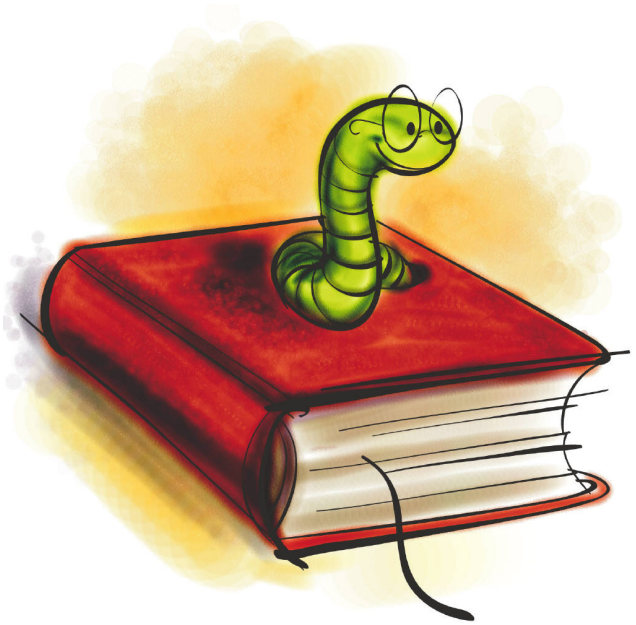
CFD Prediction of Airflow in Buildings for Natural Ventilation

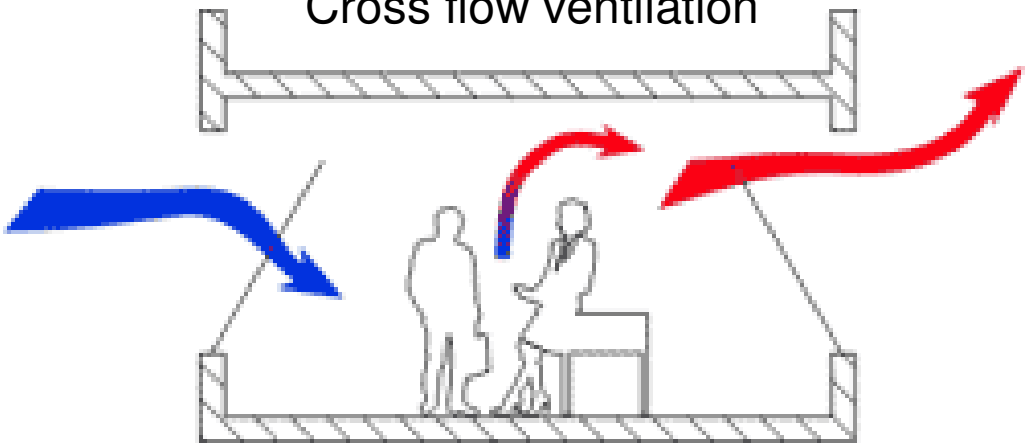


Robert N. Meroney, P.E.
Wind Engineering Software
Colorado State University

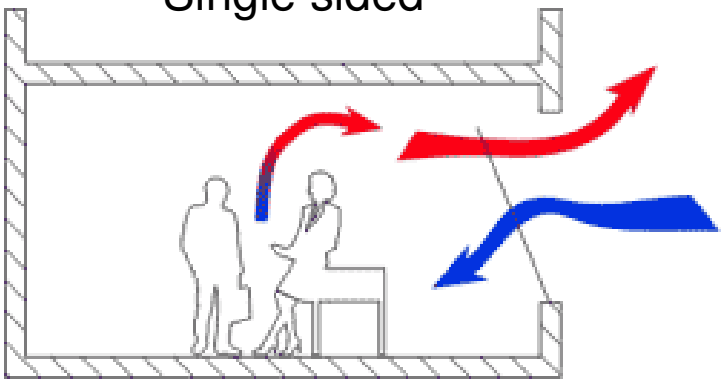
Prepared for
11th Americas Conference
on Wind Engineering
June 22-26, 2009
San Juan, Puerto Rico

Natural Ventilation

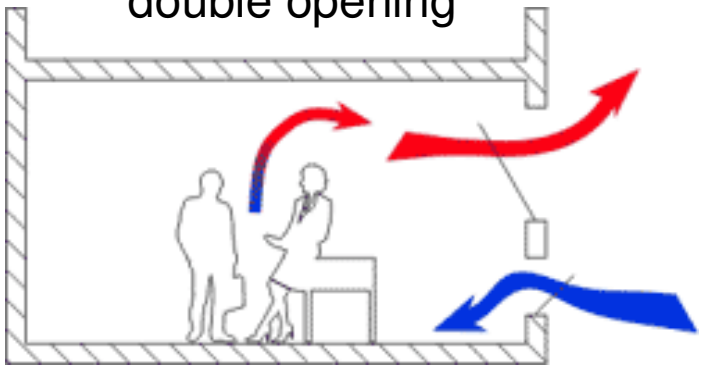
Cross flow ventilation



Single sided

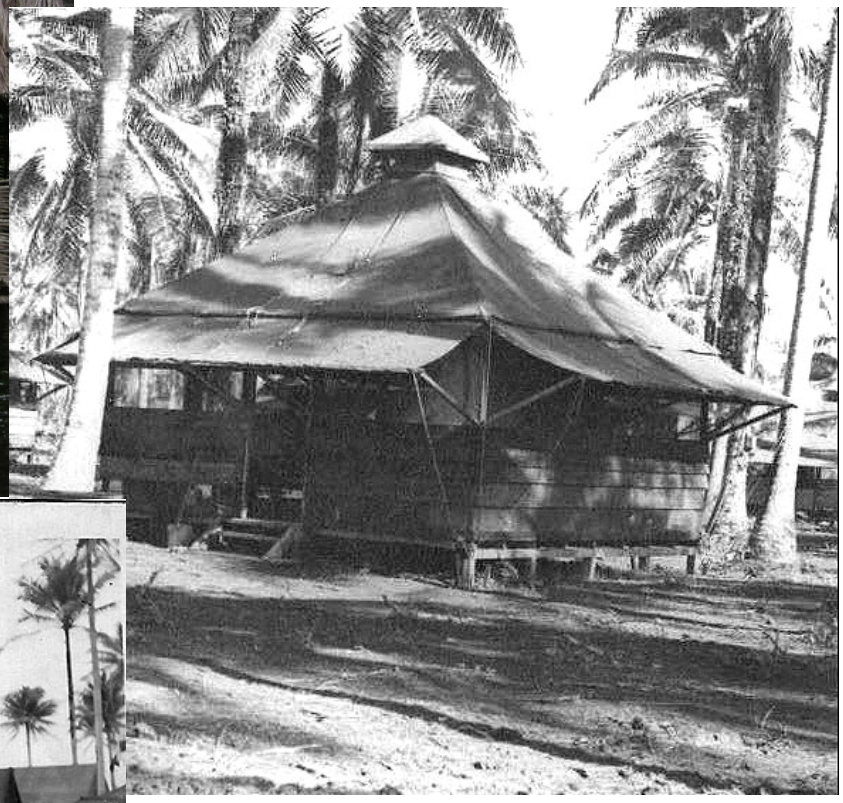


Single sided –
double opening



First Mental Images

< River Huts, Mexico



^ Papau, New Guinea 1945

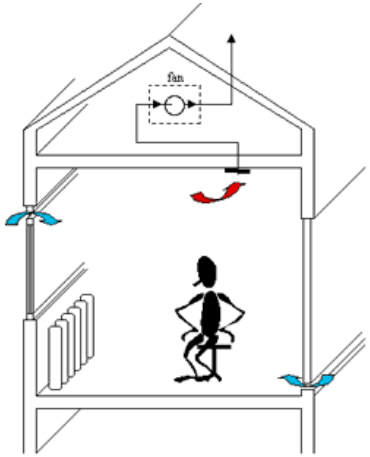
< Philippines 1940s

Rozak Stilt House

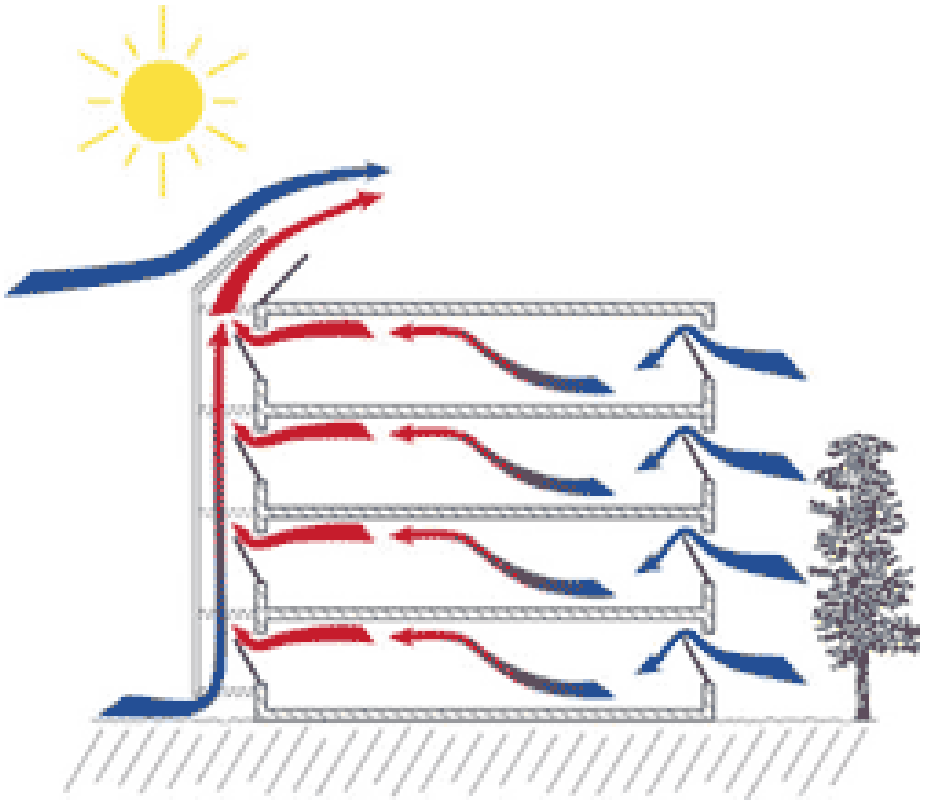
(Darwin, Australia)

Luxury Villas in Pacific Islands

Natural Ventilation in Domestic Green Architecture

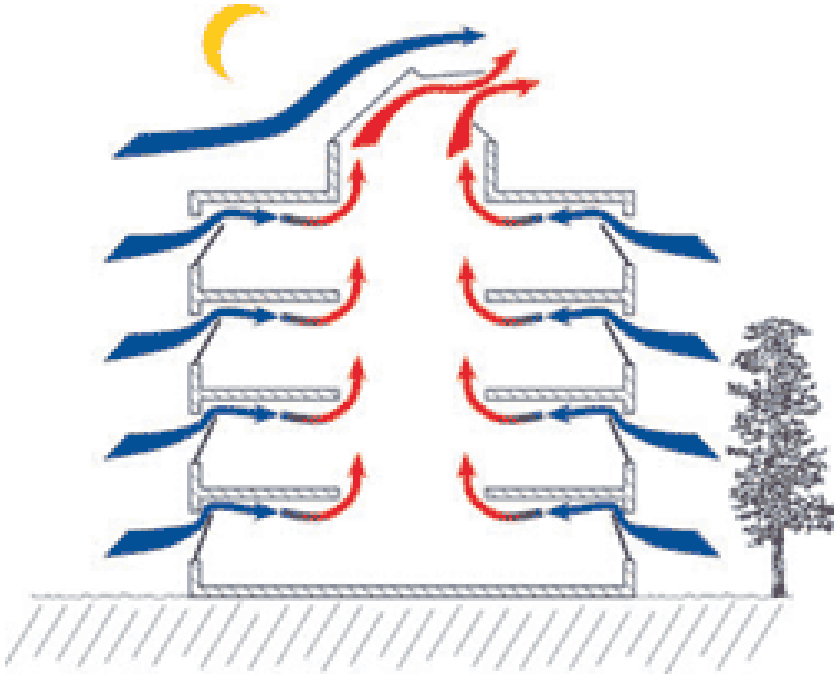


Natural Ventilation Multistory Buildings



Daytime stack effect

Double facade



Nighttime stack effect

Central atrium

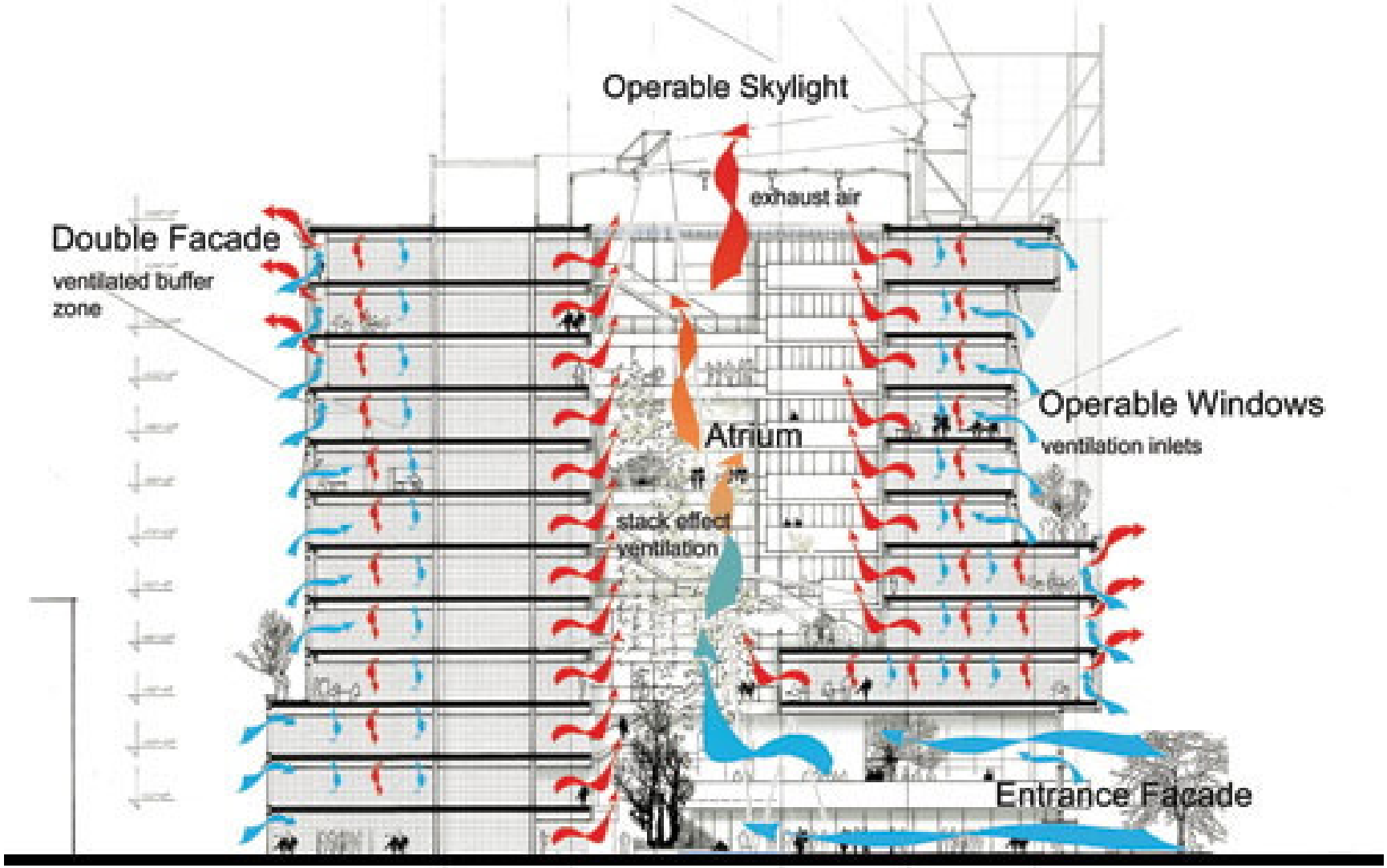
Natural Ventilation in Commercial Buildings

Genzyme Center,
Cambridge MA

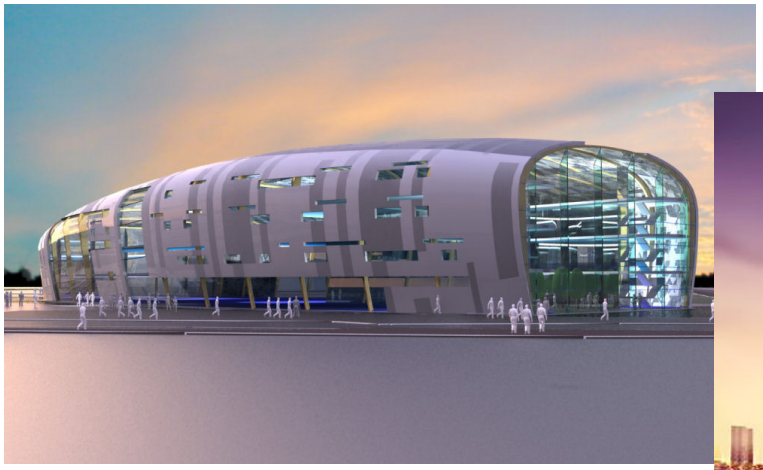
Corporate headquarters
biotechnology company

Designed from “inside – out”

Natural Ventilation with Atrium



Natural Ventilation in Skyscrapers



City of Bristol Education Building - Skills Academy

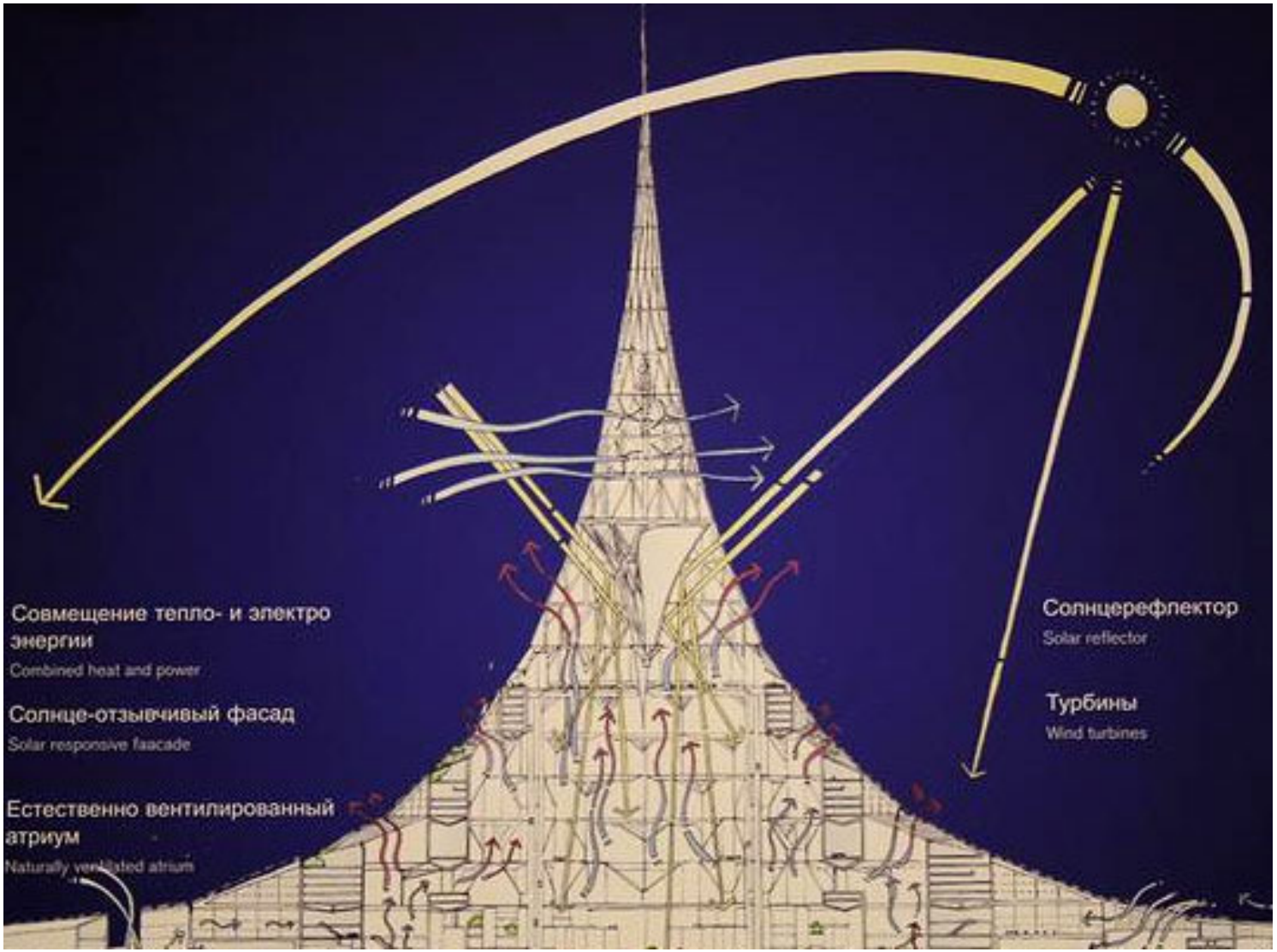
Crystal Island Tower – Norman Foster, Moscow

Russia Tower – Norman Foster, St. Petersburg

Gazprom Tower, St Petersburg

Encana Tower, Calgary, Canada

Crystal Island “Volcano”



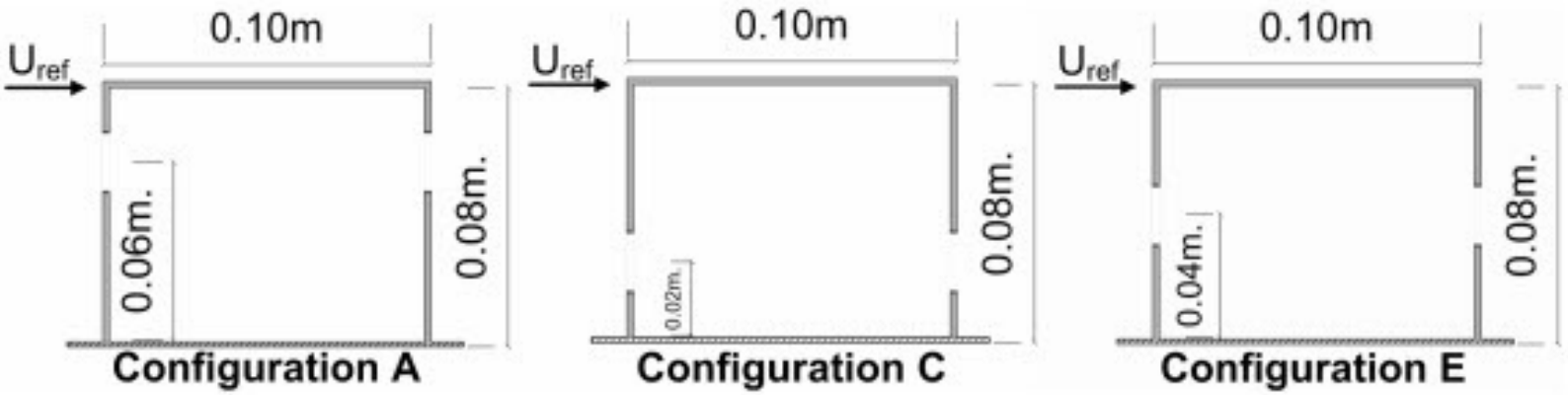
Project Goals

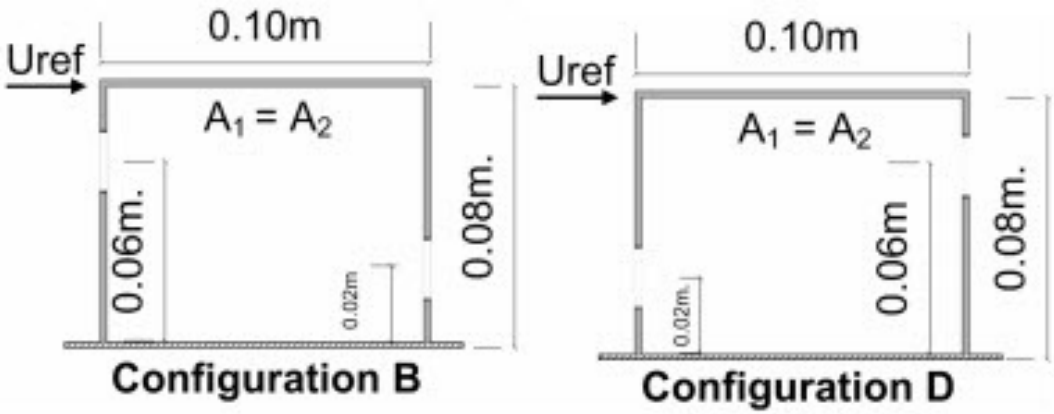
- Replicate natural ventilation measurements performed by Dr. Panagiota Karava (2008).
  - Velocity field
  - Peak pressure field
  - Opening flow rates
- Examine numerical modeling alternatives and their relative effectiveness
  - Turbulence models – Std k-ε, RNG k-ε, Realizable k-ε, k-ω, RMS, LES, & DES
  - Grid resolution, boundary conditions
- Examine domain decomposition as a numerical modeling alternative

