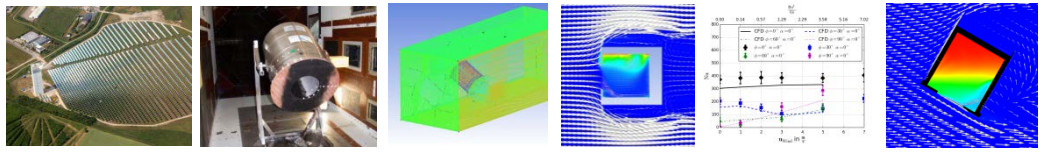
Aeronautics

Space

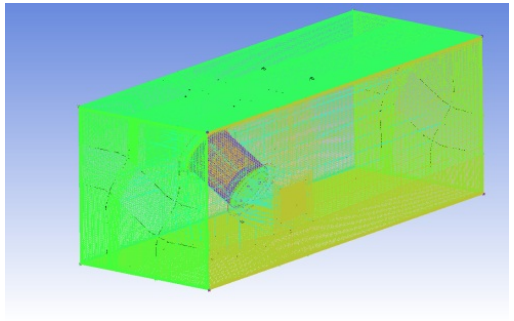
Transport

Energy

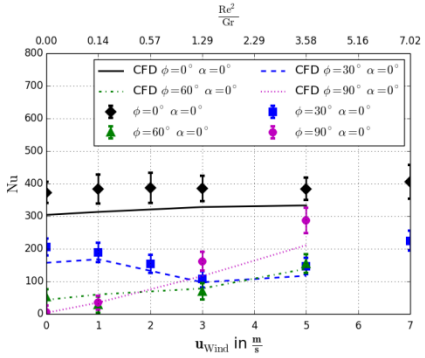
Outline



1. Introduction

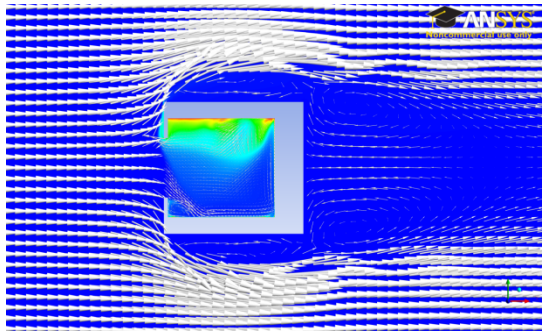


3. CFD setup

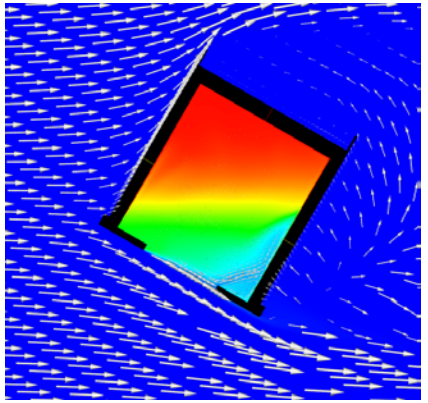


5. Validation

2. Experiment

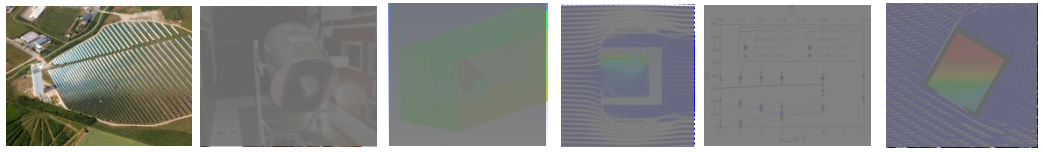


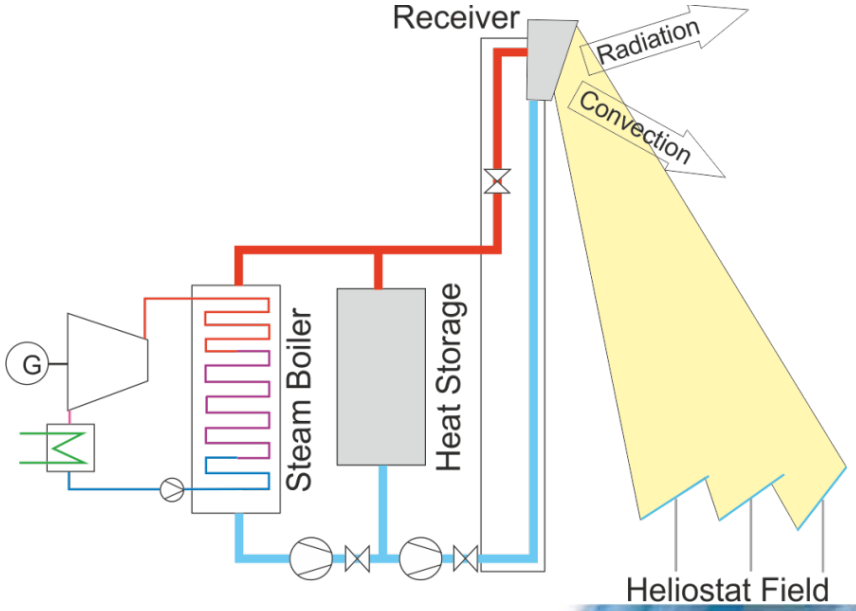
4. CFX comparison

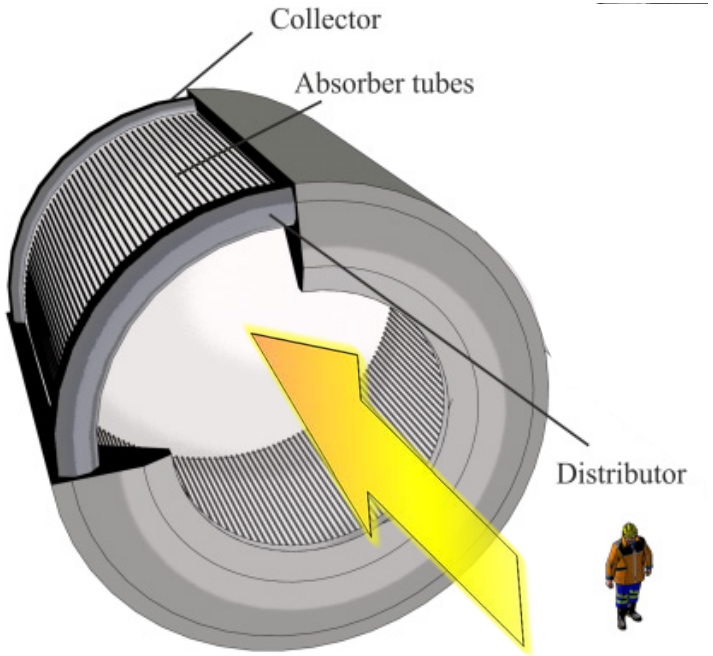


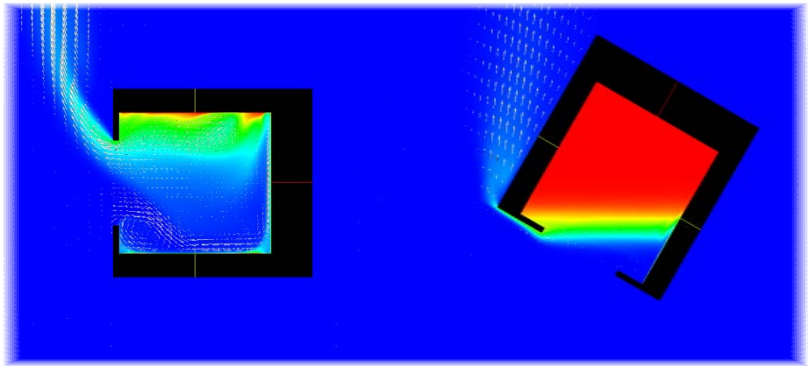
6. Heat loss mechanism

Cavity Receiver for Solar Power Towers

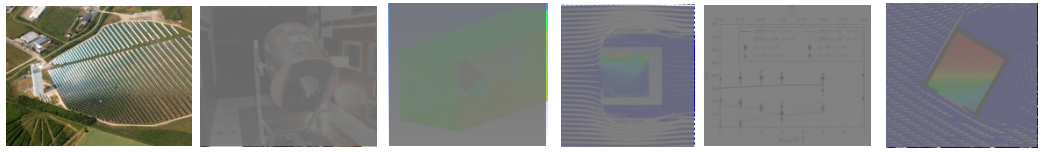








Aim and Approach



Questions

(1) What influence has wind on the losses?

- Different receiver inclinations
- Different wind directions
- Different wind speeds

(2) Can the influence of wind be analyzed with CFD?

