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Evaporative cooling for low-energy thermal comfort in the tropics

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Self-Intro

- PhD (Building Science) – National University of Singapore
- Lecturer – Singapore University of Technology & Design
- Architecture & Sustainable Design
- Green Mark (AP)
- WELL (AP)

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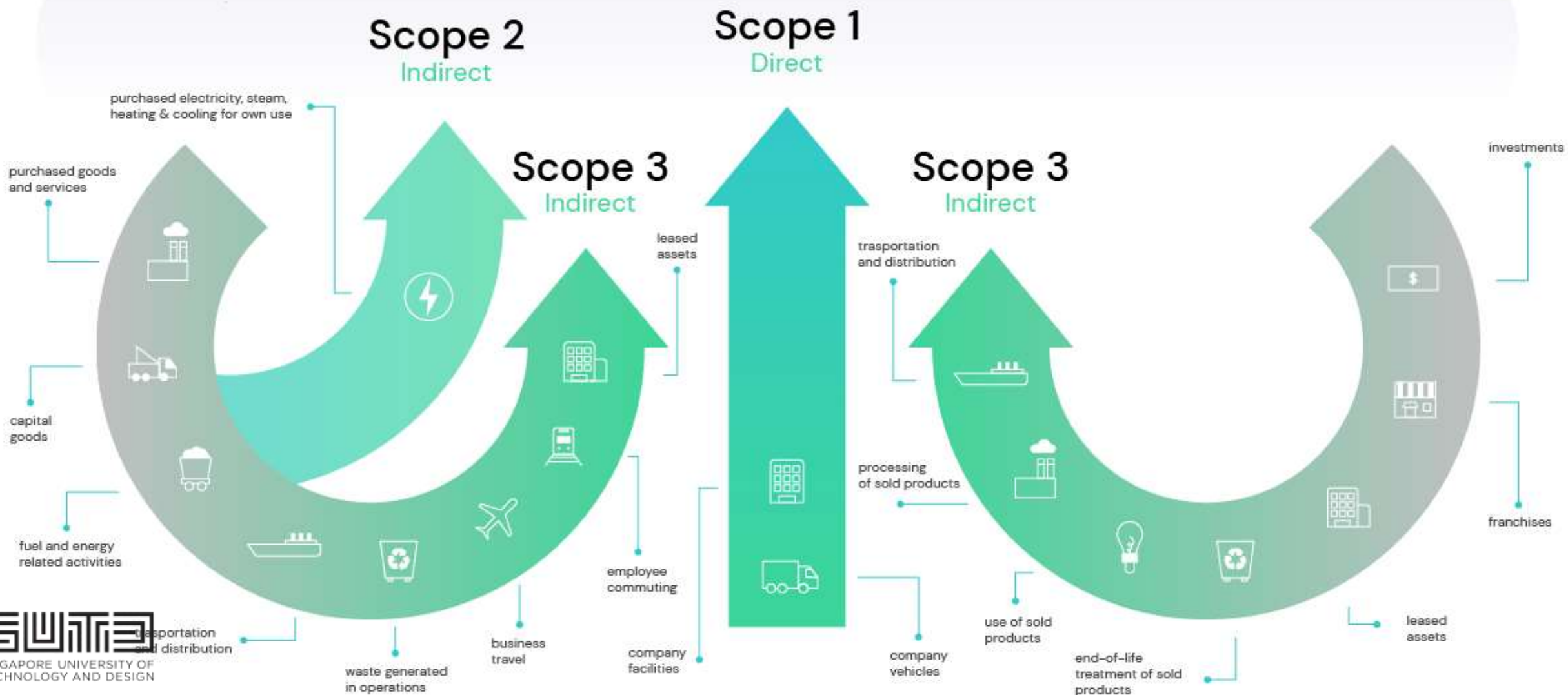
CO^2 CH_4 N_2O HFCs PFCs SF_6 NF_3



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SG GREEN PLAN

The Singapore Green Plan 2030 is a national sustainability movement which seeks to rally bold and collective action to tackle climate change, to keep Singapore a green and liveable home.