Karava Natural Ventilation Study

- **Dr. Panagiota Karava**, University of Western Ontario, – specialist in natural ventilation design.
- PhD Thesis: *Airflow Prediction in Buildings for Natural Ventilation Design: Wind Tunnel Measurements and Simulation*, Concordia University, 2008
  - Building Model 20 x 20 x 16 m high (1:200 scale ration), openings placed on different walls
  - Simulated atmospheric boundary, p = 0.11
  - Measurements with PIV & hot-film anemometry and fast-response pressure transducers

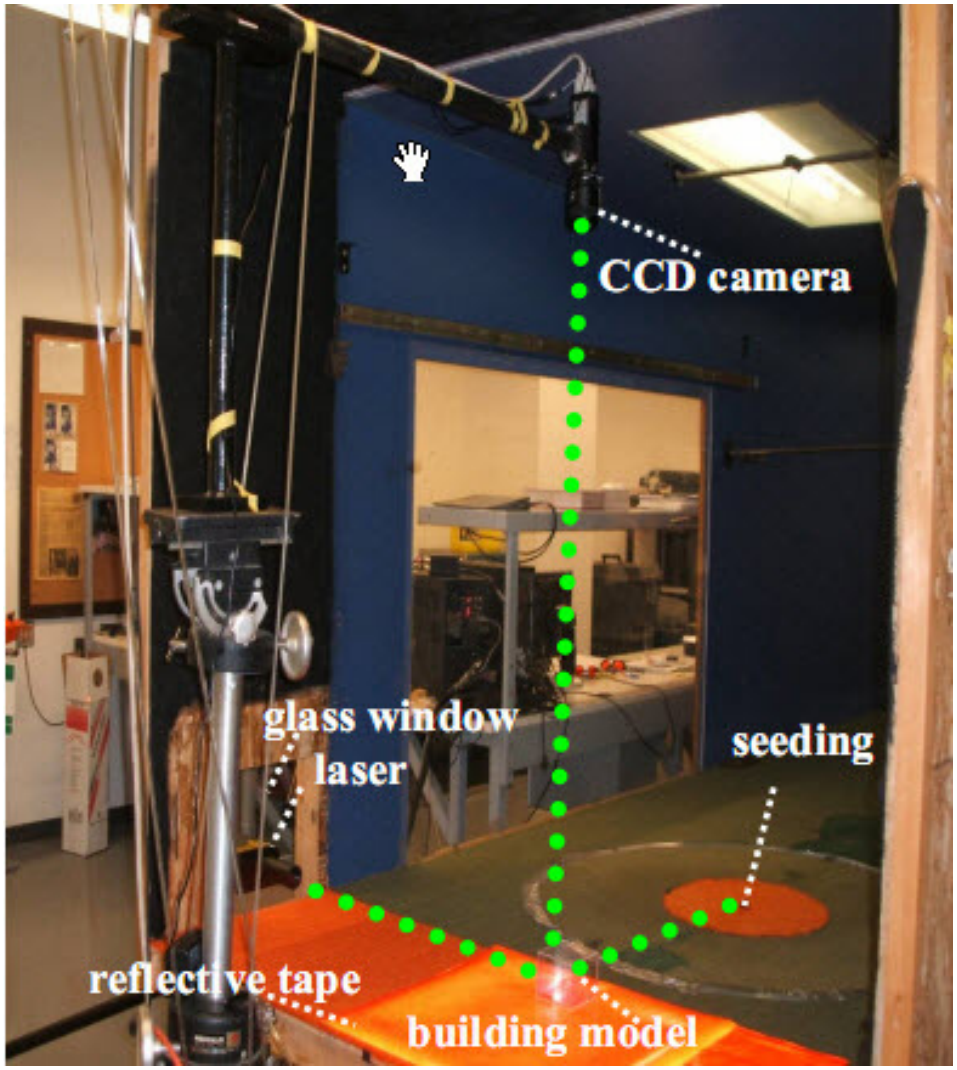
Model & Opening Configurations



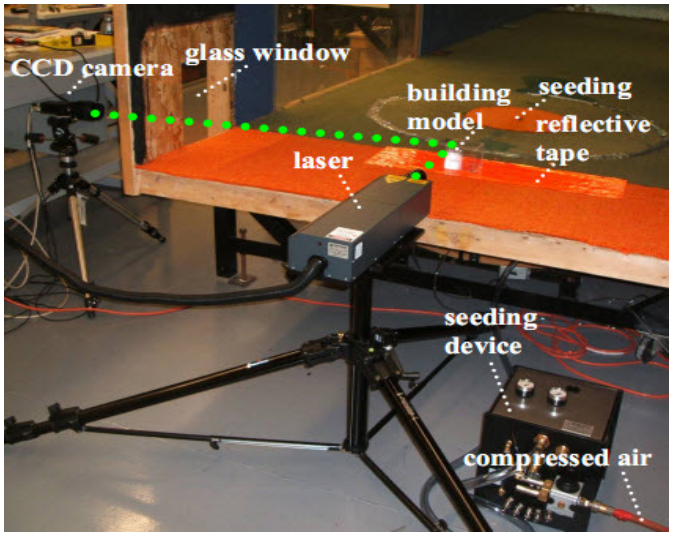


PIV System

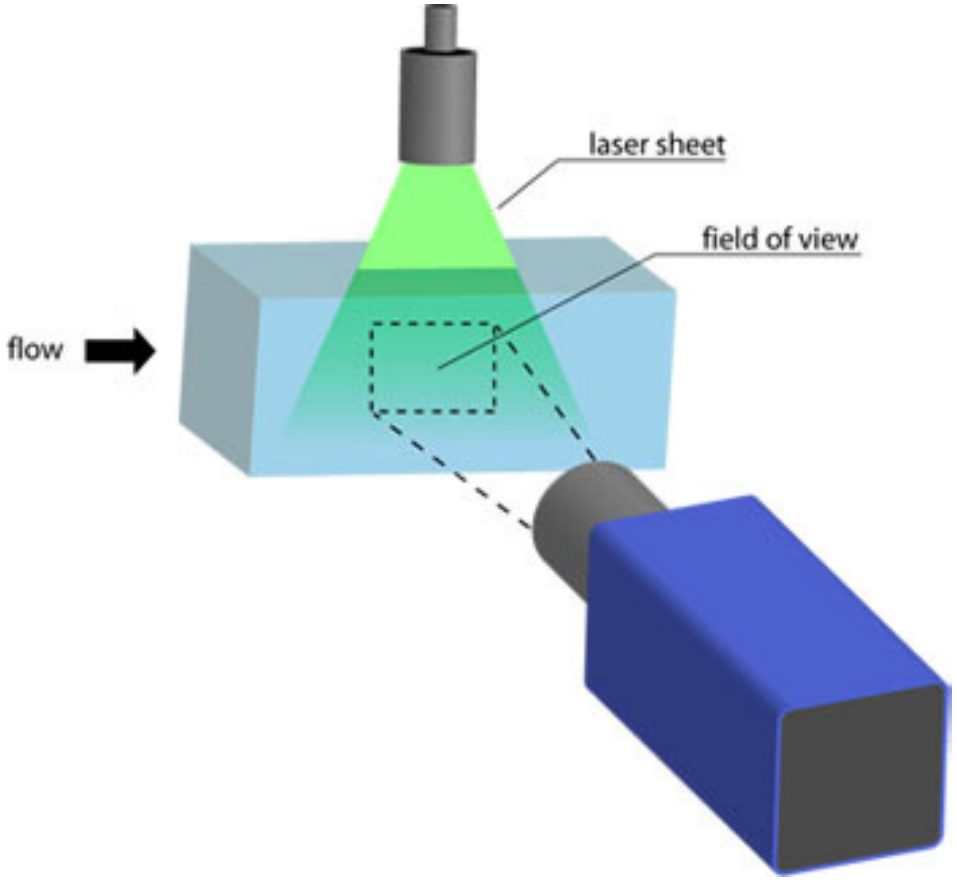
Horizontal Plane Measurements

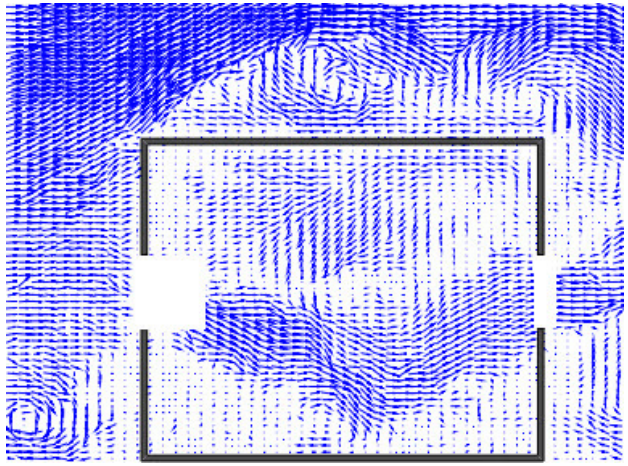


Vertical Plane Measurements

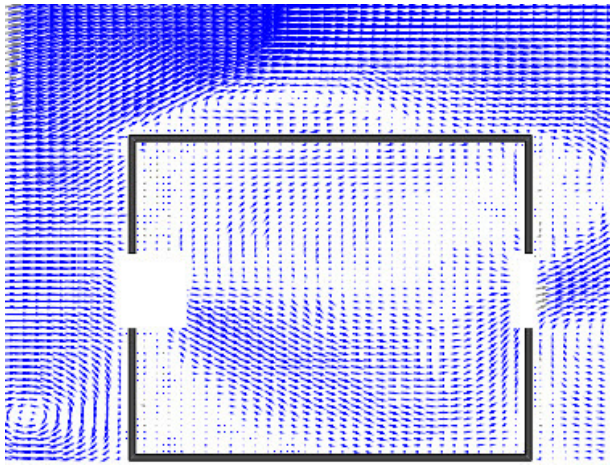


PIV System

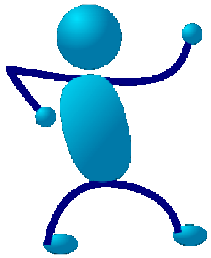




Instantaneous



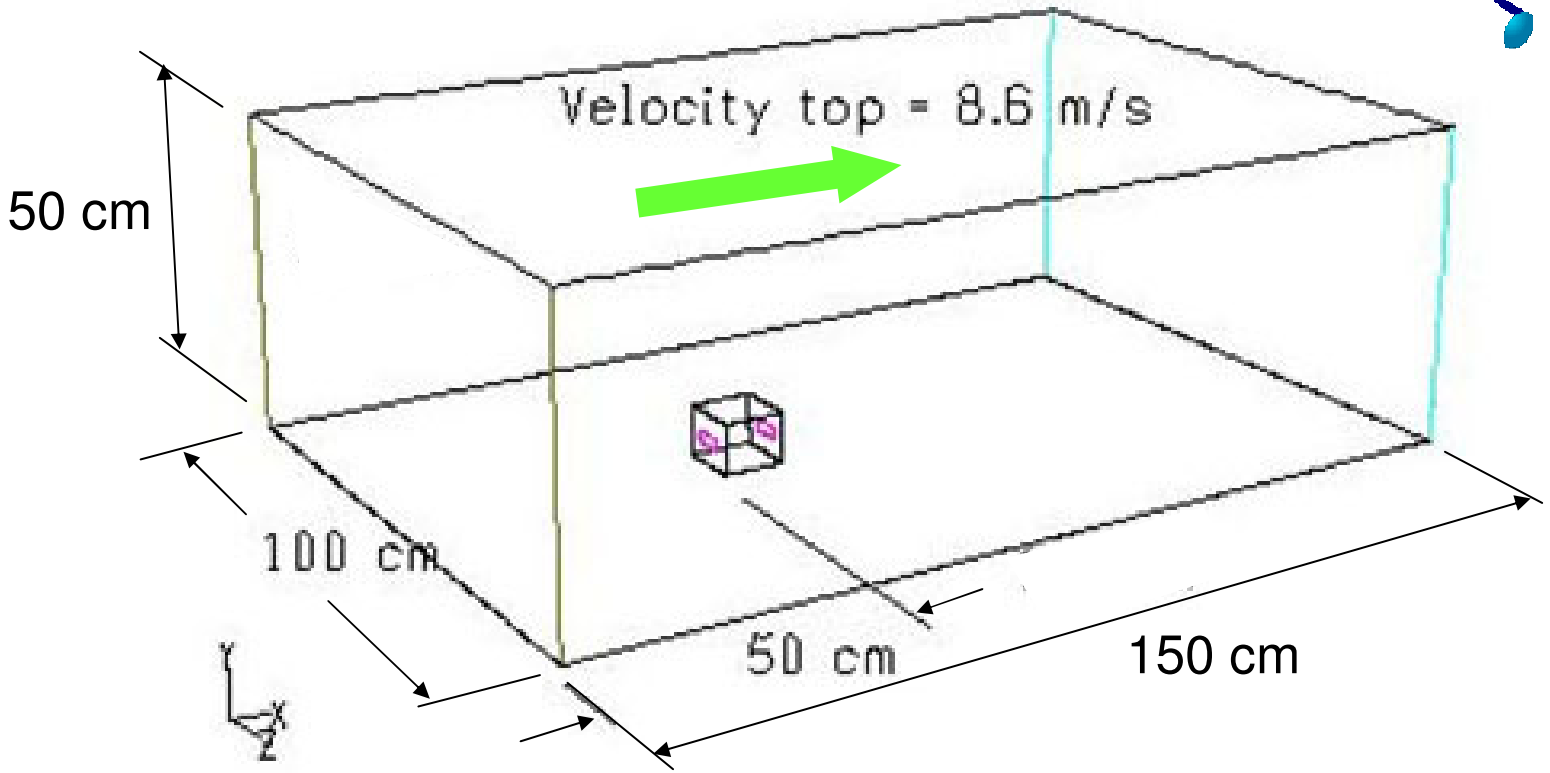
Mean



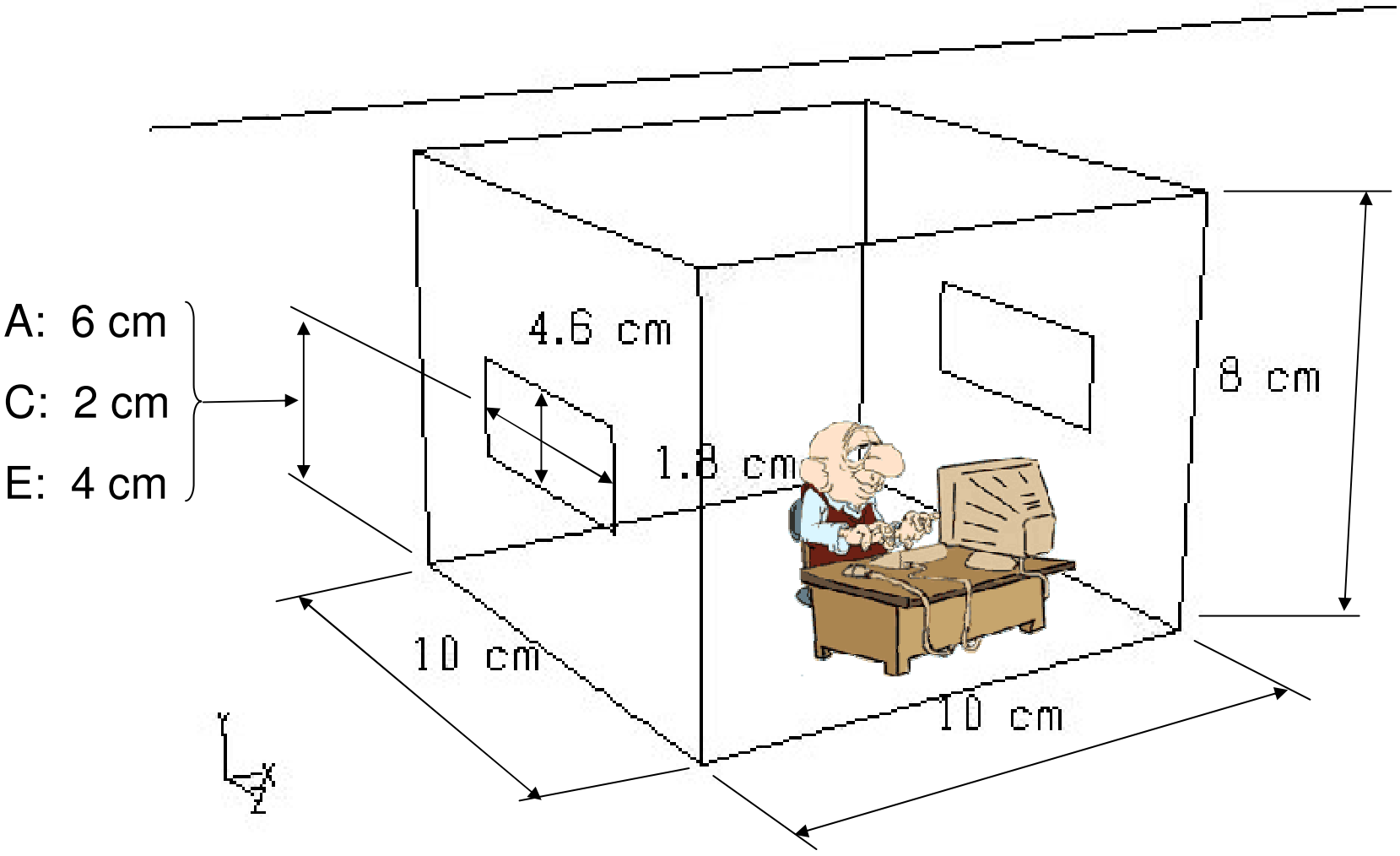
Numerical Model

- Domain size and flow conditions set to meet COST harmonization recommendations.
- Computational domain prepared with a combination of hexagonal and tetrahedral shapes totaling ~1 to 2 million cells. Cells adapted near walls to sizes less than 0.03 cm for the wind-tunnel scale model (8 x 10 x 10 cm)
- Wall boundaries had zero or 2 mm thickness.
- Only configurations with wind normal to openings considered.
- All solutions obtained with the FLUENT 6.3 CFD code.

