Single sided ventilation rates and dominant driving forces in cooling mode for a slot louver ventilation system

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Background & Context

- CIT refurbished 1.5% of 29,000m^2 1974 building envelope
- pilot project for longer term refurbishment
- Single sided louver slot design ventilation chosen as cooling strategy
- No openable windows / ventilated doors used as mechanism
- Modification in ventilation rate and regime key parameter of interest
- Complete a comparative analysis of existing and retrofit spaces
- Approx 30% of PhD work (1st chapter in thesis)

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Climate Cooling Potential

- Nearly-zero energy buildings have lead to an increased need for cooling – not only in summer but all year.
- Elevated temperature levels are the most reported problem in post occupancy studies - even in the "heating season"
- Cooling requirements in low energy buildings designed around heating energy reduction principles in cold climates are being underestimated with simplified tools
- Utilization of the cooling potential of outdoor air can be an attractive and energy efficient solution
- Cooling is correlated with solar and internal heat load and not outdoor temperature

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Current working PhD title

"Cooling potential and characterisation of dominant flow regimes for a slot louver single sided ventilation system: experimental and model based analysis"

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Objectives for this body of work

- Compare existing and retrofit ventilation systems
- Measure and compare time averaged ventilation rate for the **retrofit and control spaces** under different conditions
- Compare the time averaged ventilation rates for different opening operating configurations in retrofit space (3 in total)
- Investigate fluctuating ventilation characteristic during tests for each configuration
- Investigate the dominance of mechanical & gravity forces for each operating configuration

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Retrofit Space & Control Space - Location

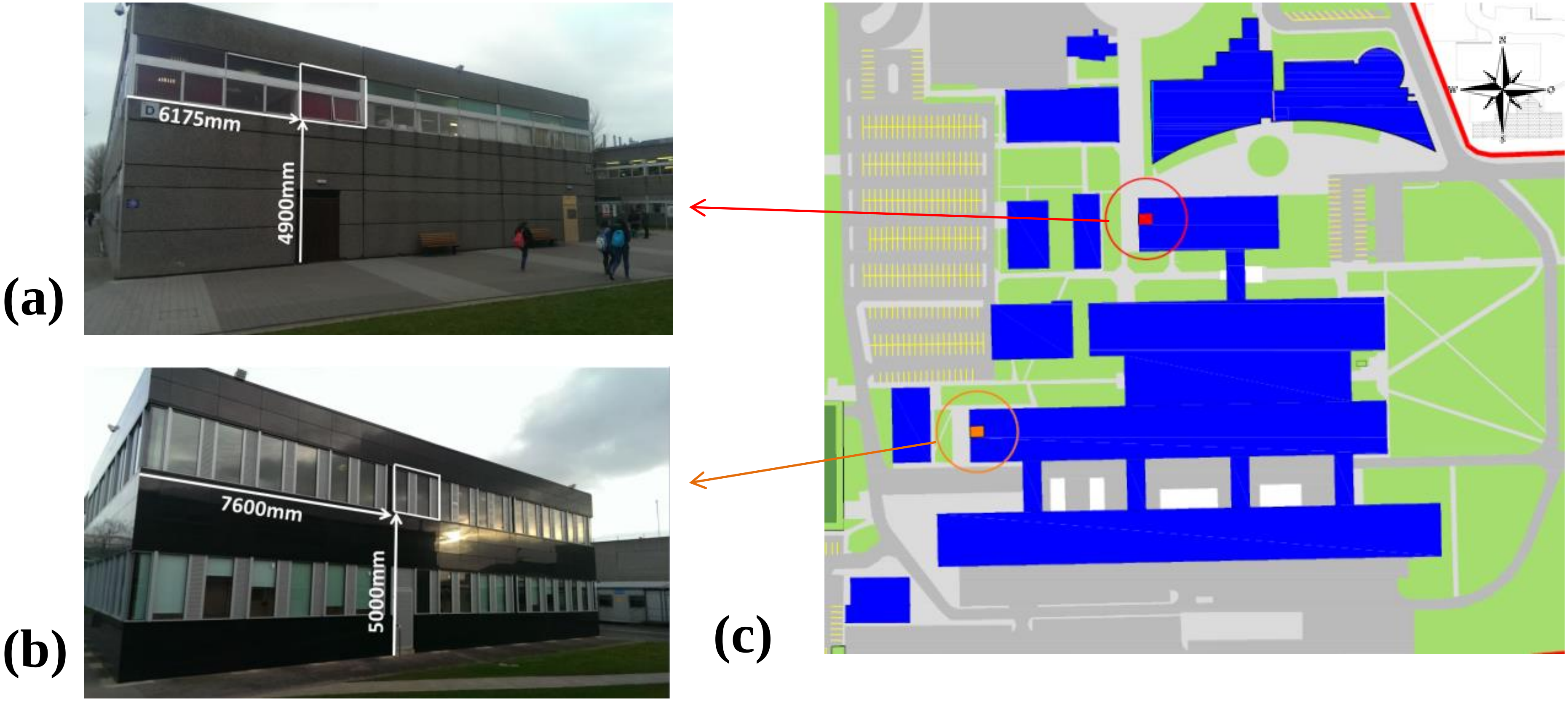

Figure 1: (a) Control space envelope location, (b) Retrofit space envelope location (c) part site plan showing location of control and retrofit spaces

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Long Term & Short Term Local Climate

Month	Cork Airport TMY3 95th Percentile				Summer 2013 95th Percentile			
	G_h (Wh/m^2)	T_a (°C)	WS (m/s)	WD (°)	G_h (Wh/m^2)	T_a (°C)	WS (m/s)	WD (°)
May	742	17.2	10.0	345	730	16.0	6.3	304
June	815	19.5	9.3	344	826	20.6	5.0	343
July	707	20.7	9.0	352	795	25.0	4.3	344
August	662	20.0	9.3	342	592	20.1	4.7	306
September	574	19.4	9.0	341	511	18.5	4.6	326
October	385	17.3	10.3	338	340	18.1	4.4	336

† Data up to 15th August only for short term; *Data not yet available for short term; **Data taken from zero2020 weather station

Ventilation Air Exchange – ACH^{-1}

- Ventilation effectiveness characterised with air change rate (amongst other indicators)
- Difficulties with prediction when using single sided natural ventilation
- Complex flows at the inlet
- Unsteady nature
- Multiple forces present (wind & buoyancy)
- Body of work aimed to measure ACH for different single sided ventilation and investigating conditions

