

## *Windsimulaties op de meteorologische microschaal*

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**TU/e** Technische Universiteit  
Eindhoven  
University of Technology

Where innovation starts

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## Introduction

### 1. ASSESSMENT METHODS

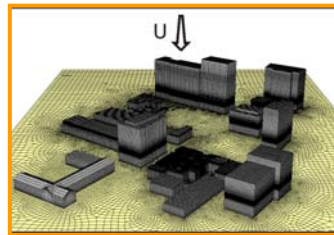
Bluff body aerodynamics is very complex.

→ Bluff body aerodynamics research is performed by:

(1) On-site measurements

(2) Wind tunnel measurements

(3) Numerical simulation with Computational Fluid Dynamics (CFD)



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## Introduction

### 1. ASSESSMENT METHODS

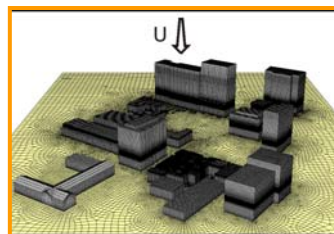
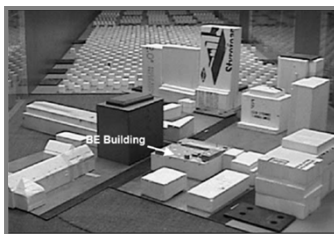
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## Introduction

### 2. COMPUTATIONAL FLUID DYNAMICS (CFD)

- **Large range of length scales**
  - Several cm to several km
  - For heat transfer even to  $\mu\text{m}$
- **Large range of complexity**
  - Single building to large parts of an urban area



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## Introduction

### 2. COMPUTATIONAL FLUID DYNAMICS (CFD)

**Three case studies, with increasing spatial length scale:**

- I. **Aerodynamics of Venturi-shaped roof**
- II. **Natural ventilation of Amsterdam ArenA**
- III. **Wind flow in harbor of Rotterdam**



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# AERODYNAMICS OF VENTURI-SHAPED ROOF

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Prof.dr.ir. Bert Blocken  
Dr.ir. Ben Bronsema  
Dr.ir. Lourens Aanen

TU Eindhoven | KU Leuven  
TU Eindhoven | KU Leuven  
TU Delft | Bronconsult  
Peutz BV



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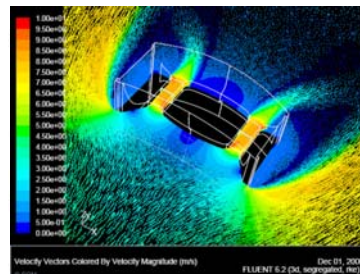
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## Aerodynamics of Venturi-shaped roof

- Introduction
  - Wind energy in the built environment (example)
    - Pearl River tower (Guangzhou, China)



<http://mktalibati.com>



<http://www.sordi.com>



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## Aerodynamics of Venturi-shaped roof

- Introduction

- Natural ventilation enhancement (examples)

- Liberty Tower of Meiji University in Japan (Chikamoto et al. 1999)
- GSW headquarters in Berlin, Germany (Sauerbruch et al. 2000)



<http://en.wikipedia.org/wiki/>



<http://architecture.mapolismagazin.com/>

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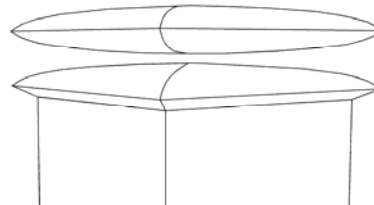
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## Aerodynamics of Venturi-shaped roof

- Introduction

- Research topic

- The influence of the dimensions of a venturi-shaped roof, designed by Bronsema (Earth, Wind & Fire – Air-conditioning powered by Nature, Bronsema 2010), on the flow.
- Guiding vanes
- Dimensions/curvature



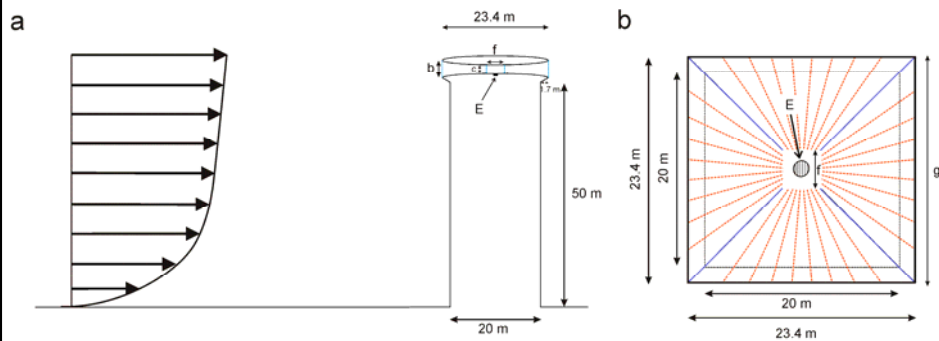
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## Aerodynamics of Venturi-shaped roof

- Geometry
  - Geometry used in wind tunnel and CFD



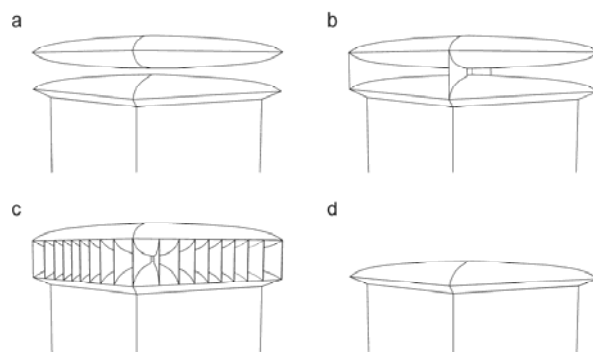
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## Aerodynamics of Venturi-shaped roof

- Geometry
  - Four different configurations



a-c tested in  
wind tunnel

Guiding vanes thickness = 0.55 mm, no roof supports in CFD model

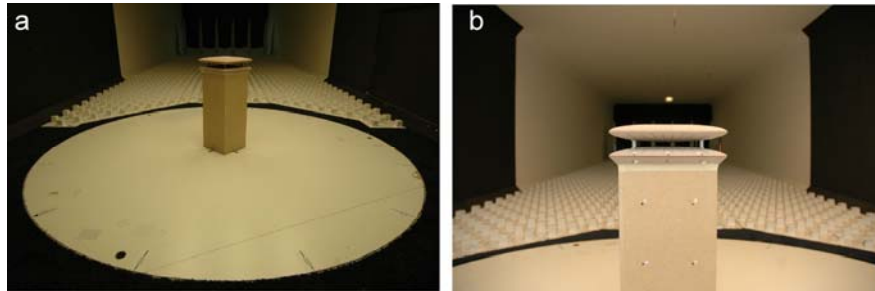
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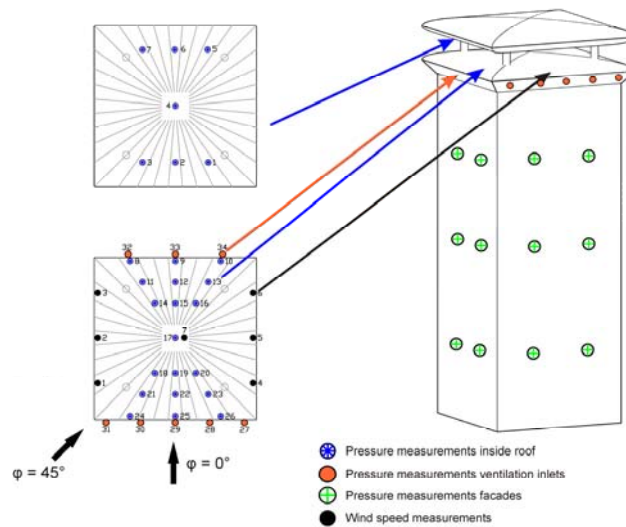
## Aerodynamics of Venturi-shaped roof