Our Key Focus Areas:

City in Nature

Create a green, liveable and sustainable home for Singaporeans

Green Government

Public sector will lead on sustainability

Sustainable Living

Save precious resources and reduce our carbon footprint

Energy Reset

Use cleaner energy and increase energy efficiency

Green Economy

Harness sustainability as a new engine of jobs and growth

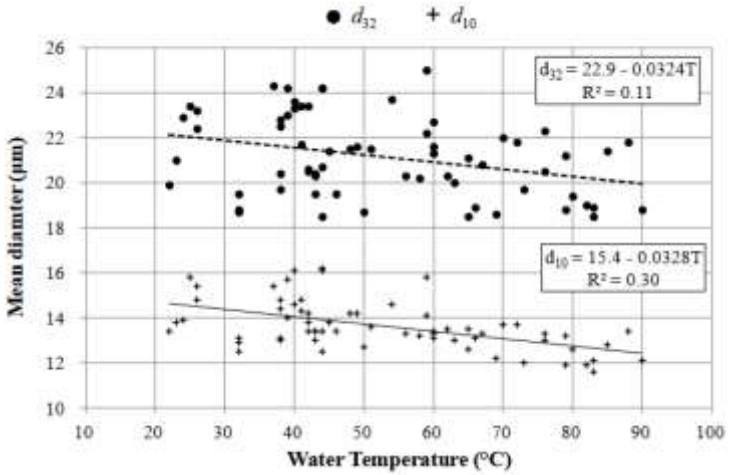
Resilient Future

Build up Singapore's climate resilience, including enhancing our food security

www.GreenPlan.gov.sg

Evaporative Cooling

- More heat absorbed than gained
  - Heat capacity of water, CP = 4184 J/kgK
  - Latent heat of evaporation, L = 2.45×10^6 J/kg
- Attenuates solar radiation
  - UV to IR range

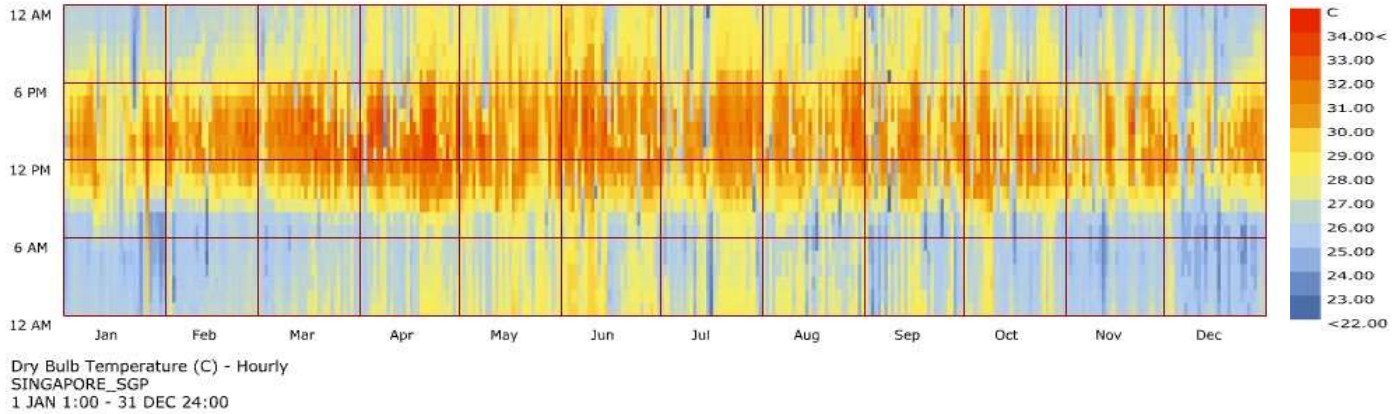


Effect of temperature on droplet diameter

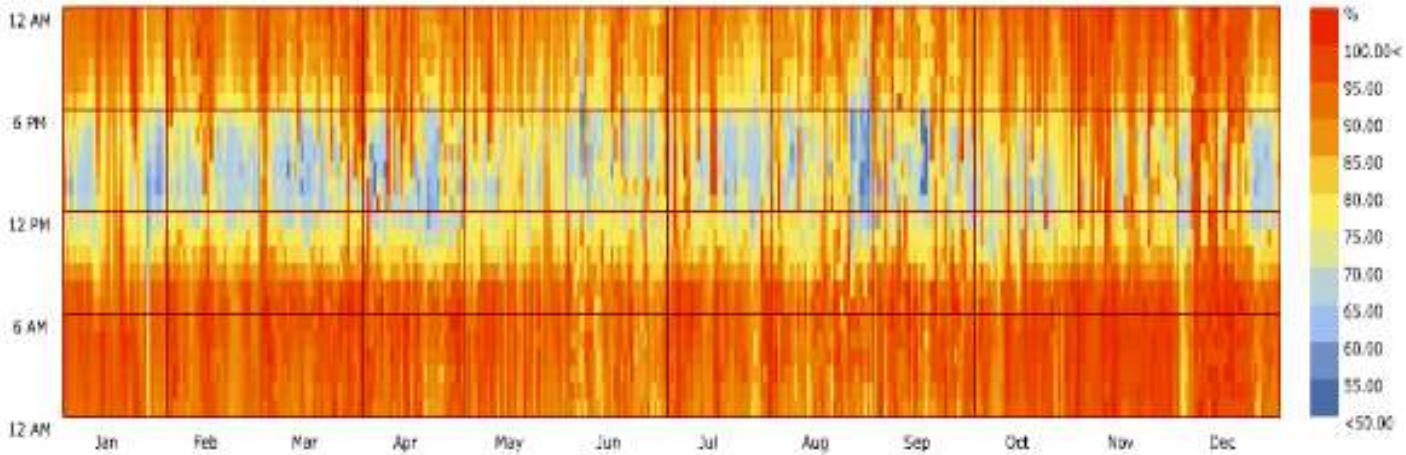
Farnham, C., Nakao, M., Nishioka, M., Nabeshima, M., & Mizuno, T. (2015). Effect of water temperature on evaporation of mist sprayed from a nozzle. *Journal of Heat Island Institute International*, 35-44.