- RANS approach

Approach

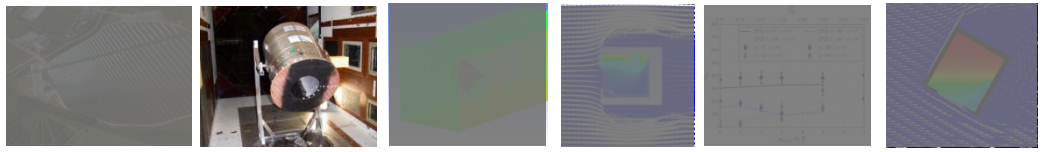
(1) Experiment

- Wind tunnel experiment
- Similarity approach

(2) CFD simulations

- Wind tunnel setup

Experimental Approach



- Similarity – main dimensionless numbers
  - Reynolds number $\mathrm{Re} = \frac{u_\infty D_i \rho}{\mu_{\mathrm{ref}}}$
  - Grashof number $\mathrm{Gr} = \frac{g D_i^3 \rho^2}{\mu_{\mathrm{ref}}^2} \frac{\mathrm{T_w} - \mathrm{T_\infty}}{T_{\mathrm{ref}}}$

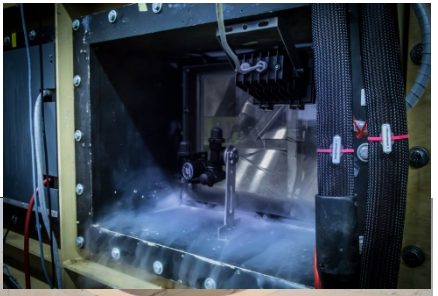
⇩

Reducing the ambient temperature

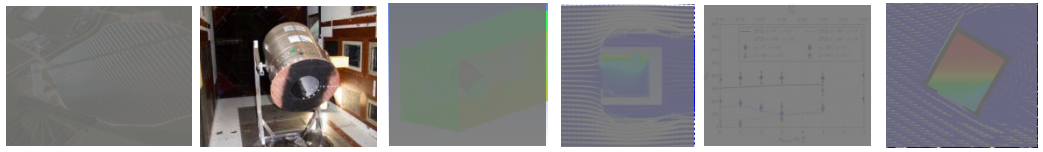
⇩

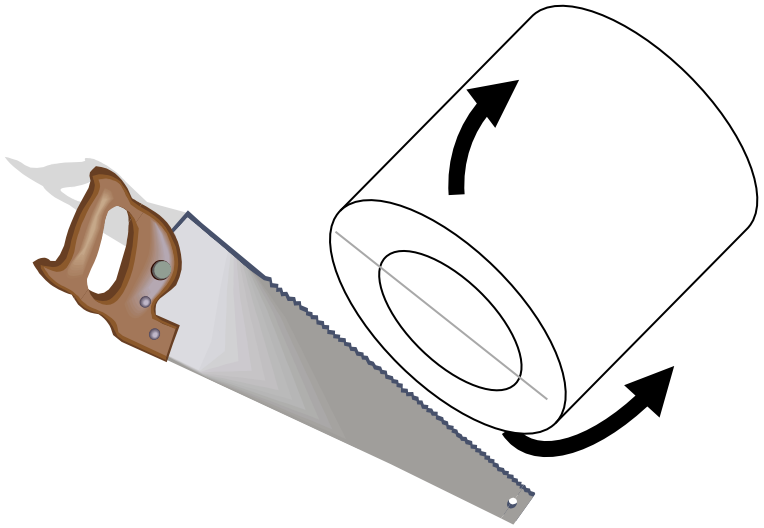
Upscaling

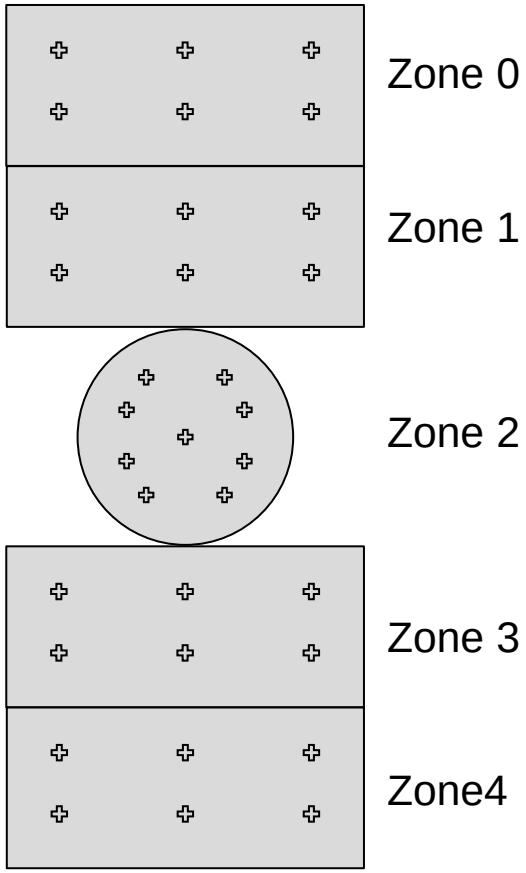
- Cryogenic wind tunnel cologne
  - Ambient temperature -173°C
  - Scaling factor 3.5



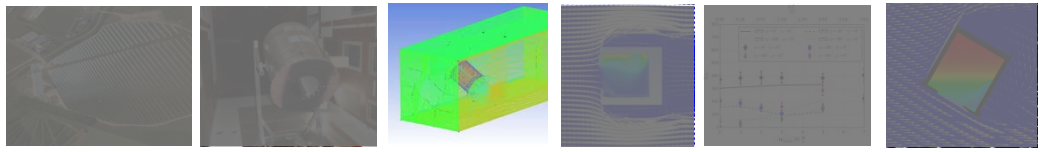
Experimental Approach
Local heat transfer







CFD approach
Why using OpenFOAM?



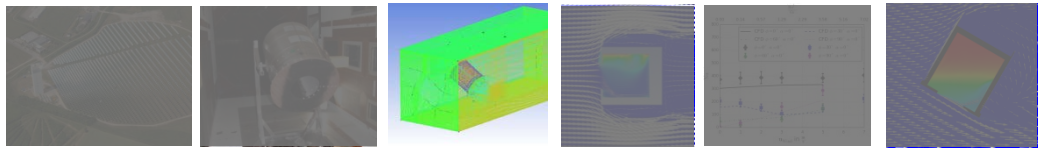
Benefits using OpenFOAM

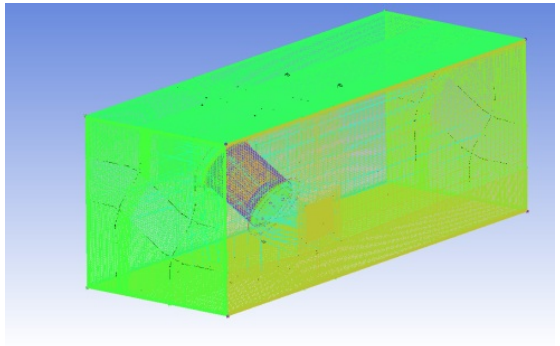
- **License costs**
  - High computational effort for heat loss simulation
- **Open source code**
  - Expandability
  - Clarity concerning the used models

Concerns about using OpenFOAM

- **Training period**
  - Lack of documentation
- **Reliability (Results)**
- **Prevalence**

CFD approach
Model setup





Mesh creation

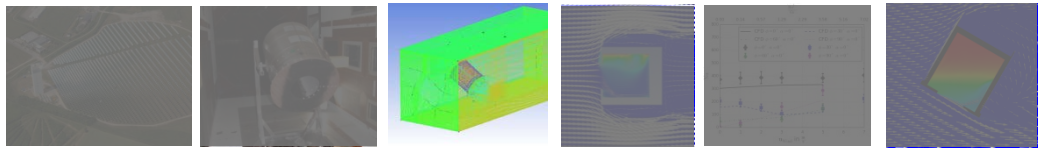
- ANSYS ICEM
- Appr. $3.5 \cdot 10^6$ Elements

- **Environment**
  - Wind tunnel setup
  - Nitrogen -173°C
    - Ideal Gas
    - Janaf thermo
    - Polynomial transport

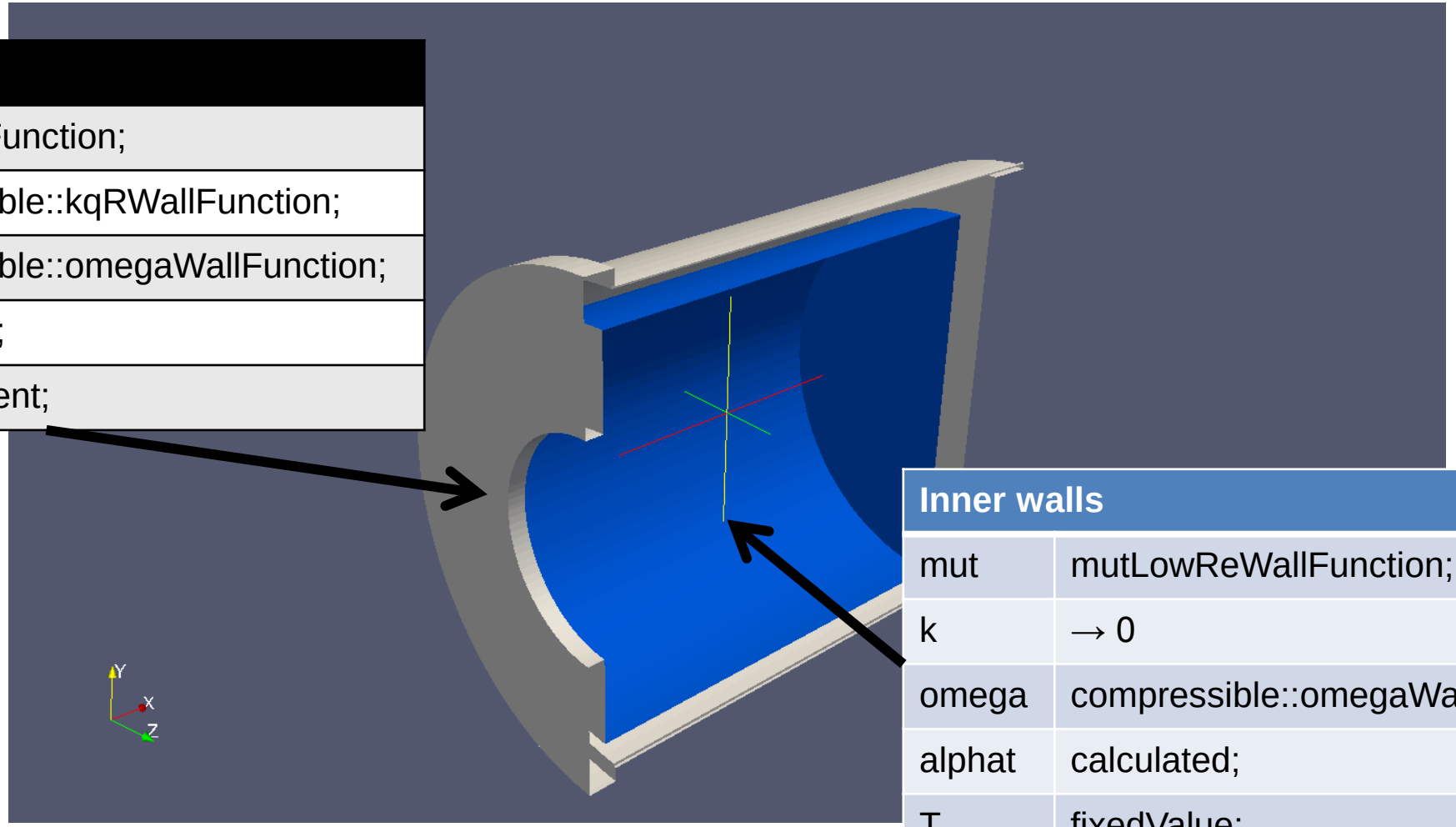
- **Turbulence model**
  - k-ω-SST
  - Prt=0.85