- Wind tunnel measurements
- Model



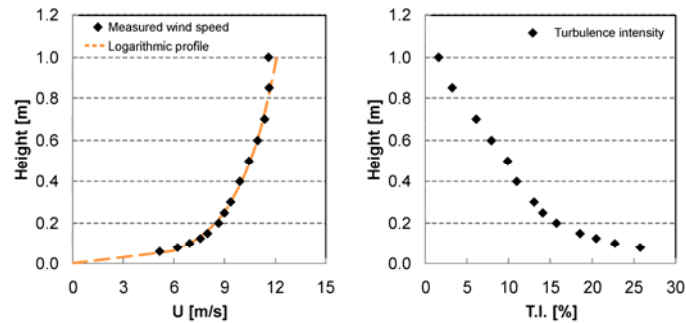
Atmospheric Boundary Layer wind tunnel of Peutz BV at Molenhoek

## Aerodynamics of Venturi-shaped roof



## Aerodynamics of Venturi-shaped roof

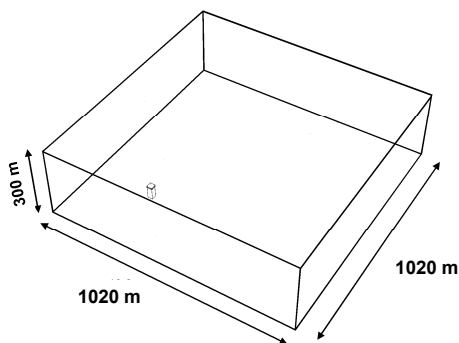
- Wind tunnel measurements by Peutz
- Incident profiles



The measured incident mean wind speed profile resembles a log law profile with  $u^* = 0.956$  m/s and  $y_0 = 0.005$  m (full-scale  $y_0 = 0.5$  m)

## Aerodynamics of Venturi-shaped roof

- Computational model and parameters
- Model



van Hooff, T., Blocken, B., Aanen, L., Bronsema, B., 2011. A venturi-shaped roof for wind-induced natural ventilation of buildings: wind tunnel and CFD evaluation of different design configurations. *Building and Environment*, 46(9), 1797-1807.

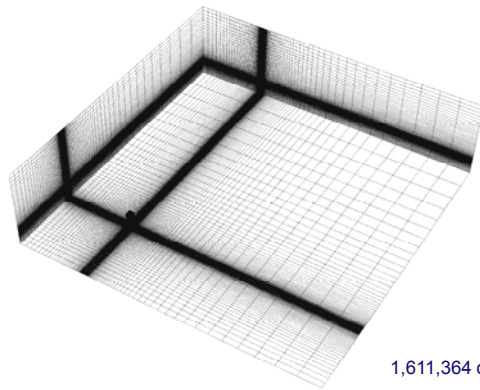
Blocken, B., van Hooff, T., Aanen, L., Bronsema, B., 2011. Computational analysis of the performance of a venturi-shaped roof for natural ventilation: venturi-effect versus wind-blocking effect. *Computers & Fluids*, 48(1), 202-213.

- Domain:  $1,020 \times 1,020 \times 300$  m<sup>3</sup> (L x W x H); in accordance with best practice guidelines of Franke et al. (2007) and Tominaga et al. (2008)



## Aerodynamics of Venturi-shaped roof

- Computational model and parameters
  - Grids



1,611,364 cells

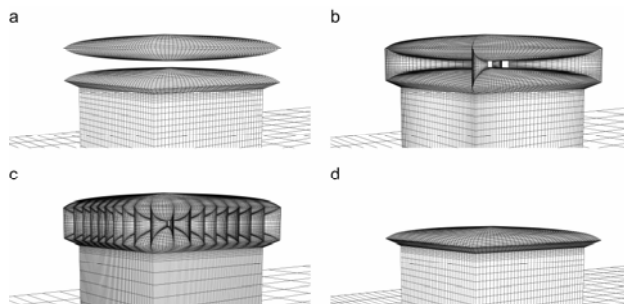


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## Aerodynamics of Venturi-shaped roof

- Computational model and parameters
  - Grids



- Grids created using the surface-grid extrusion technique described in:

Van Hooff, T., Blocken, B., 2010. Coupled urban wind flow and indoor natural ventilation modelling on a high resolution grid: A case study for the Amsterdam ArenA stadium. *Environmental Modelling & Software* 25, 51-65.



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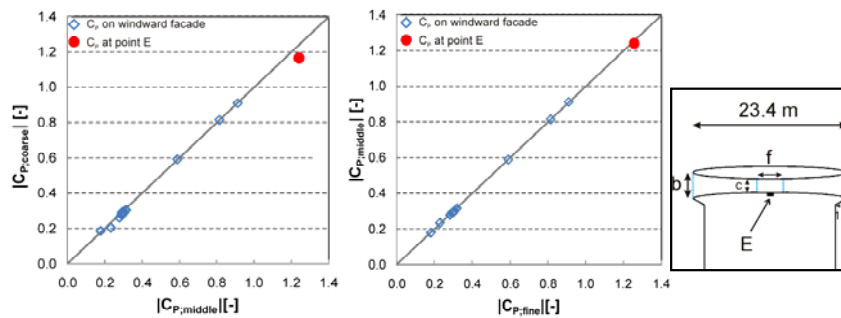
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## Aerodynamics of Venturi-shaped roof

- Computational model and parameters

- Grids

- Grid-sensitivity analysis ( $C_p$  windward facade)



## Aerodynamics of Venturi-shaped roof

- Computational model and parameters

- Boundary conditions

- Measured incident profile of  $U$
- Turbulent kinetic energy  $k$  and turbulence dissipation rate  $\varepsilon$ :

$$k = 0.5(I_U U)^2 \quad \varepsilon = \frac{(u_{ABL}^*)^3}{\kappa(y + y_0)}$$

With  $u_{ABL}^* = 0.956$  m/s,  $y_0 = 0.5$  m. Assuming  $\sigma_u \gg \sigma_v$  and  $\sigma_w$ .

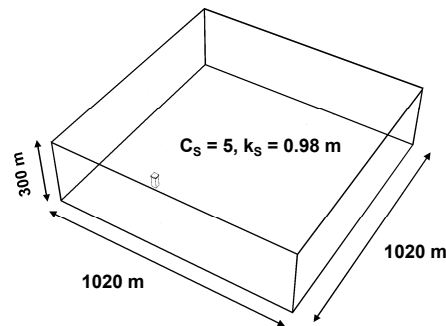
- Zero static pressure at the outlet of the domain
- Slip wall (zero normal velocity and zero normal gradients of all variables) at top of domain

## Aerodynamics of Venturi-shaped roof

- Computational model and parameters

- Boundary conditions (2)

- $C_s = 5$ ,  $k_s = 0.98$  m to fulfill:  $k_s = \frac{9.793 y_0}{C_s}$ ;  $k_s \leq y_p$



Blocken, B., Stathopoulos, T., Carmeliet, J., 2007.  
CFD simulation of the Atmospheric Boundary  
Layer: wall function problems. *Atmospheric  
Environment* 41(2), 238-252.

## Aerodynamics of Venturi-shaped roof

- Computational model and parameters

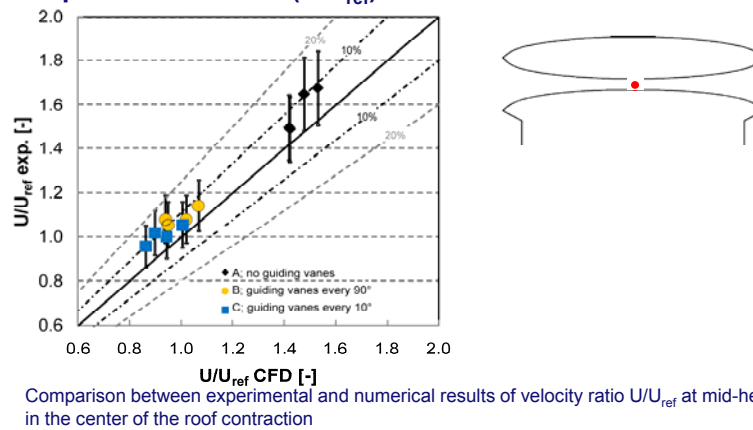
- Other computational parameters

- 3D steady-state CFD simulations
- RANS in combination with RNG k- $\epsilon$  model (Yakhot et al. 1992)
- Standard wall functions (Launder and Spalding 1974) with sand-grain roughness modifications (Cebeci and Bradshaw 1977)