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Single Sided Ventilation

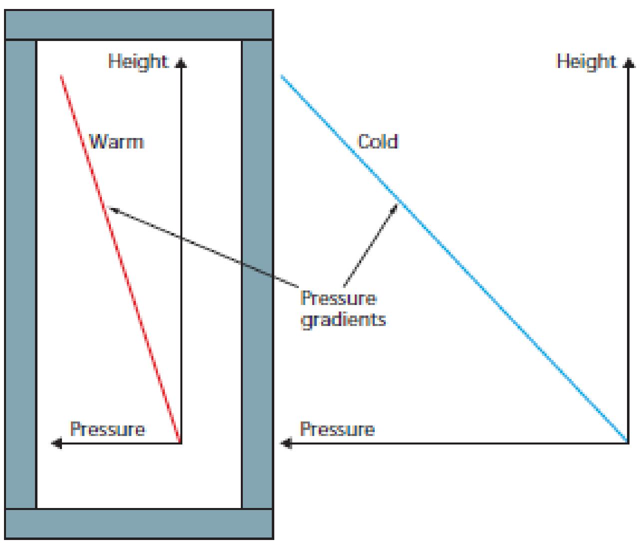

Figure 2.11 Schematic of pressure gradients

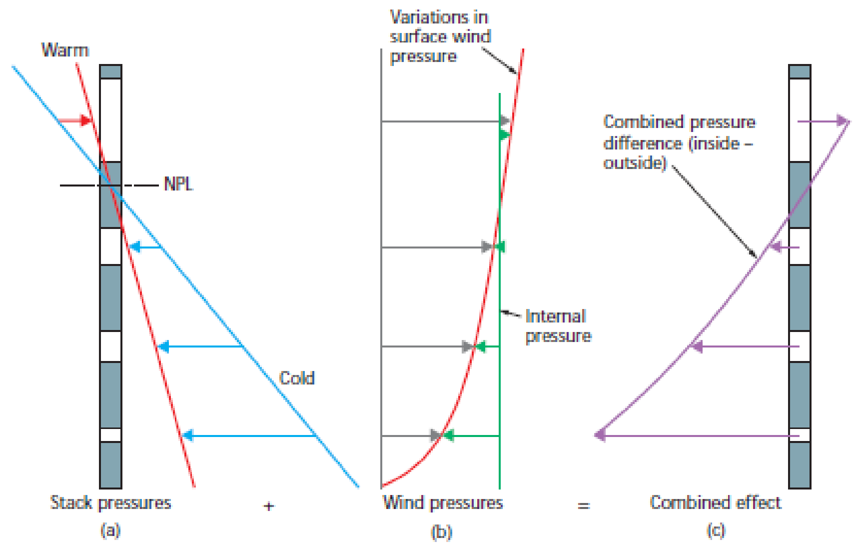

Figure 2.17 Combining wind and stack pressures

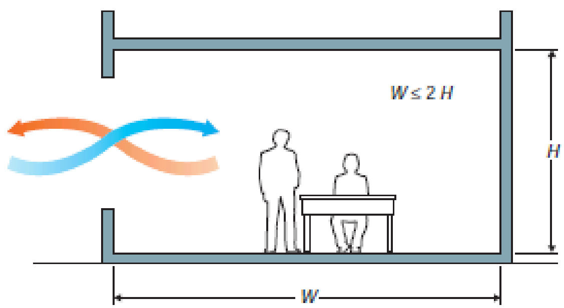

Figure 2.18 Single sided ventilation, single opening

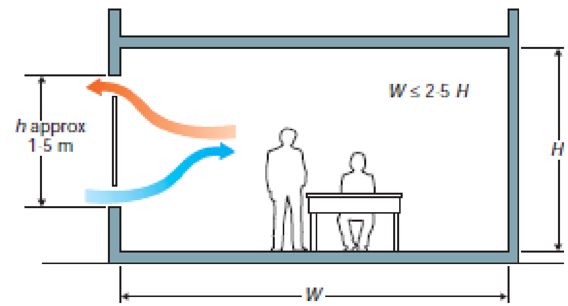

Figure 2.19 Single sided ventilation, double opening

- Airflow exchange mechanism dependant on wind direction

Single Sided Ventilation

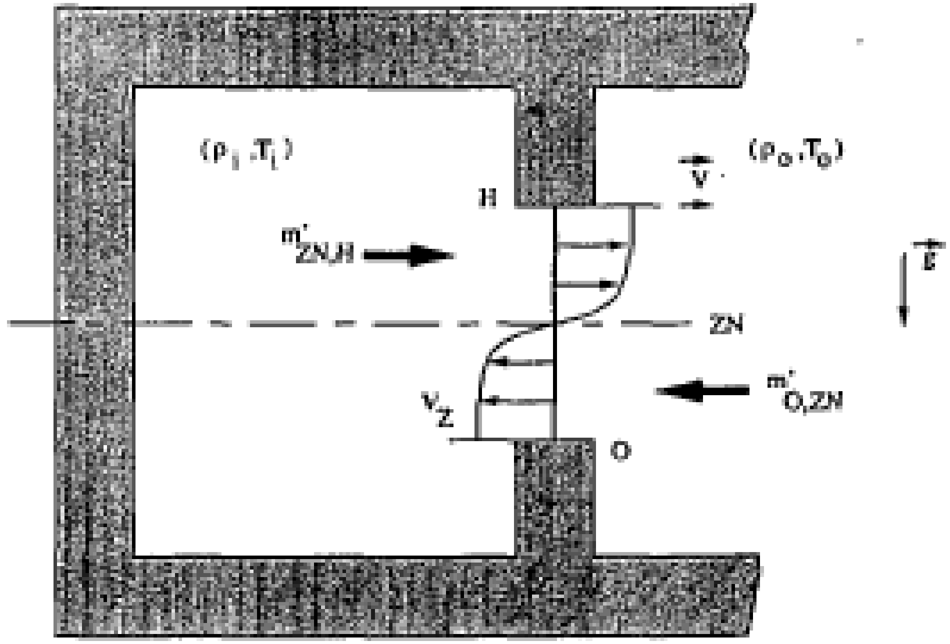

Figure 2.5: The basic problem of gravitational flow through a vertical opening.

Single Sided Ventilation – local flow phenomena

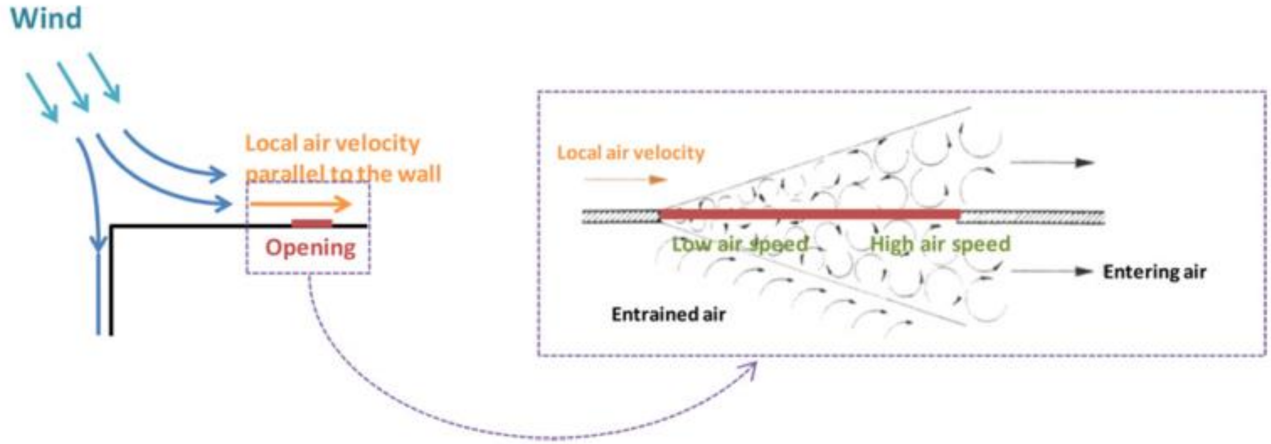

Fig. 11. Schematic representation of a mixing layer.

- Leeward - Turbulent diffusion Reduces stack effect and ACH
- Windward mixing layer increases movement and ACH

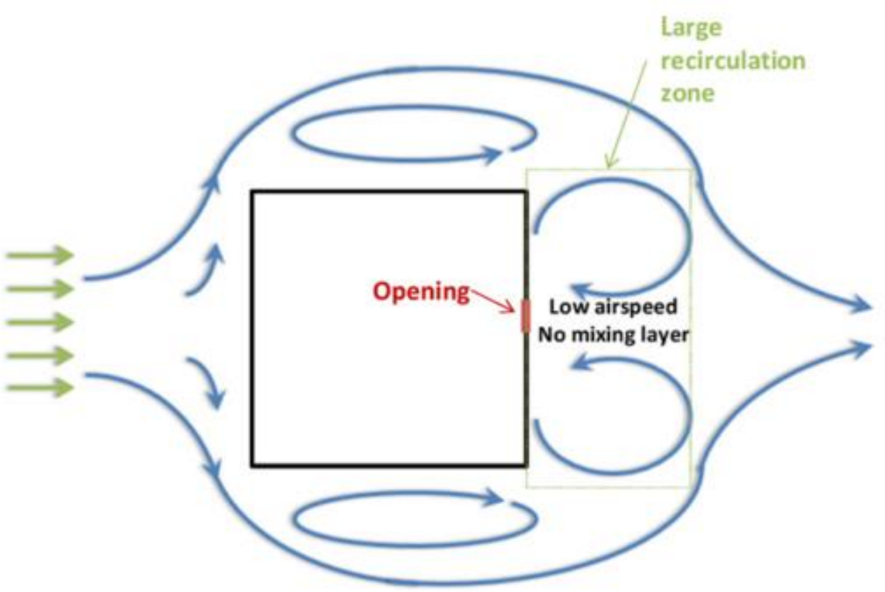

Fig. 13. Schematized representation of the air flow pattern around the building in the case of leeward opening.

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C_p, Wind Pressure Coefficient

C_p used to study similarity of control and retrofit space locations response to wind forces

C_p is defined as the portion of the dynamic wind pressure, which acts on the specific façade or roof at a certain wind direction

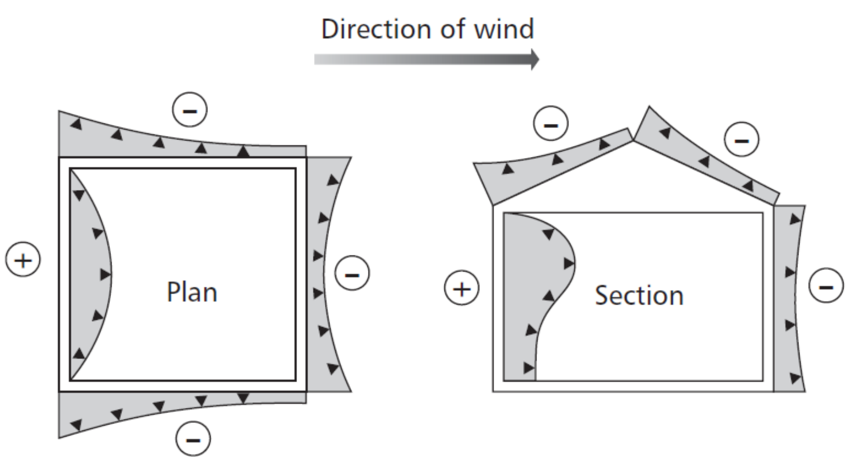
'Cp Generator' predicts the dimensionless static wind pressure coefficients, C_p, on the facades and roofs of block shaped buildings with or without pitched roofs.

- Time mean pressure due to wind flow onto or away from a surface is given by:

$$p_w = \frac{C_p \rho v^2}{2}$$

- C_p expressed in terms of pressure and velocity:

$$C_p = \frac{2\,\overline{\Delta p}}{\rho v^2}$$



(a) Wind pressure on building

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Obstacle Study

TNO Webapplications
Cp Generator

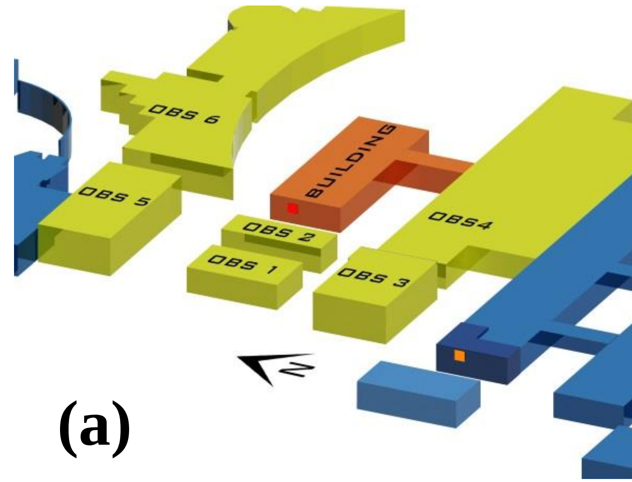
```
{file=input}
+--------------------------------+
| title                          |
+--------------------------------+
      title: retrofit
    version: IJOVENT
    made by: Paul O Sullivan
    comment: This file is for IJOVENT paper submission
+--------------------------------+
| wind.Zo                        |
+--------------------------------+
   Direction:   0        180      315
          Zo:   3        0.5      3

+----------------------------------------+
| north arrow compass direction in plan  |
+----------------------------------------+
   Direction:  1.3

+--------------------------------+
| obstacles (position in m(=meter))|
+--------------------------------+

 Ground level:  0.
 Roof height :  8.0

      Name : retrofit
       x,y : 0.       0.
    Azimut : 180.
 L,W,H,#,à,w: 150  22.250   7.9000

       Name: meteo
        x,y: -200    -200
     Azimut: 90.
      L,W,H: 0.1      0.1      40.0

       Name: 1 A Block
        x,y: -14.9        -45.1
     Azimut: 180.0000
      L,W,H: 218.3  22.7   8.00

       Name: 2 F block
        x,y: -28  0
     Azimut: 180.0000
      L,W,H: 16.0   31.8   7.00

       Name: 3 Create
        x,y: 9.0   43.3
     Azimut: 180.0000
      L,W,H: 34.3   23.2   12

      Name: 4 C Block
        x,y: 67.7   22.7
     Azimut: 180.0000
      L,W,H: 128.0   45.2   7.9000

+--------------------------------+
| cp-positions                   |
+--------------------------------+
       unit: m

Building side: facade 4
   Pos.  x,y : 9.31    5.8
```