Leonid A., D., Vladimir P., S., & Brent W., W. (2011). Attenuation of solar radiation by a water mist from the ultraviolet to the infrared range. *Journal of Quantitative Spectroscopy & Radiative Transfer*, 1182-1190.

Singapore Climate



Dry Bulb Temperature (C) - Hourly
SINGAPORE_SGP
1 JAN 1:00 - 31 DEC 24:00



Relative Humidity (%) - Hourly
SINGAPORE_SGP
1 JAN 1:00 - 31 DEC 24:00

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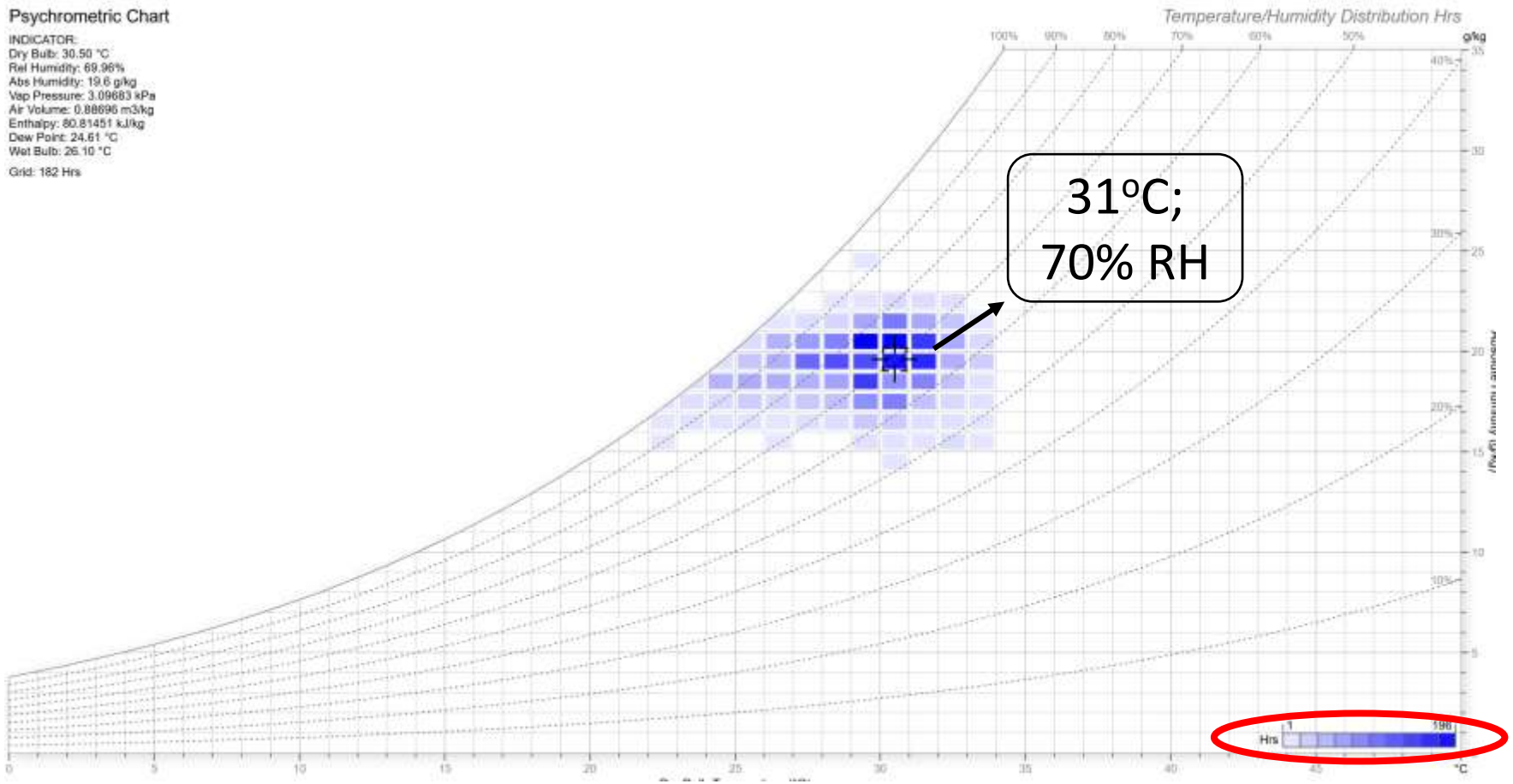
Potential for cooling in SG