## Aerodynamics of Venturi-shaped roof

- Results

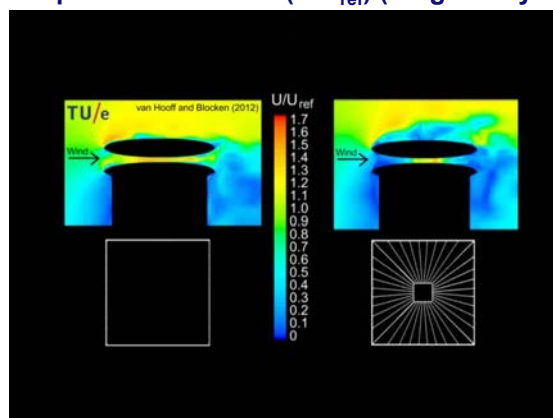
- Amplification factors ( $U/U_{ref}$ ) in center of roof



## Aerodynamics of Venturi-shaped roof

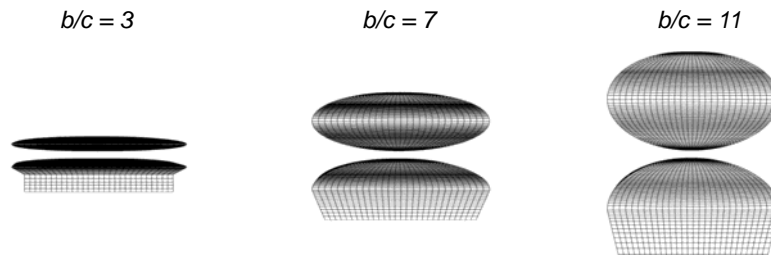
- Results

- Amplification factors ( $U/U_{ref}$ ) (Large Eddy Simulation)



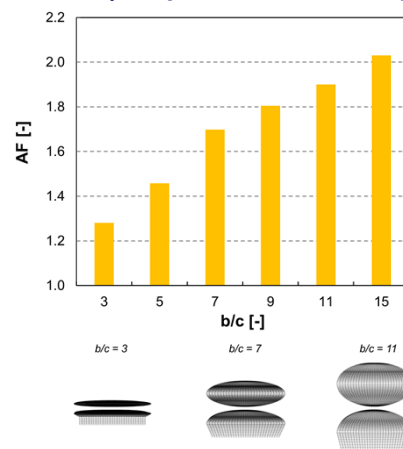
## Aerodynamics of Venturi-shaped roof

- Additional geometries
- Six different roof curvatures tested using CFD simulations



## Aerodynamics of Venturi-shaped roof

- Additional geometries
- Results | Amplification factors (averaged over centerline)



## Aerodynamics of Venturi-shaped roof

- **More information:**

1. van Hooff T, Blocken B, Aanen L, Bronsema B, 2011. A venturi-shaped roof for wind-induced natural ventilation of buildings: wind tunnel and CFD evaluation of different design configurations. **Building and Environment** 46(9): 1797-1807.
2. Blocken B, van Hooff T, Aanen L, Bronsema B, 2011. Computational analysis of the performance of a venturi-shaped roof for natural ventilation: venturi-effect versus wind-blocking effect. **Computers & Fluids** 48(1): 202-213.
3. van Hooff T, Blocken B, Aanen L, Bronsema B, 2012. Numerical analysis of the performance of a venturi-shaped roof for natural ventilation: influence of building width. **Journal of Wind Engineering and Industrial Aerodynamics** 104-106, 419-427.



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## NATURAL VENTILATION OF AMSTERDAM ARENA

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TU Eindhoven | KU Leuven



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## Natural ventilation of Amsterdam Arena

- Introduction

- Sports stadia are becoming increasingly multifunctional.
  - Concerts, congresses etc.
- Stadia are more often equipped with a retractable roof.
- Stadia are not always equipped with HVAC systems.



Stadium indoor climate can become a problem!



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## Natural ventilation of Amsterdam Arena

- Stadium description

- Amsterdam 'ArenA'
  - Completed in 1995 in Amsterdam
  - Multifunctional stadium
  - Capacity of 51,628 spectators
  - Retractable (semi-)transparent roof
  - No HVAC systems
  - Natural ventilation through the roof and openings in the building facade



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## Natural ventilation of Amsterdam Arena

- Stadium description

- Surroundings



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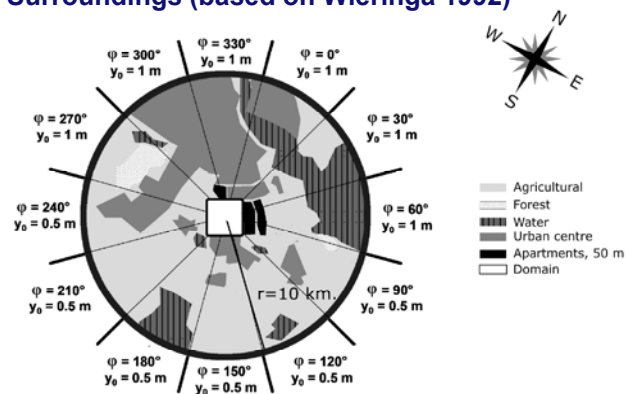
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## Natural ventilation of Amsterdam Arena

- Stadium description

- Surroundings (based on Wieringa 1992)



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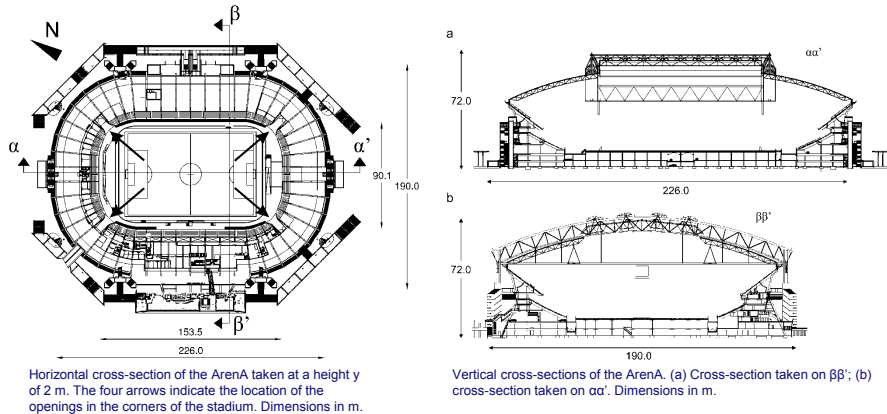
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## Natural ventilation of Amsterdam ArenA

- Stadium description



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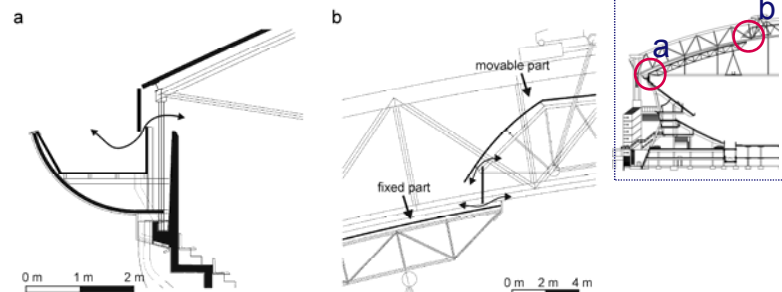
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## Natural ventilation of Amsterdam ArenA

- Stadium description

- Natural ventilation through the roof, corners of stadium and relatively small openings in the building facade



Detailed cross-sections of the ventilation openings in the upper part of the stadium; (a) ventilation opening between the steel roof construction, the gutter and the concrete stand; (b) ventilation opening between the fixed and movable part of the roof, only present at the two longest edges of the stadium. Dimensions in m.