- **Solver**
  - OpenFOAM 2.3.0
  - buoyantPimpleFoam

CFD approach
Boundary conditions I

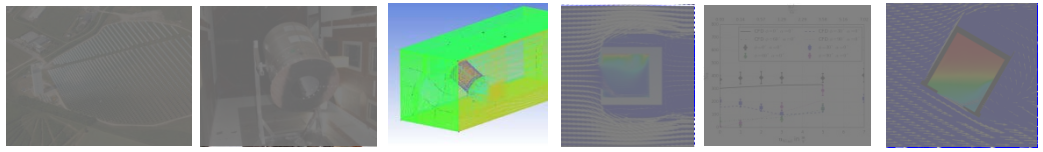


Outer walls	
mut	mutkWallFunction;
k	compressible::kqRWallFunction;
omega	compressible::omegaWallFunction;
alphat	calculated;
T	zeroGradient;



Inner walls	
mut	mutLowReWallFunction;
k	→ 0
omega	compressible::omegaWallFunction;
alphat	calculated;
T	fixedValue;

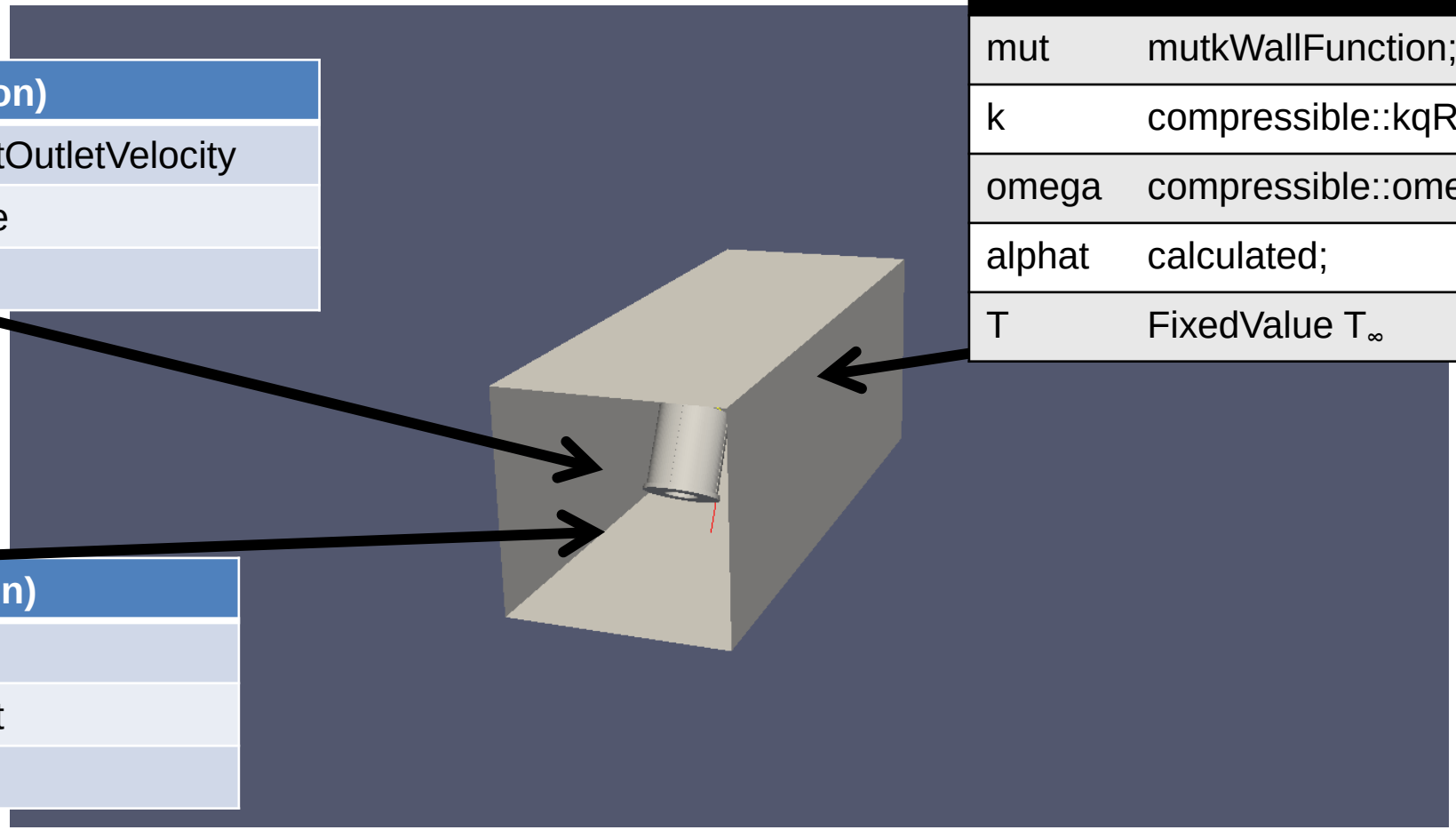
CFD approach
Boundary conditions II

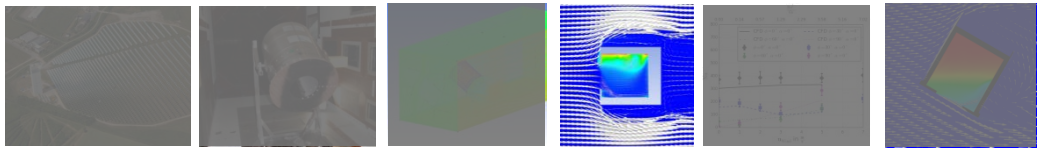


Inlet (natural convection)	
U	pressureInletOutletVelocity
p_rgh	totalPressure
T	inletOutlet

Inlet (forced convection)	
U	fixedValue
p_rgh	zeroGradient
T	fixedValue

Outer walls	
mut	mutkWallFunction;
k	compressible::kqRWallFunction;
omega	compressible::omegaWallFunction;
alphat	calculated;
T	FixedValue T_∞



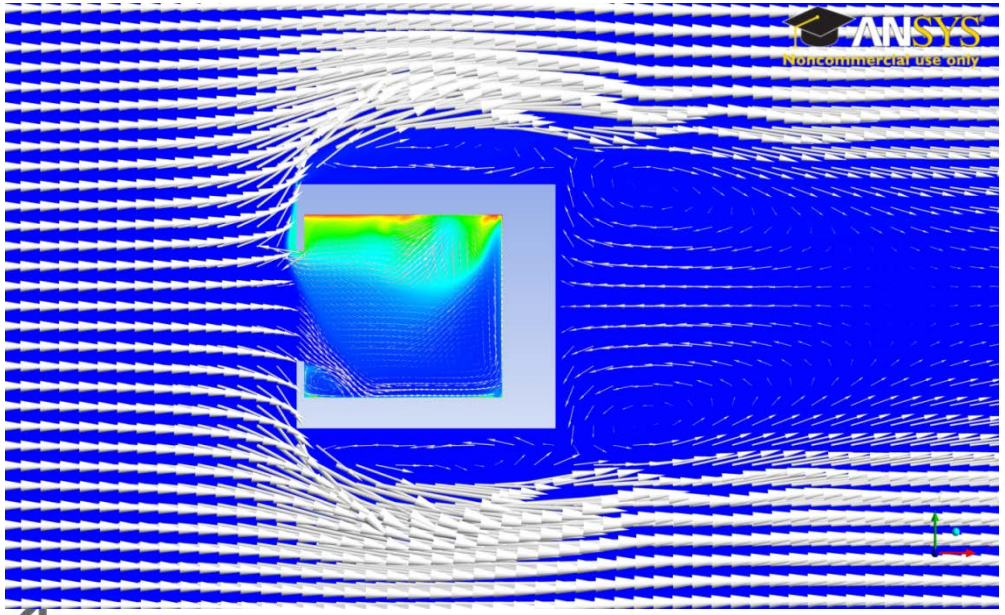


Results
CFX comparison

- Highest velocity 5 m/s
- Horizontal receiver
- Head-on wind
- Same fluid property functions