Terrain Roughness

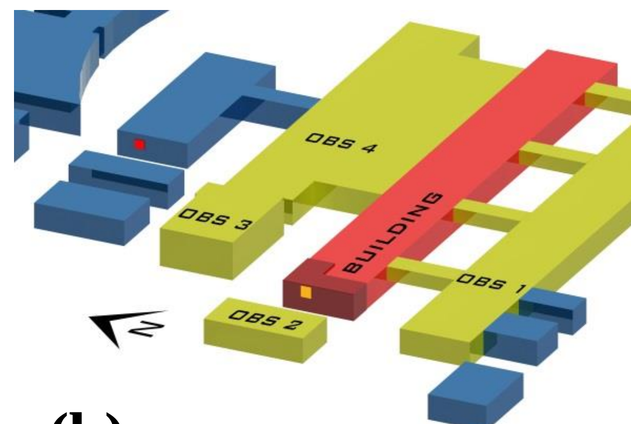
Obstacle data

Vent Location

http://cpgen.bouw.tno.nl/cp/



(a)



(b)

Figure 2: (a) Obstacle study control space (orange square), (b) Obstacle study retrofit space (red square)

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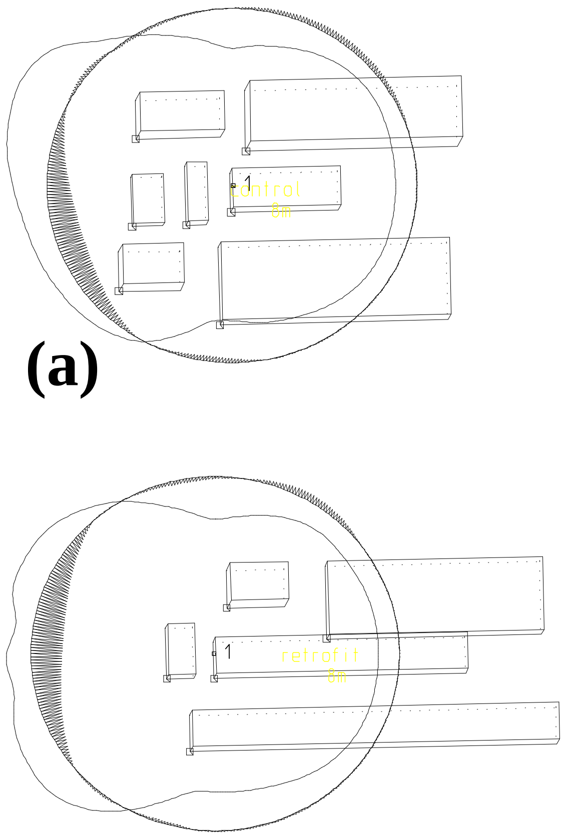
C_p Generator Results



(a)

(b)

Figure 3: C_p Generator polar plots of obstacle correction factors, (a) control space (b) retrofit space

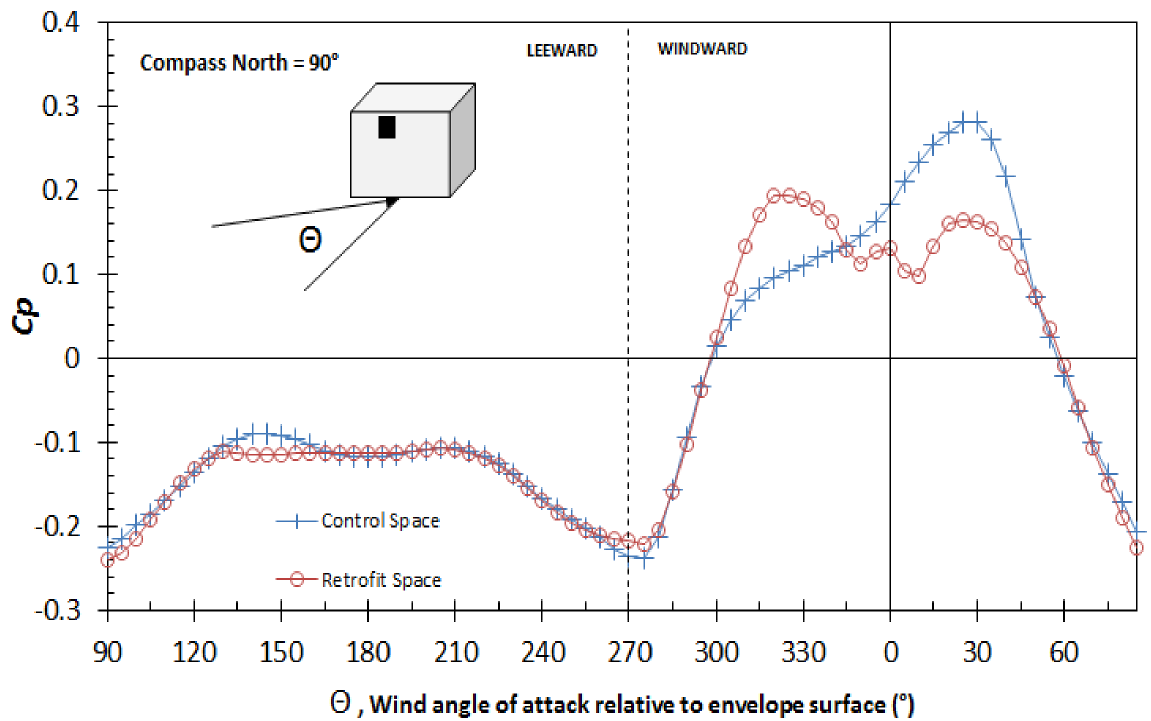


Figure 4 : C_p Characteristics for control and retrofit spaces as a function of wind angle of attack

Slot Louver ventilation system

(a)

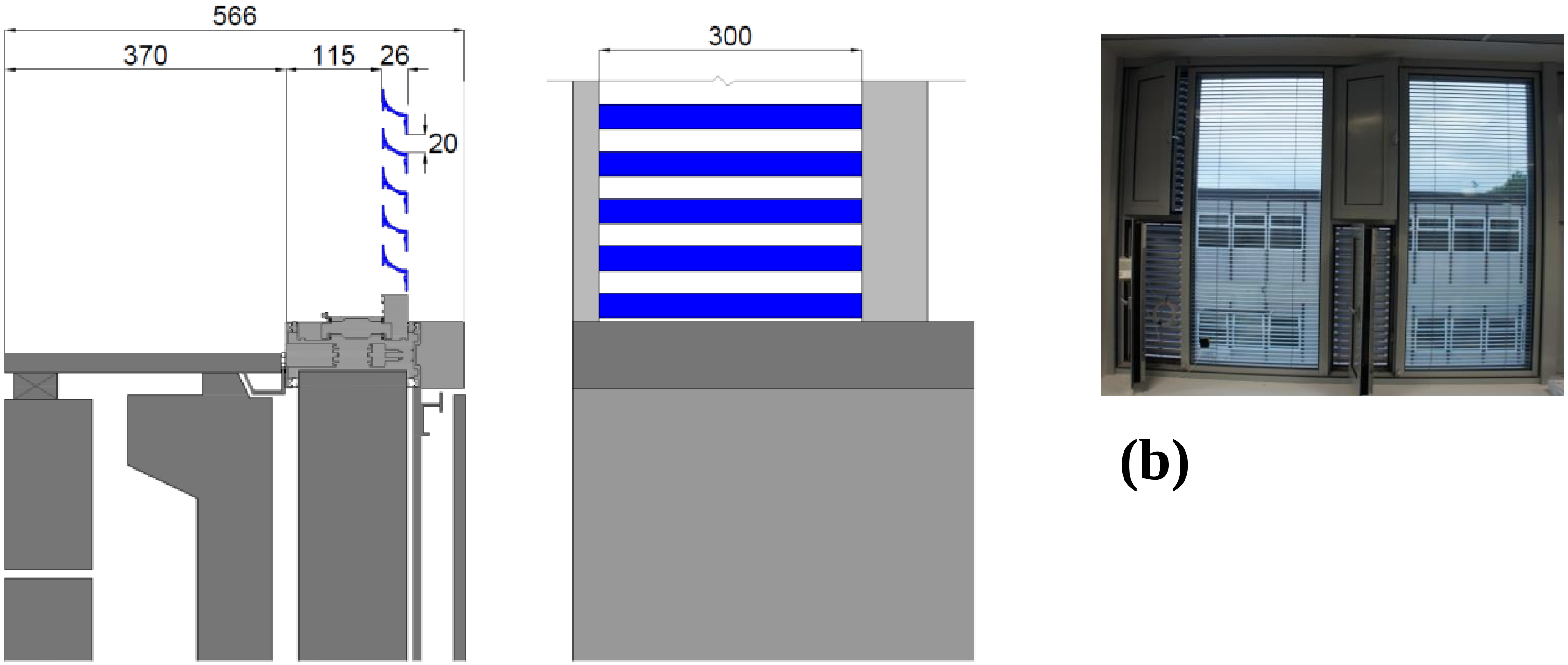


Figure 5: (a) Ventilation Opening detail elevation & section, (b) Internal view of installed fenestration module

Geometry of opening critical to defining flow characteristic

Properties of Fenestration Module

Fully integrated factory assembled module

Quadruple glazed unit c/w sealed triple glazed Argon filled system/ manual interstitial blinds / inner clear float pane

Integrated insulated ventilation doors low level occupancy controlled & high level BMS automated

U-value	1.0 W/m^{2}k,	SHGC	0.296
COG value	0.82 W/m^{2}k.	VT	0.150

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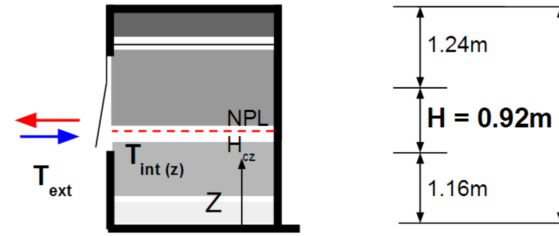
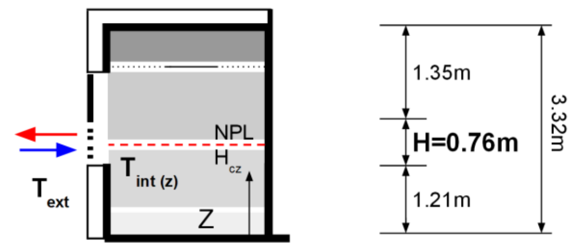
Ventilation opening configurations