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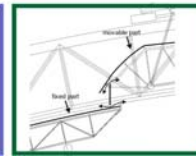
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## Natural ventilation of Amsterdam Arena

- Stadium description
- Natural ventilation through the roof, corners of stadium and relatively small openings in the building facade

Ventilation opening	Surface area (m <sup>2</sup> )
Roof	4,400
Four openings in corners of stadium	166
Opening between stand and roof construction	130
Opening between fixed roof and movable roof	85



## Natural ventilation of Amsterdam Arena

- Problem statement
- During summer the roof is closed most of the time in order to protect equipment and spectators during concerts. This can lead to high indoor air temperatures!



Interior of ArenA during a concert.

## Natural ventilation of Amsterdam Arena

- Full-scale measurements (1)

- During summer:

- Temperature
- Relative humidity
- Air speed
- Globe temperature
- CO<sub>2</sub> concentration

(All measured on 4 positions inside the stadium. T en RH also measured outside the stadium)

- Irradiance of the sky



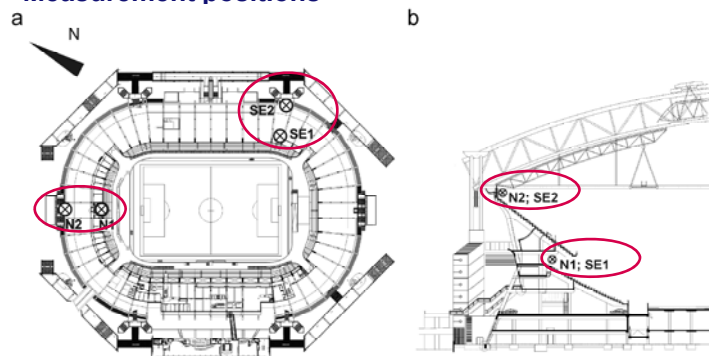
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## Natural ventilation of Amsterdam Arena

- Full-scale measurements (1)

- Measurement positions



Measuring positions for the air temperature, relative humidity, CO<sub>2</sub> concentration and air speed (⊗) inside the stadium with (a) positions in a horizontal plane; (b) positions in a vertical plane.



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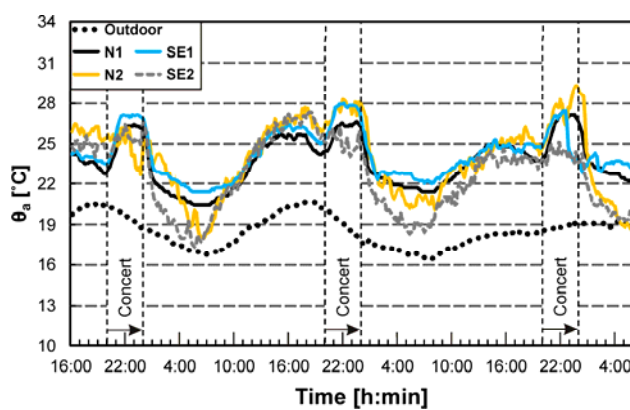
## Natural ventilation of Amsterdam Arena

- Full-scale measurements (1)
- Measurement positions



## Natural ventilation of Amsterdam Arena

- Full-scale measurements (1)



*van Hooff T, Blocken B, 2012. Full-scale measurements of indoor environmental conditions and natural ventilation in a large semi-enclosed stadium: possibilities and limitations for CFD validation. Journal of Wind Engineering and Industrial Aerodynamics 104-106: 330-341.*

## Natural ventilation of Amsterdam Arena

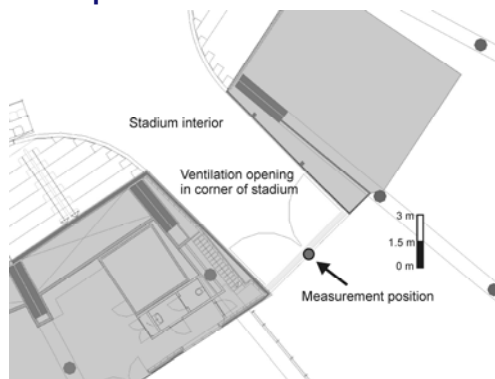
- Full-scale measurements (2)
  - Wind speed measurements inside and around the stadium



Measurement with ultrasonic anemometer outside the ArenA

## Natural ventilation of Amsterdam Arena

- Full-scale measurements (2)
  - Wind speed measurements inside and around the stadium



Measurement with ultrasonic anemometer in the corners of the ArenA

## Natural ventilation of Amsterdam Arena

- CFD simulations
  - 3D steady state CFD simulations
    - Domain:  $2,900 \times 2,900 \times 908.5 \text{ m}^3$  (L x W x H)
    - Hybrid grid (5.5 million cells)
    - Realizable k- $\epsilon$  turbulence model (Shih et al. 1995)
    - Standard wall functions (Launder and Spalding 1974)
    - Logarithmic wind speed profile ( $U_{10}=5 \text{ m/s}$ ,  $y_0=0.5 \text{ m}$  or  $1.0 \text{ m}$ )
    - Eight wind directions
    - Estimated surface temperatures imposed to take into account solar irradiation

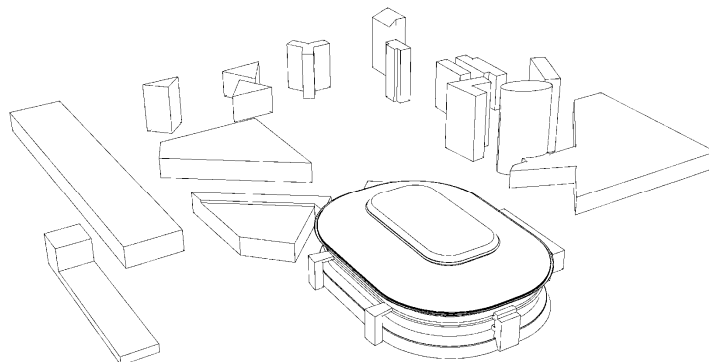


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## Natural ventilation of Amsterdam Arena

- CFD simulations
  - Model



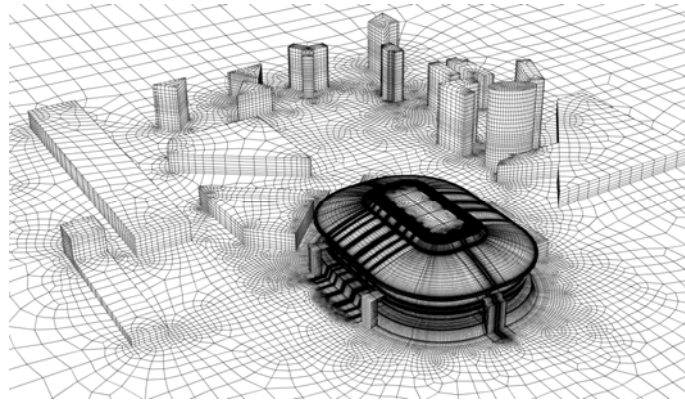
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## Natural ventilation of Amsterdam Arena