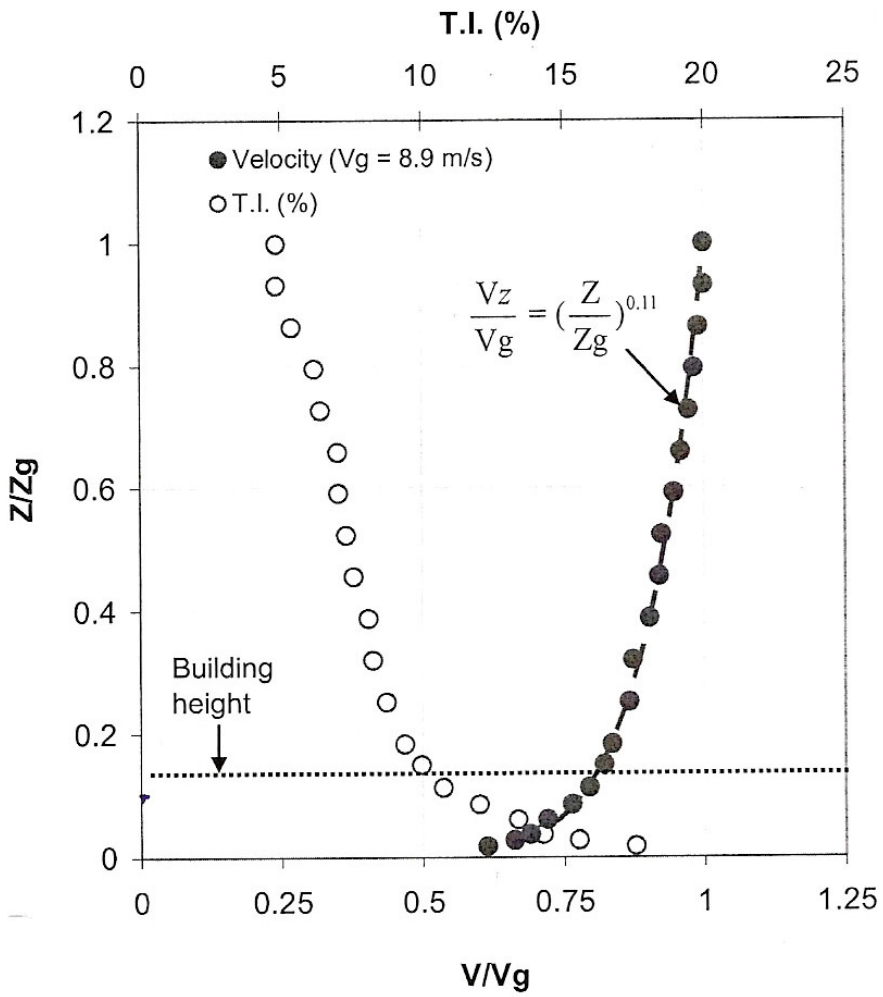
CFD Domain Size

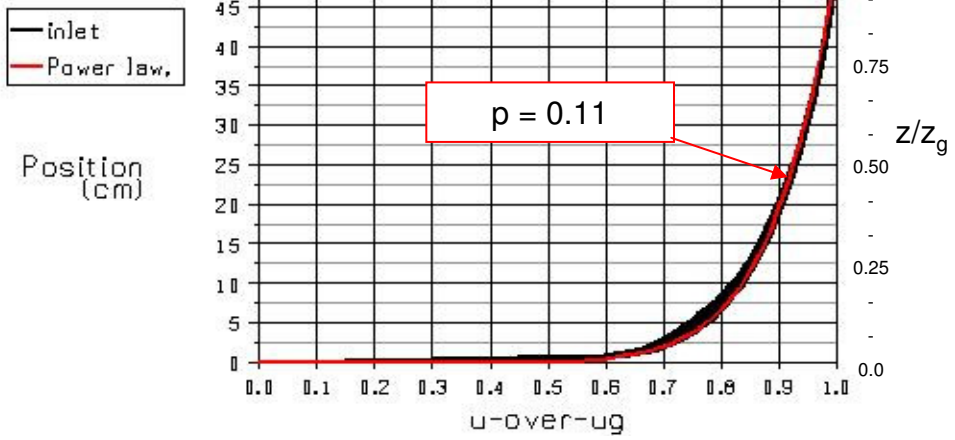


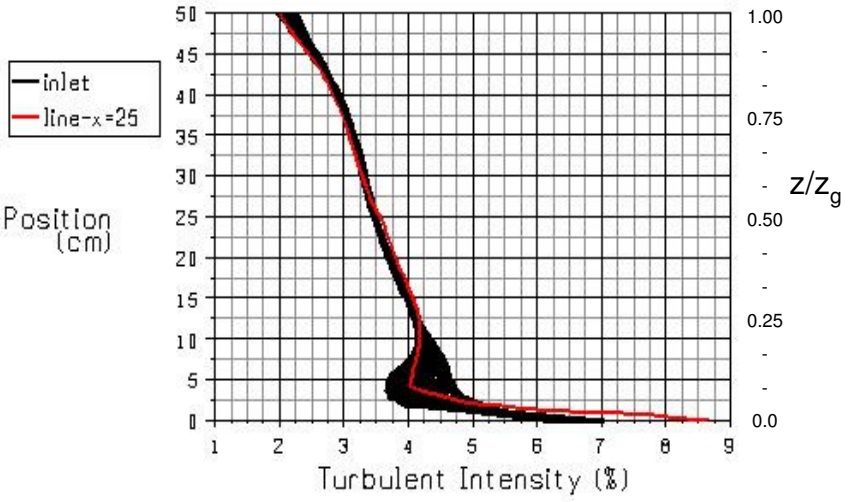
Model Dimensions



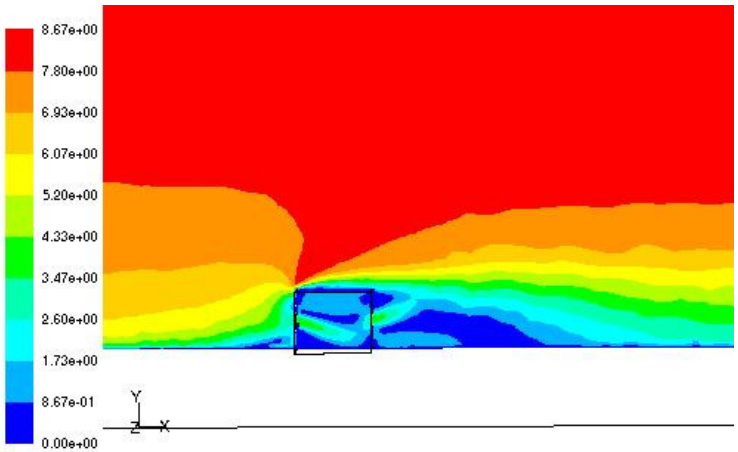
Approach Flow Conditions



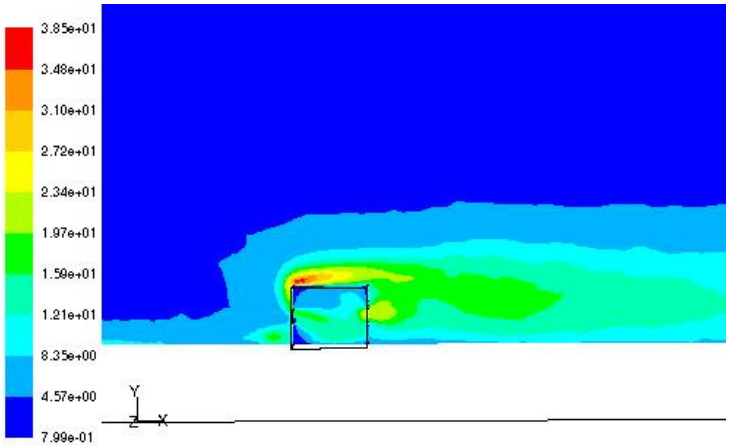




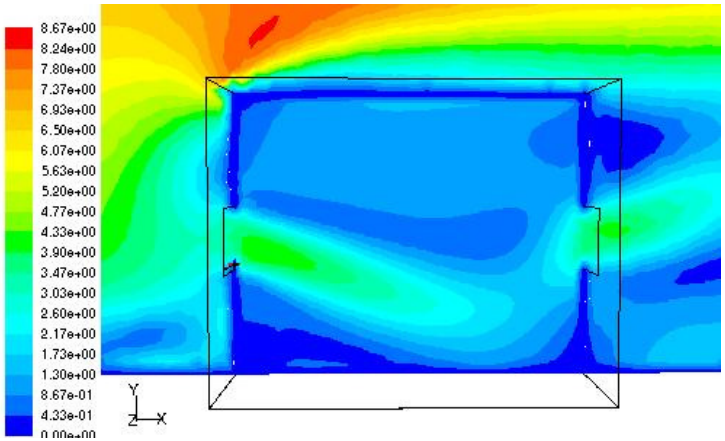
Flow field – Standard k-ε

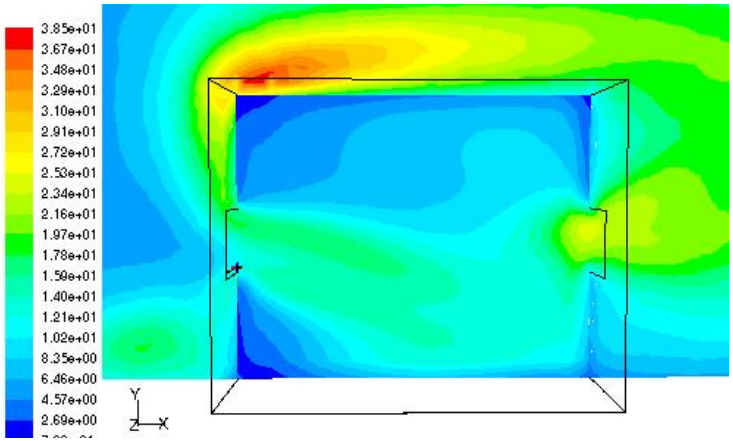


Velocity Magnitude z = 50 cm

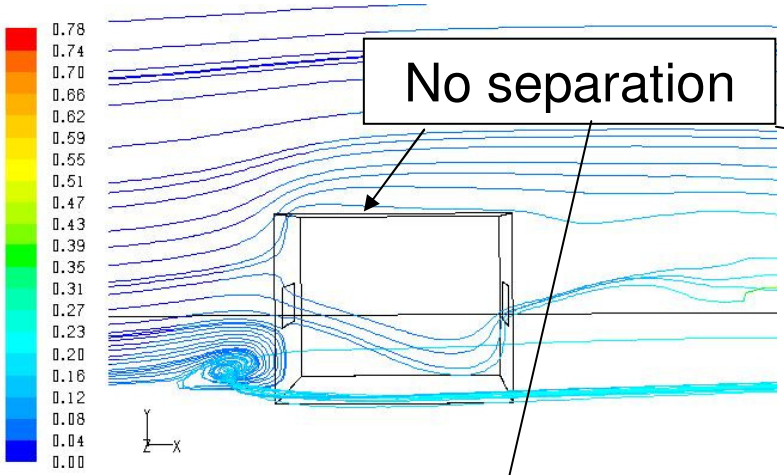


Turbulent Intensities z = 50 cm

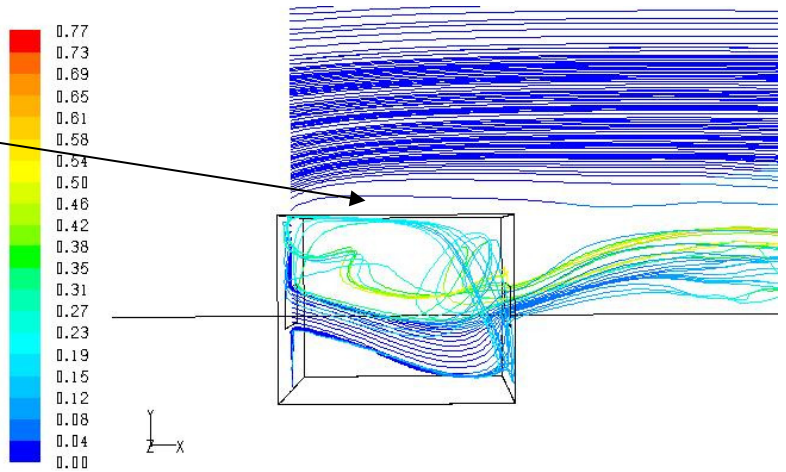


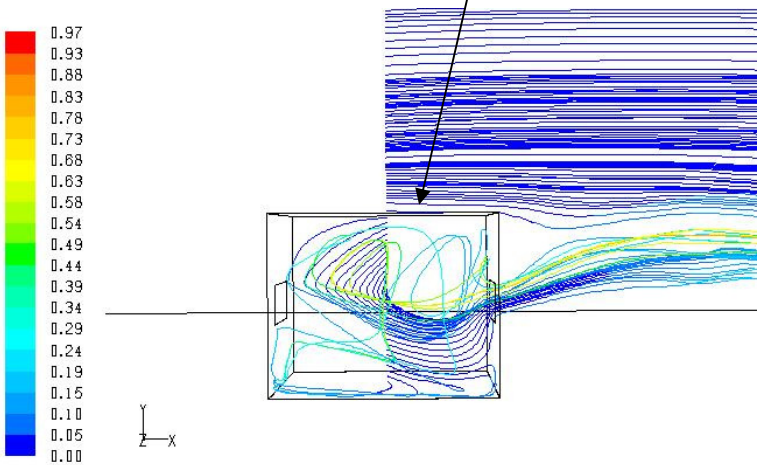


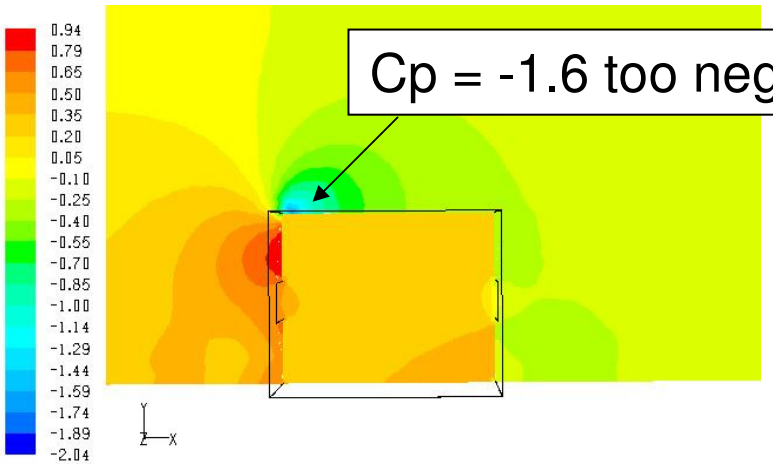
Flow field – Standard k-ε



No separation



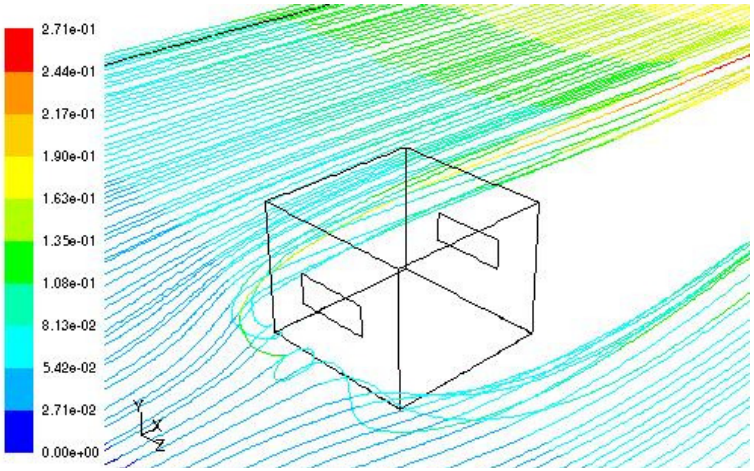


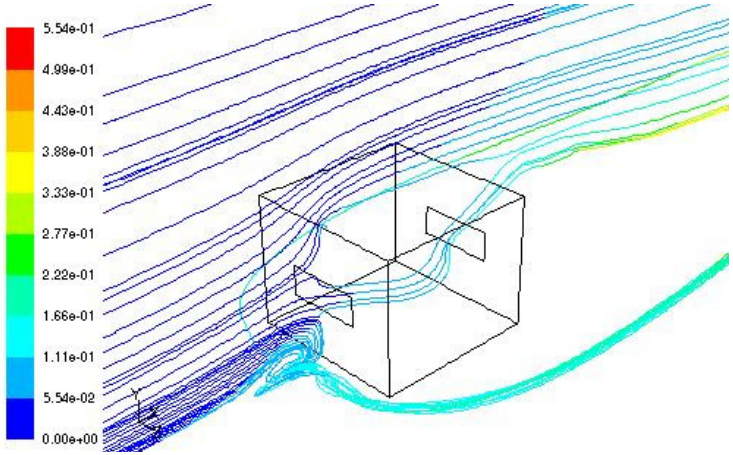


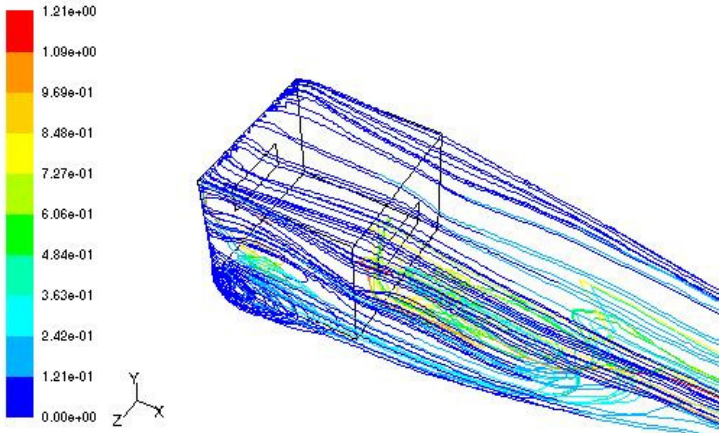
Cp = -1.6 too negative

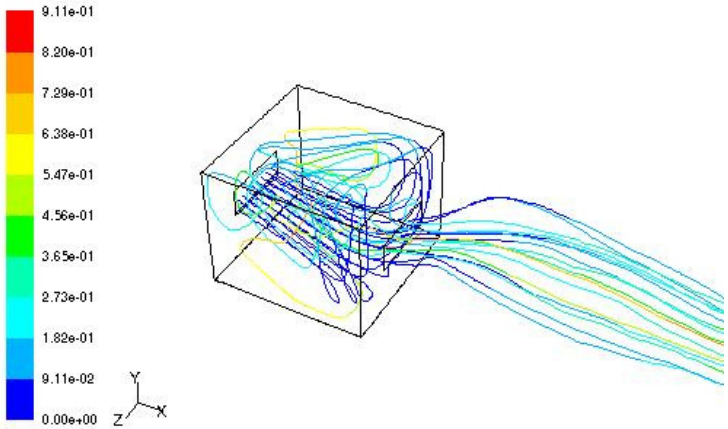
Pressure Coefficient, Cp

Path lines - Standard k-ε

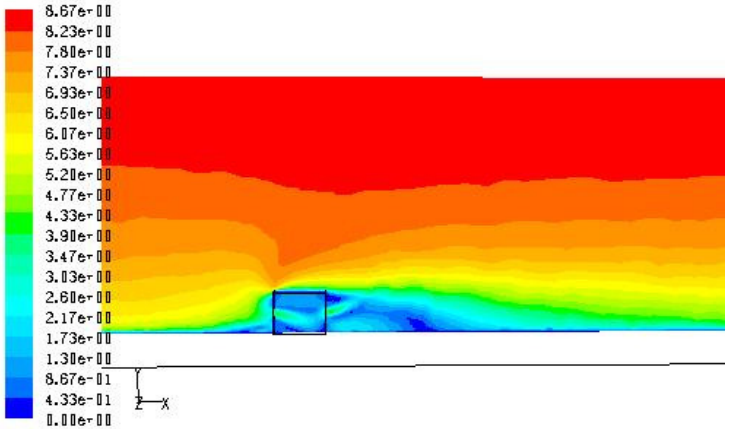




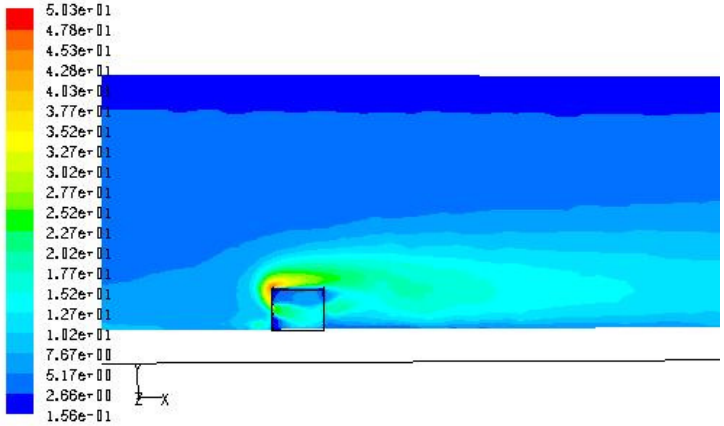




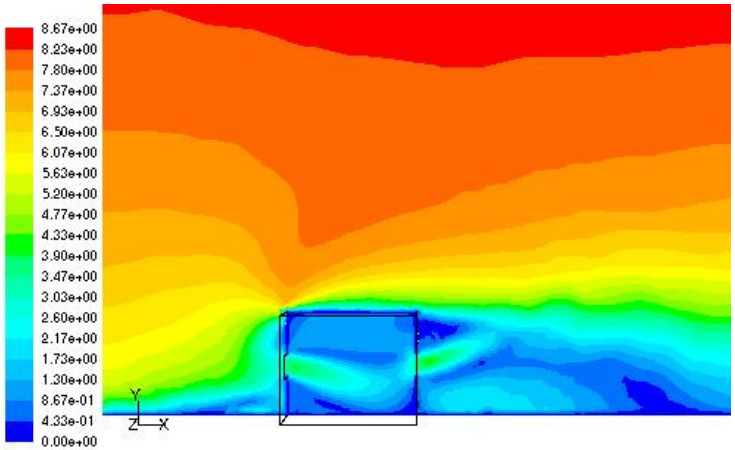
Flow field – SST k-ω

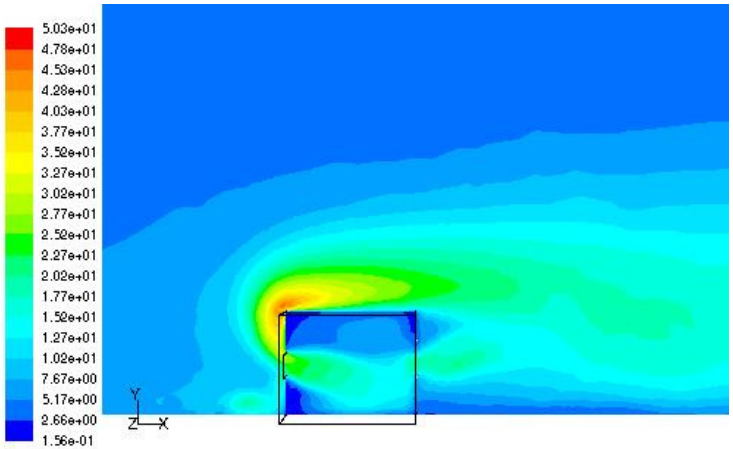


Velocity Magnitude z = 50 cm

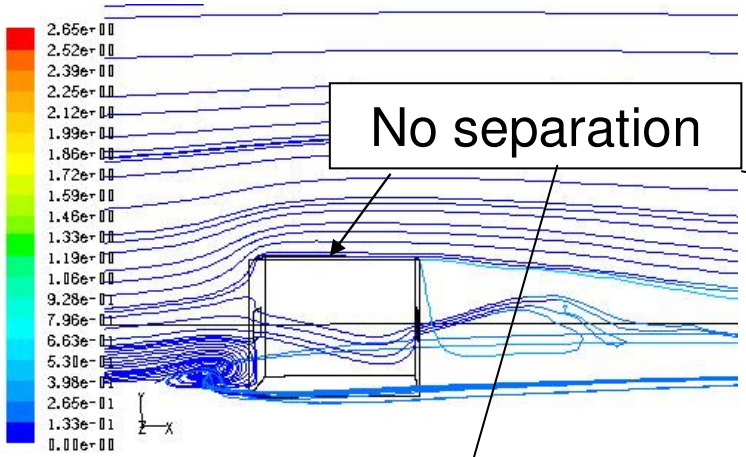


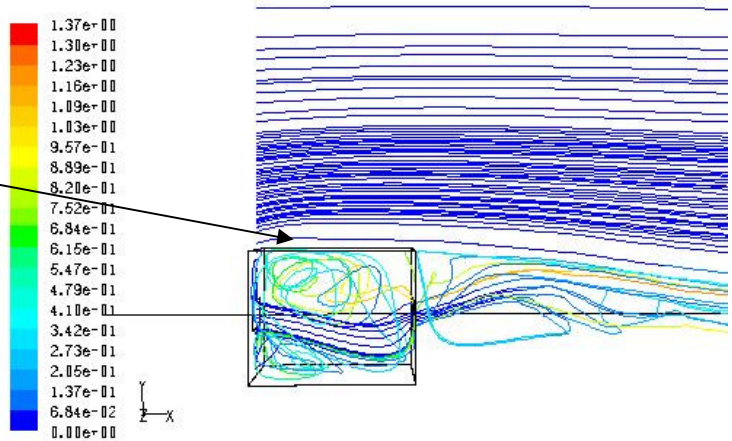
Turbulent Intensities z = 50 cm

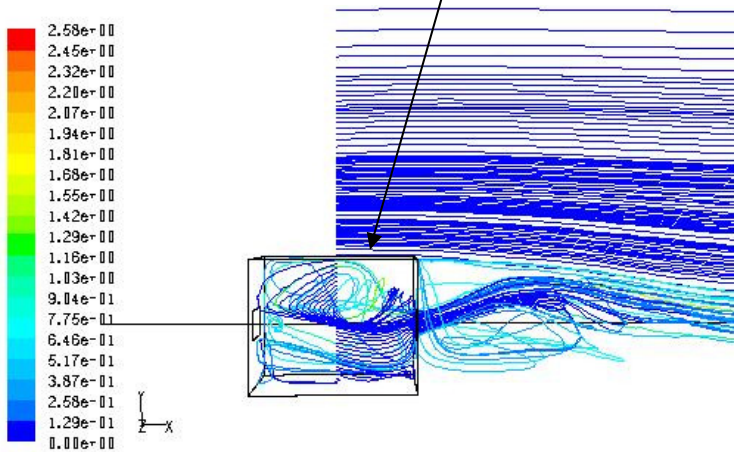


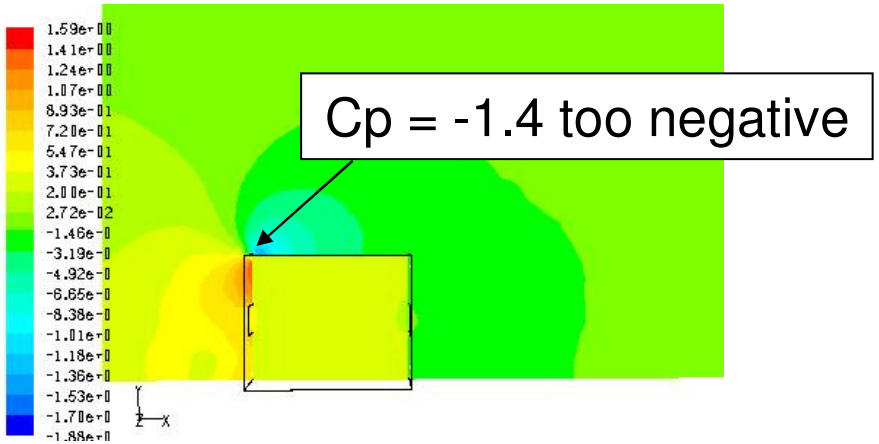


Flow field – SST k-ω



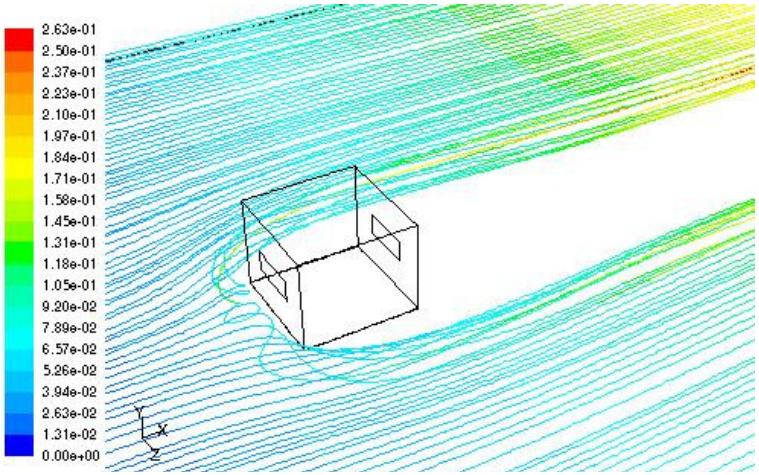


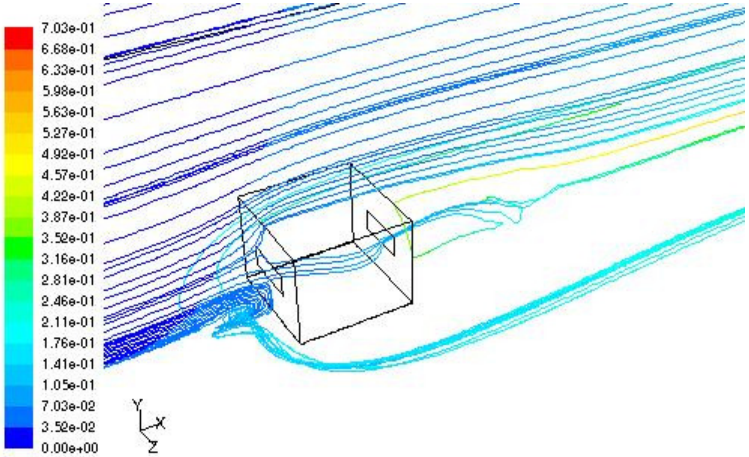


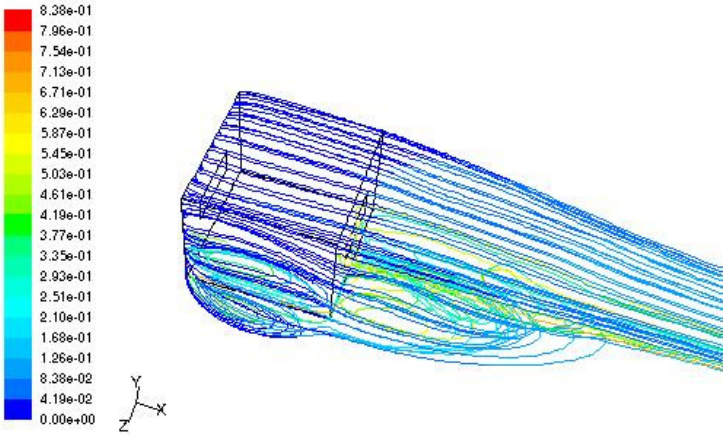


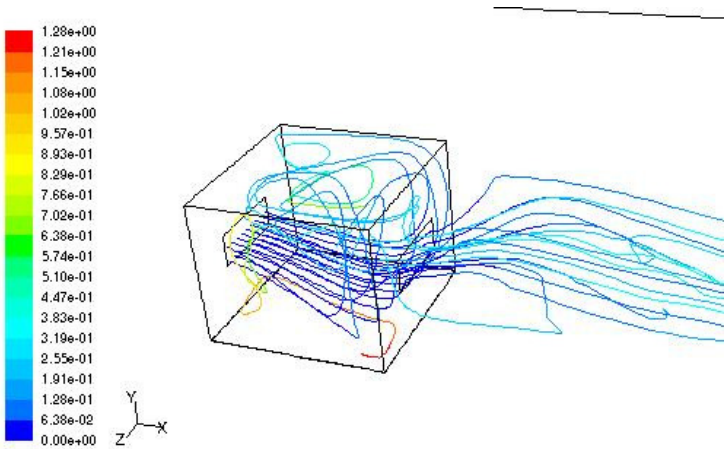
Pressure Coefficient, Cp

Path lines – SST k-ω