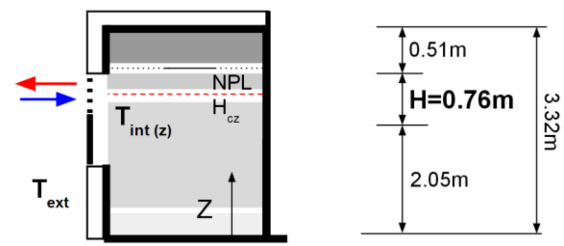
CS-1.0 / Manual



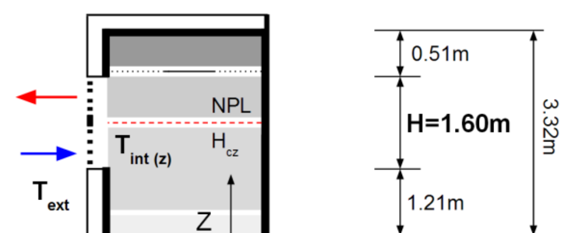
RS-2.0 / Manual



RS-3.0 / Automated



RS-3.0 / Automated



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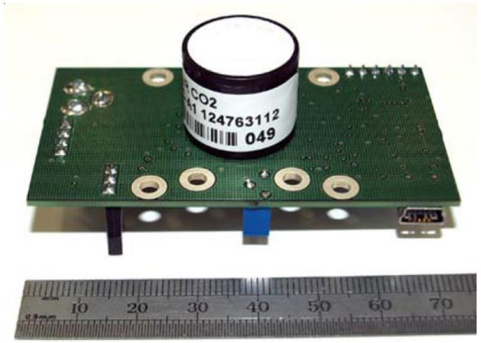
Tracer Gas Decay Technique

- Measures airflow exchange due to ventilation openings
- Consists of “marking” space air with tracer gas
- CO_2 chosen (see table overleaf)
- Outdoor & indoor conc. monitored during each test
- Suitable quantity injected for initial conc., $C_{io}(0)$
- After initial period CO_2 injection stopped, $\dot{m}_t(0) = 0$
- CO_2 mixed to acceptable average uniformity conc. difference (5%)
- Gas conc. monitored using NDIR sensors
- Frequency 1 hz
- Allows investigation of “unsteadiness” in ventilation rate
- All tests and analysis completed in accordance with ASTM-741



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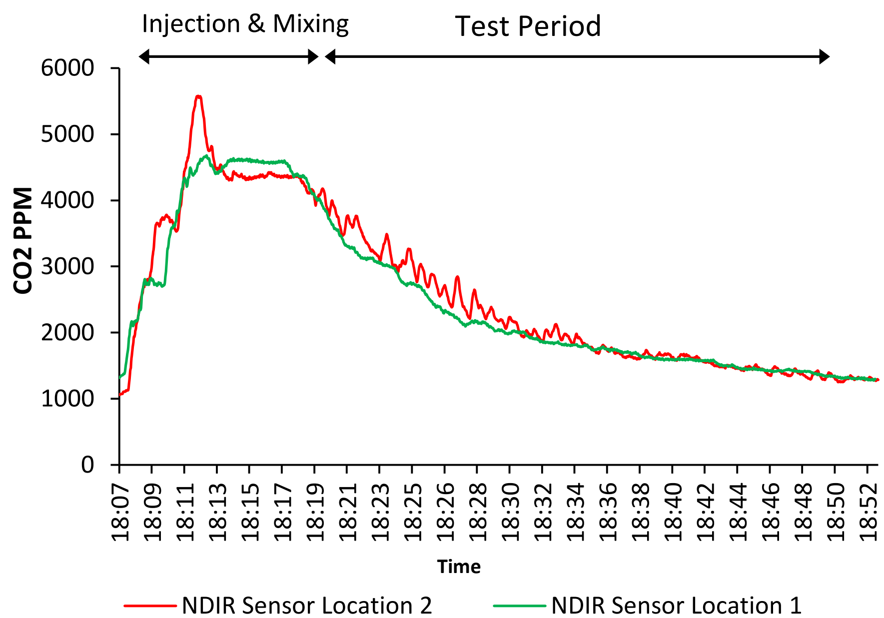
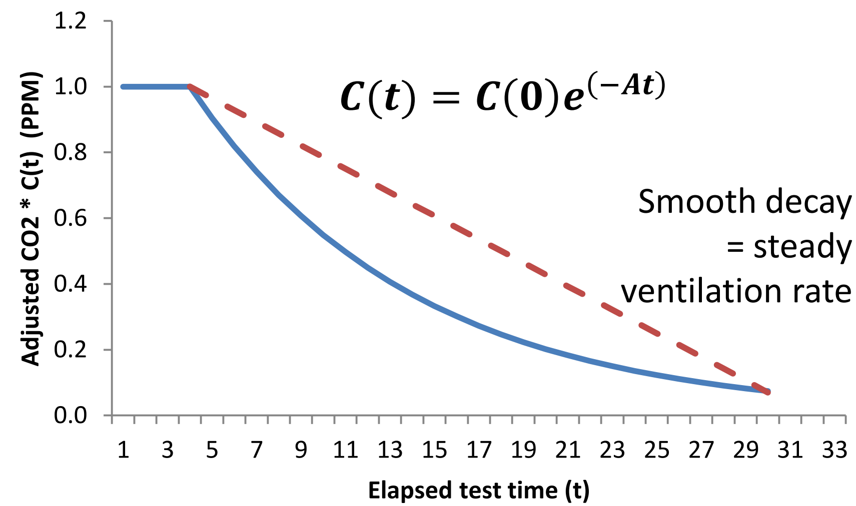
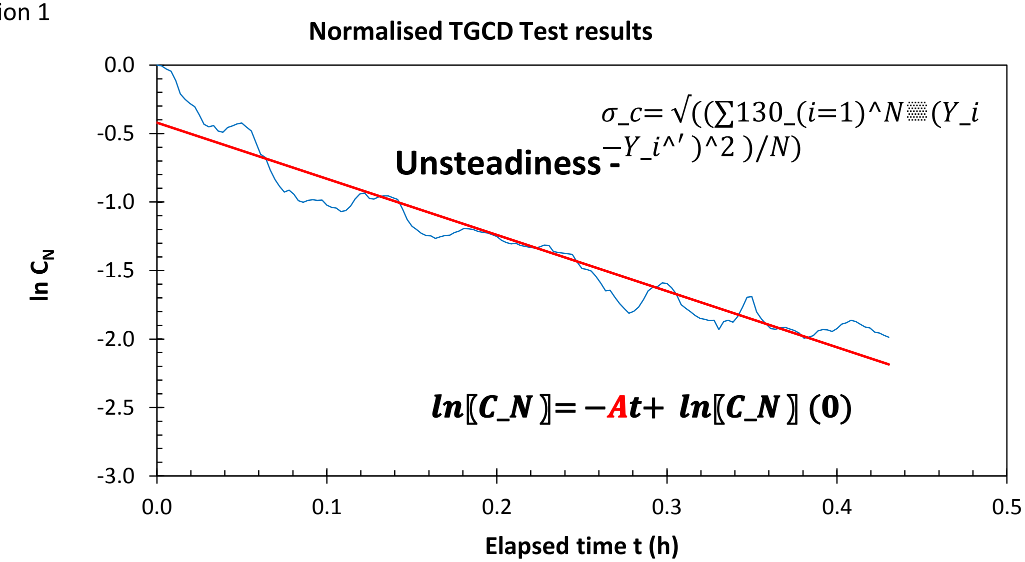
TGC Decay – Regression method





Normalised Concentration used

$$C_N = ln\frac{C(t) - C_0}{C(0) - C_0}$$



TGC Decay Test conditions

Config.	No of tests	Range of test durations	Average Conc. uniformity	(Ave) Start PPM Range (Adjusted.)	(Ave) End PPM Range (Adjusted.)	Average B.G. PPM (%)
CS-1.0/M	13	24 – 90 min	2.57 %	3181-6203	175-1214	10.3
RS-2.0/M	6	26 – 60 min	1.51 %	3538-5431	364-1481	12.3
RS-3.0/A	6	31 – 60 min	4.46 %	3511-5051	703-1327	13.4
RS-4.0/A/M	13	30 – 161 min	2.37 %	3647-4746	212-1067	13.0

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Test equipment layout

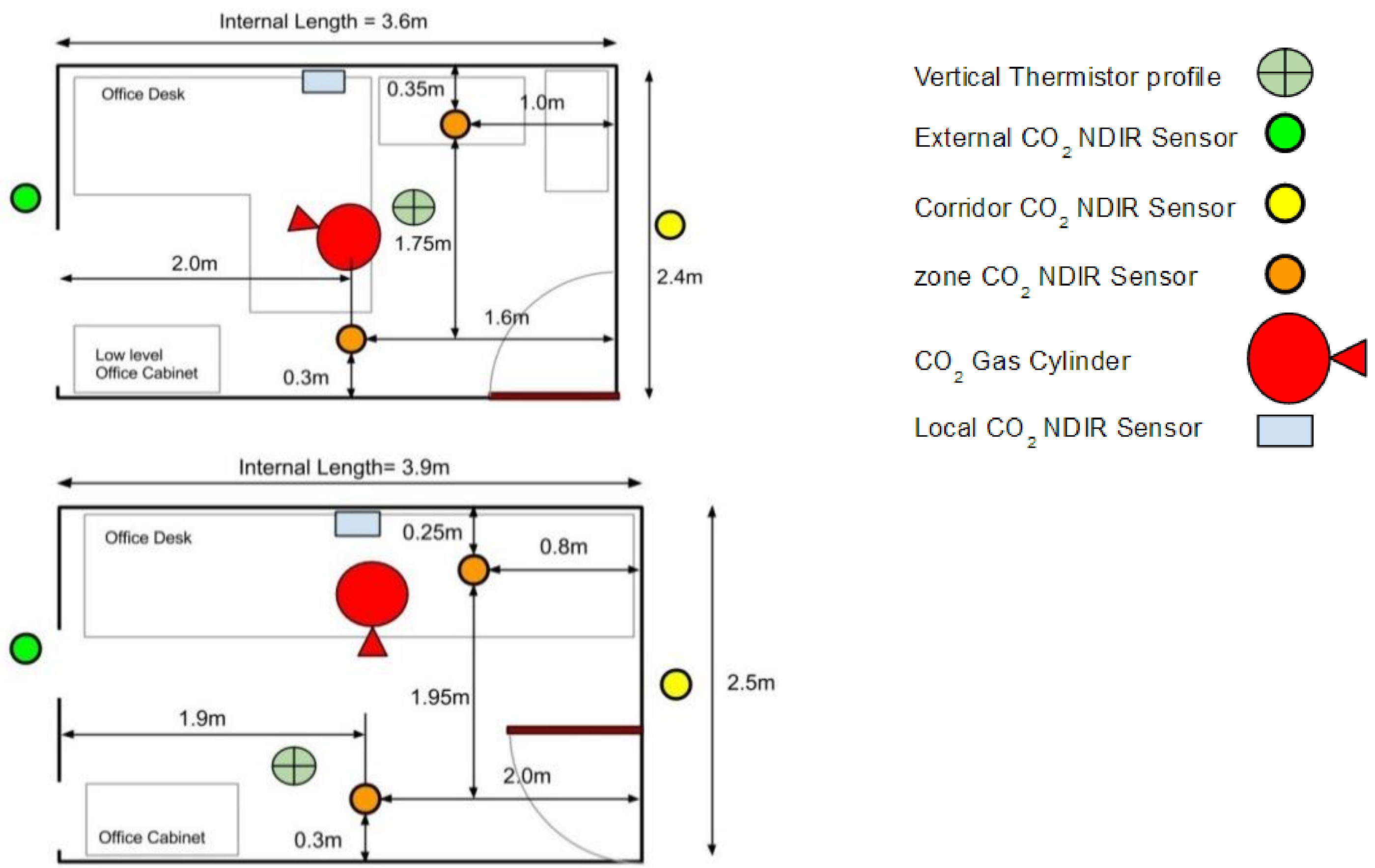

Figure 6: TCG Decay test equipment location drawing (NTS) (a) control space (b) retrofit space