- CFD simulations

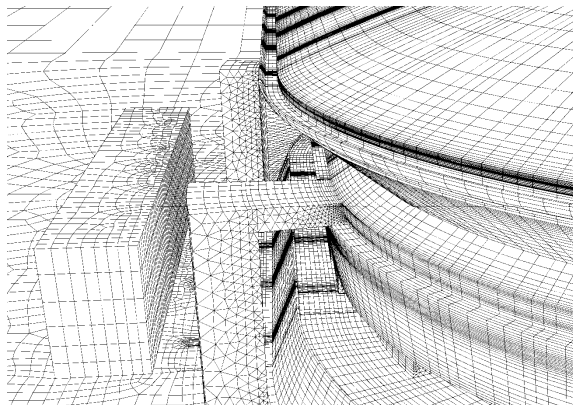
- Grid



## Natural ventilation of Amsterdam Arena

- CFD simulations

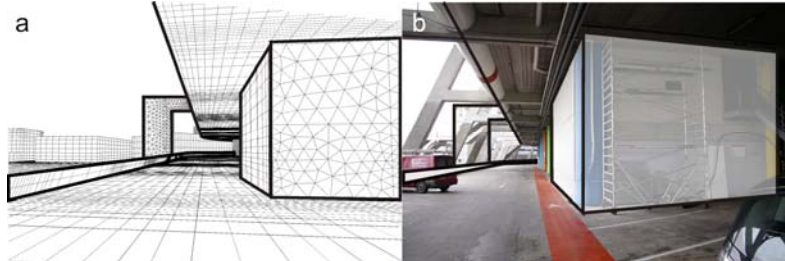
- Grid



## Natural ventilation of Amsterdam Arena

- CFD simulations

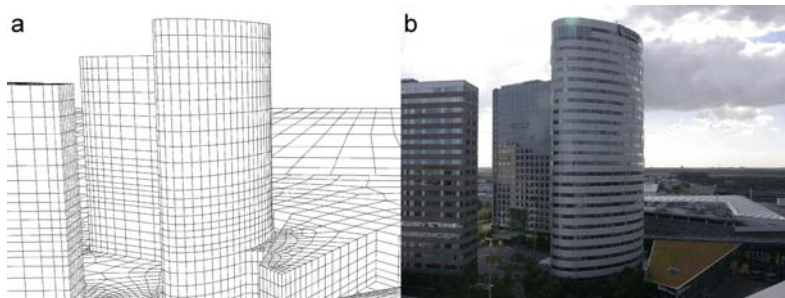
- Grid



## Natural ventilation of Amsterdam Arena

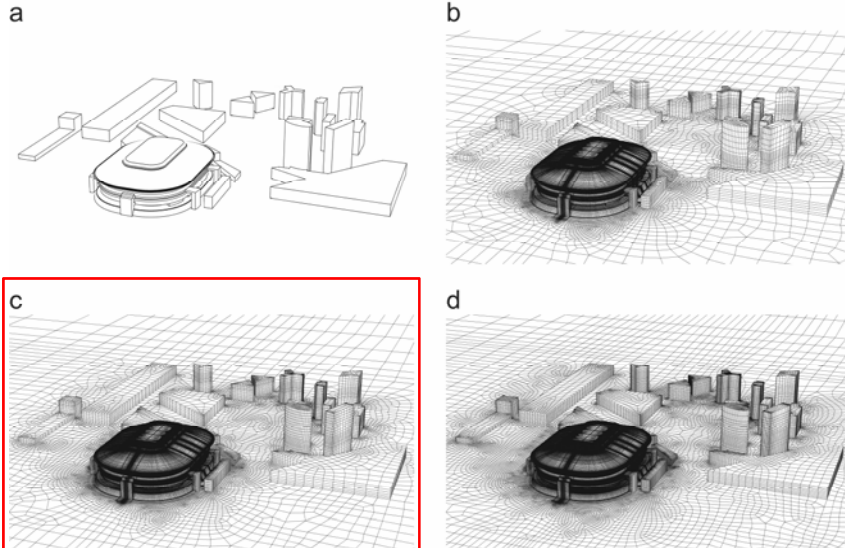
- CFD simulations

- Grid





## Natural ventilation of Amsterdam Arena



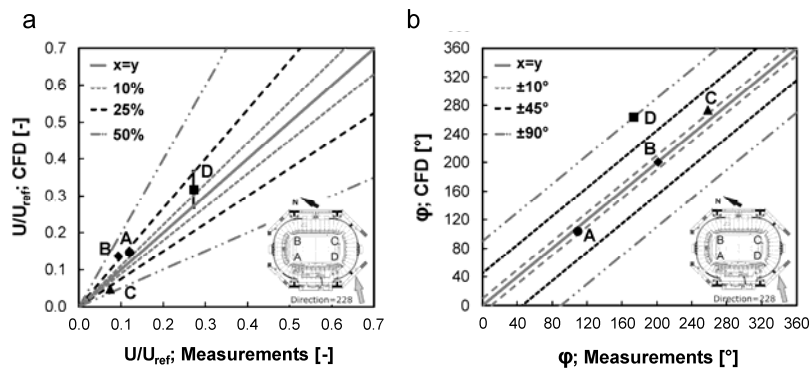
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## Natural ventilation of Amsterdam Arena

- CFD simulations
- Validation using wind speed measurements

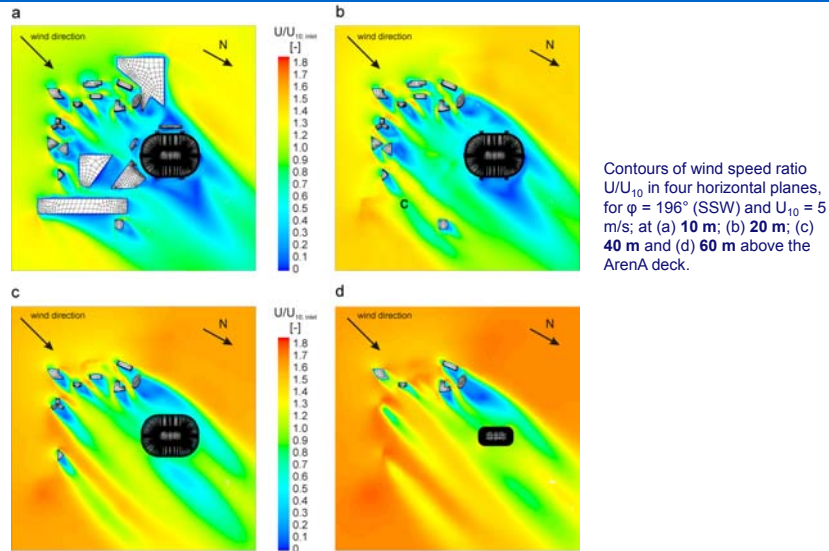


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## Natural ventilation of Amsterdam Arena



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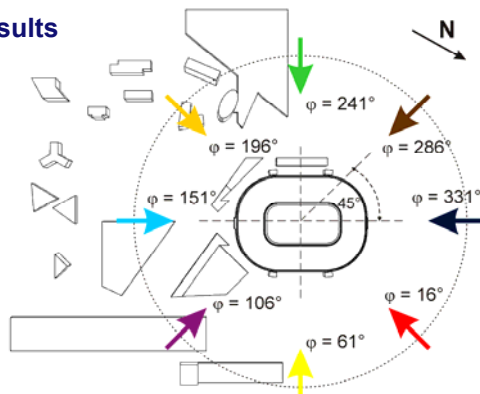
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## Natural ventilation of Amsterdam Arena

- CFD simulations

- Results



Van Hooff, T., Blocken, B., 2010. On the effect of wind direction and urban surroundings on natural ventilation of a large semi-enclosed stadium. *Computers & Fluids* 39, 1146-1155.

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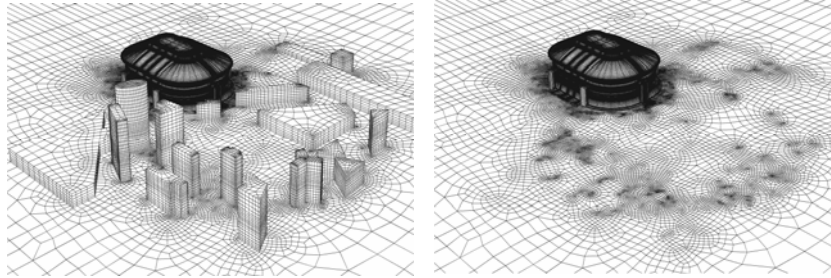
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## Natural ventilation of Amsterdam Arena

- CFD simulations

- Results

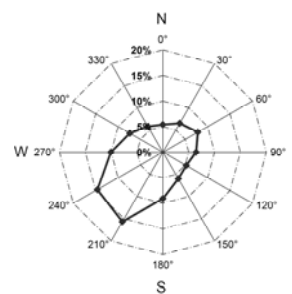
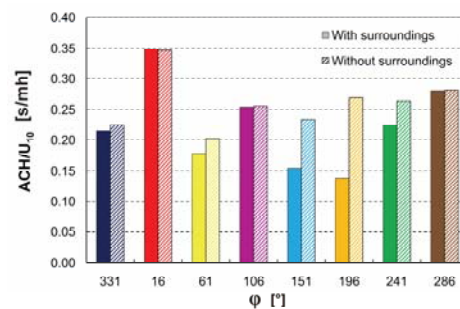


Van Hooff, T., Blocken, B., 2010. On the effect of wind direction and urban surroundings on natural ventilation of a large semi-enclosed stadium. Computers & Fluids 39, 1146-1155.