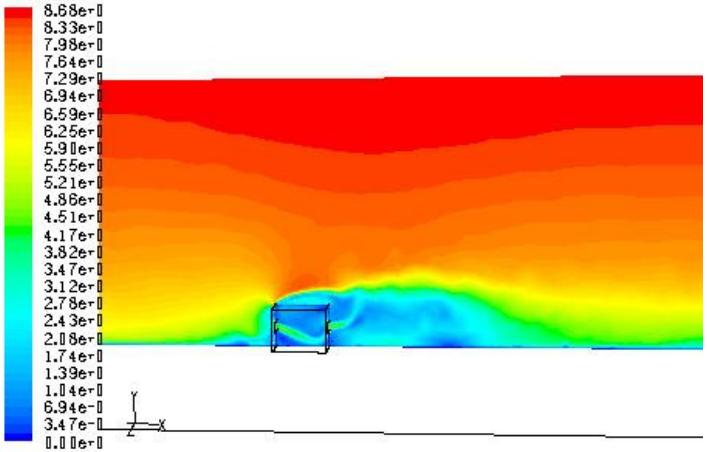




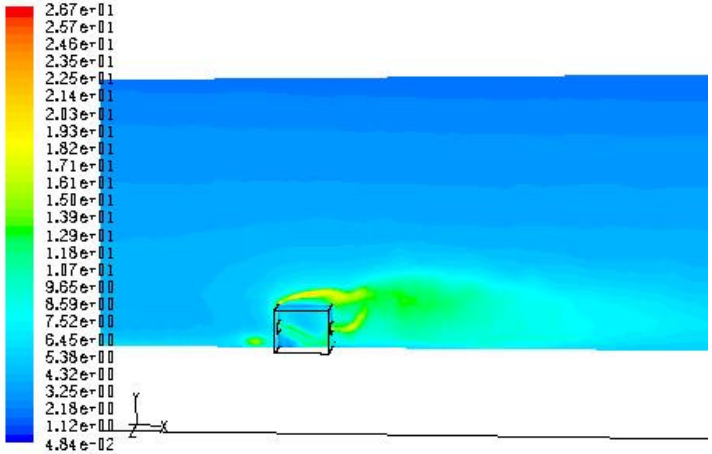




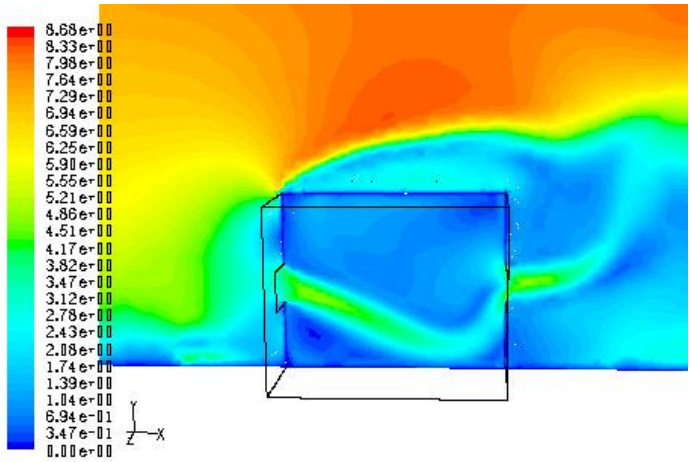
Flow field – RNG k-ε

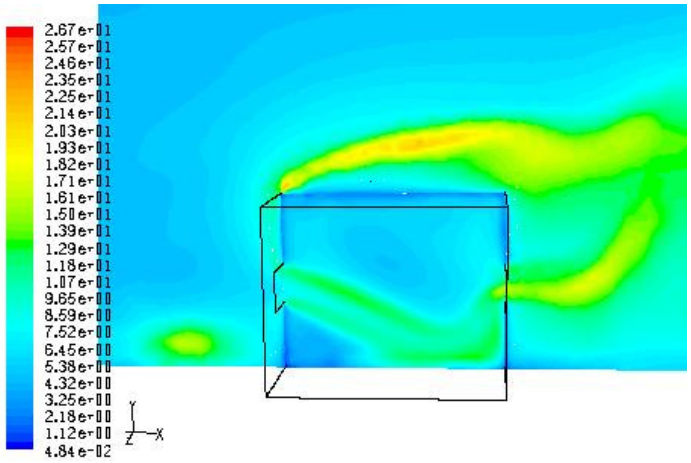


Velocity Magnitude z = 50 cm

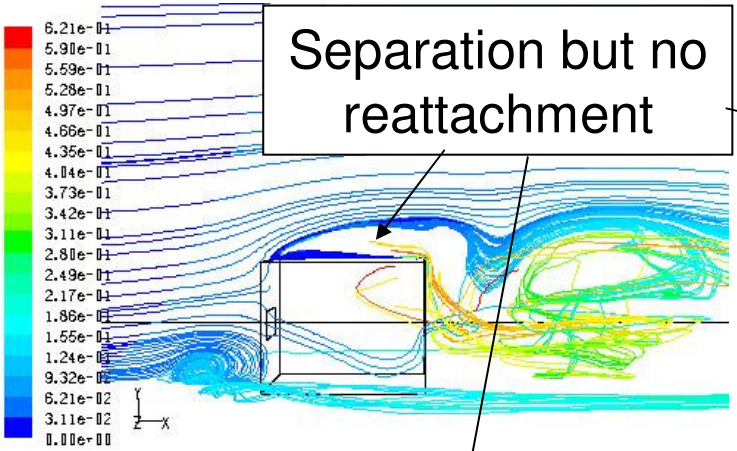


Turbulent Intensities z = 50 cm

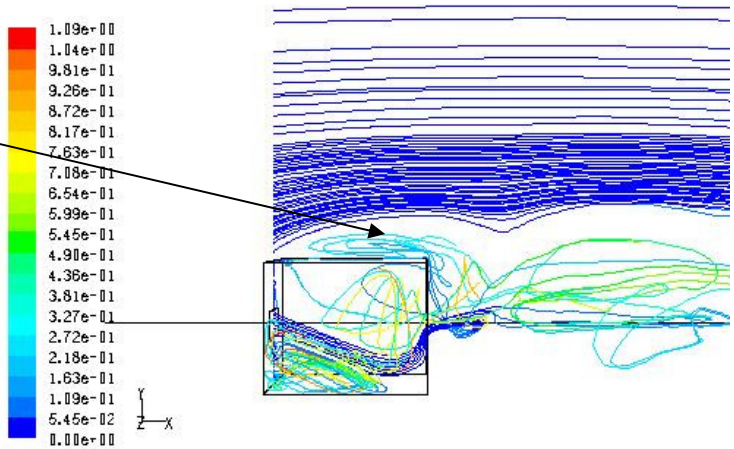


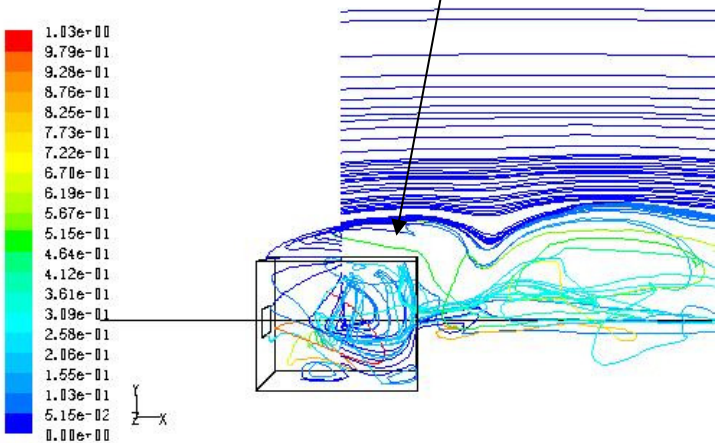


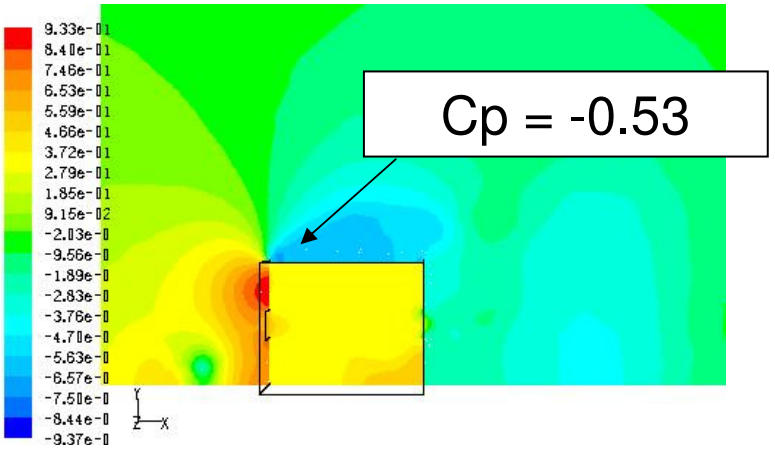
Flow field – RNG k-ε



Separation but no reattachment



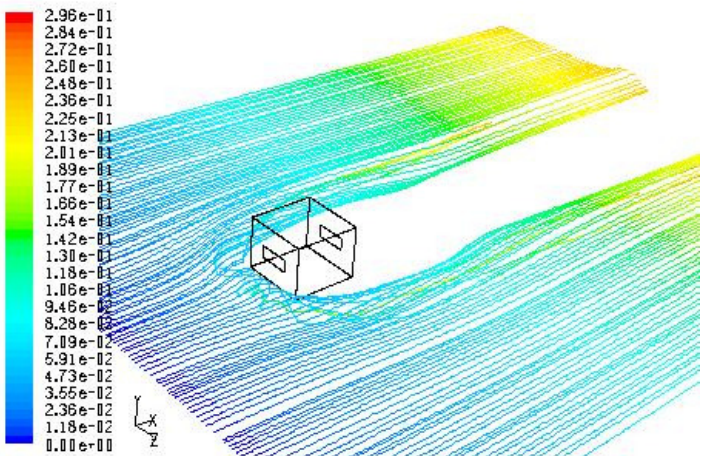


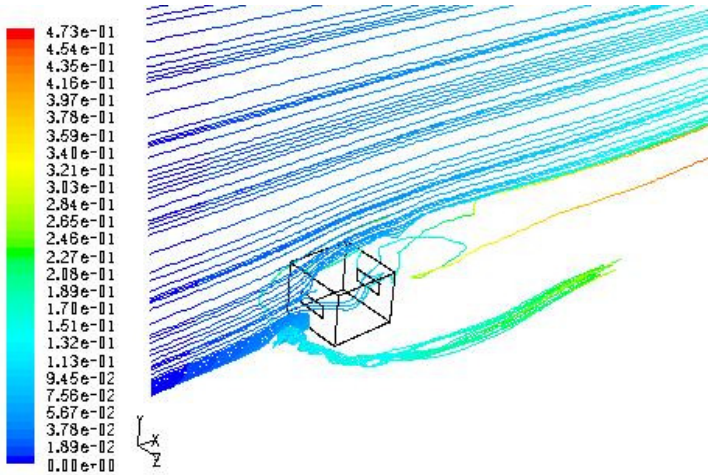


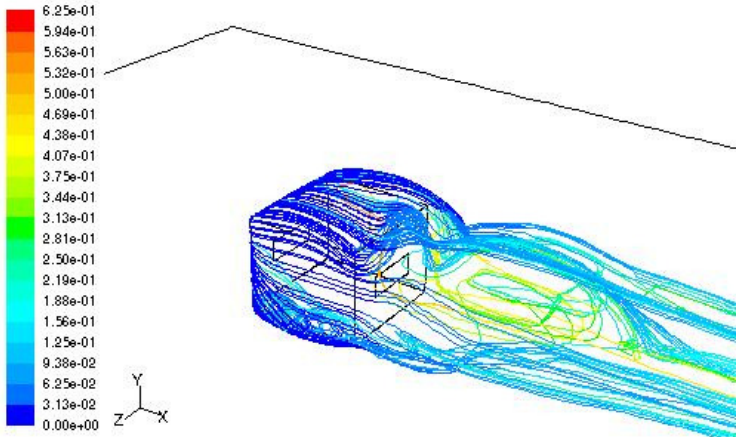
Cp = -0.53

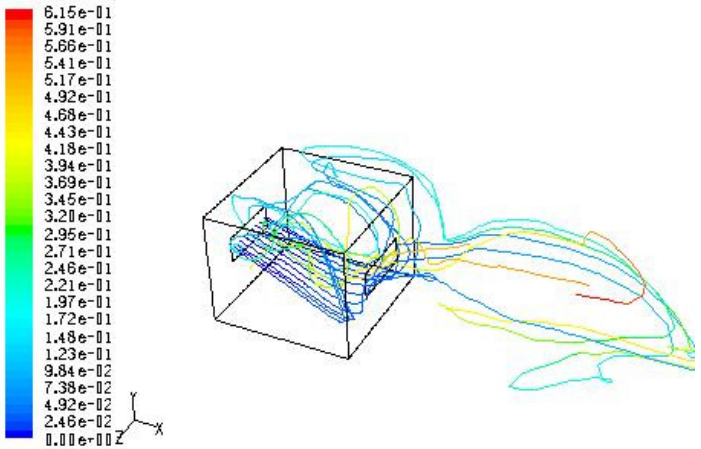
Pressure Coefficient, Cp

Path lines – RNG k-ε

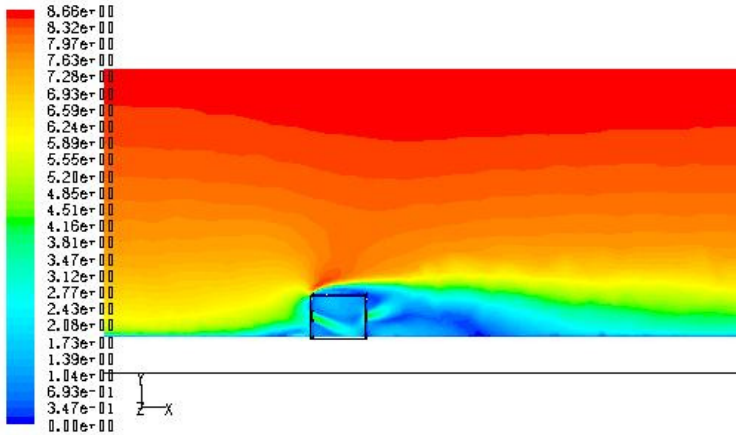




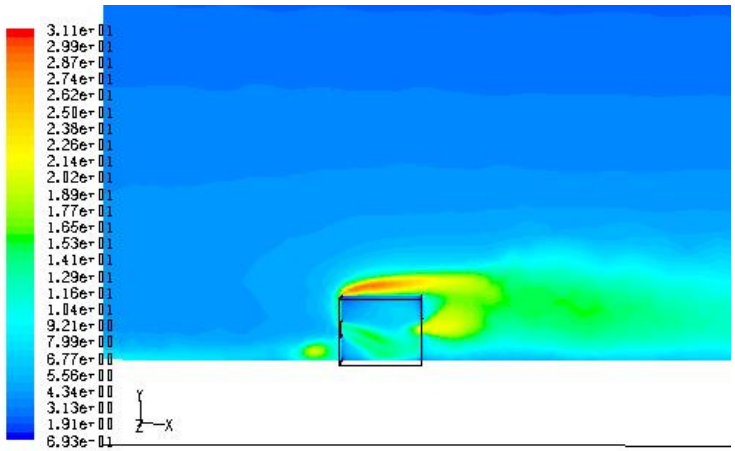




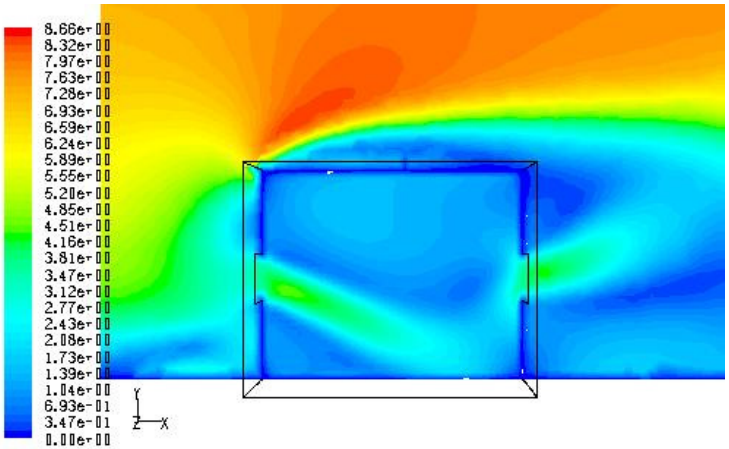
Flow field – Realizable k-ε

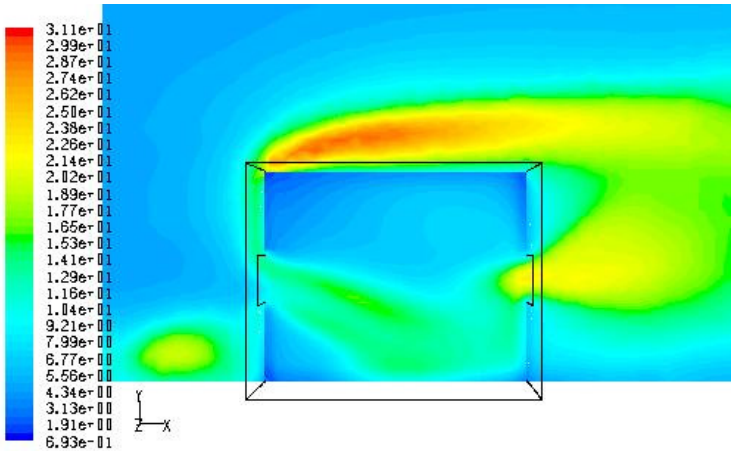


Velocity Magnitude z = 50 cm

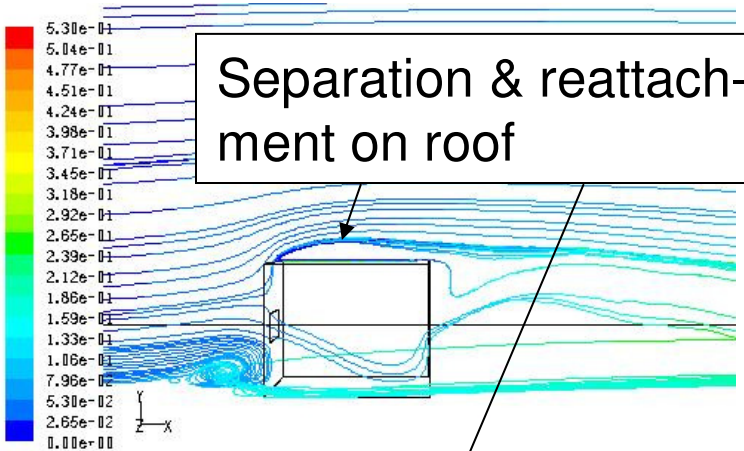


Turbulent Intensities z = 50 cm

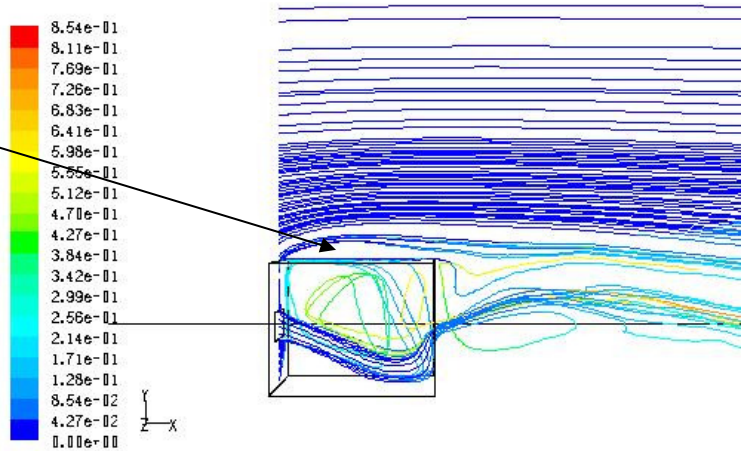


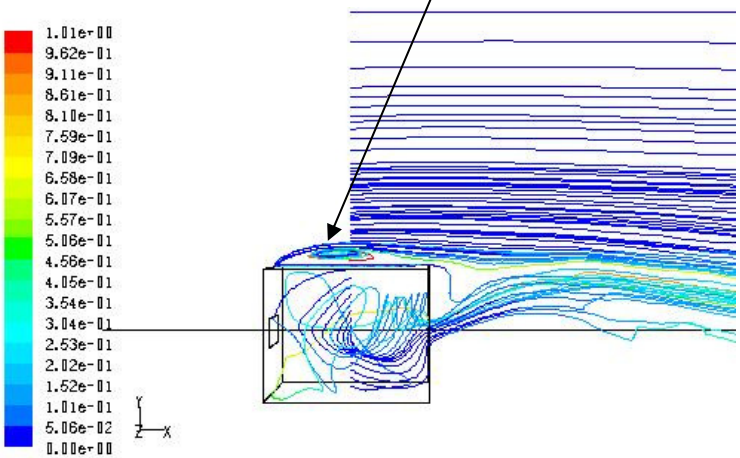


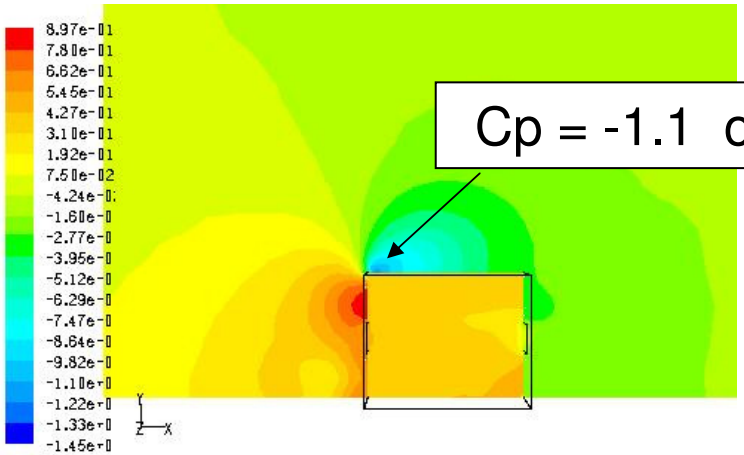
Flow field – Realizable k-ε



Separation & reattach-ment on roof



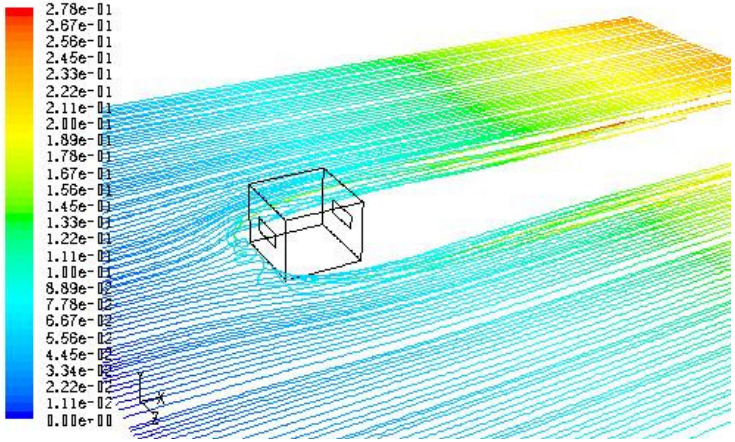


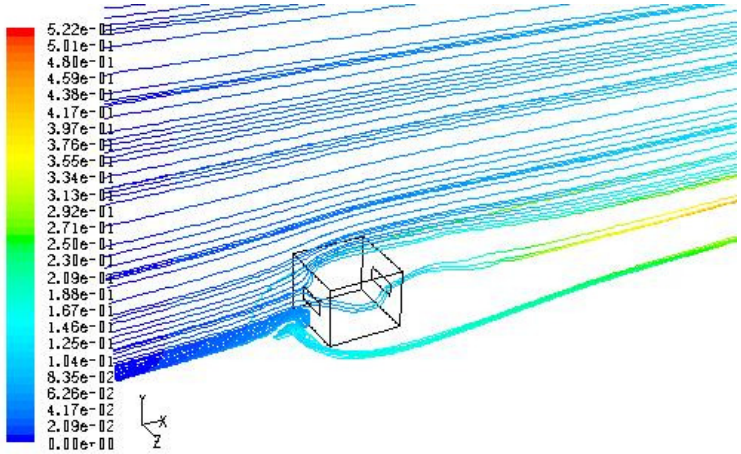


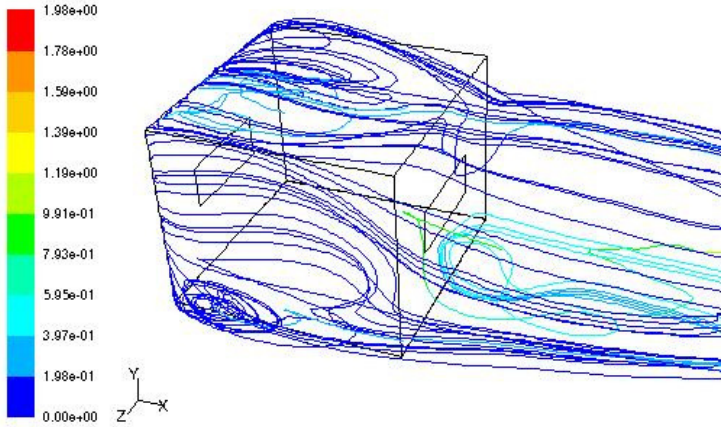
Cp = -1.1 ok

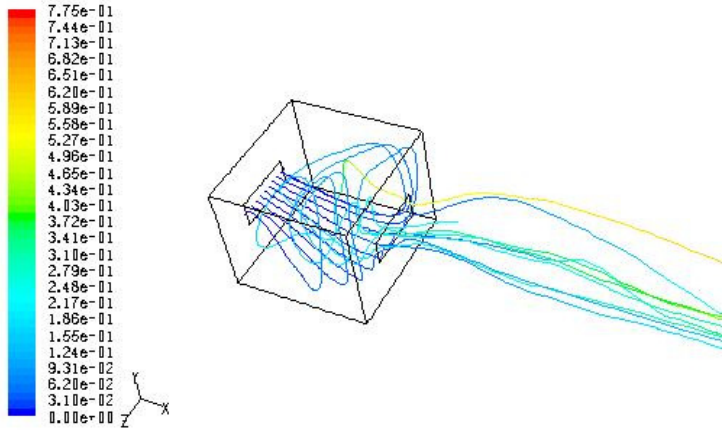
Pressure Coefficient, Cp

Path lines – Realizable k-ε

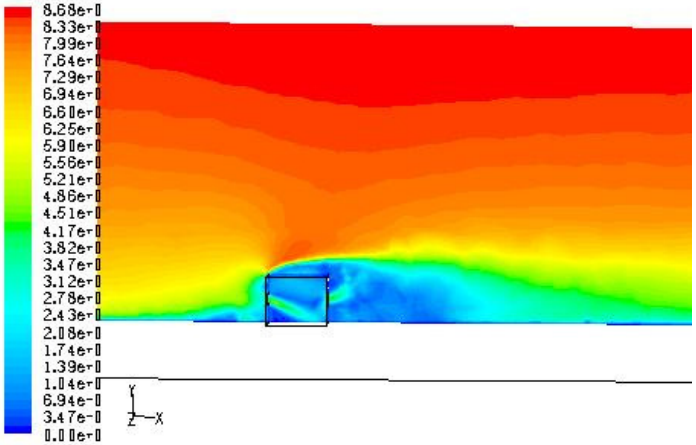




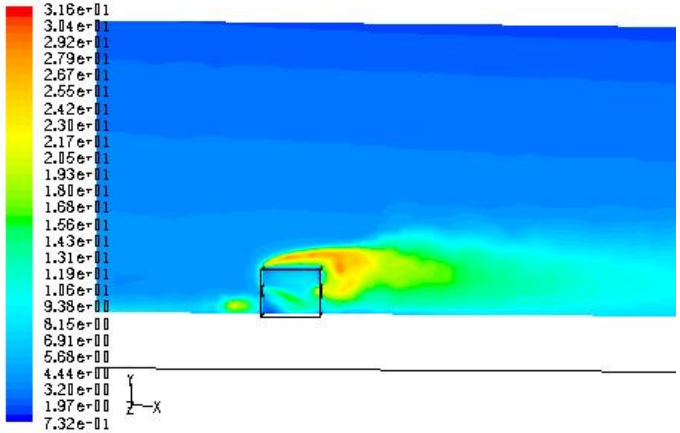




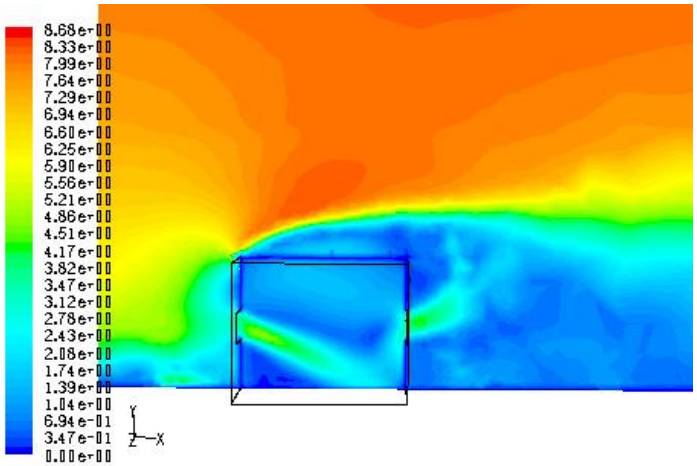