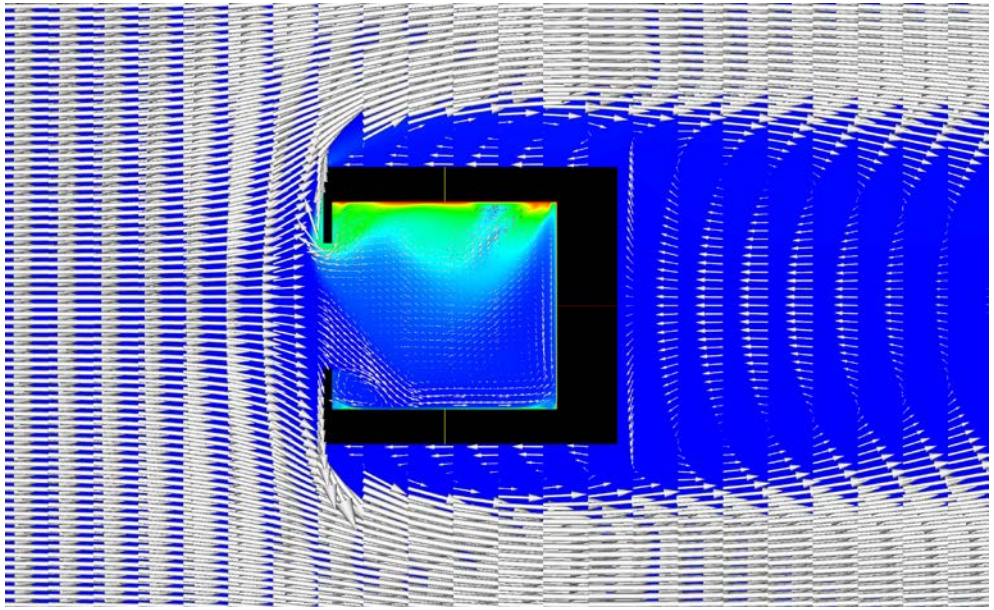
CFX

Nu = 305

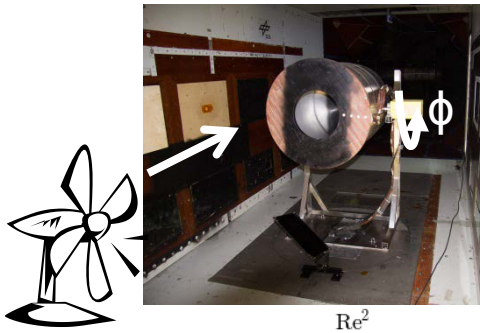


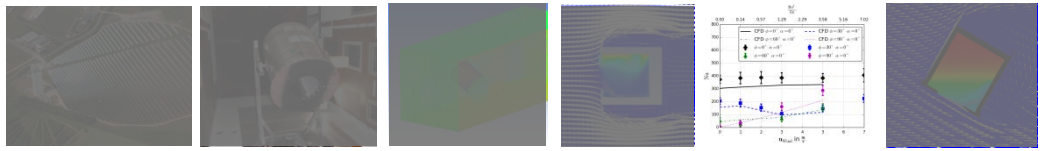
OpenFOAM

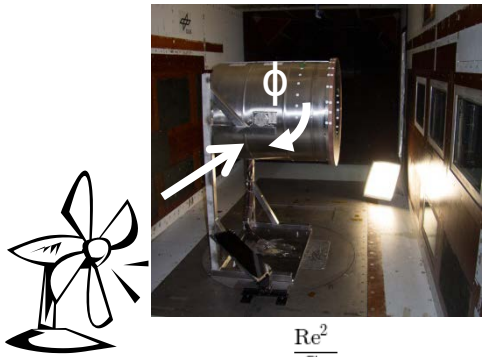
Nu = 308

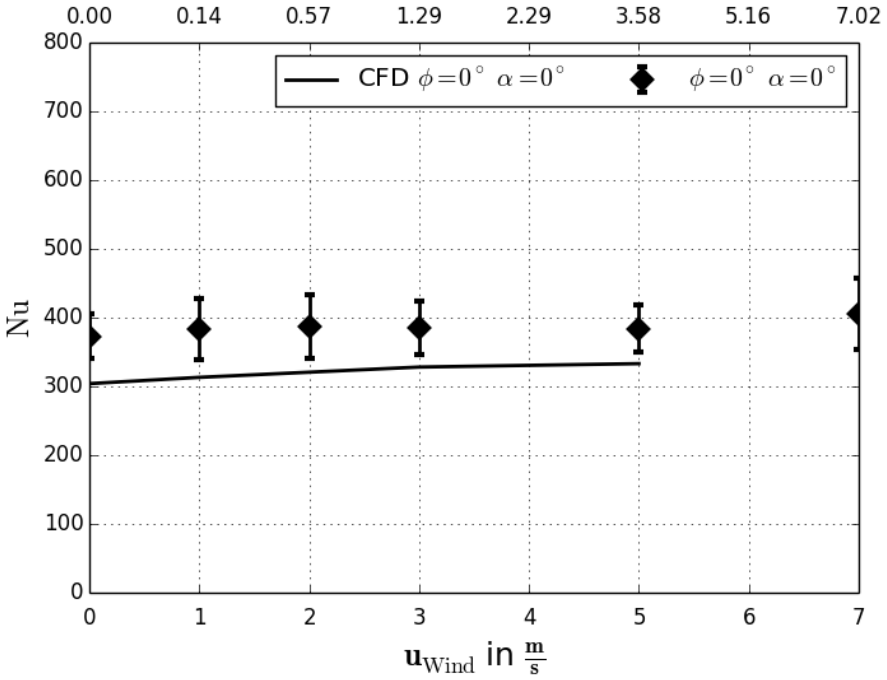


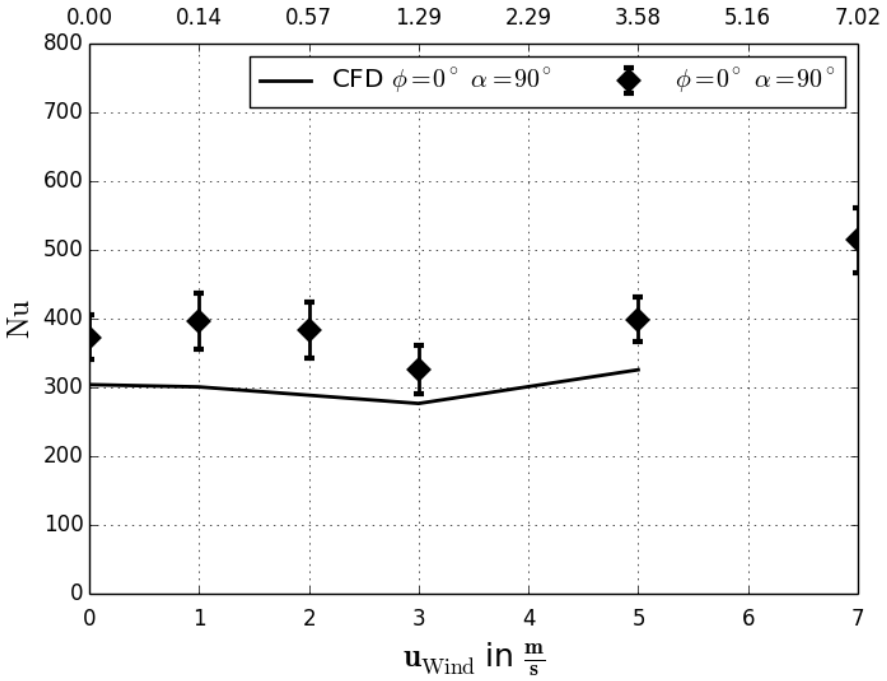
Validation


ϕ

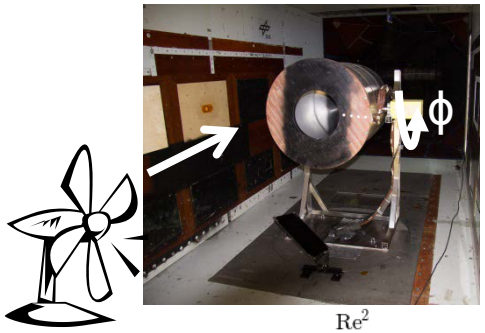


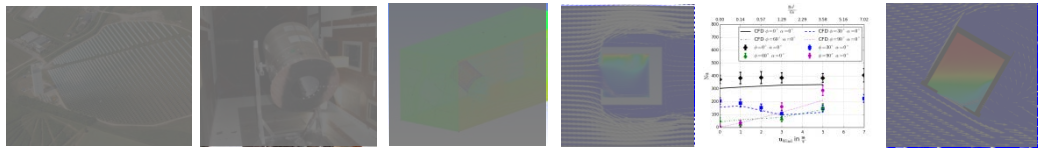

ϕ

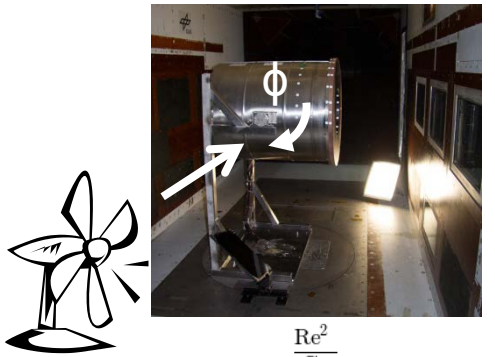

$\frac{Re^2}{Gr}$
0.00 0.14 0.57 1.29 2.29 3.58 5.16 7.02
CFD $\phi=0^\circ$ $\alpha=0^\circ$
$\phi=0^\circ$ $\alpha=0^\circ$
Nu
u_{Wind} in $\frac{m}{s}$