## Natural ventilation of Amsterdam Arena

- CFD simulations

- Results



Deviations between wind directions with surroundings: up to 152%  
 Deviations between wind directions without surroundings: up to 75%  
 Deviations with v.s. without surroundings for one wind direction: up to 96%

## Natural ventilation of Amsterdam ArenA

- CFD simulations
- Conclusions
  - CFD most suitable for natural ventilation studies of complex buildings in an urban environment
  - Natural ventilation differs for each wind direction
  - Urban surroundings affect natural ventilation to a large extent
  - Natural ventilation studies should not be conducted without taking into account the urban surroundings



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## Natural ventilation of Amsterdam ArenA

- More information:

1. van Hooff T, Blocken B, 2010. Coupled urban wind flow and indoor natural ventilation modelling on a high-resolution grid: A case study for the Amsterdam ArenA stadium. **Environmental Modelling & Software** 25(1): 51-65.
2. van Hooff T, Blocken B, 2010. On the effect of wind direction and urban surroundings on natural ventilation of a large semi-enclosed stadium. **Computers & Fluids** 39(7): 1146-1155.
3. van Hooff T, Blocken B, 2012. Full-scale measurements of indoor environmental conditions and natural ventilation in a large semi-enclosed stadium: possibilities and limitations for CFD validation. **Journal of Wind Engineering and Industrial Aerodynamics** 104-106: 330-341.
4. van Hooff T, Blocken B, 2013. CFD simulation of natural ventilation of indoor environments by the concentration decay method: CO<sub>2</sub> gas dispersion from a large semi-enclosed stadium. **Building and Environment** 61, 1-17.



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### *III. WIND FLOW IN HARBOR OF ROTTERDAM*

Ir. Wendy Janssen      TU Eindhoven  
Prof.dr.ir. Bert Blocken      TU Eindhoven | KU Leuven  
Ing. Herm Jan van Wijhe      Haven van Rotterdam



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#### Wind flow in harbor of Rotterdam

- **Goal**
  - Prediction of wind speeds in harbor area for wind loading on ships.
  - Create application to show wind velocities and directions for a given reference wind speed and direction.



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## Wind flow in harbor of Rotterdam

- **Measurement campaign:**



- Measuring period: 13 December 2010 - 9 May 2011
- Measuring frequency: 1 Hz
- Reference position (Noorderhoofd, Hoek van Holland): 15 m above land
- Other positions: in general 10 m above land

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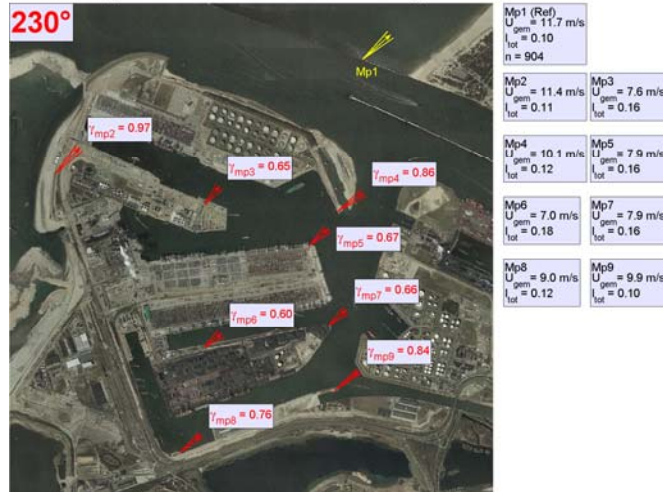




## Wind flow in harbor of Rotterdam

### • Measurement results: Amplification factors

Versterkingsfactoren Rotterdam Haven 13-Dec-2010 - 09-May-2011



$$\gamma = \frac{U_{mp}}{U_{mp1}}$$

## Wind flow in harbor of Rotterdam

### • Numerical domain and grid

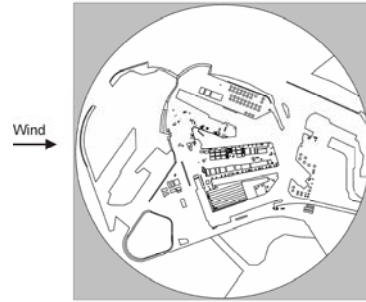
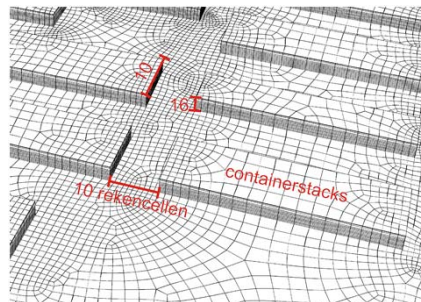


- Total surface area region of interest: > 100 km<sup>2</sup>.
- Included in domain: land surfaces, water surfaces, locations of obstacles (buildings, containers, dikes, etc.).
- Obstacles at a distance of 6-10H (H = obstacle height) from the waterside are not included.

## Wind flow in harbor of Rotterdam

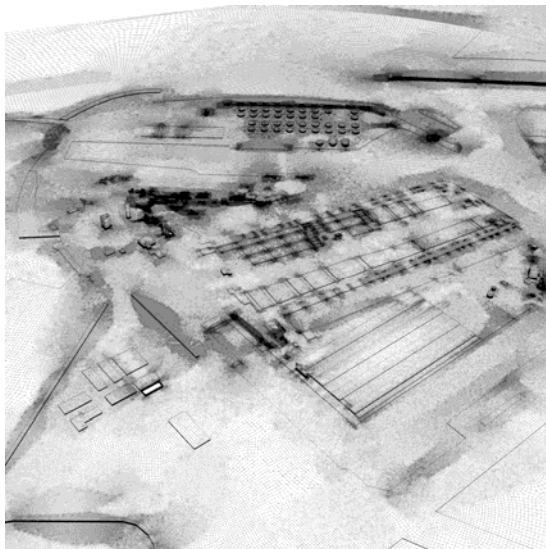
- Numerical domain and grid

- In accordance with Best Practice Guidelines (Franke et al. 2007, Tominaga et al. 2008)
- Domain dimensions: 11,750 x 11,740 x 500 m<sup>3</sup>



## Wind flow in harbor of Rotterdam

- Numerical domain and grid

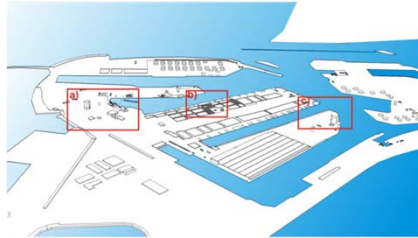


- 86 million cells
- No tetrahedral cells.
- Cell size ranges from 0.24 m to 124 m in the ground plane.
- Cell size ranges from 0.5 m to 36 m in the upper part of the domain.

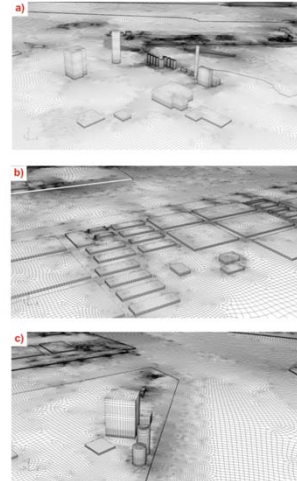


## Wind flow in harbor of Rotterdam

- Numerical domain and grid



Picture HbR October 2010

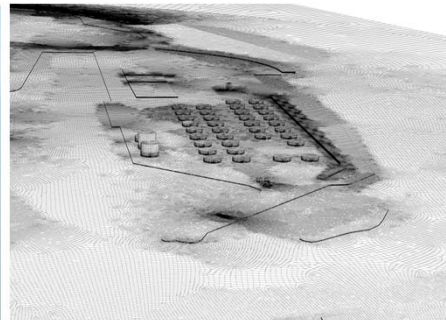


## Wind flow in harbor of Rotterdam

- Numerical domain and grid



View from Beerkanaal



## Wind flow in harbor of Rotterdam

- **Boundary conditions**

- Inlet profiles (Richards & Hoxey 1993)