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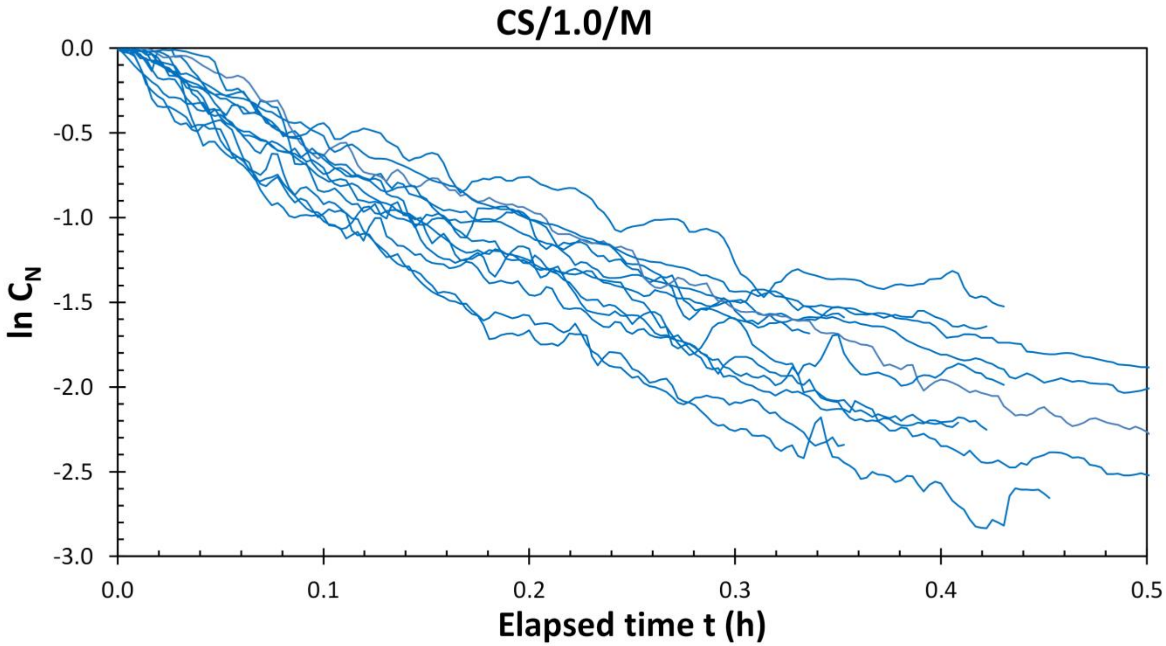
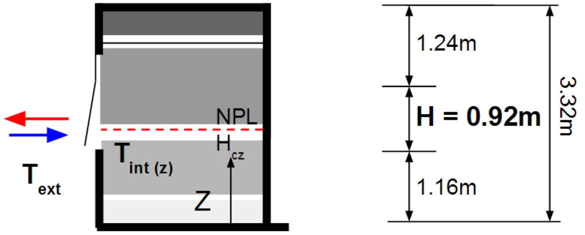
Results $\bar{Q}$ (h^{-1}) - CS-1.0 Config



TGCD Test Data - CS-1.0

Test No.	ACH	σ_c	R^2
1	6.0	0.098	0.959
2	5.3	0.104	0.955
21	1.9	0.038	0.852
22	3.9	0.077	0.943
26	3.4	0.048	0.942
3	5.9	0.050	0.990
4	5.0	0.080	0.963
14	4.1	0.093	0.927
27	4.5	0.122	0.916
33	3.6	0.061	0.958
34	2.0	0.050	0.781
35	6.4	0.103	0.968
36	2.7	0.042	0.928



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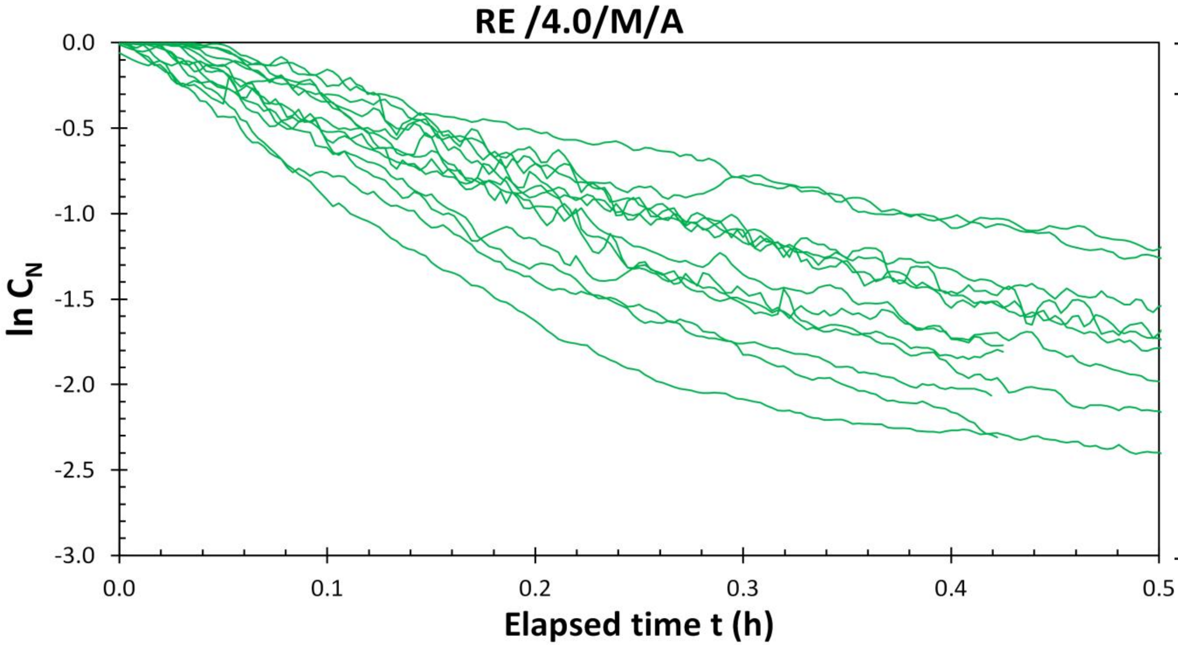
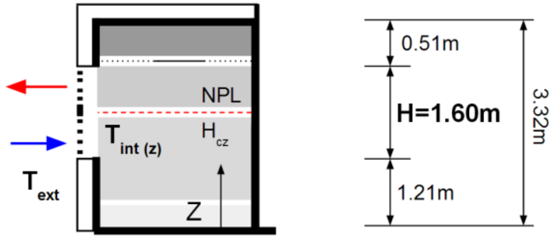
Results $\bar{Q}$ (h^{-1}) - RS-4.0 Config



TGCD Test Data - RS-4.0

Test No.	ACH	σ_c	R^2
8	5.8	0.063	0.982
10	4.3	0.034	0.987
11	4.8	0.077	0.962
12	4.2	0.120	0.858
13	4.2	0.045	0.980
17	4.5	0.056	0.977
18	3.2	0.047	0.960
19	2.6	0.011	0.996
20	2.5	0.023	0.975
24	3.3	0.030	0.980
28	4.5	0.077	0.958
30	3.1	0.030	0.973
32	2.3	0.019	0.980



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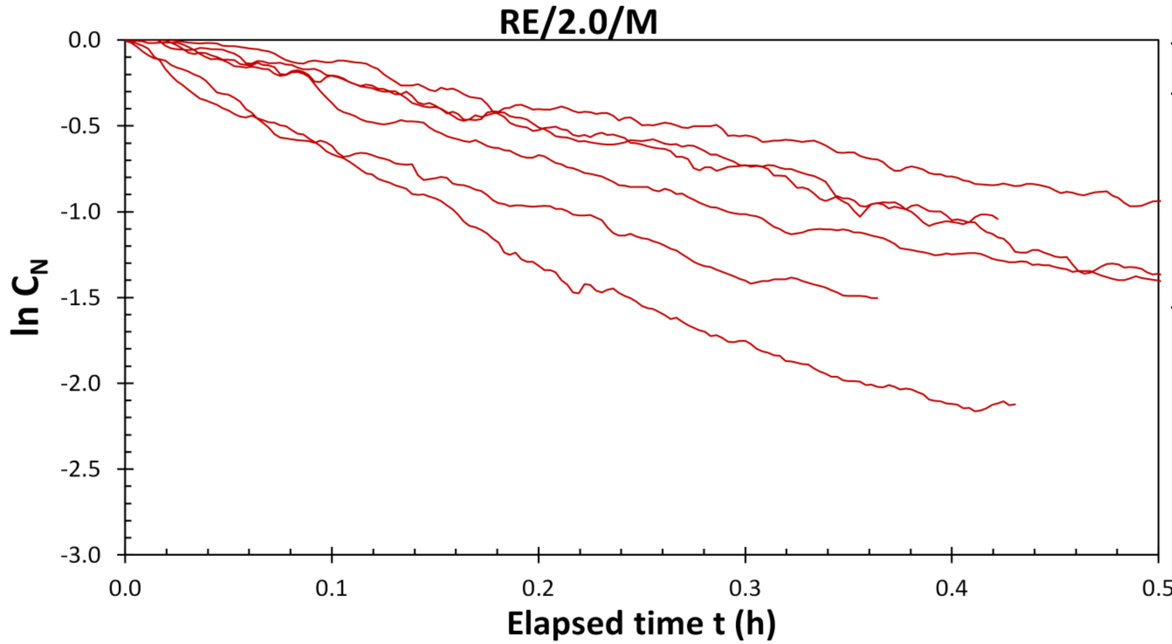
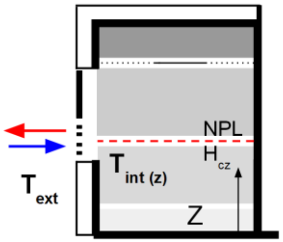
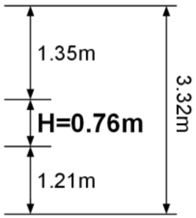
Results $\bar{Q}$ (h^{-1}) - RS-2.0 Config