Flow field - RMS

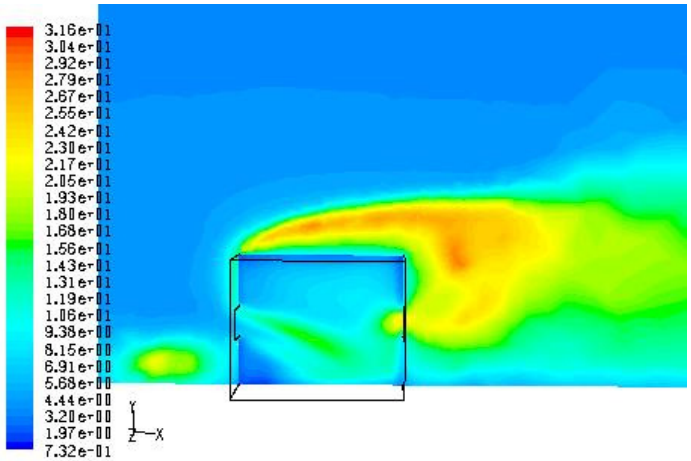


Velocity Magnitude z = 50 cm

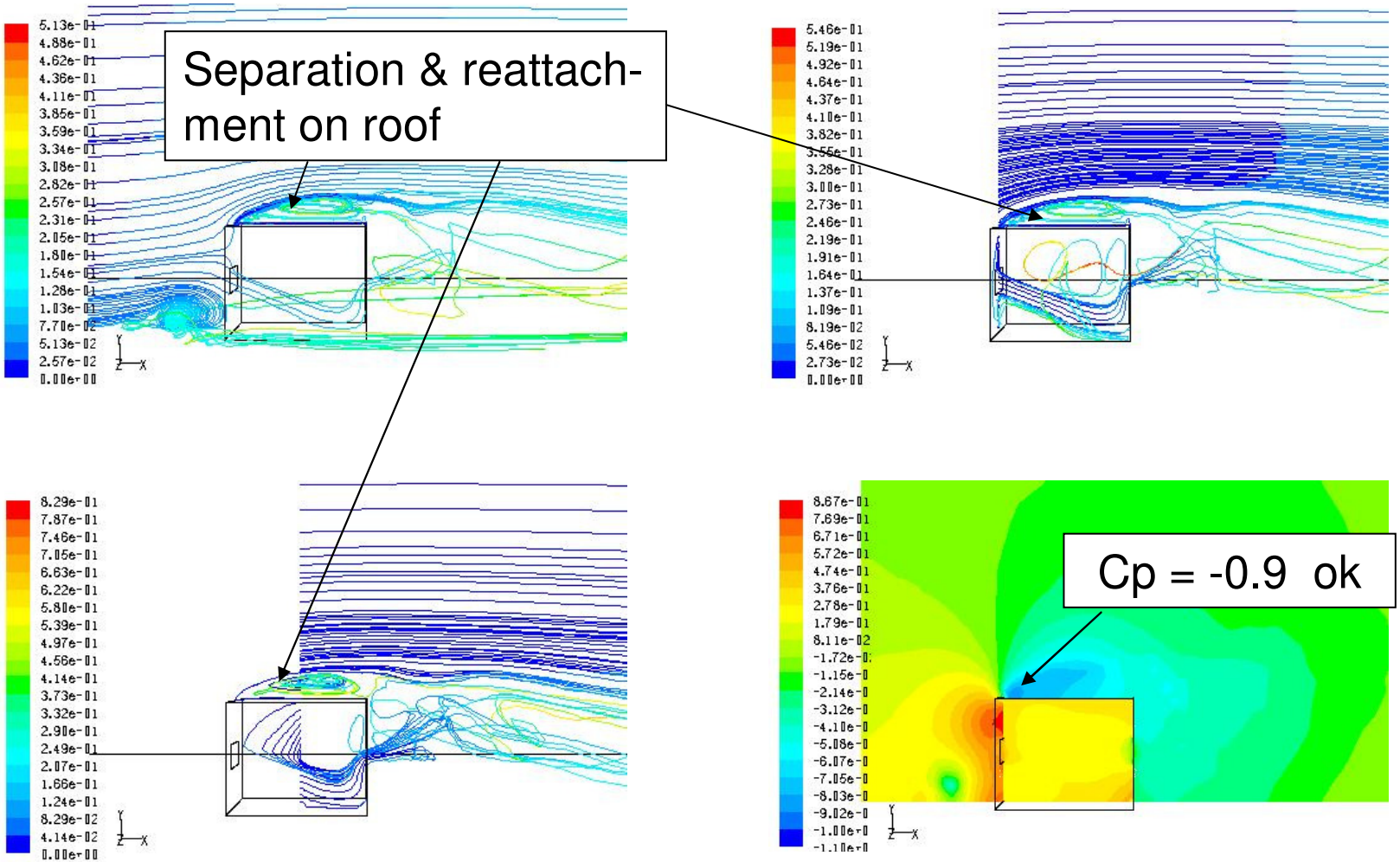


Turbulent Intensities z = 50 cm



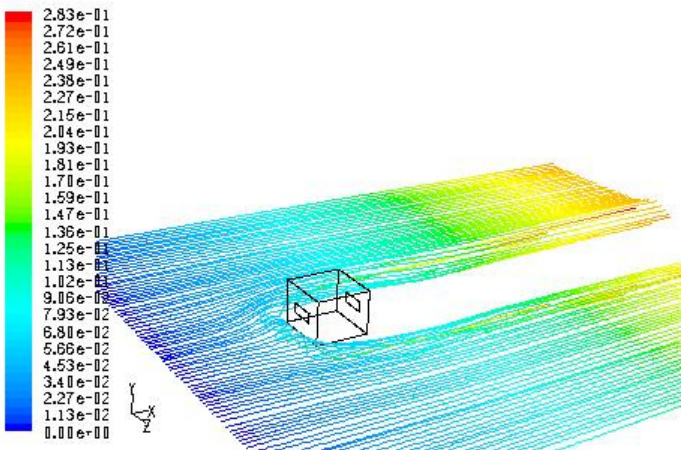


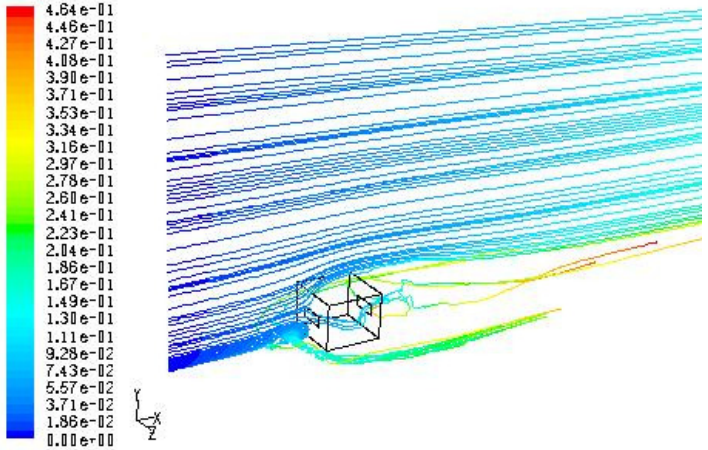
Flow field - RMS

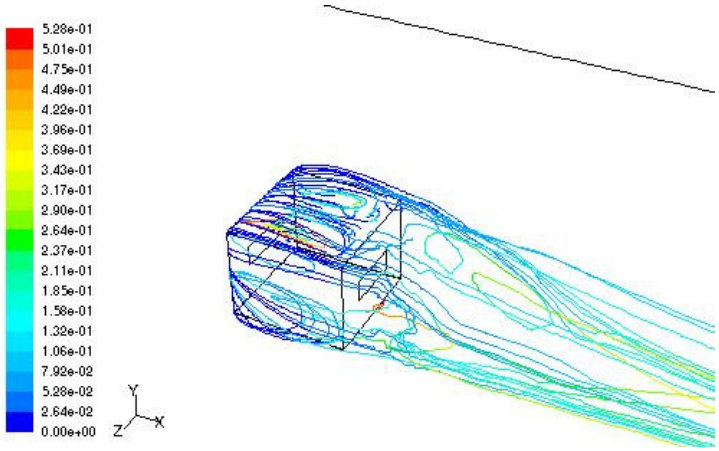


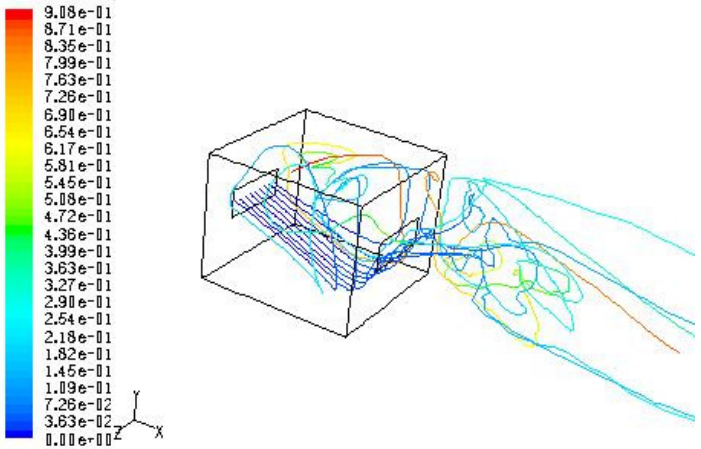
Pressure Coefficient, Cp

Path lines – RMS

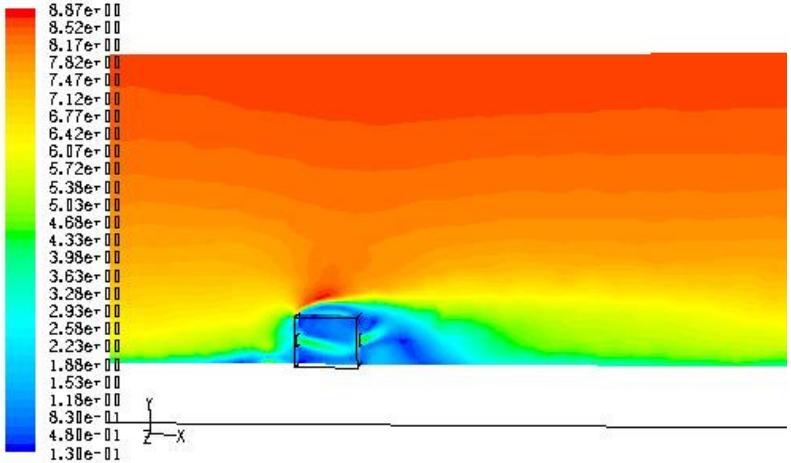




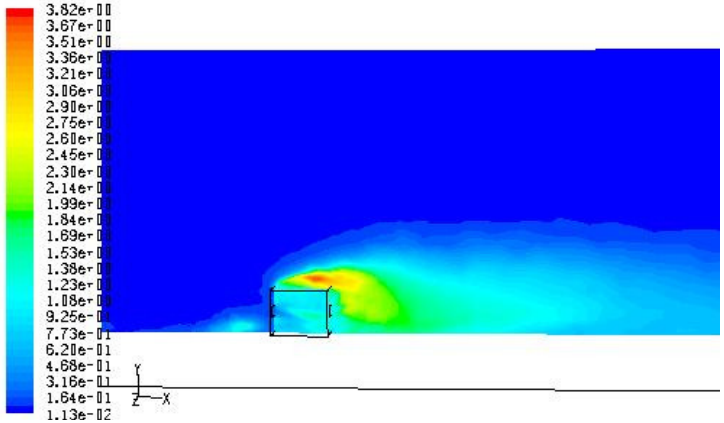




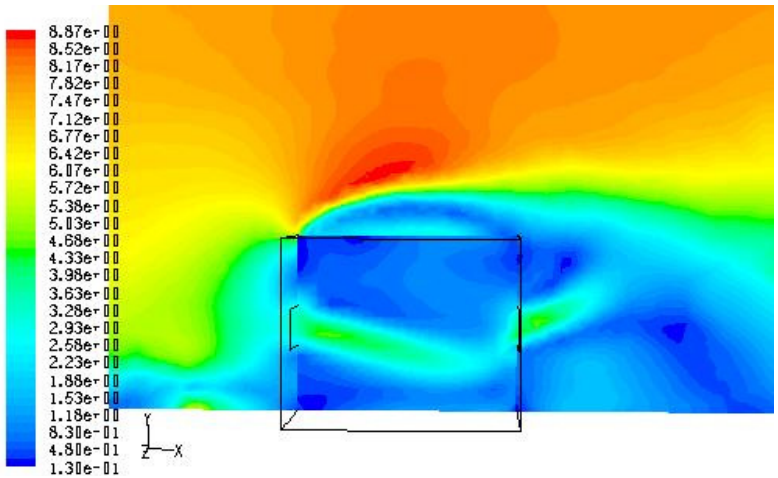
Flow field – LES

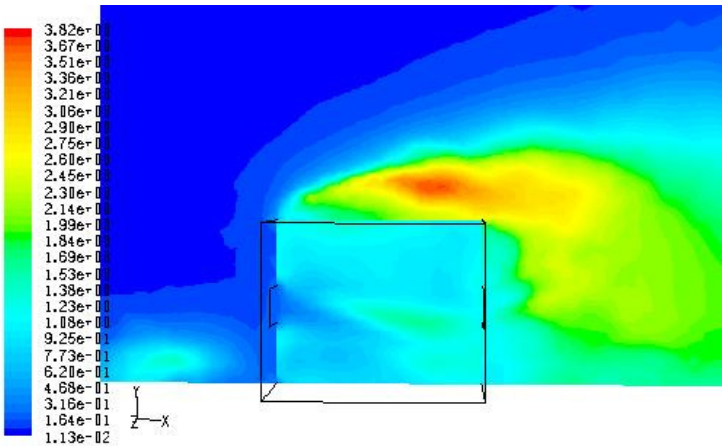


Mean Velocity Magnitude z = 50 cm

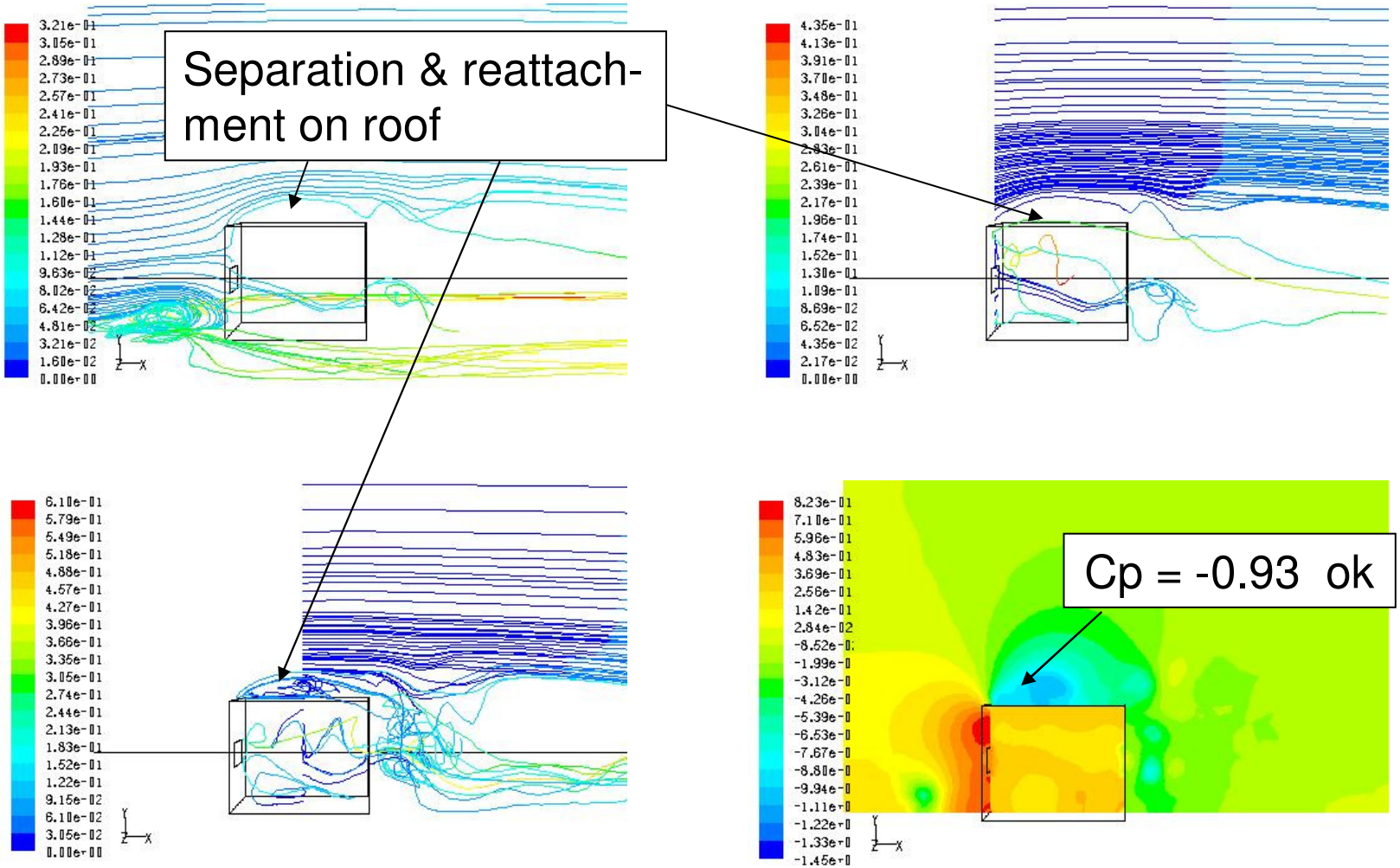


RMS Velocity Magnitude z = 50 cm



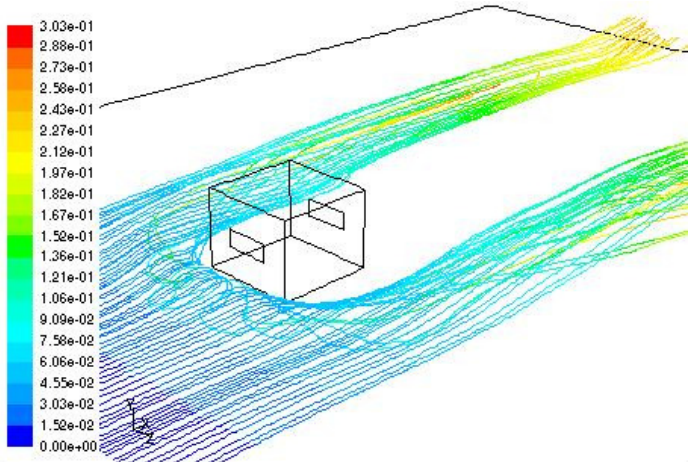


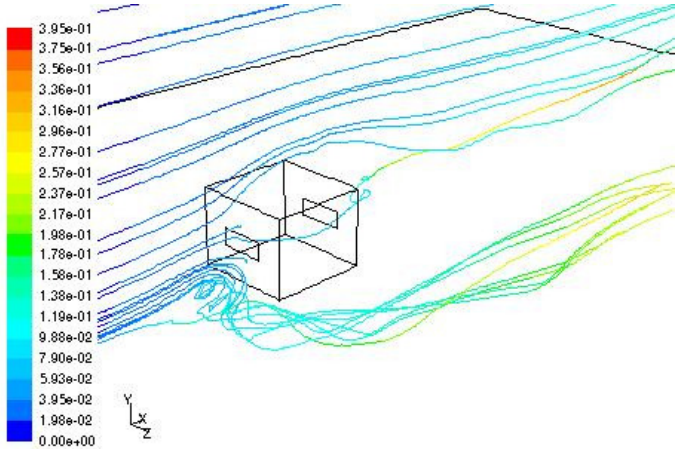
Flow field – LES

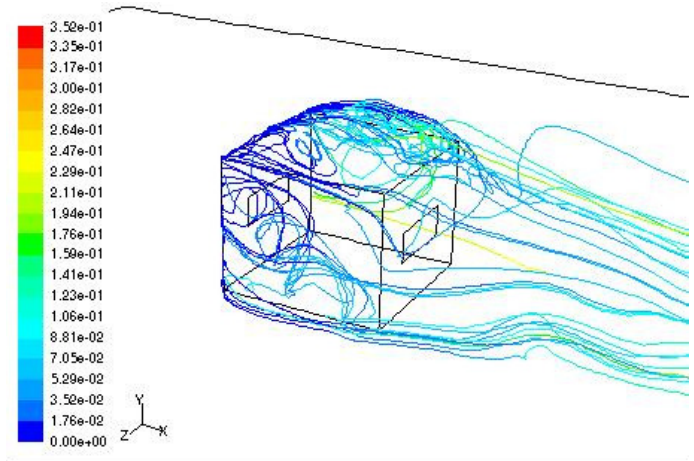


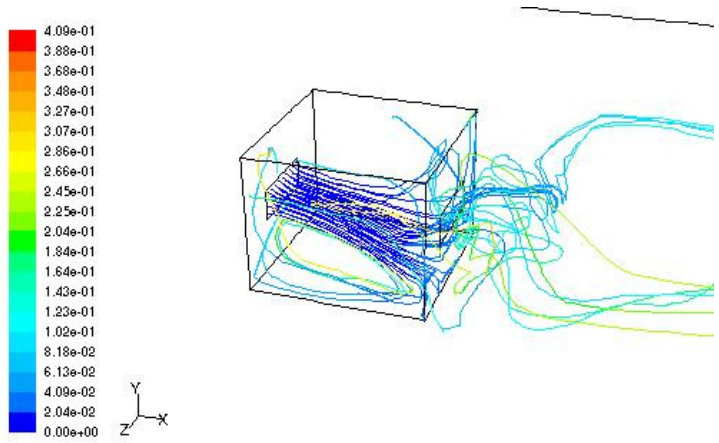
Pressure Coefficient, Cp

Path lines – LES



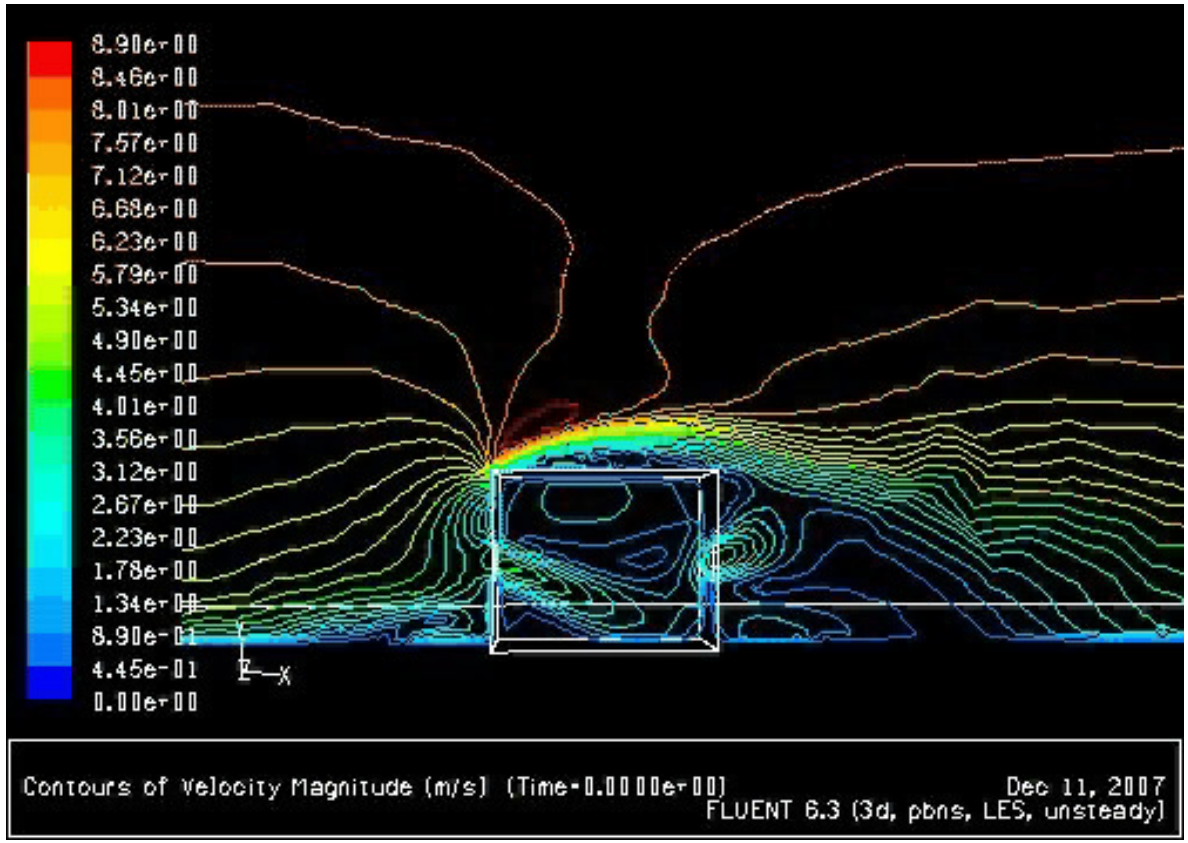






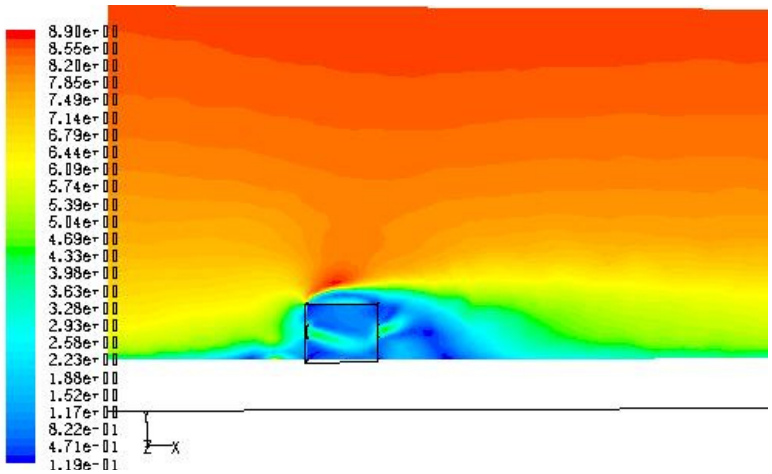
Flow field – LES

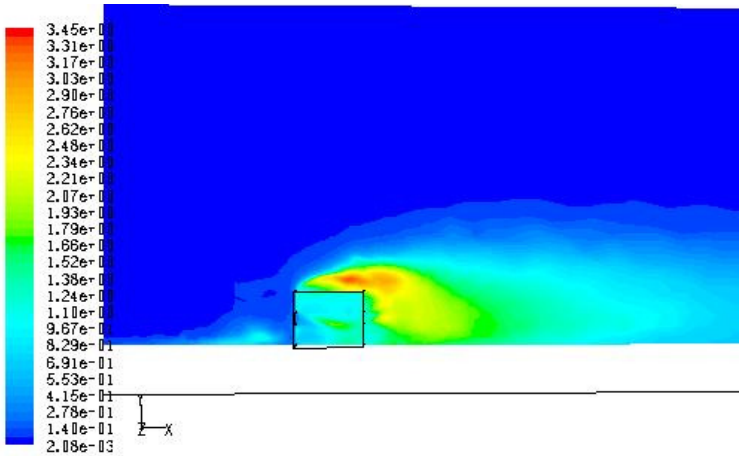
Full field computation



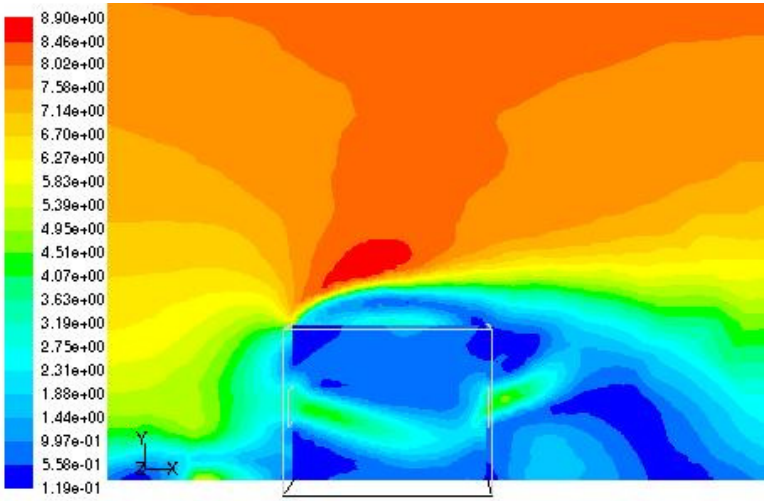
Flow field - DES

Realizable k-ε at wall

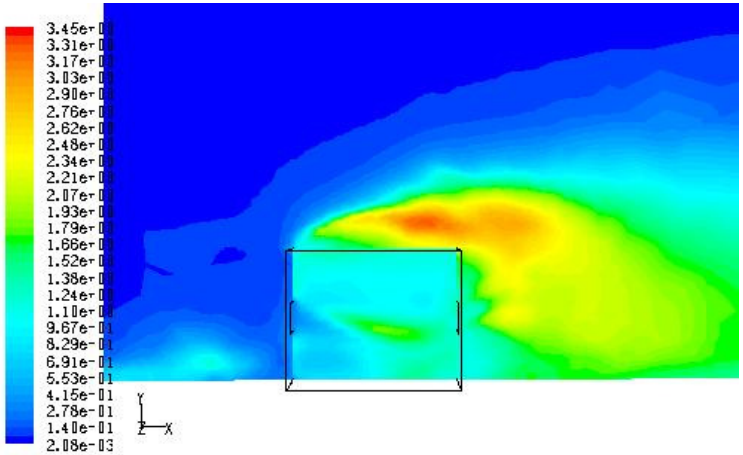




Mean Velocity Magnitude z = 50 cm

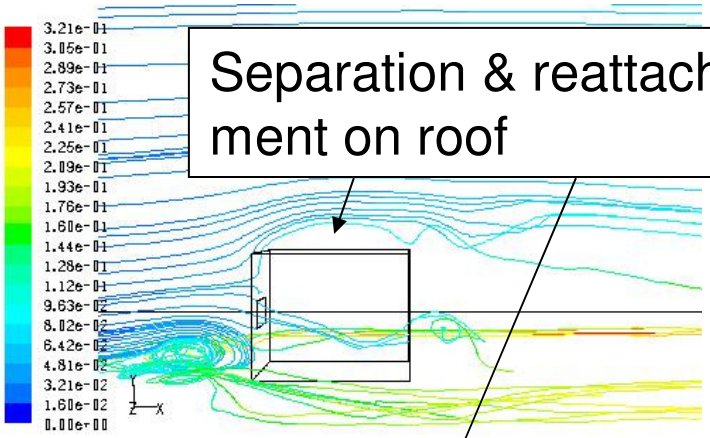


RMS Velocity Magnitude z = 50 cm

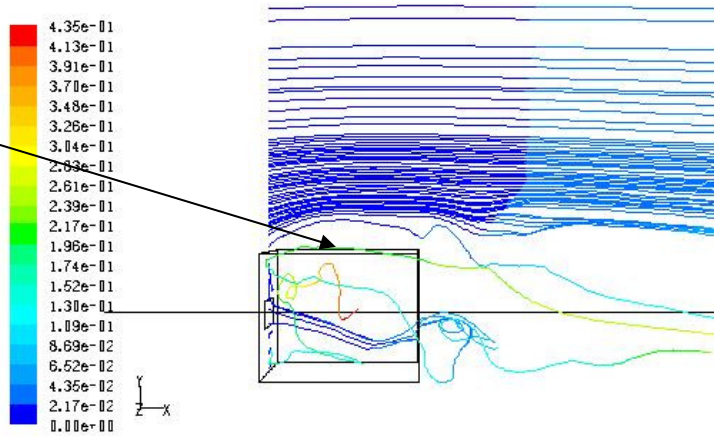


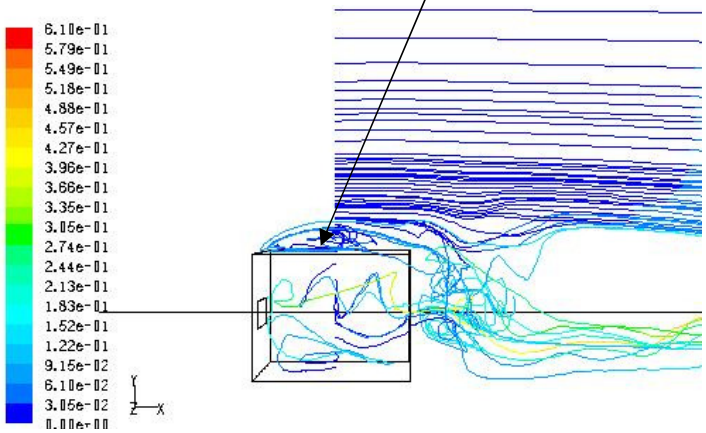
Flow field - DES

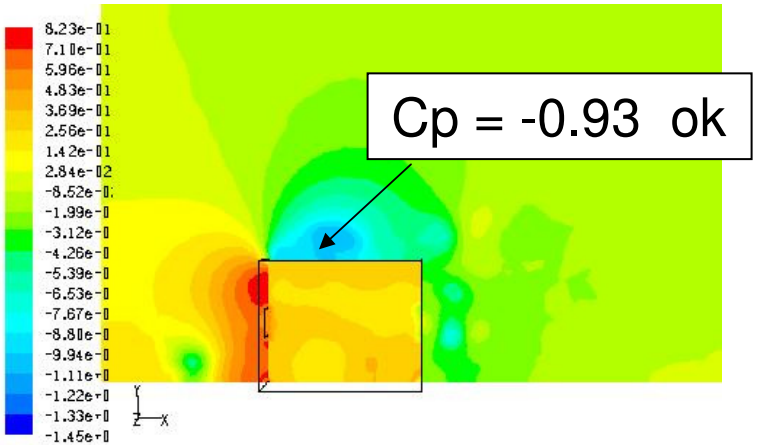
Realizable k-ε at wall



Separation & reattach-ment on roof