**U** = mean wind velocity (m/s)  
**k** = turbulent kinetic energy (m<sup>2</sup>/s<sup>2</sup>)  
**ε** = turbulence dissipation rate (m<sup>2</sup>/s<sup>3</sup>)

$u_{ABL}^*$  = friction velocity (m/s)  
 $\kappa$  = von Karman constant (0.42)  
 $z$  = vertical coordinate  
 $z_0$  = aerodynamic roughness length (m)  
 $z_{ref}$  = reference height (= 10 m above NAP)  
 $U_{ref}$  = wind speed at reference height (= 10 m/s)

$$U(z) = \frac{u_{ABL}^*}{\kappa} \cdot \ln\left(\frac{z + z_0}{z_0}\right)$$

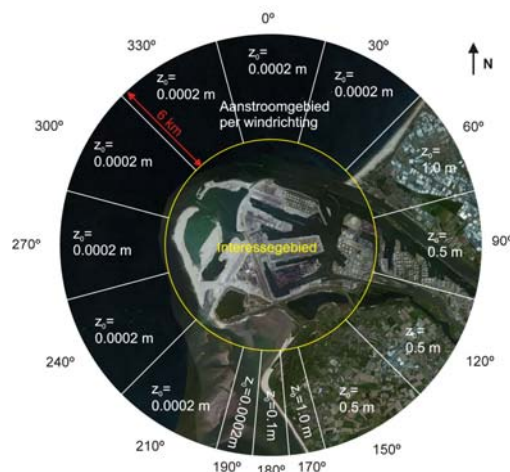
$$k(z) = 3.33 \cdot u_{ABL}^{*2}$$

$$\varepsilon(z) = \frac{u_{ABL}^{*3}}{\kappa(z + z_0)}$$

$$u_{ABL}^* = \frac{\kappa \cdot U_{ref}}{\ln\left(\frac{z_{ref} + z_0}{z_0}\right)}$$

## Wind flow in harbor of Rotterdam

- Aerodynamic roughness length  $z_0$  for each wind direction (inlet profile)



- $z_0 = 0.0002$  "Sea"
- $z_0 = 0.1$  "Roughly Open"
- $z_0 = 0.5$  "Very rough"
- $z_0 = 1.0$  "Closed"

• (Wieringa 1992)

## Wind flow in harbor of Rotterdam

- **Other computational parameters**

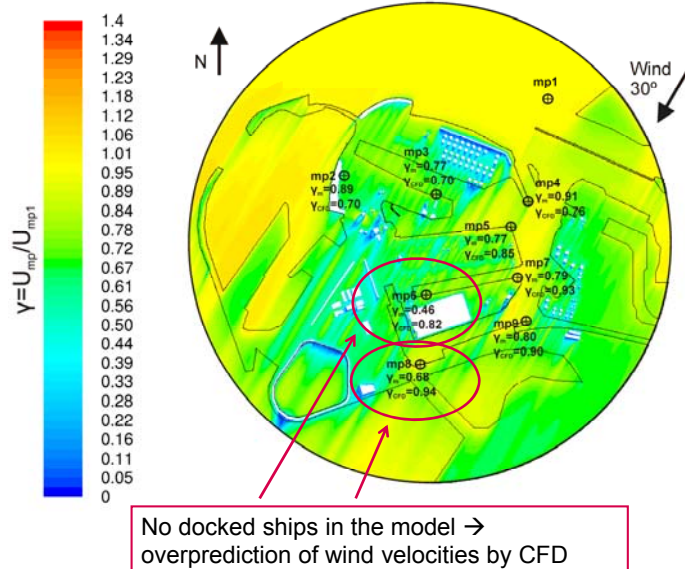
- Steady 3D Reynolds-averaged Navier-Stokes (RANS)
- Turbulence model: Realizable k- $\epsilon$  (Shih et al. 1995)
- Discretization schemes: second order upwind
- Pressure-velocity coupling method: SIMPLE
- Standard wall functions (Launder & Spalding, 1974) with sand-grain based roughness modifications by Cebeci & Bradshaw (1977)

## Wind flow in harbor of Rotterdam

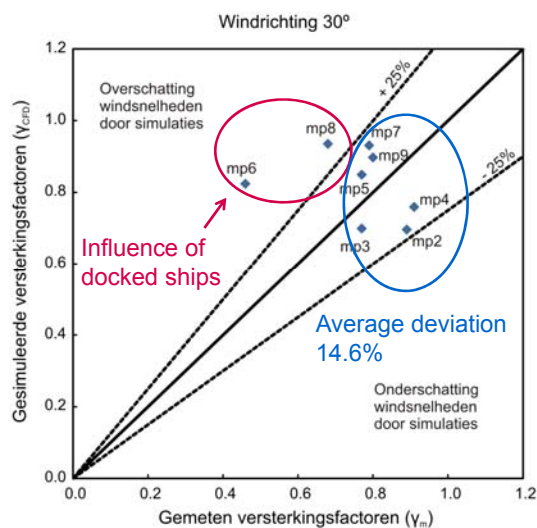
- **Results: Amplification factors**

$$\gamma = \frac{U_{mp}}{U_{mp1}}$$

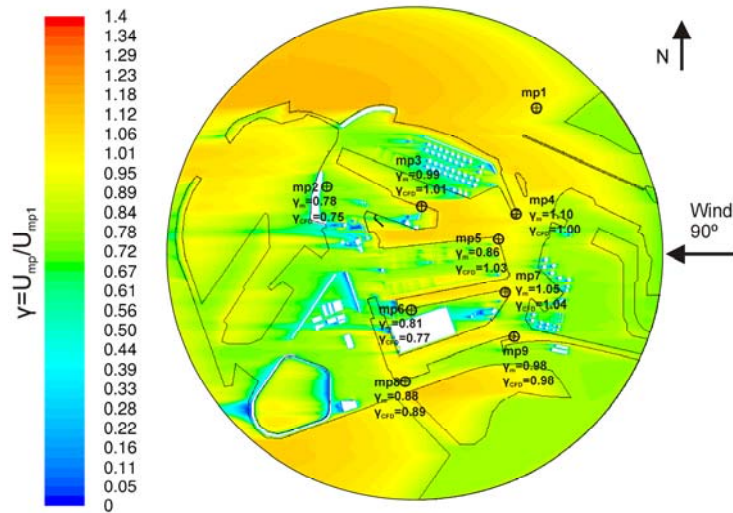
## Wind flow in harbor of Rotterdam



## Wind flow in harbor of Rotterdam



## Wind flow in harbor of Rotterdam

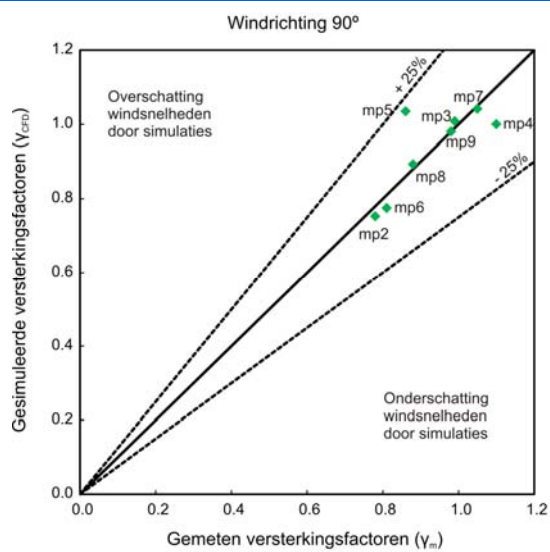


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## Wind flow in harbor of Rotterdam