TGCD Test Data - RS-2.0

Test No.	ACH	σ_c	R^2
5	5.1	0.058	0.981
6	4.0	0.051	0.979
15	2.6	0.032	0.967
23	2.8	0.010	0.996
29	2.6	0.017	0.994
31	1.5	0.021	0.948





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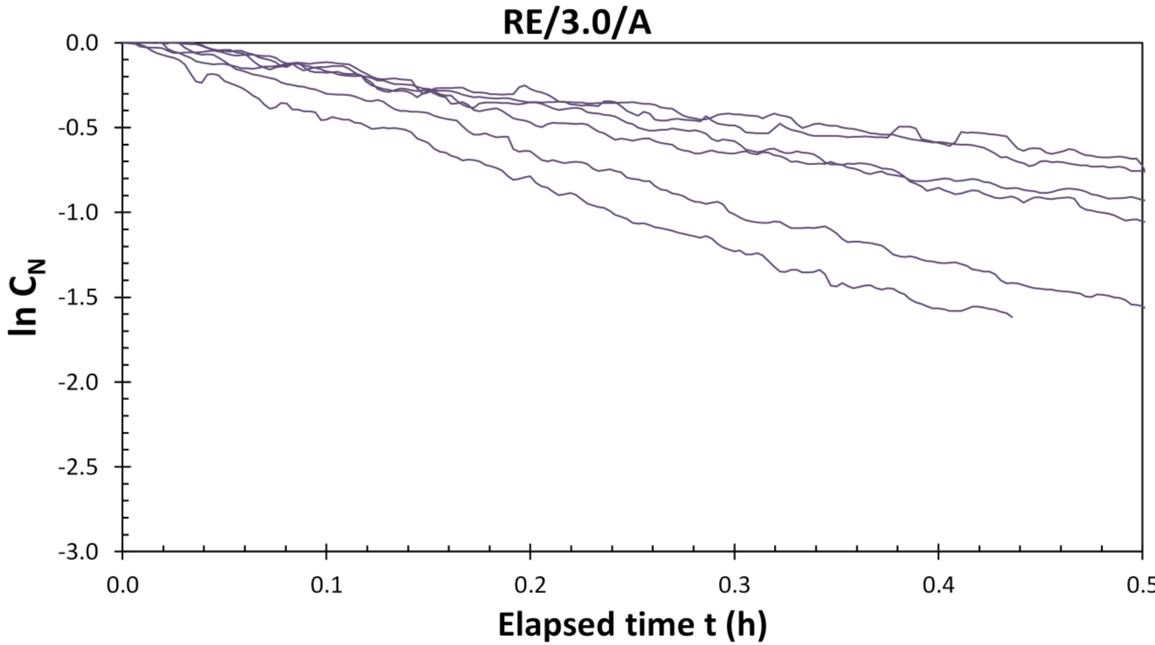
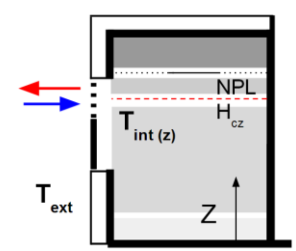
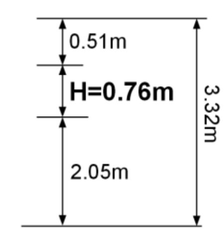
Results $\bar{Q}$ (h^{-1}) - RS-3.0 Config



TGCD Test Data - RS-3.0

Test No.	ACH	σ_c	R^2
7	3.8	0.024	0.994
16	1.9	0.021	0.975
25	2.2	0.007	0.997
37	2.9	0.015	0.992
38	1.4	0.029	0.942
39	1.5	0.009	0.991





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Results $\bar{Q}$ (h^{-1}) Summary

Analysis of Dominant Driving Forces

Archimedes number, $Ar = (Gr/Re^2)$ described as:

$$Ar^{0.5} = \frac{\Delta TgH}{Tv_{wind}^2}$$

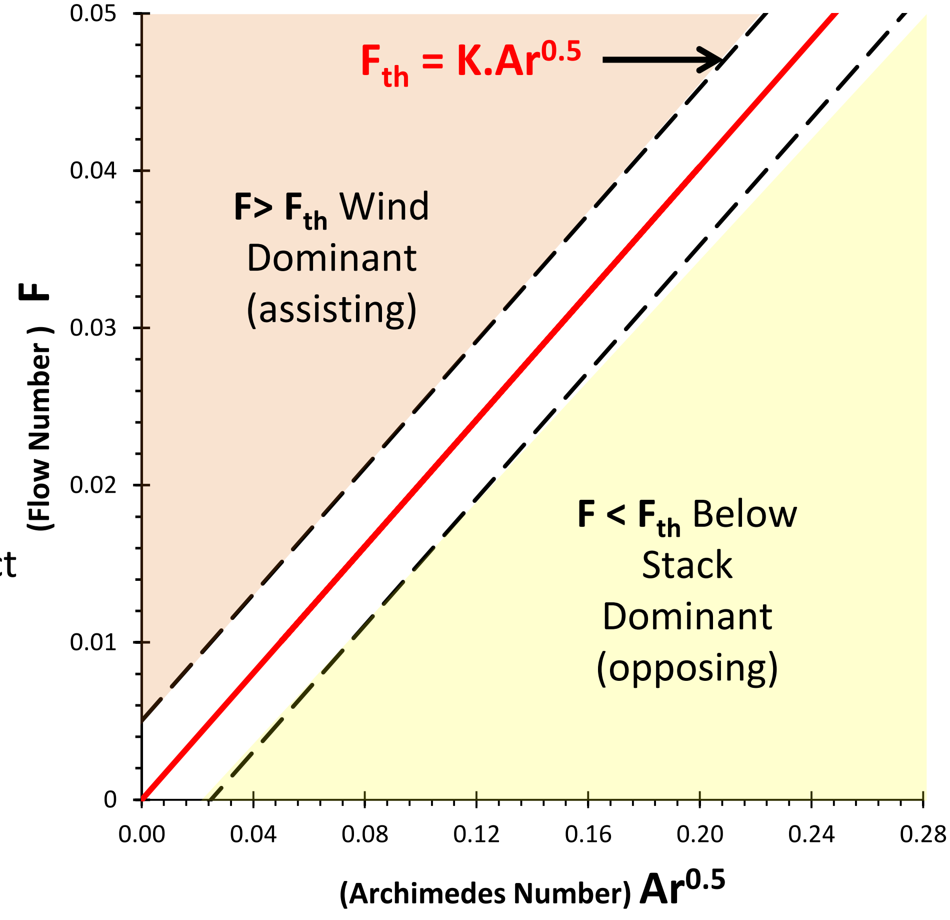
Dimensionless Flow number, F, described as:

$$F = \frac{q_{ACH}}{A_{eff}v_{wind}}$$

The use of a flow number due to thermal stack effect alone, F_{th}, is introduced to the plot.

$$F_{th} = C_d A_{eff}.Ar^{0.5}$$

(Stack Dominant)



Warren Plot

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Flow due to stack effect alone, F_{th}

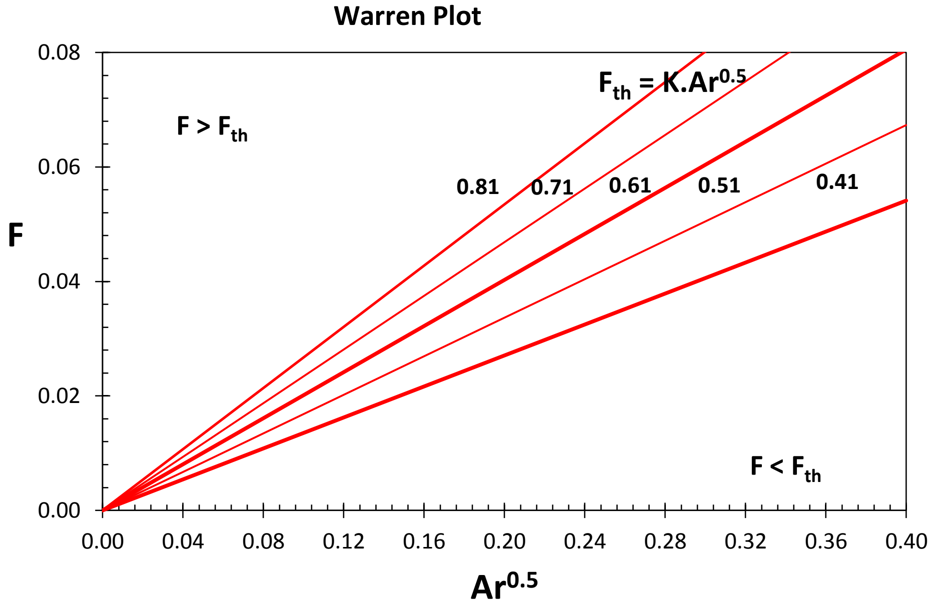
- Warren plot based around using F_{th} for separating out forces
- Correctly estimating asymptote key to the analysis
- Based on flow/pressure power law equation

$$q = \alpha \Delta p^{\beta}$$

- Orifice equation (Bernoulli free streamline theory, β=0.5)
- Using boussinesq approximation

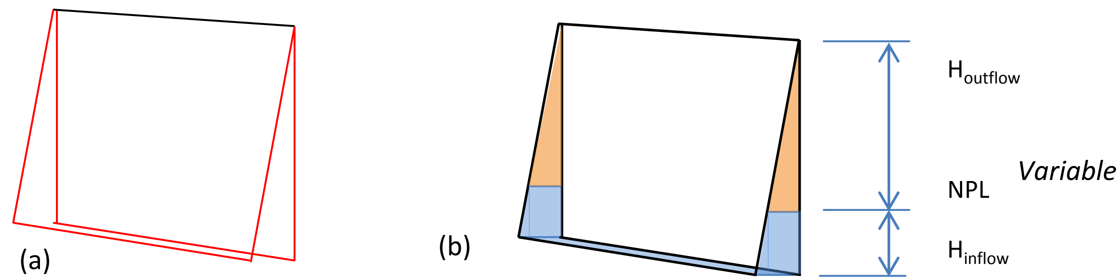
$$\boldsymbol{q_{stack}} = \boldsymbol{C_d A_{eff}} \sqrt{\boldsymbol{gH \frac{\Delta T}{T}}}$$