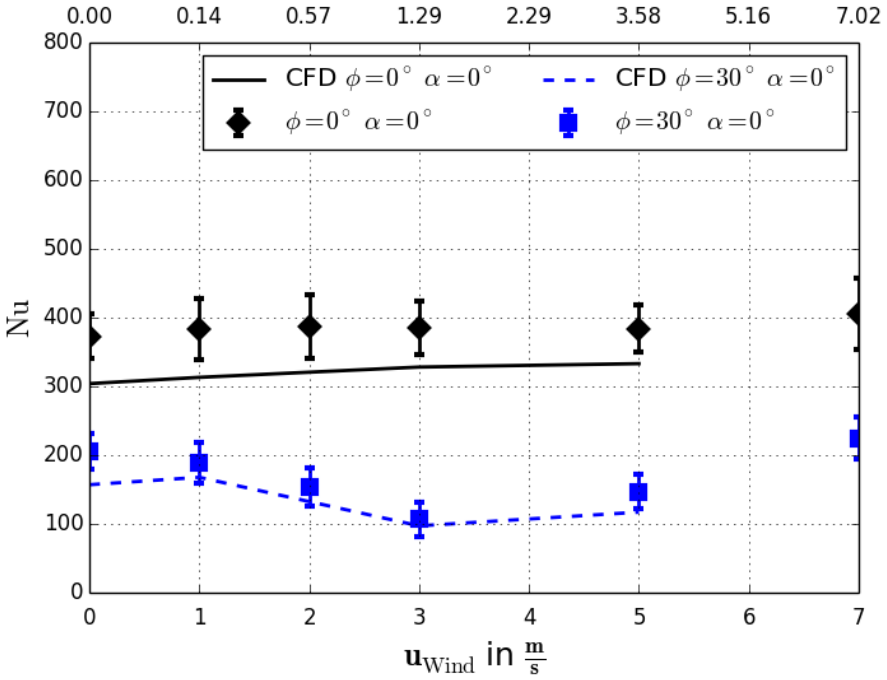

$\frac{Re^2}{Gr}$
0.00 0.14 0.57 1.29 2.29 3.58 5.16 7.02
CFD $\phi=0^\circ$ $\alpha=90^\circ$
$\phi=0^\circ$ $\alpha=90^\circ$
Nu
u_{Wind} in $\frac{m}{s}$

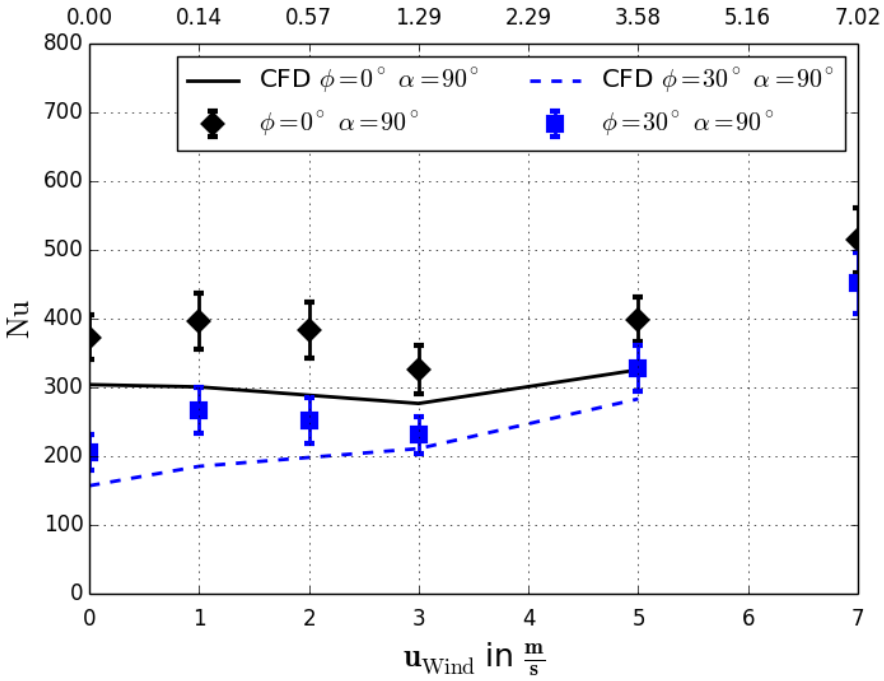
Validation


ϕ

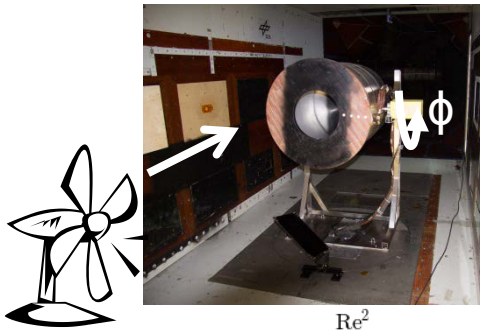


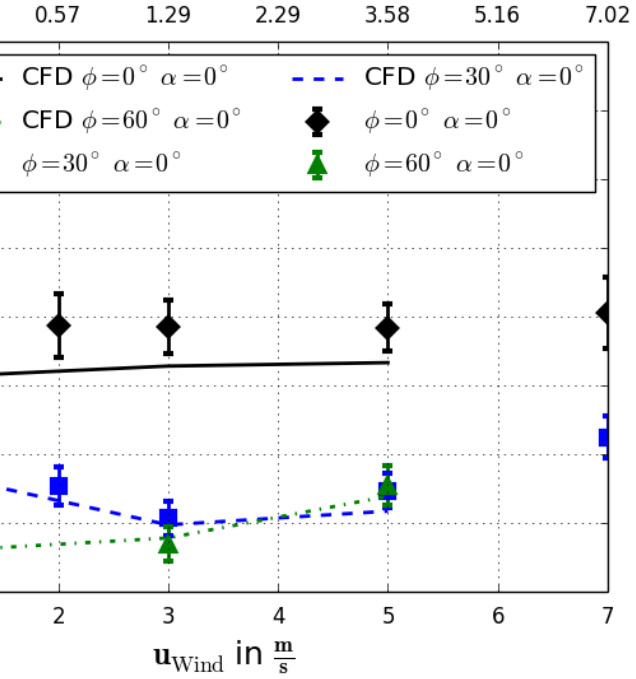

ϕ

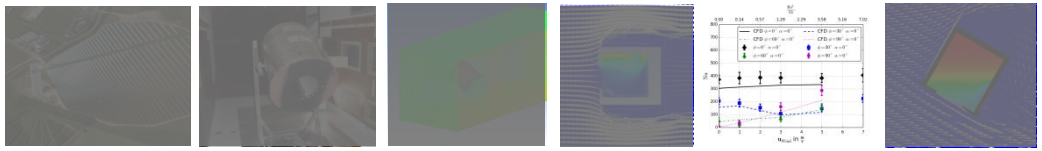

$\frac{Re^2}{Gr}$
0.00 0.14 0.57 1.29 2.29 3.58 5.16 7.02
800 700 600 500 400 300 200 100 0
CFD $\phi=0^\circ$ $\alpha=0^\circ$
CFD $\phi=30^\circ$ $\alpha=0^\circ$
$\phi=0^\circ$ $\alpha=0^\circ$
$\phi=30^\circ$ $\alpha=0^\circ$
Nu
0 1 2 3 4 5 6 7
$\mathbf{u}_{Wind}$ in $\frac{m}{s}$

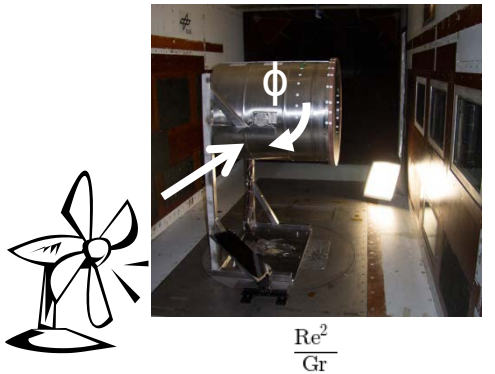

$\frac{Re^2}{Gr}$
0.00 0.14 0.57 1.29 2.29 3.58 5.16 7.02
800 700 600 500 400 300 200 100 0
CFD $\phi=0^\circ$ $\alpha=90^\circ$
CFD $\phi=30^\circ$ $\alpha=90^\circ$
$\phi=0^\circ$ $\alpha=90^\circ$
$\phi=30^\circ$ $\alpha=90^\circ$
Nu
0 1 2 3 4 5 6 7
$\mathbf{u}_{Wind}$ in $\frac{m}{s}$