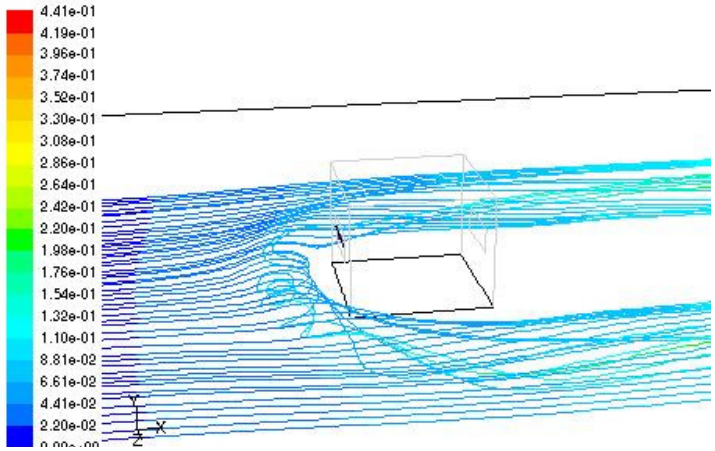


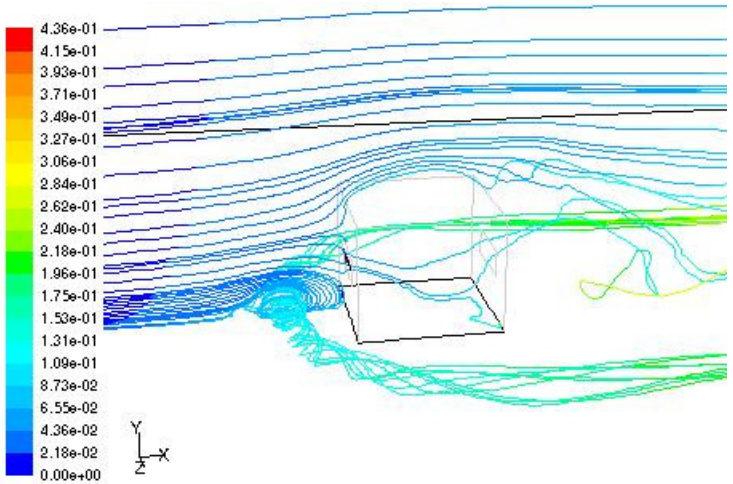


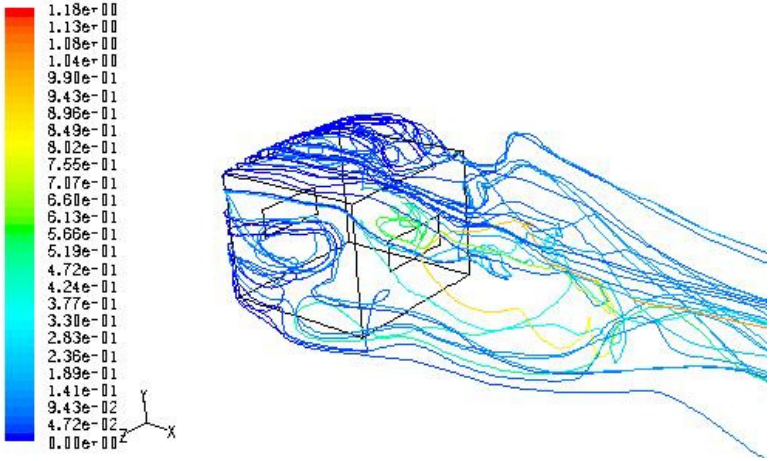
Pressure Coefficient, Cp

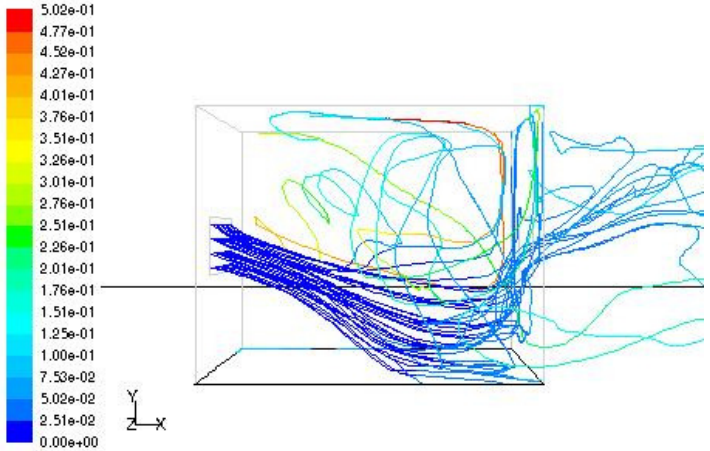
Path lines –DES

Realizable k-ε at wall

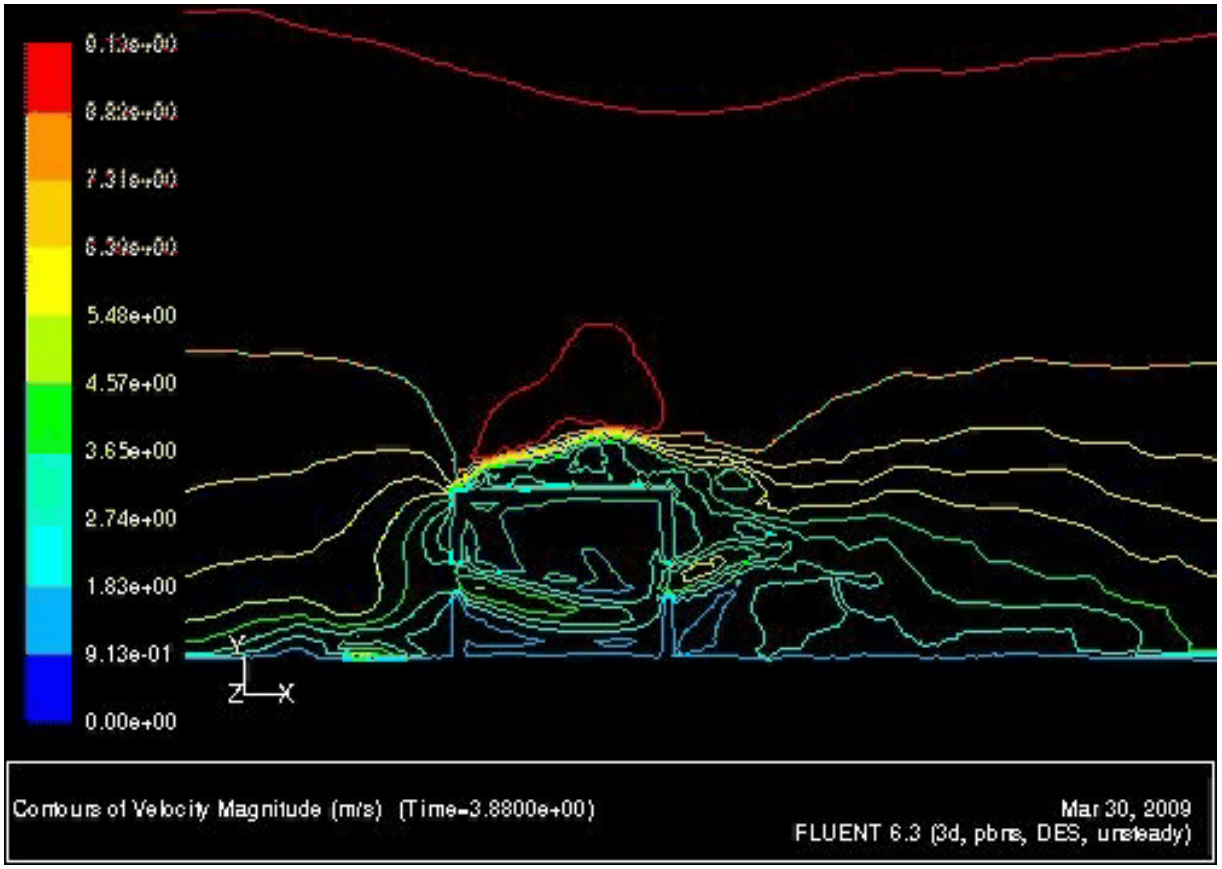


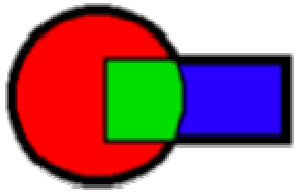






Flow field DES





Domain Decomposition

- Kurabuchi et al. (2009) proposed one perform a full domain calculation around a sealed building, then calculate internal flows separately (fast)
  - Predict external flow over sealed building with CFD
  - Note external pressures,
  - Note adjusted internal pressure
  - Note tangential dynamic pressure at surface or θ
- Calculate Q and $Cp_{internal}$
  - $Q = C_{Din} A V_H (Cp_{in} - Cp_{internal})^{1/2}$……..…Eq (1)
  - $Cp_{internal} = (Cp_{in} + Cp_{out})/2$……Eq (2)
- Calculate internal flow using Q and $V_{tangential}$

External Cp Variation, (rke model)

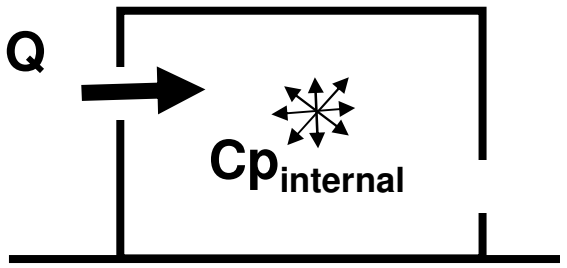
	Upwind Face			Downwind Face		
Case y(cm) =	6	4	2	6	4	2
Box - sealed	0.856	0.856	0.695	-0.306	-0.226	-0.186
A	0.514	0.809	0.640	+0.050	-0.245	-0.203
B	0.540	0.802	0.644	-0.250	-0.250	+0.013
C	0.873	0.828	0.397	-0.269	-0.269	-0.031
D	0.867	0.817	0.414	-0.054	-0.241	-0.168
E	0.873	0.545	0.592	-0.301	-0.025	-0.168
E-walls	0.893	0.507	0.604	-0.313	-0.025	-0.168

Denotes opening locations

Boundary Conditions for Domain Decomposition

Case	Cp_{in}	$Cp_{internal}$	C_{Din}	Q (m^3/sec)	V_{in} (m/sec)	Θ (degrees)
A	0.856	0.275	0.67	0.0029	3.50	20
C	0.675	0.250	0.67	0.0025	3.01	-45
E	0.856	0.315	0.67	0.0028	3.38	-20