Absolute Humidity

Dry Bulb Temp

No. of hours

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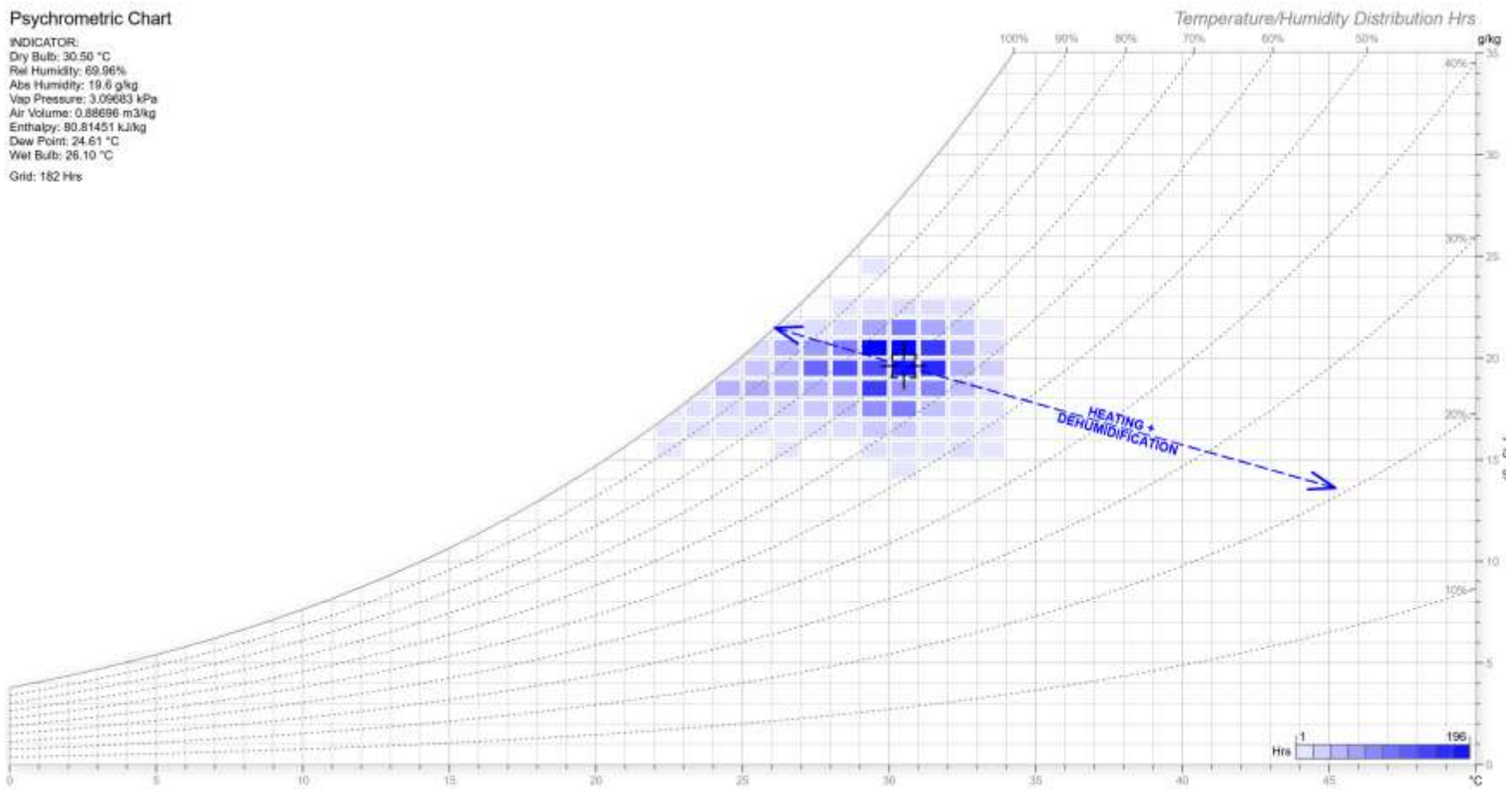
Adiabatic Humidification