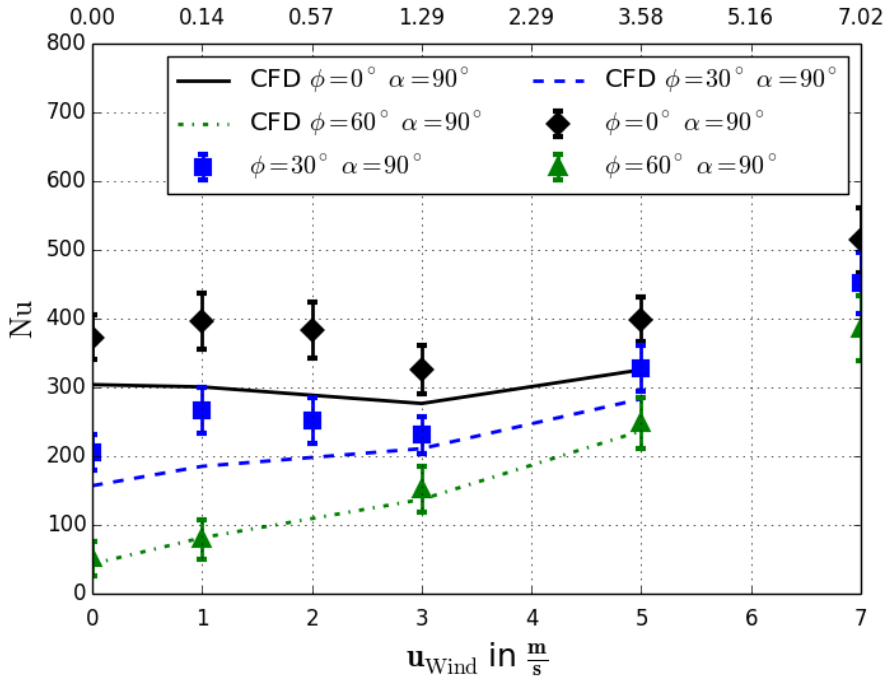
Validation


ϕ

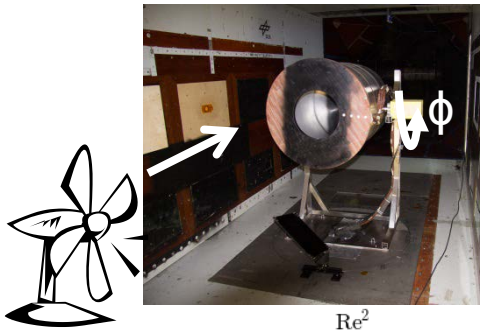

$\frac{Re^2}{Gr}$
0.00 0.14 0.57 1.29 2.29 3.58 5.16 7.02
CFD $\phi=0^\circ$ $\alpha=0^\circ$
CFD $\phi=30^\circ$ $\alpha=0^\circ$
CFD $\phi=60^\circ$ $\alpha=0^\circ$
$\phi=0^\circ$ $\alpha=0^\circ$
$\phi=30^\circ$ $\alpha=0^\circ$
$\phi=60^\circ$ $\alpha=0^\circ$
Nu
$\mathbf{u}_{Wind}$ in $\frac{m}{s}$

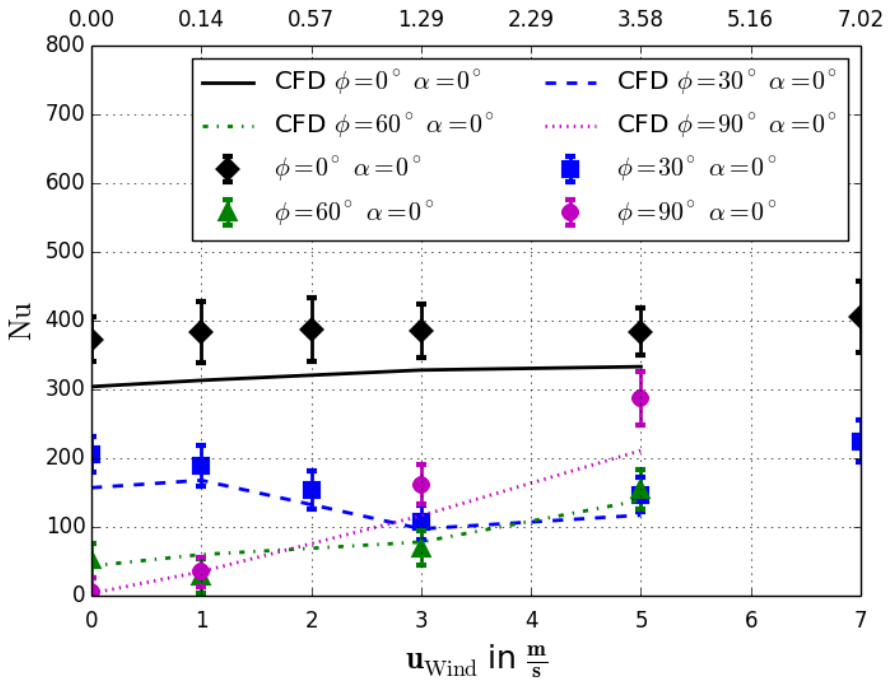


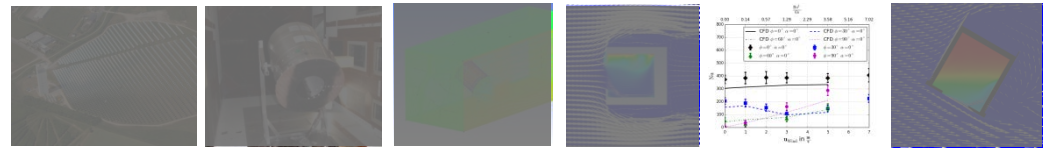

ϕ

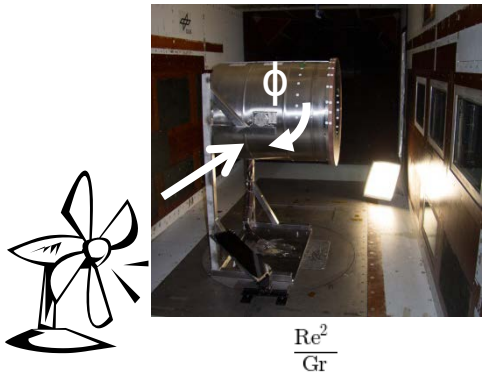

$\frac{Re^2}{Gr}$
0.00 0.14 0.57 1.29 2.29 3.58 5.16 7.02
CFD $\phi=0^\circ$ $\alpha=90^\circ$
CFD $\phi=30^\circ$ $\alpha=90^\circ$
CFD $\phi=60^\circ$ $\alpha=90^\circ$
$\phi=0^\circ$ $\alpha=90^\circ$
$\phi=30^\circ$ $\alpha=90^\circ$
$\phi=60^\circ$ $\alpha=90^\circ$
Nu
$\mathbf{u}_{Wind}$ in $\frac{m}{s}$

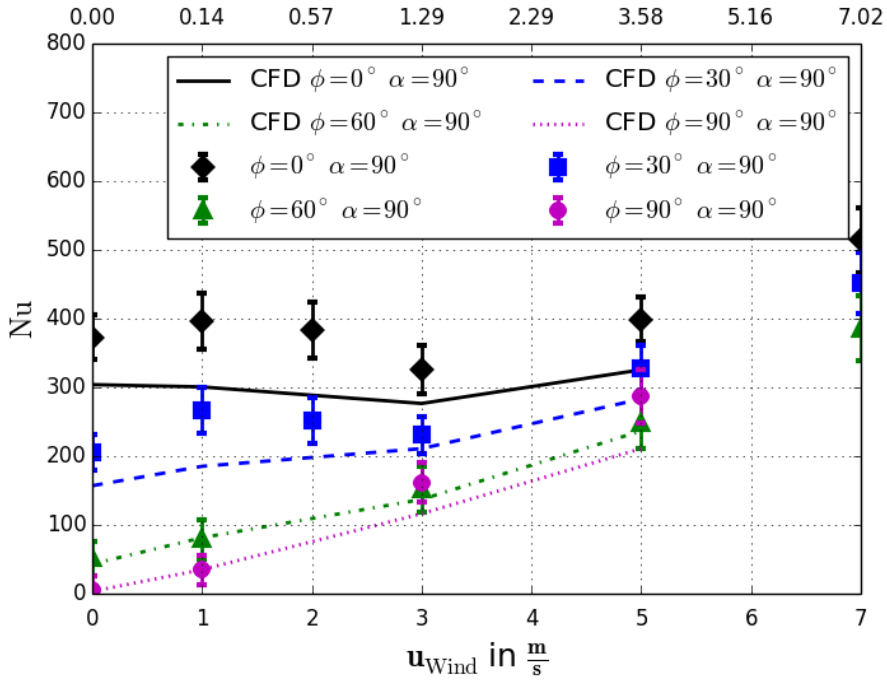
Validation


ϕ

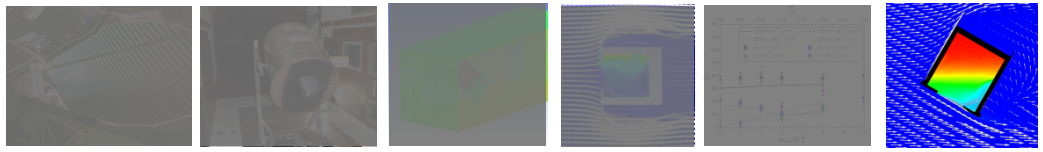

$\frac{Re^2}{Gr}$
0.00 0.14 0.57 1.29 2.29 3.58 5.16 7.02
CFD $\phi=0^\circ$ $\alpha=0^\circ$
CFD $\phi=30^\circ$ $\alpha=0^\circ$
CFD $\phi=60^\circ$ $\alpha=0^\circ$
CFD $\phi=90^\circ$ $\alpha=0^\circ$
$\phi=0^\circ$ $\alpha=0^\circ$
$\phi=30^\circ$ $\alpha=0^\circ$
$\phi=60^\circ$ $\alpha=0^\circ$
$\phi=90^\circ$ $\alpha=0^\circ$
Nu
u_{Wind} in $\frac{m}{s}$