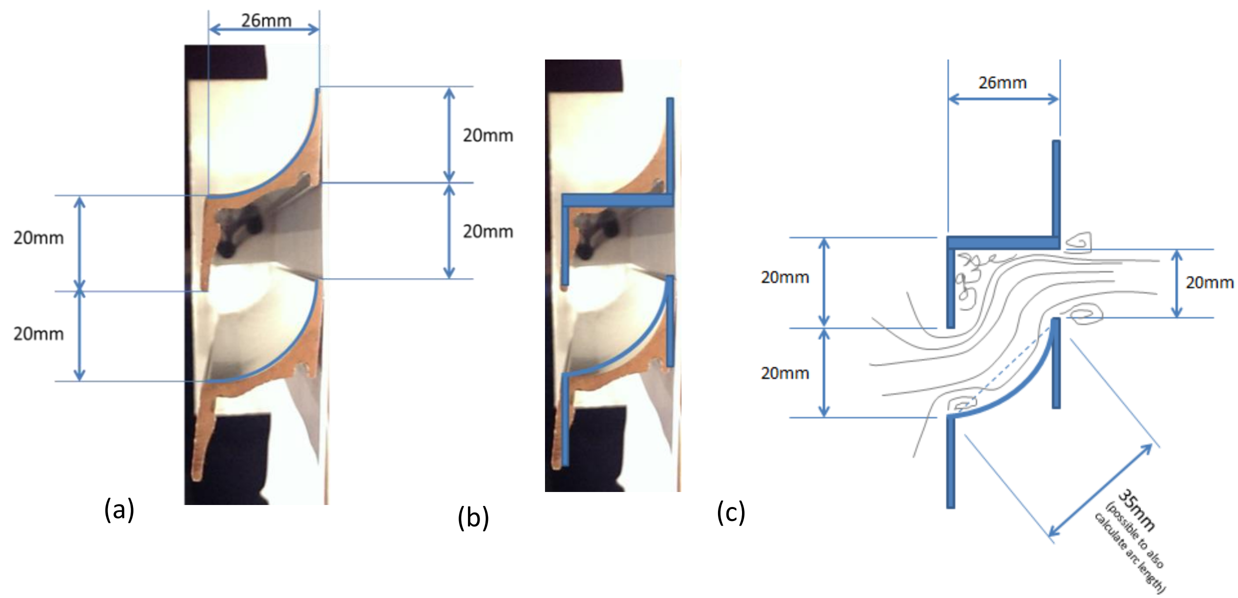
- **C_d key to estimating asymptote for F_{th}**
- $C_d = constant = 0.611$
- (flush faced sharp edged orifice)



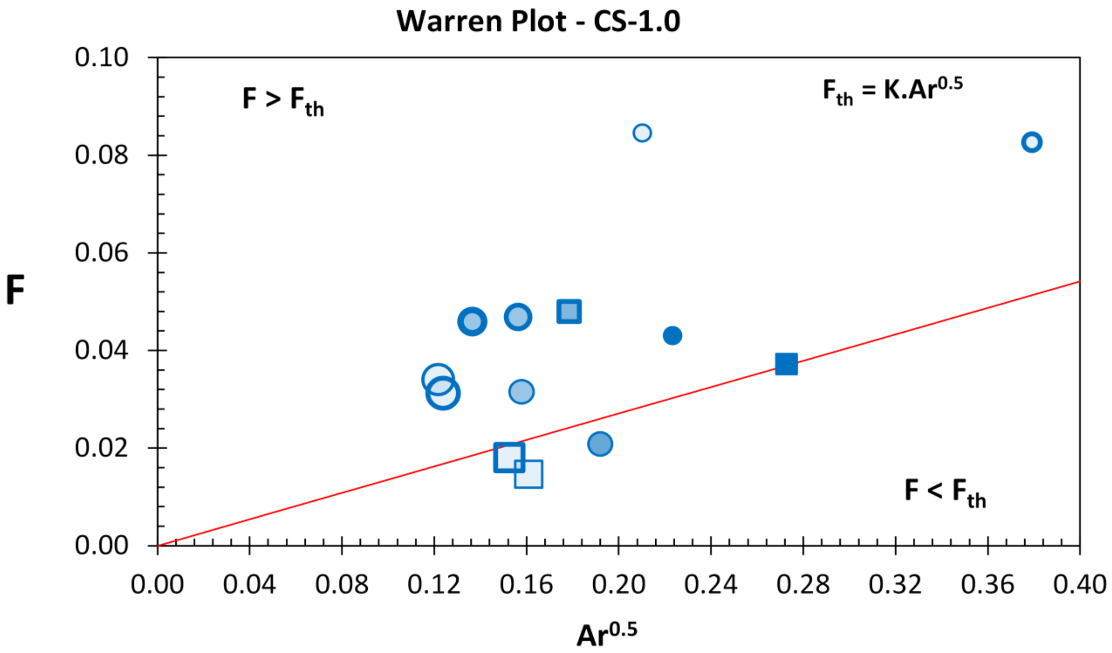
C_d - flow characteristic

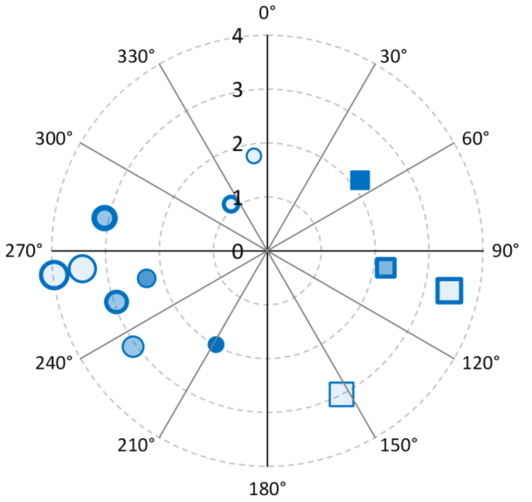
Source	Method	C_D
Aynsley et al (1977)	empirical	C_D = f(opening porosity)
Vickery and Karakatsanis (1987)	wind tunnel	C_D = f(opening porosity) C_D = f(Re)
Murakami et al (1991), Kato et al (1992; 2004)	wind tunnel	power balance model C_D = f(configuration) C_D = f(opening area)
Flourenzou et al (1998)	real building	$C_D = 0.6 \pm 0.1$
Heiselberg et al (1999, 2001, 2002a and 2002b)	lab test	C_D = f(configuration) C_D = f(opening area) $C_D = f(\Delta P)$
Sandberg (2002 and 2004), Jensen et al (2002a; 2002c)	wind tunnel and CFD	C_D = f(configuration) C_D = f(opening porosity) 0.7 at large porosities or flow catchment problem
Jensen et al (2002b)	CFD	$C_D = f(\theta)$
Ohba et al (2002 and 2004) Kurabuchi et al (2002 and 2004) Akamine et al (2004) Endo et al (2004)	wind tunnel and CFD	local similarity model $C_D = f(P_R^*)$
Sawachi (2002), Sawachi et al (2004) and Nishizawa et al (2004)	full scale wind tunnel and CFD	$C_D = f(\theta)$, $C_D = f(\Delta C_p)$
Andersen (2002)	empirical	C_D = f(opening angle)
Carey and Etheridge (1999), Etheridge (2004)	wind tunnel	C_D = f(Re)

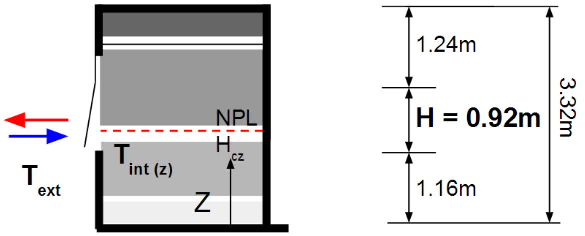




Warren & Polar Plot- CS-1.0 Config







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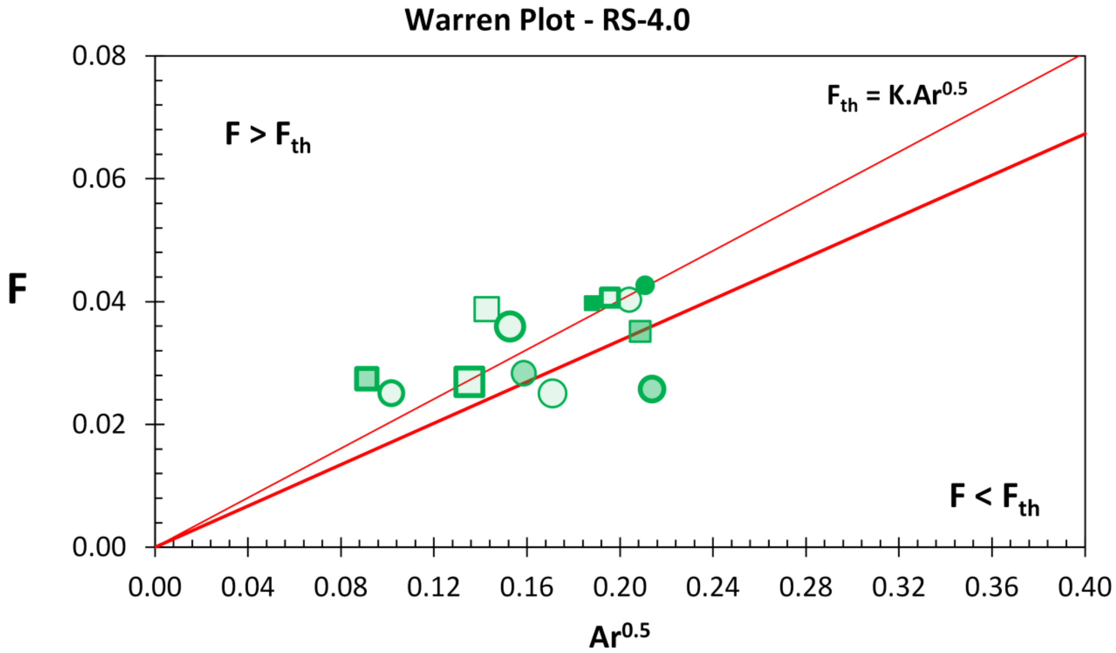
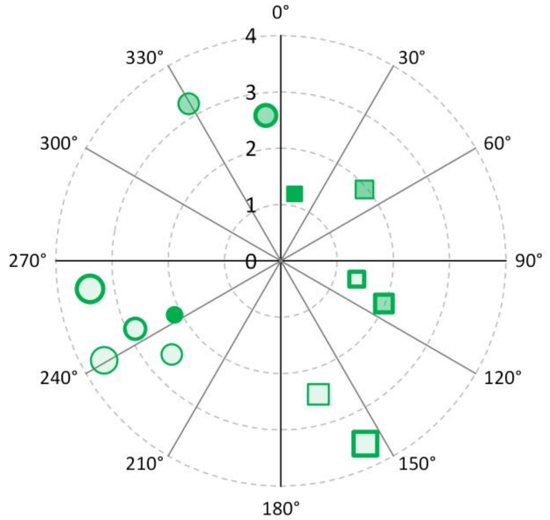
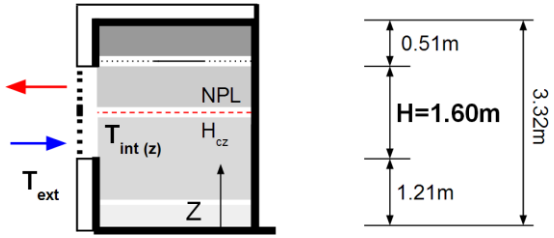
Warren & Polar Plot- RS-4.0 Config