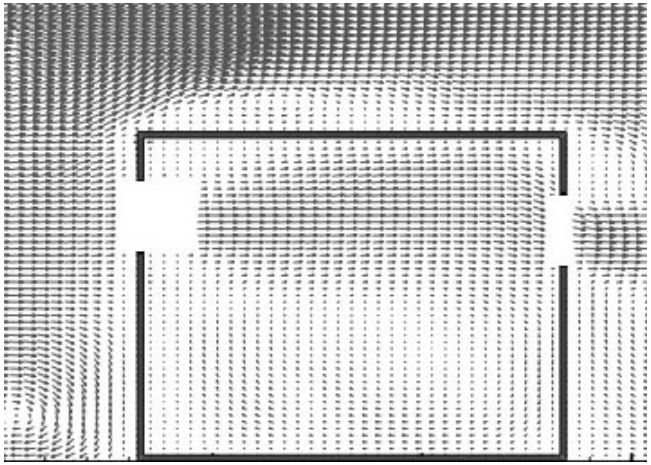
Sealed Building



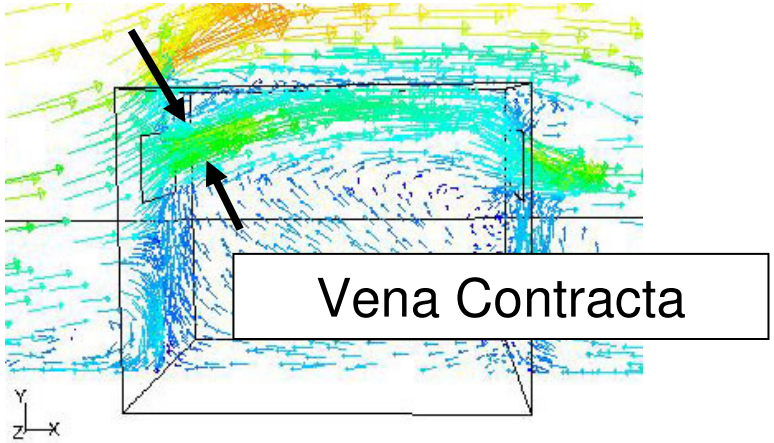
Ventilated Building

Vector Section – Case A: rke

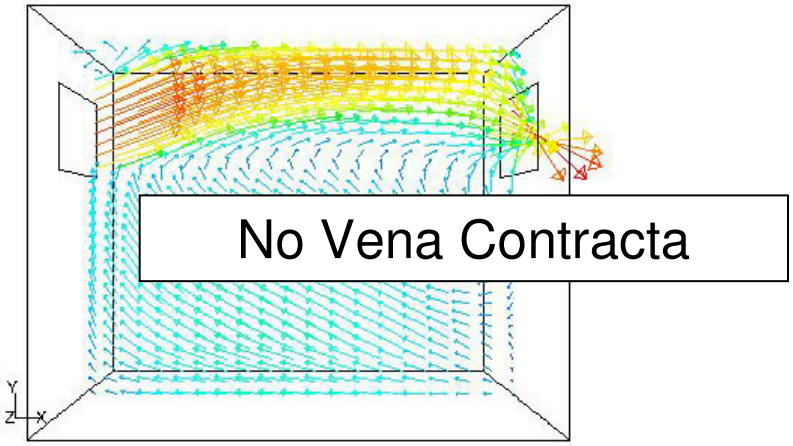
PIV Measurements

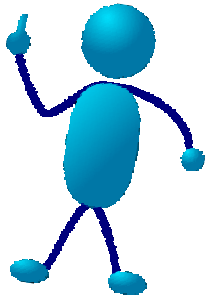


Full domain CFD calculation



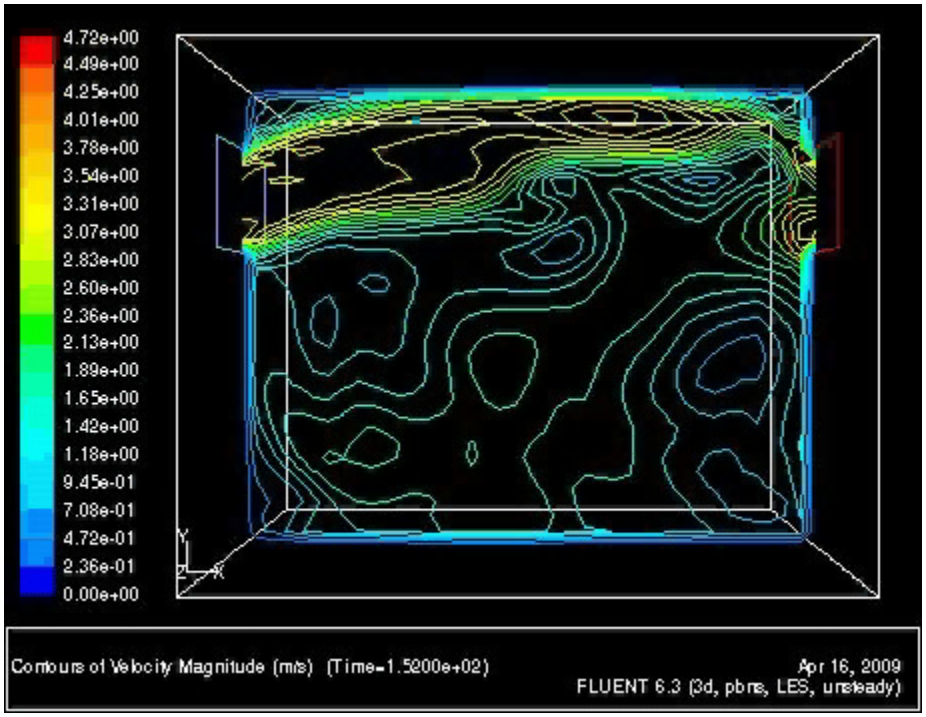
Domain Decomposition





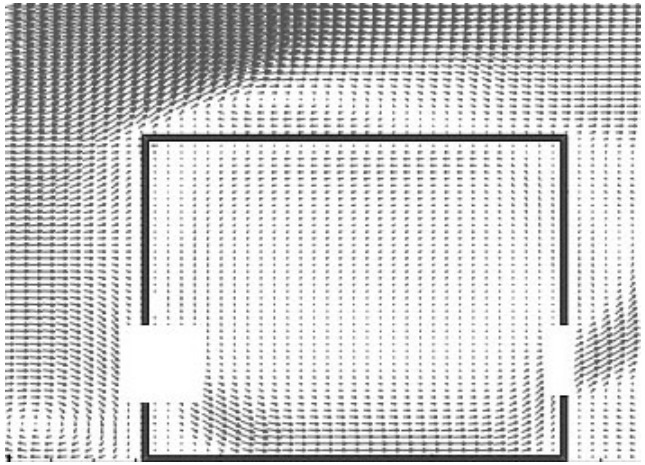
Flow field – LES

Domain decomposition computation

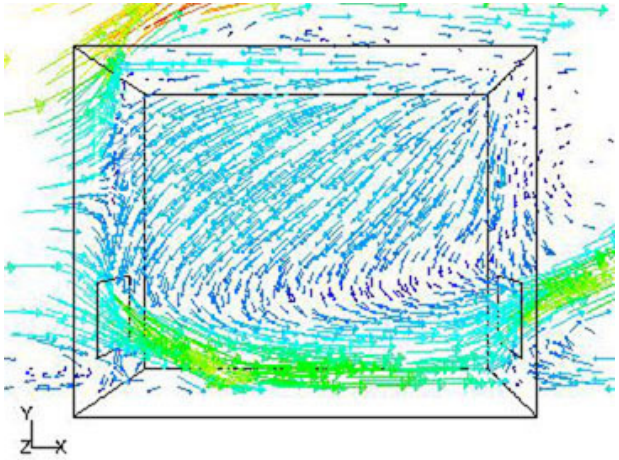


Vector Section – Case C: rke

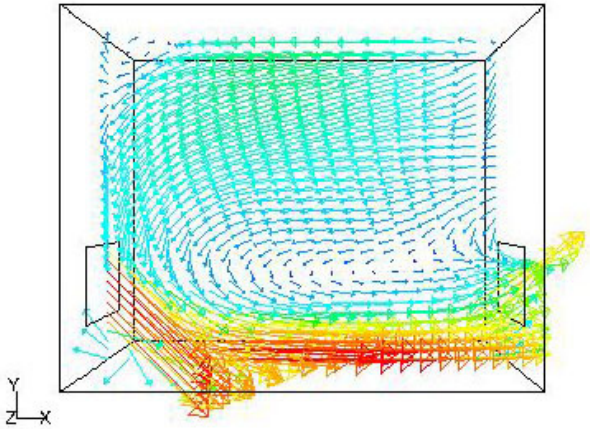
PIV Measurements

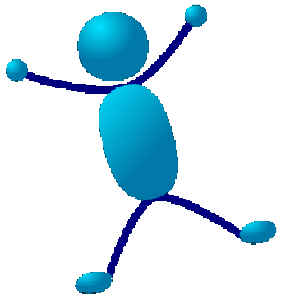


Full domain CFD calculation



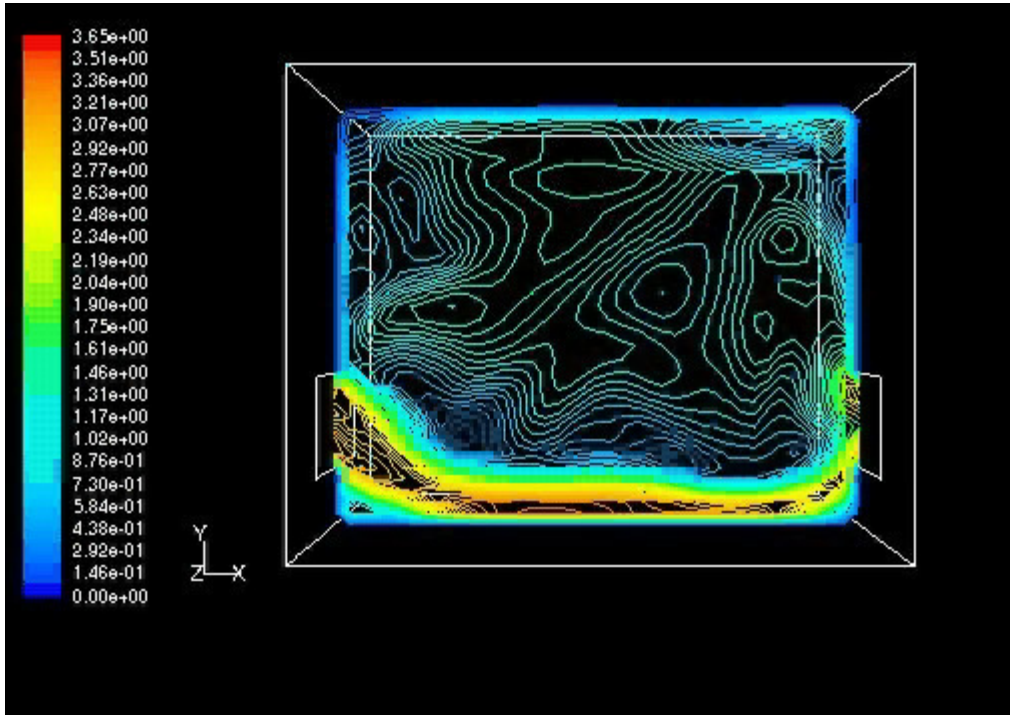
Domain Decomposition





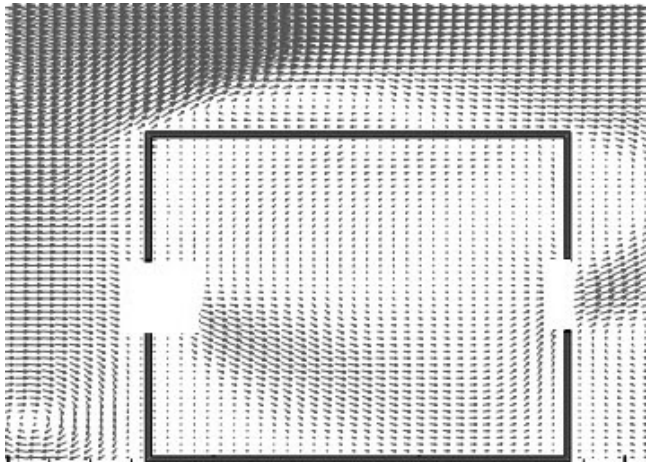
Flow field – LES

Domain decomposition computation

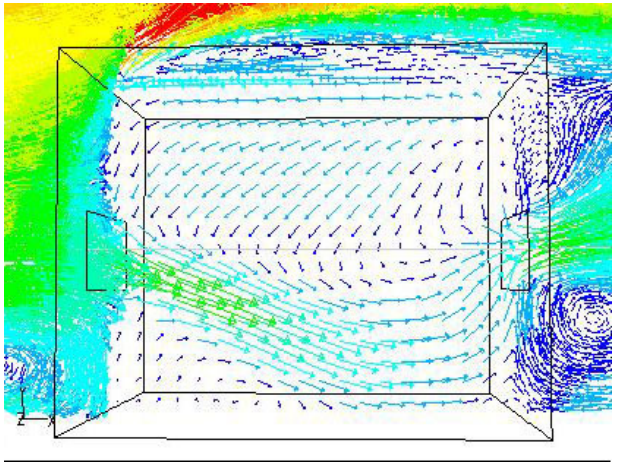


Vector Section – Case E: rke

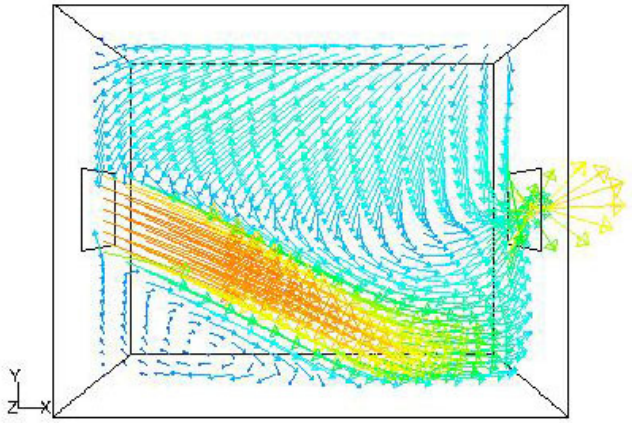
PIV Measurements

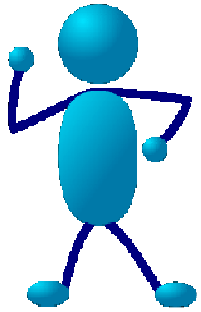


Full domain CFD calculation



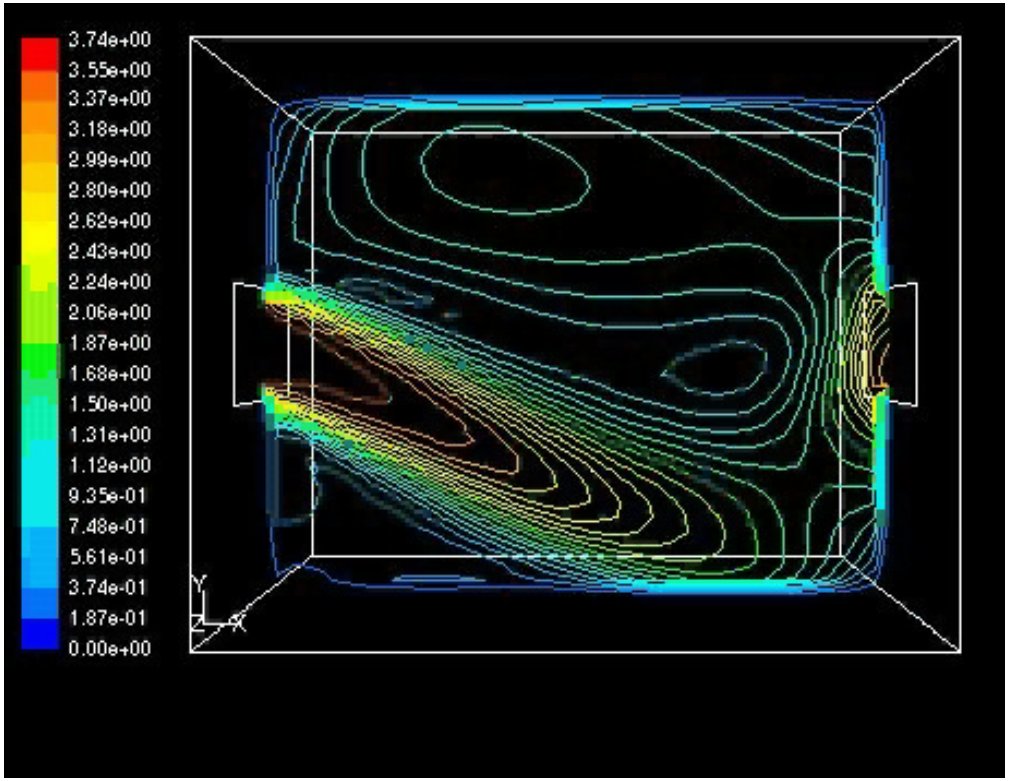
Domain Decomposition





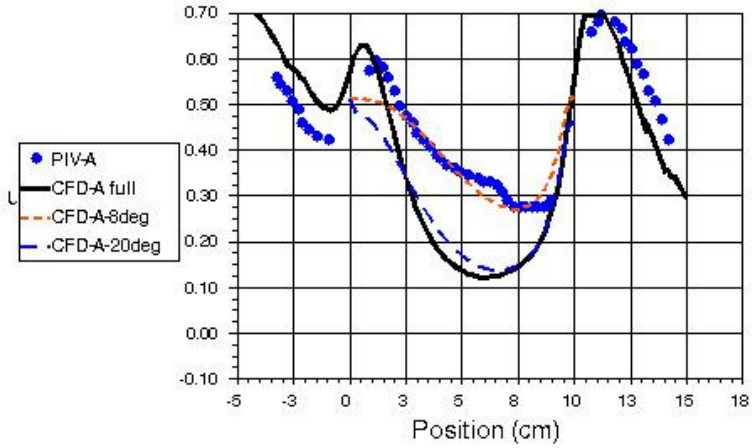
Flow field – LES

Domain decomposition computation

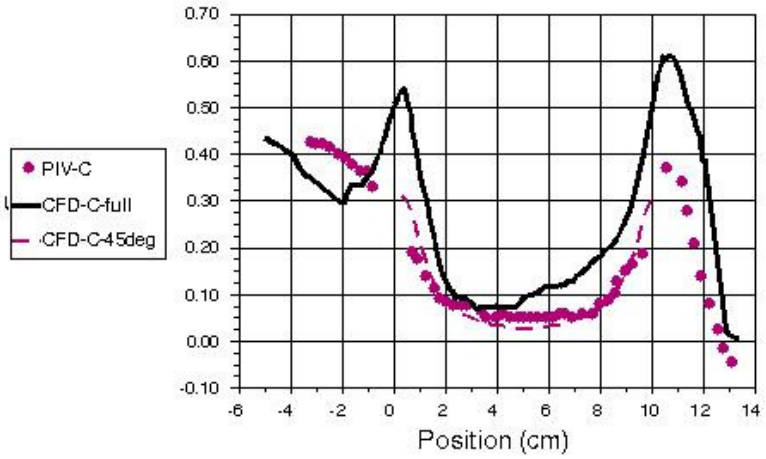


Velocity Ratio – V_X/V_H

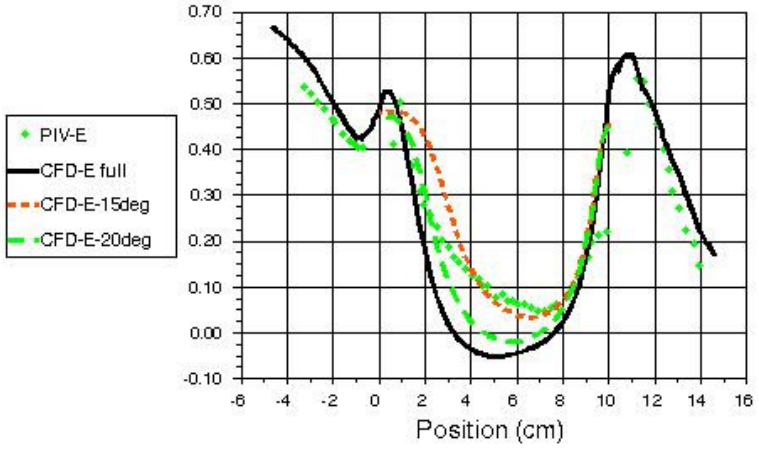
CASE A



CASE C



CASE E



PIV A, C & E

CFD full domain

CFD decomposition, various angles

External Flow Characteristics

Case	Turbulence Model	Cp_{upwind} Average	$Cp_{downwind}$ Average	$Cp_{rooftop}$ Minimum
E	Rke	0.556	-0.243	-1.180
B	Rke	0.587	-0.238	-1.280
C	Rke	0.545	-0.218	-1.090
D	Rke	0.535	-0.235	-1.220

$C_{drag} = (Cp_{upwind} - Cp_{downwind})_{Average}$. Drag coefficient for sealed building is 0.85, whereas drag coefficient for paired openings sets is 0.80 ± 0.03. Drag coefficients for Case E over various turbulence models ranged from 0.80 to 1.07.

Discounting Ske, RNG & k-ω, then average upwind Cp = -0.594 ± 0.027, and average downstream Cp = -0.273 ± 0.037. Deviations are less than AIJ Working Group study in multiple wind tunnels.

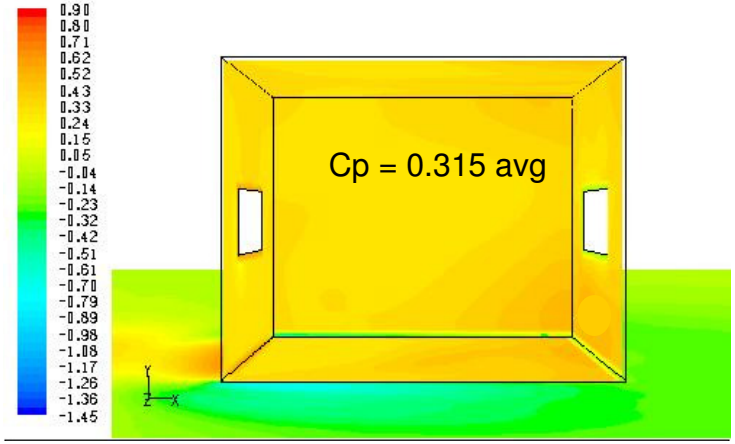
Cross ventilation flow rate & $Cp_{internal}$

Case	Turb. model	DFR_{CFD}	DFR_{WT}	$Cp_{internal}$ CFD	$Cp_{internal}$ WT	$Cp_{internal}$ Eq 2
E	Ske	0.484	0.400	0.305		0.315
E	Rke	0.488	0.400	0.315		0.315