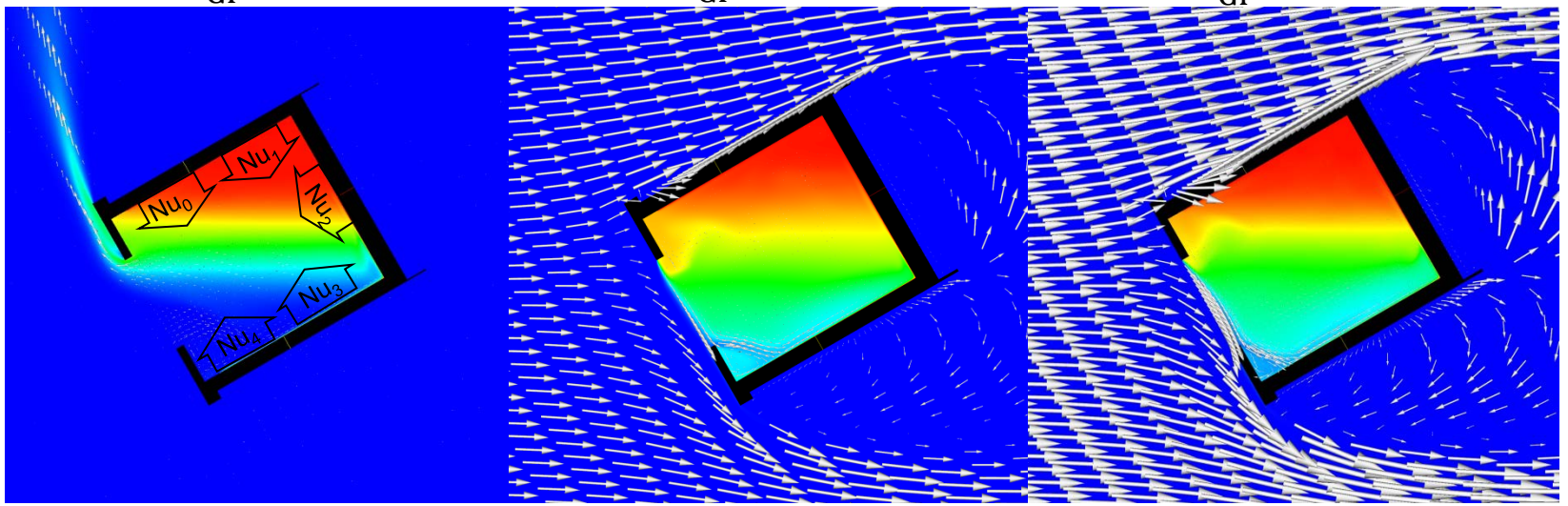

ϕ

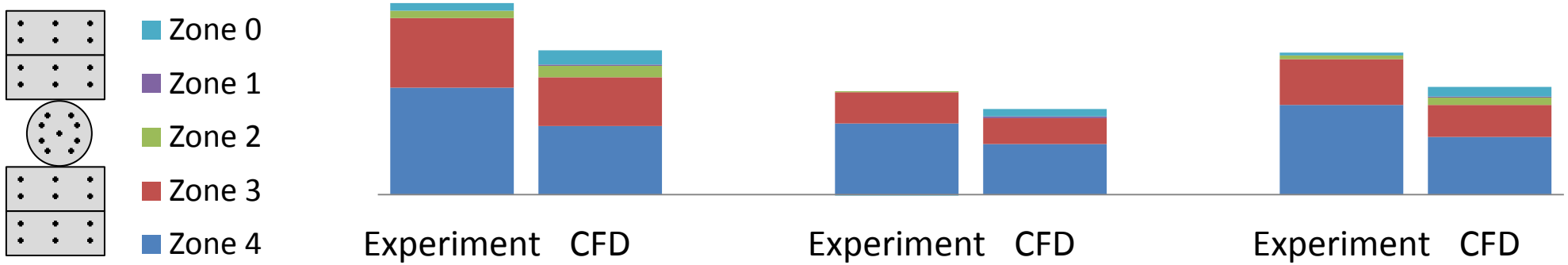

$\frac{Re^2}{Gr}$
0.00 0.14 0.57 1.29 2.29 3.58 5.16 7.02
CFD $\phi=0^\circ$ $\alpha=90^\circ$
CFD $\phi=30^\circ$ $\alpha=90^\circ$
CFD $\phi=60^\circ$ $\alpha=90^\circ$
CFD $\phi=90^\circ$ $\alpha=90^\circ$
$\phi=0^\circ$ $\alpha=90^\circ$
$\phi=30^\circ$ $\alpha=90^\circ$
$\phi=60^\circ$ $\alpha=90^\circ$
$\phi=90^\circ$ $\alpha=90^\circ$
Nu
u_{Wind} in $\frac{m}{s}$