Absolute Humidity

Dry Bulb Temp

No. of hours

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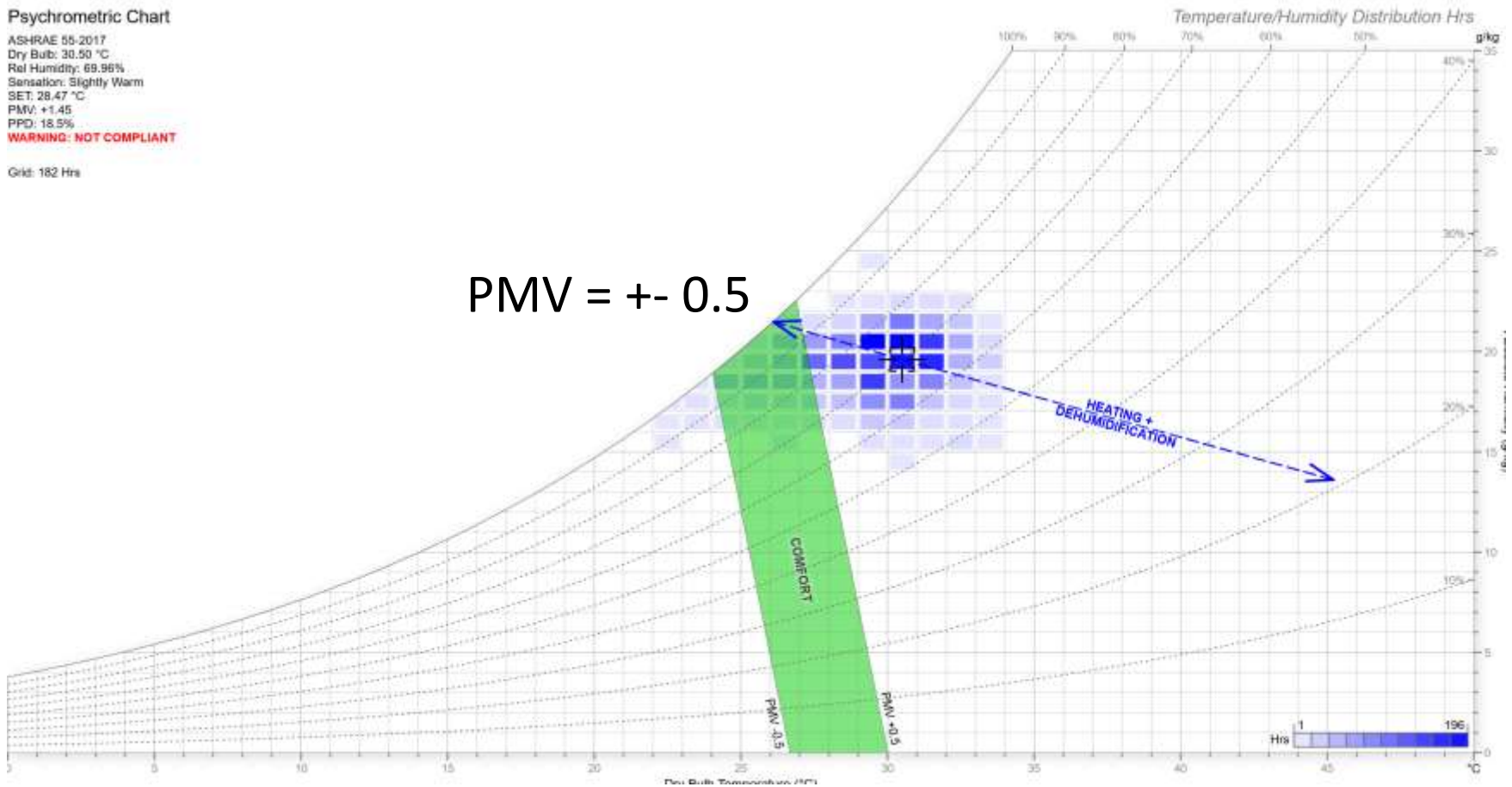
Psych Chart – ASHRAE 55 Thermal Comfort