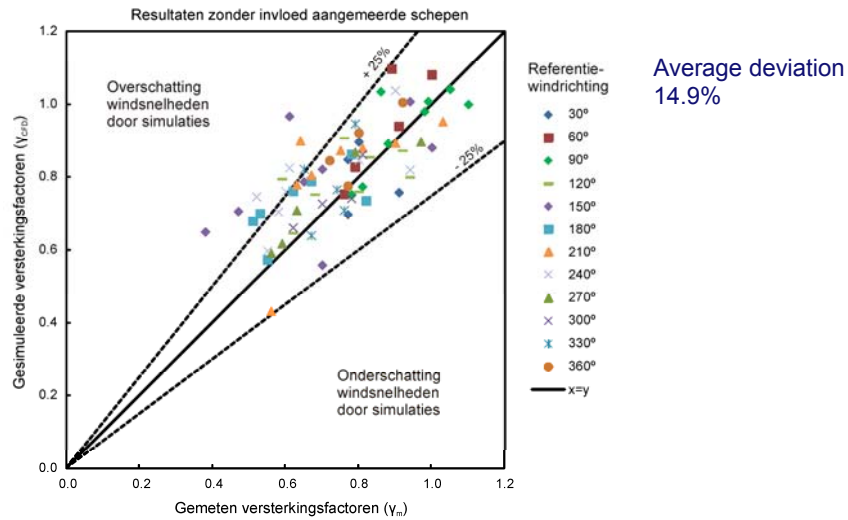


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## Wind flow in harbor of Rotterdam

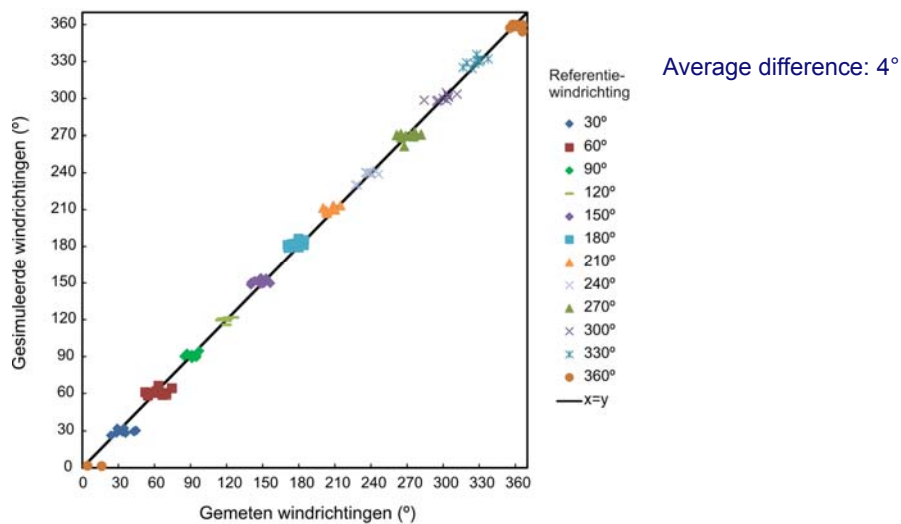


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## Wind flow in harbor of Rotterdam

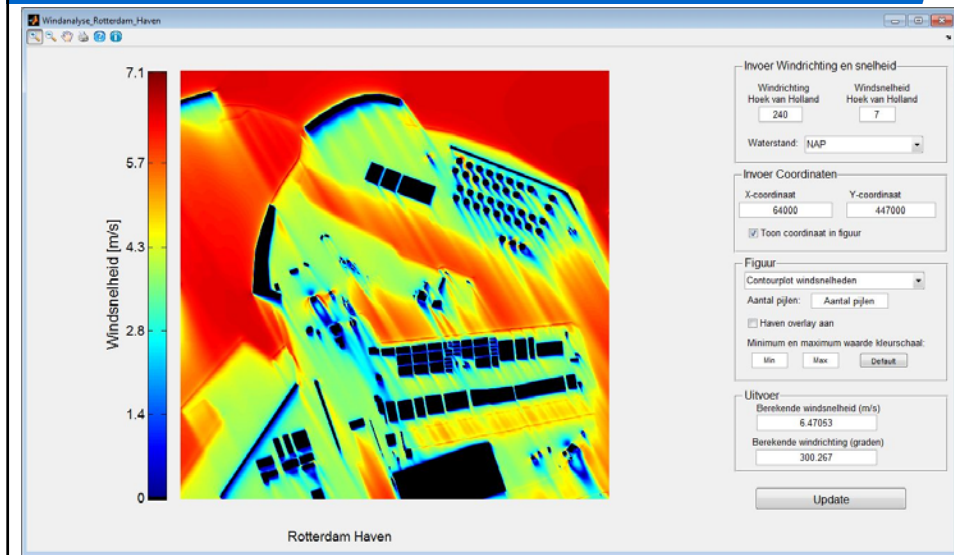


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## Wind flow in harbor of Rotterdam



*FINAL REMARKS*

## Final remarks

- Using output of meso-scale models as boundary conditions could improve the accuracy of micro-scale simulations of wind flow.
- Modeling the transient behavior of wind flows at the meteorological micro-scale is difficult, among others due to the large computational costs.
- Explicit modeling of the urban environment (buildings, trees, etc.) is essential in wind simulations on the meteorological micro-scale (e.g. wind comfort, natural ventilation).
- Verification and validation studies are imperative for meteorological micro-scale simulations.

*ANNOUNCEMENT*



## Symposium: WIND ON BUILDINGS & CITIES

**TU/e** Technische Universiteit  
Eindhoven  
University of Technology

### ANNOUNCEMENT:

#### Honorary Symposium and Honorary Doctorate Ceremony for

**Prof.dr. Theodore Stathopoulos**  
Concordia University, Montreal



#### Honorary Symposium

29 April 2015, Blauwe Zaal, TU/e Campus, 8 a.m.

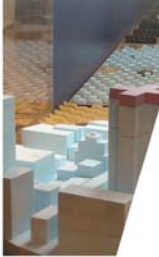
#### Early-bird registration (before or on March 15)

- Regular: 175 €
- PhD students: 95 €
- BSc and MSc students: free (up to max. 25)

#### Late registration (after March 15)

- Regular: 225 €
- PhD students: 125 €
- BSc and MSc students: free (up to max. 25)

REGISTER HERE: [www.tue.nl/windonbuildingsandcities](http://www.tue.nl/windonbuildingsandcities)



#### Honorary Ceremony

30 April 2015, Sint-Catharinakerk, 3 p.m.



#### Symposium Invited Speakers

- Prof. Chris Baker - University of Birmingham, UK
- Prof. Bert Blocken - Eindhoven University of Technology, The Netherlands & Universitat Politècnica de Catalunya, Spain
- Prof. Claudio Borri - University of Florence, Italy
- Prof. Jan Carmeliet - ETH Zurich and EMPA, Switzerland
- Dr. Chris Geurts - TNO, The Netherlands
- Dr. Christof Gromke - Helmholtz Institute of Technology, Germany
- Prof. Jan Hansen - Eindhoven University of Technology, The Netherlands
- Dr. Maarten Hornikx - Eindhoven University of Technology, The Netherlands
- Dr. Panagiotis Karava - Purdue University, USA
- Prof. Peter Moonen - University of Paris, France
- Prof. Elghi Nelissen - Eindhoven University of Technology, The Netherlands
- Dr. Marina Neophytou - University of Cyprus
- Dr. Rubina Rampori - ARUP, UK
- Prof. Giovanni Solari - University of Genova, Italy
- Prof. Theodore Stathopoulos - Concordia University, Canada
- Prof. Mark Sterling - University of Birmingham, UK
- Prof. Yukio Tamura - Beijing Jiaotong University, China
- Prof. Yoshihide Tomiyaga - Nagoya Institute of Technology, Japan
- Prof. Jeroen van Beeck - von Karman Institute for Fluid Dynamics, Belgium
- Prof. Gert-Jan van Heijst - Eindhoven University of Technology, The Netherlands
- Dr. Tsan van Hooff - Leuven University, Belgium

Ter gelegenheid van het eredoctoraat  
van prof.dr. Ted Stathopoulos  
(Concordia University, Canada)  
29 april, TU Eindhoven

[www.tue.nl/windonbuildingsandcities](http://www.tue.nl/windonbuildingsandcities)

**Bedankt voor jullie aandacht!**

**Vragen?**

**fwo**

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## ***Windsimulaties op de meteorologische microschaal***

dr.ir. Twan van Hooff  
prof.dr.ir. Bert Blocken

**Building Physics Section – KU Leuven  
Unit Building Physics and Services – TU/e**



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