Validation
Loss Mechanism

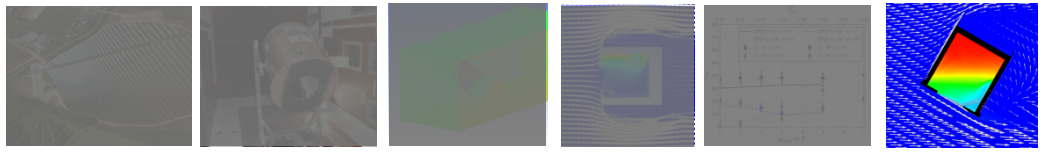


$\frac{Re^2}{Gr} = 0$ $\frac{Re^2}{Gr} = 1{,}29$ $\frac{Re^2}{Gr} = 3{,}59$

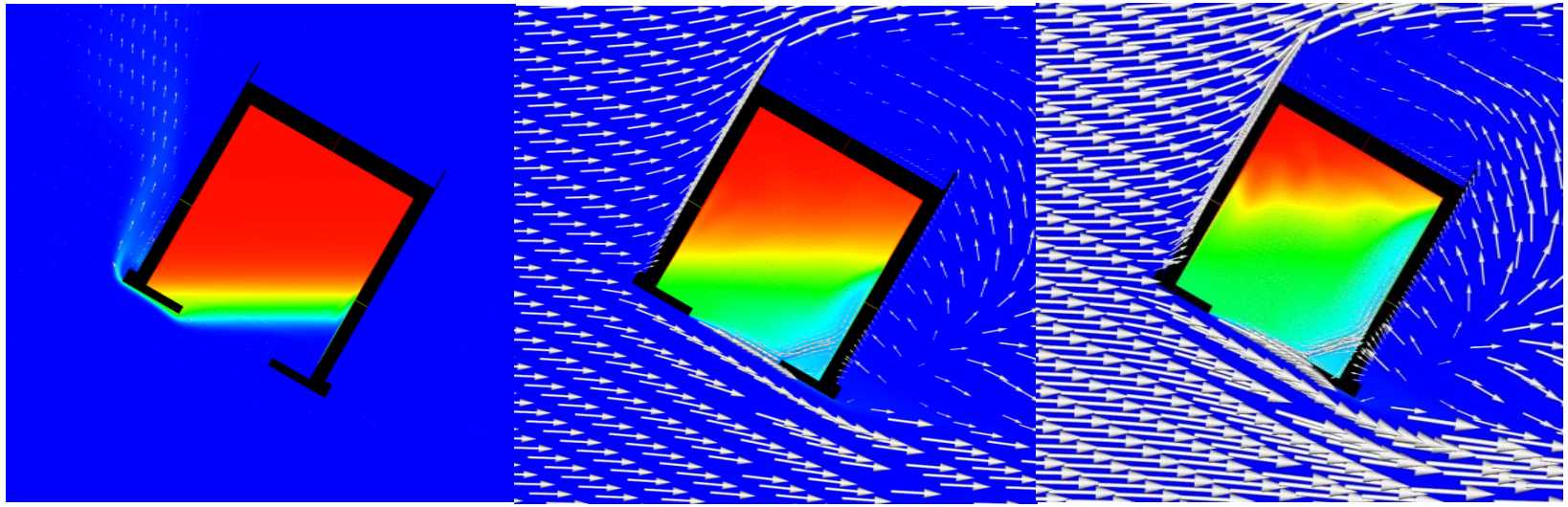


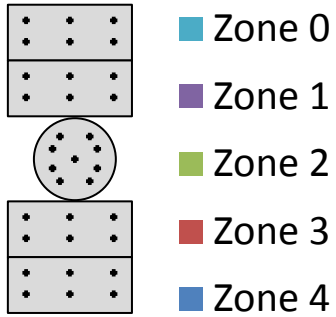


Validation
Loss Mechanism

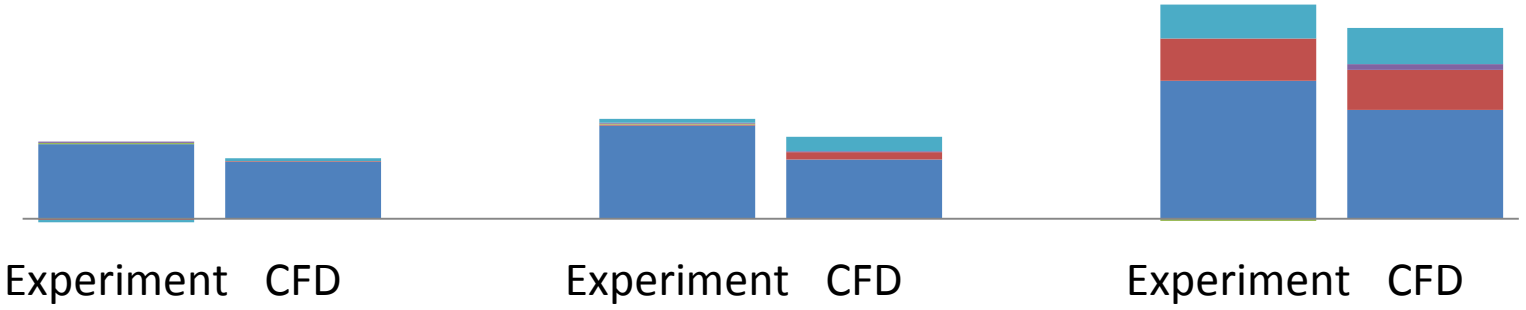


$\frac{Re^2}{Gr} = 0$ $\frac{Re^2}{Gr} = 1{,}29$ $\frac{Re^2}{Gr} = 3{,}59$

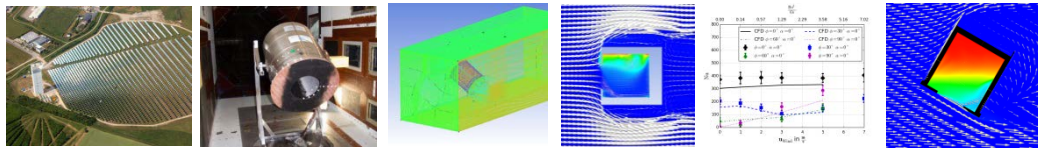




Zone 0
Zone 1
Zone 2
Zone 3
Zone 4



Validation
Model errors



Simulation

- Constant wall temperature
- No conduction
- Aperture is adiabatic

Experiment

- Constant heat flux in zones
  - Deviation in cases of nonuniform heat transfer
- Conduction in cylinder and through insulation
- Aperture is not adiabatic

Summary and Outlook

Summary

- **Influence of wind**
  - horizontal receivers → small influence
  - increasing inclination angle → increasing influence
- **CFD simulations**
  - Capable to predict the changes due to wind
  - Absolute values are slightly underpredicted
- **OpenFOAM**
  - Powerful CFD tool
  - Improvable documentation

Outlook

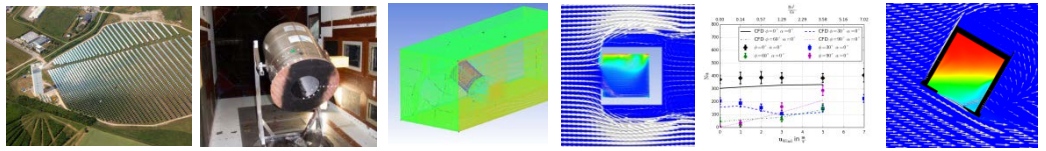
- Analysis of reduction strategies using OpenFOAM
- Prospective use of OpenFOAM in solar research

Thank you for your attention! Questions?

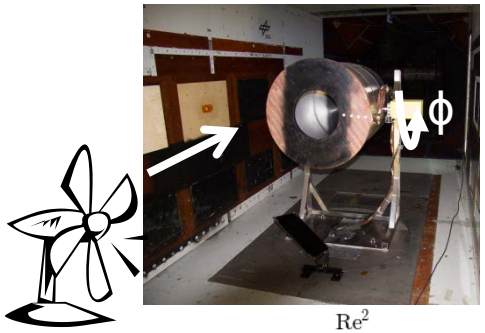
Ministerium für Innovation,
Wissenschaft und Forschung
des Landes Nordrhein-Westfalen

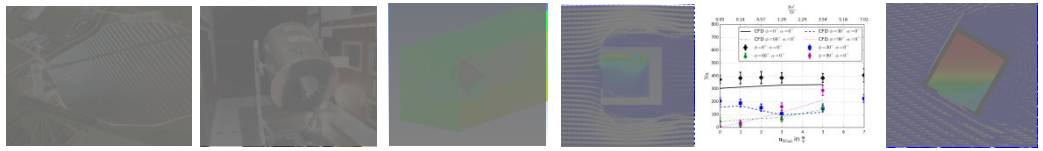
Project Start-SF
contract 323-2010-006

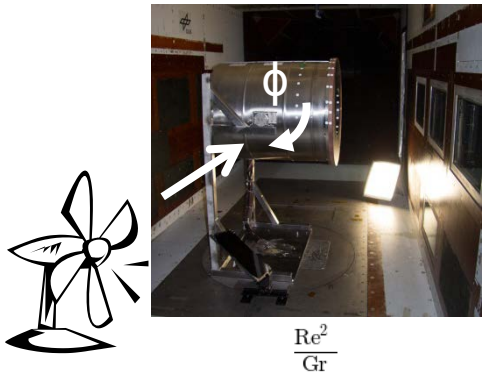
Backup

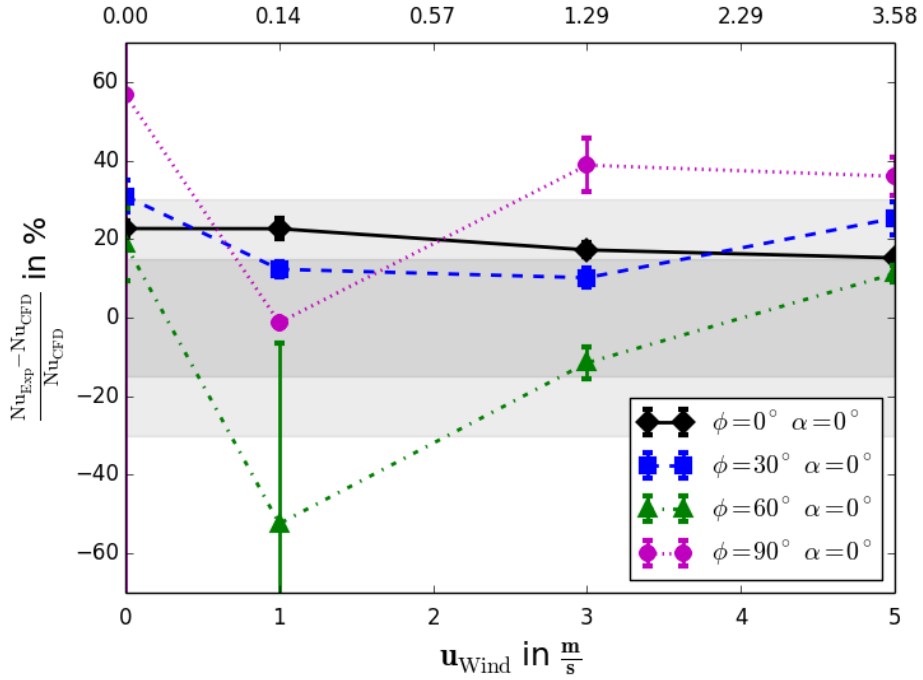


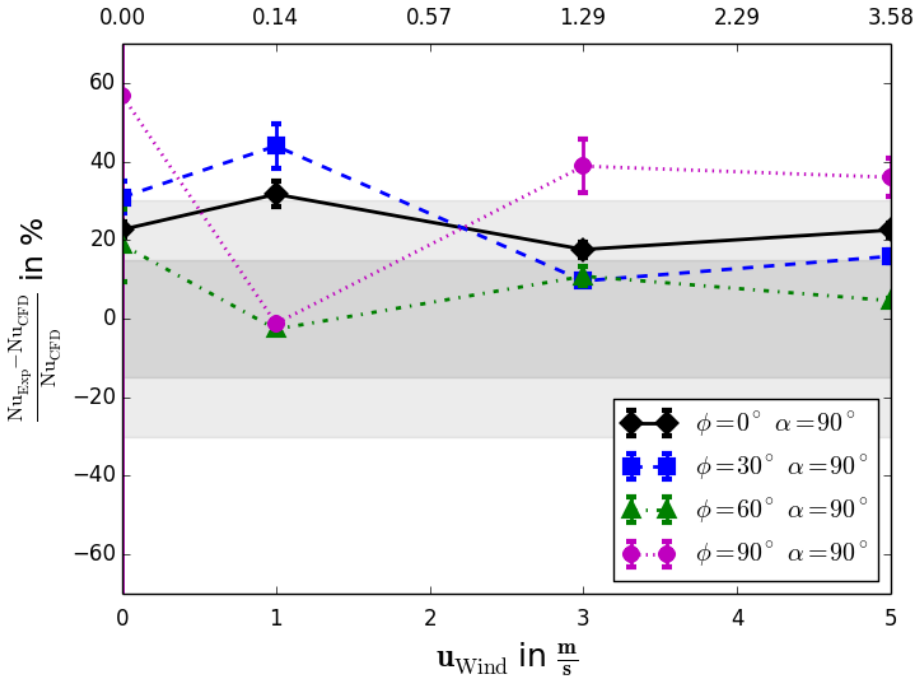
Validation


ϕ




ϕ


$\frac{Re^2}{Gr}$
0.00
0.14
0.57
1.29
2.29
3.58
60
40
20
0
−20
−40
−60
$\frac{Nu_{Exp}-Nu_{CFD}}{Nu_{CFD}}$ in %
0
1
2
3
4
5
u_{Wind} in $\frac{m}{s}$
$\phi=0°$ $\alpha=0°$
$\phi=30°$ $\alpha=0°$
$\phi=60°$ $\alpha=0°$
$\phi=90°$ $\alpha=0°$


$\frac{Re^2}{Gr}$
0.00
0.14
0.57
1.29
2.29
3.58
60
40
20
0
−20
−40
−60
$\frac{Nu_{Exp}-Nu_{CFD}}{Nu_{CFD}}$ in %
0
1
2
3
4
5
u_{Wind} in $\frac{m}{s}$
$\phi=0°$ $\alpha=90°$
$\phi=30°$ $\alpha=90°$
$\phi=60°$ $\alpha=90°$
$\phi=90°$ $\alpha=90°$

Turbulent heat transfer