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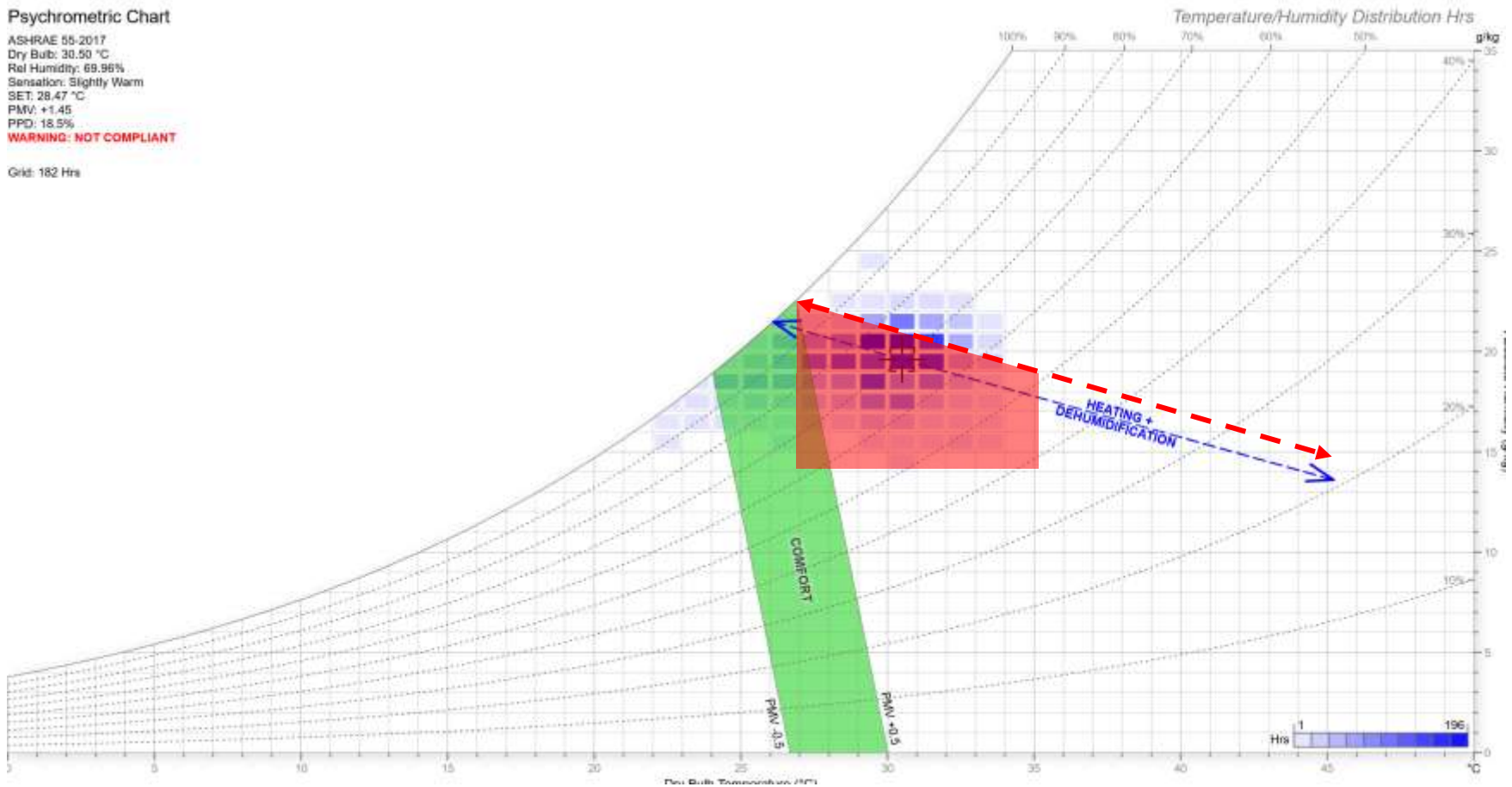
Psych Chart – Evaporative Cooling Potential



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Sensitivity to humidity

- Sample size of 2000 Singaporeans
- Conducted in 13 different outdoor spaces
- Humidity sensation has insignificant influence on thermal sensation

Correlations analysis among thermal responses votes.

		TSV	HSV	WSV	SSV
TSV	Correlation coefficient	1.000	−.094[a]	−.206[a]	.470[a]
	Sig. (2-tailed)	–	.000	.000	.000
	N	2036	2036	2036	1784
HSV	Correlation coefficient	−.094[a]	1.000	−.018	−.099[a]
	Sig. (2-tailed)	.000	–	.404	.000
	N	2036	2036	2036	1784
WSV	Correlation coefficient	−.206[a]	−.018	1.000	−.145[a]
	Sig. (2-tailed)	.000	.404	–	.000
	N	2036	2036	2036	1784
SSV	Correlation coefficient	.470[a]	−.099[a]	−.145[a]	1.000
	Sig. (2-tailed)	.000	.000	.000	–
	N	1784	1784	1784	1784

[a] Correlation is significant at the 0.01 level (2-tailed).