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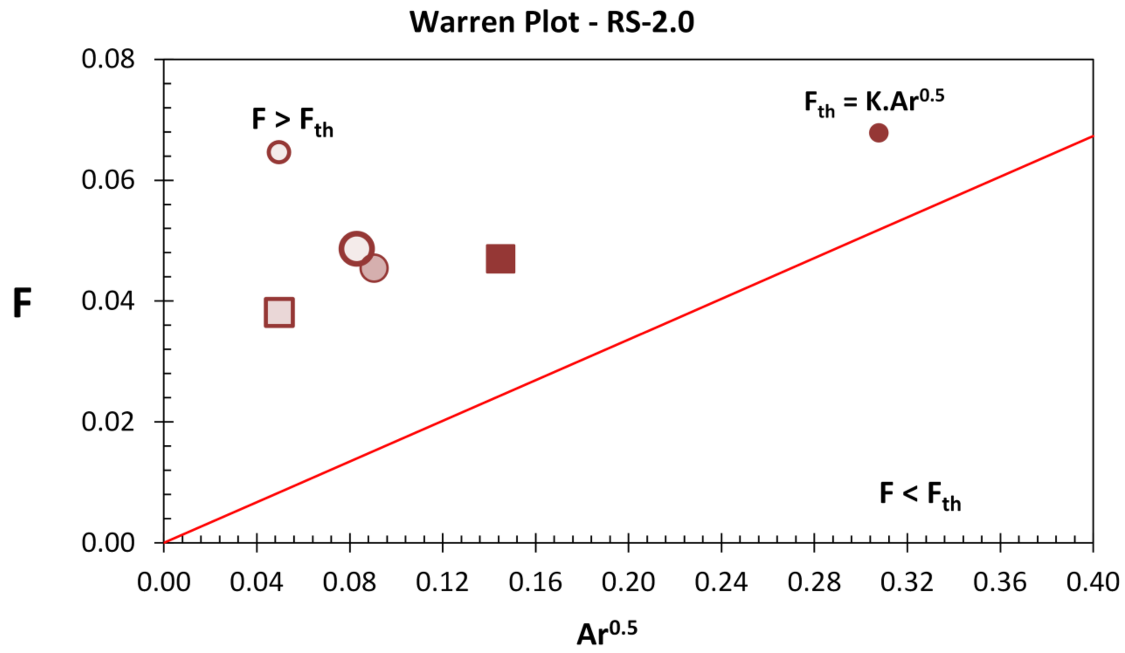
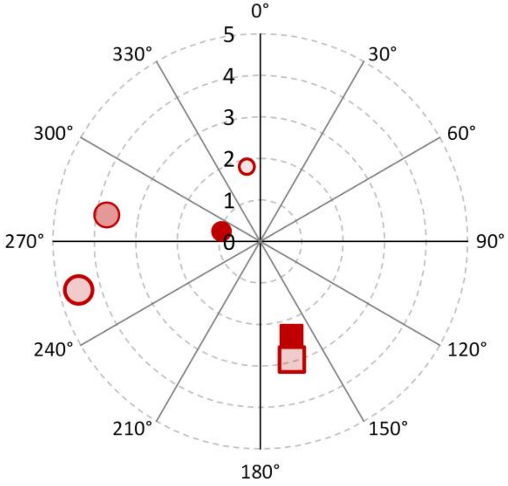
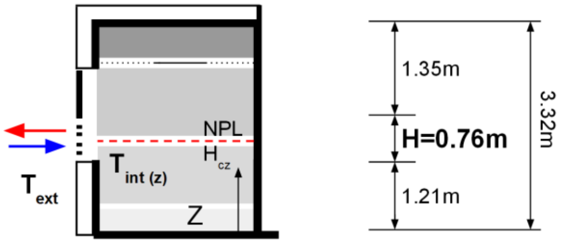
Warren & Polar Plot- RS-2.0 Config







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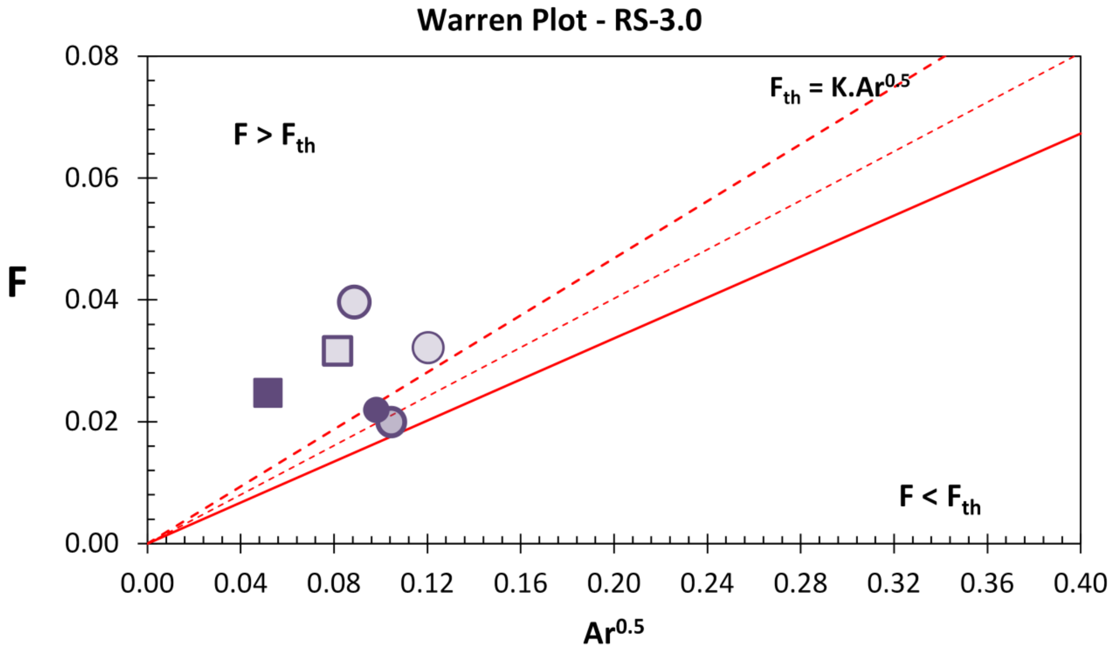
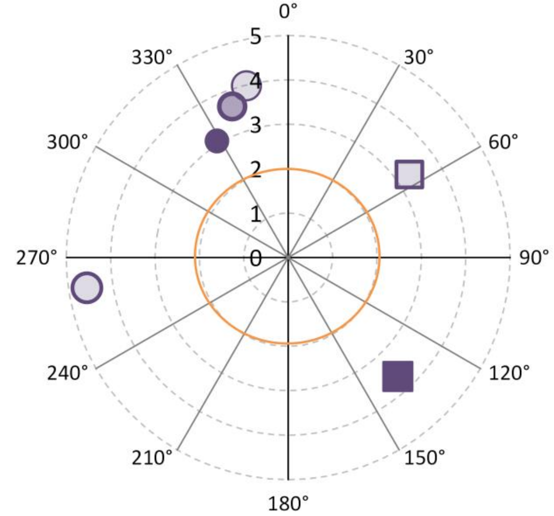
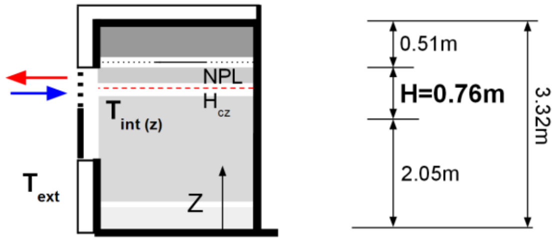
Warren & Polar Plot- RS-3.0 Config







Dominant Forces Summary

- Analysis still on-going
- correct system characteristics $(C_d, H_{npl}, A_{in}, A_{out})$
- Existing single sided empirical models also being tested against dataset for predictive accuracy
- Velocities measured at 8 points along openings due to be analysed (issue relating to measuring frequency)

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Conclusions

- Experimental findings suggest that the retrofit works have modified mean ventilation rates during the cooling season for isolated spaces with single sided ventilation
- largest recorded ventilation rates in the retrofit space were, on average, still lower than the existing building under similar driving forces
- Results indicate increased time varying ventilation rate fluctuations in the control space during testing compared with the retrofit space, suggesting an increased presence of unsteady air flow effects (turbulent diffusion / mixing layer, pulsating flow and impinging flow)
- The new louvred ventilation opening design in the refurbished building may be contributing to more stable instantaneous ventilation rates

Other work and future plans

- Measurements of phenomena at the opening to investigate unsteadiness, turbulence, mixing and diffusion
- Effective ventilation penetration depth
- CFD modelling for parametric analysis & quantification of cooling potential

Current Progress

- Started Oct 2011
- 1st year spent working on zero2020 / 6 months spent researching PCM
- Focus established early 2013
- Conference paper presented at IMC 30 UCD Sept 2013
- Conference paper presented at AIVC Athens Sept 2013
- Journal paper accepted for publication International Journal of Ventilation (SCI indexed)
- Forces analysis & empirical models study due for submission in follow up paper with IJV
- Additional testing this summer
- CFD modelling next year - Write up end 2015 / beginning 2016
- Worked everyday summer 2013 (same again 2 more years!)

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Thank You

Questions & Discussion welcome…

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