E	RNG	0.463	0.400	0.251		0.315
E	k-ω	0.483	0.400	0.269		0.315
E	RMS	0.478	0.400	0.305		0.315
E	LES	0.520	0.400	0.305		0.315
E	DES	0.481	0.400	0.301		0.315
A	Rke	0.545	0.430	0.269	0.230	0.275
B	Rke	0.478		0.358	0.380	0.335
C	Rke	0.479	0.180	0.130	0.100	0.250
D	Rke	0.424		0.226	0.200	0.185
E-walls	Rke	0.516	0.400	0.269		0.315

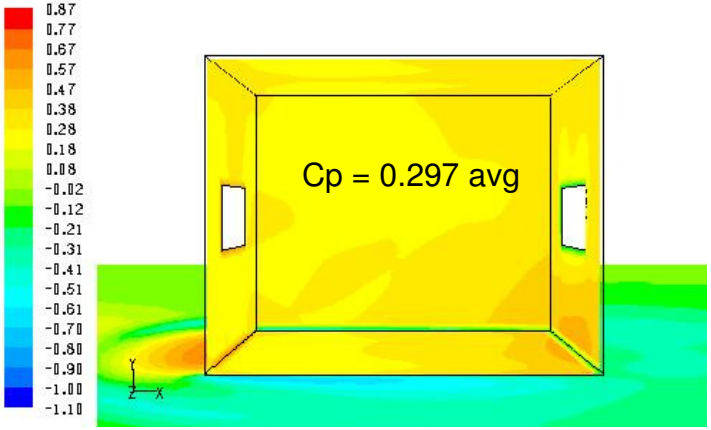
CFD = Computational Fluid Dynamics, WT = Wind Tunnel measurements of Karava

Internal Pressure Coefficients

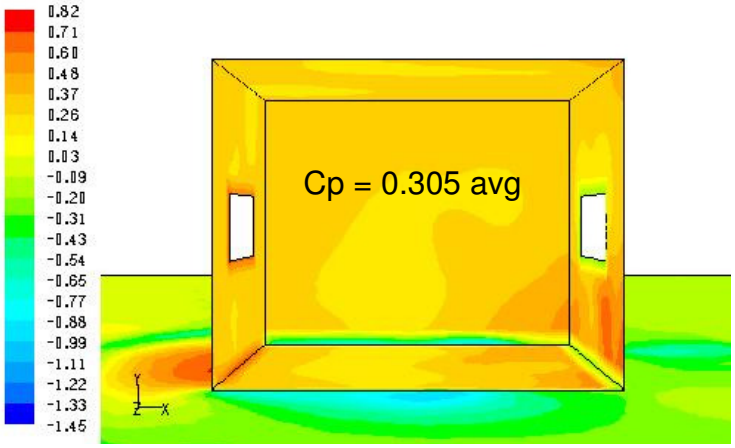
Case E: Various Turbulence Models



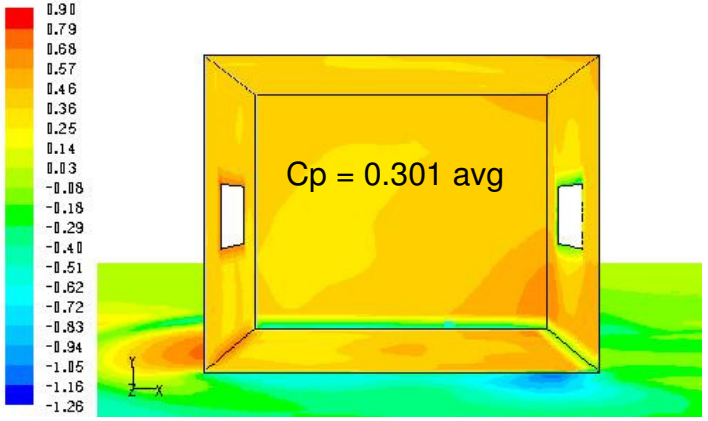
Realizable k-ε model



RMS model



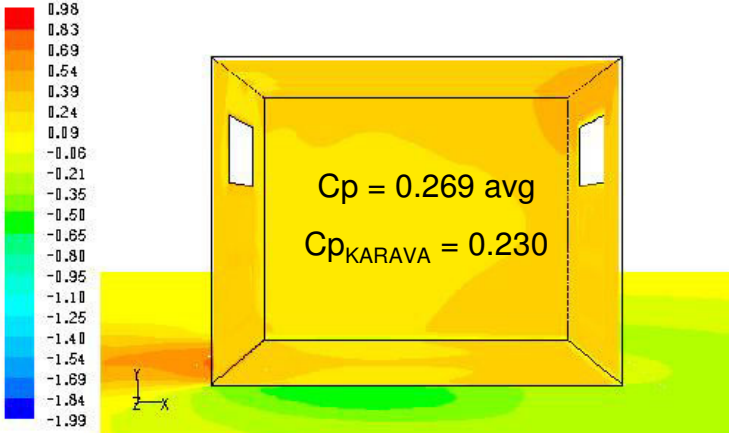
LES model



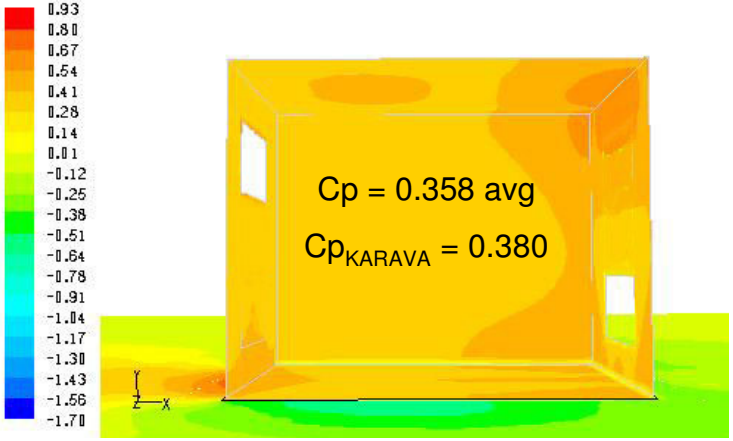
DES model

Internal Pressure Coefficients

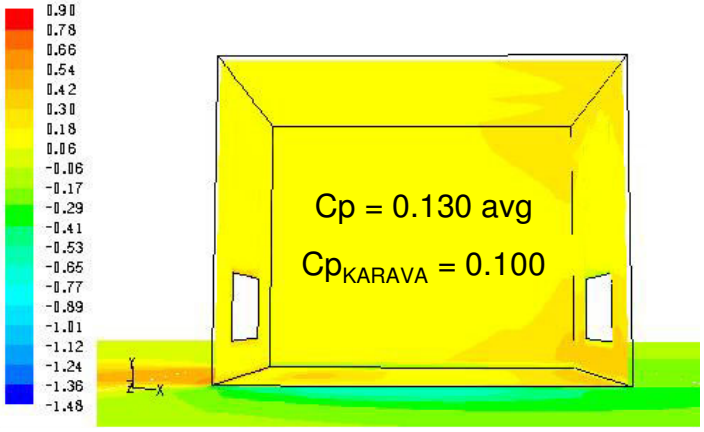
Case A-D: Realizable k-ε Model



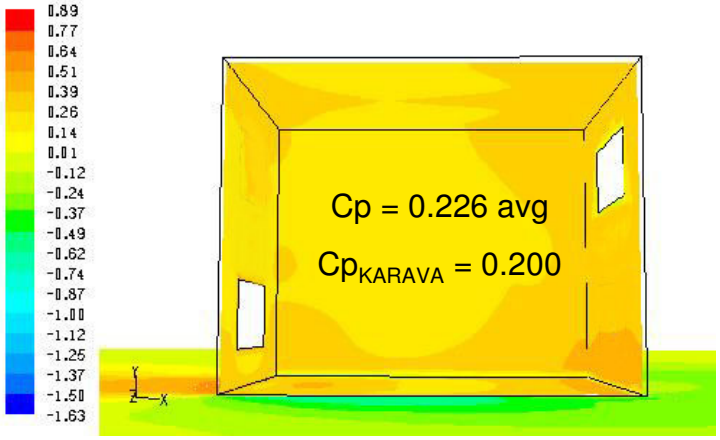
Case A



Case B



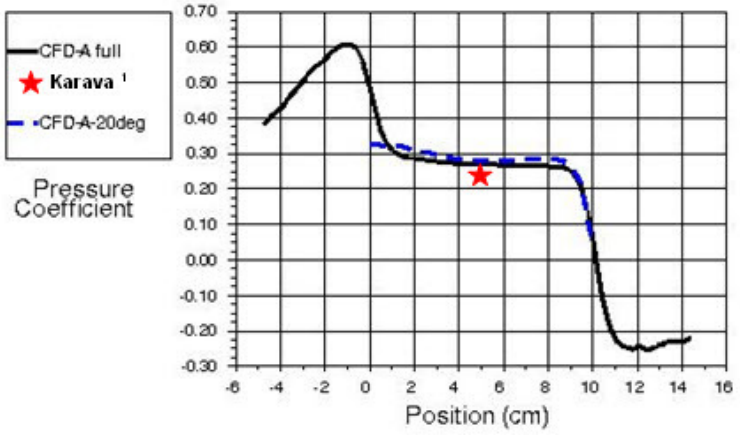
Case C



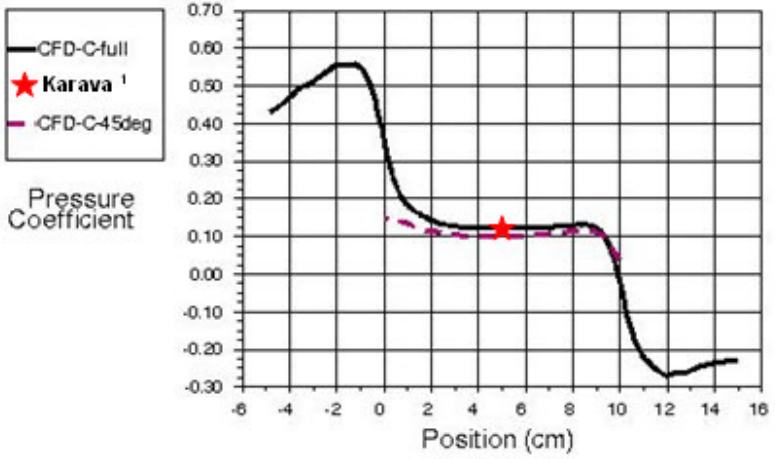
Case D

Static Pressure Coefficient, Cp

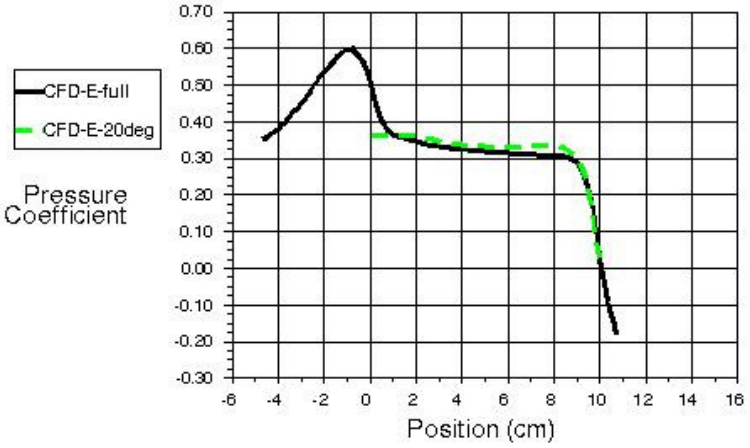
CASE A



CASE C



CASE E

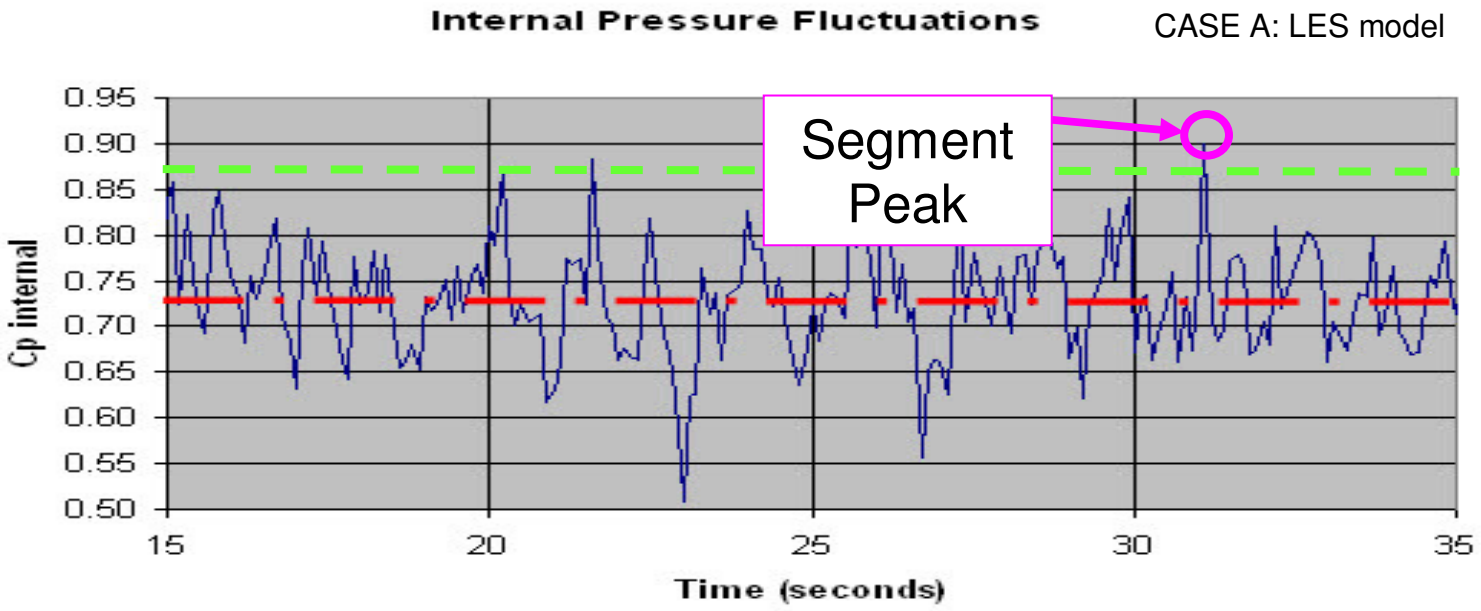


Karava pressure measurement

CFD full domain

CFD decomposition

Internal Pressure Fluctuations



- Data are vertex maximum peaks over building interior surface for Case A using the LES model.

Peak & mean internal pressure coefficients

Case	Cp_{mean} CFD	Cp_{rms} CFD	Cp_{peak} Eq 3	Cp_{peak} CFD TS#	Cp_{mean} WT	Cp_{peak} WT
A	**0.153**	**0.061**	**0.458**	**0.870 (0.339)**	**0.230**	**0.75**
C	**0.109**	**0.026**	**0.239**	**0.978 (0.288)**	**0.100**	**0.40**
E	**0.319**	**0.086**	**0.749**	**0.882 (0.713)**	—	—

CFD = Computational Fluid Dynamics,

WT = Wind Tunnel measurements of Karava, and

TS = Time Series

Numbers are vertex maximum peaks over building interior surface

Numbers in (*italics)* are peaks over five selected interior points

Conclusions

- CFD model replicated wind tunnel data
  - Internal flow field, magnitude and directions
  - Internal U_x/U_H profiles between openings
  - Internal Cp profiles between openings
  - Internal character of peak pressure variations
  - External front, rear & roof pressure values
- Domain decomposition also replicated wind tunnel data within experimental and numerical uncertainty.

The End