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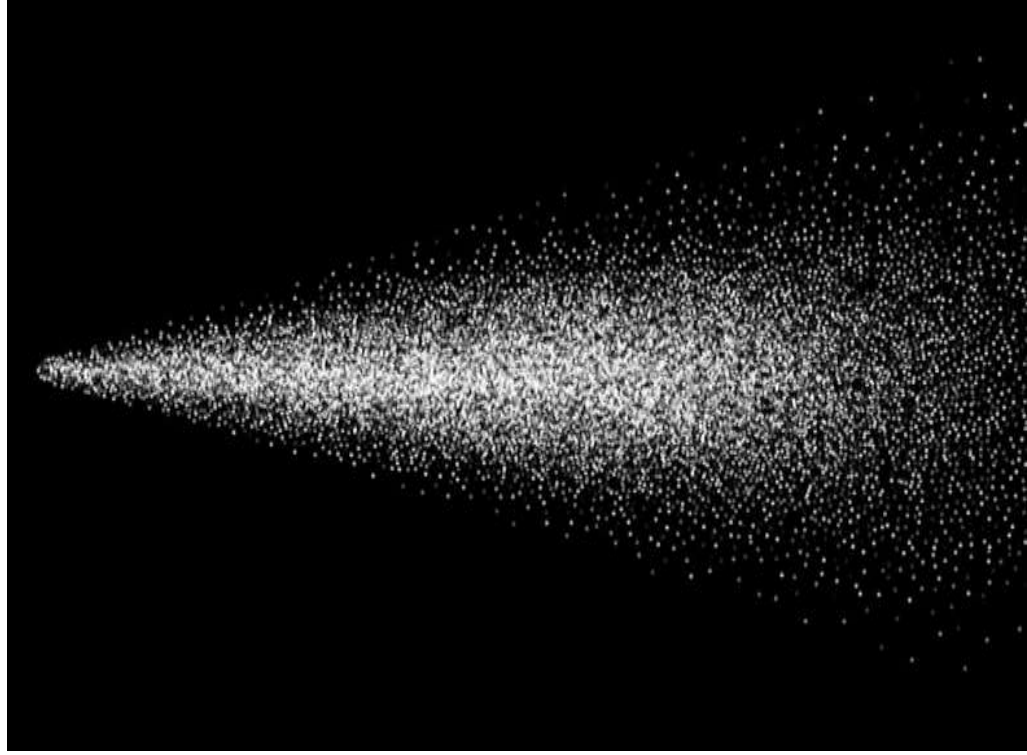
Yang, W., Wong, N., & Jusuf, S. (2013). Thermal Comfort in outdoor urban spaces in Singapore. *Building and Environment*, 426-435.

Dry Mist

- Small droplets = high surface tension
- Cohesion forces within the drop is stronger than adhesive forces between drop and surface
- Larger droplets break and form a film – which is wetting



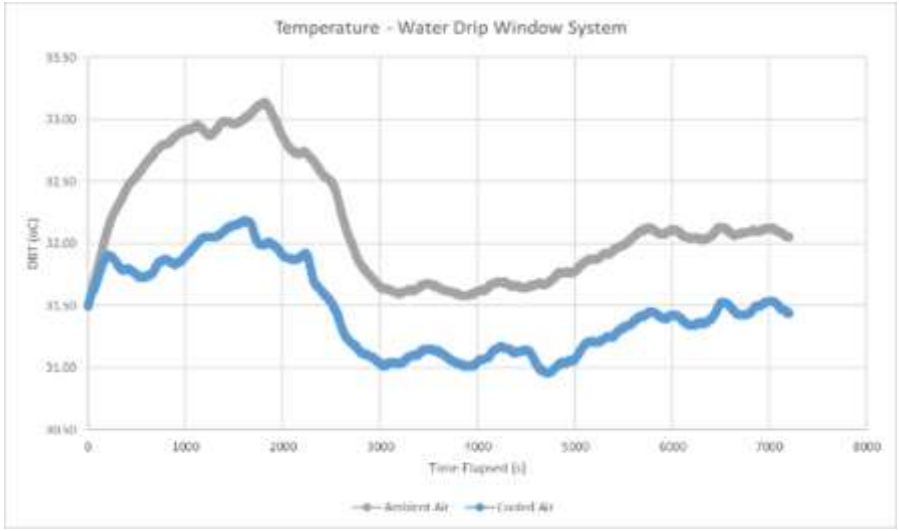

Mayfair Gardens
Sales Gallery
The Blue Leaf
Florist
Maplewoods
Methodist Girls' School
MGS Swimming Poo
2D

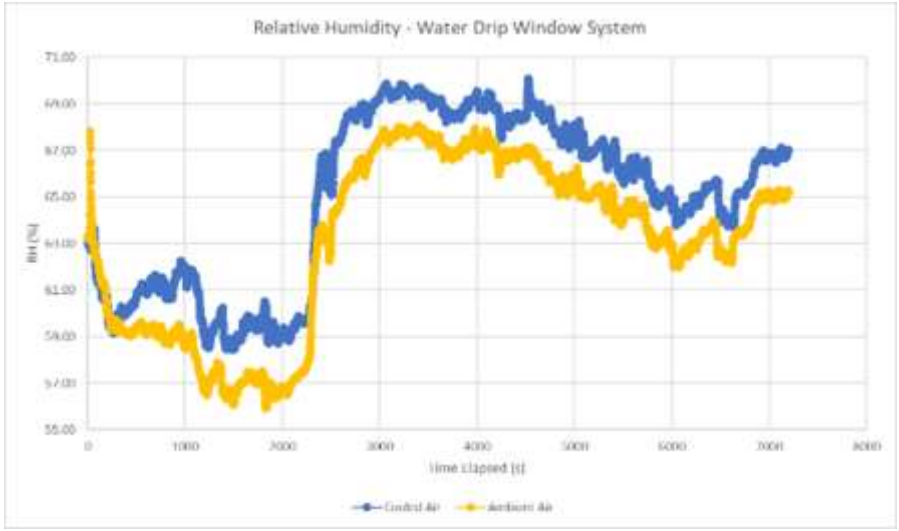

Mayfair Gardens
Sales Gallery
The Blue Leaf
Florist
Maplewoods
Methodist Girls' School
Full blown E-W sun
MGS Swimming Poo
2D


PUAN SRI HELENE
TAN CHIN TUAN BUILDING

Water drip window system

- Moving water through capillary action using water wick
- Zero energy consumption
- Potentially high air mass flow rate (CFM)
- Drop in DBT: 0.5~1 ^{o}C





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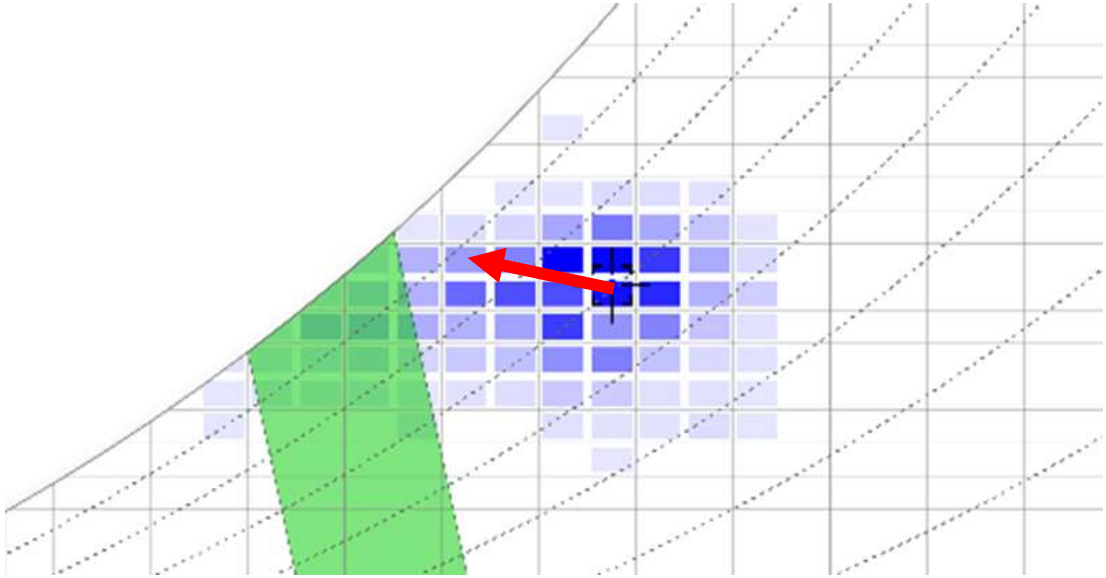
Direct Evaporative Cooler

- Moving water through cellulose cooling pad
- Cross-flow with fans
- Drop in DBT: 1.5 - 2°C
- Energy consumption – 40Wh



Psychrometric chart showing change in air conditions from evaporative cooler

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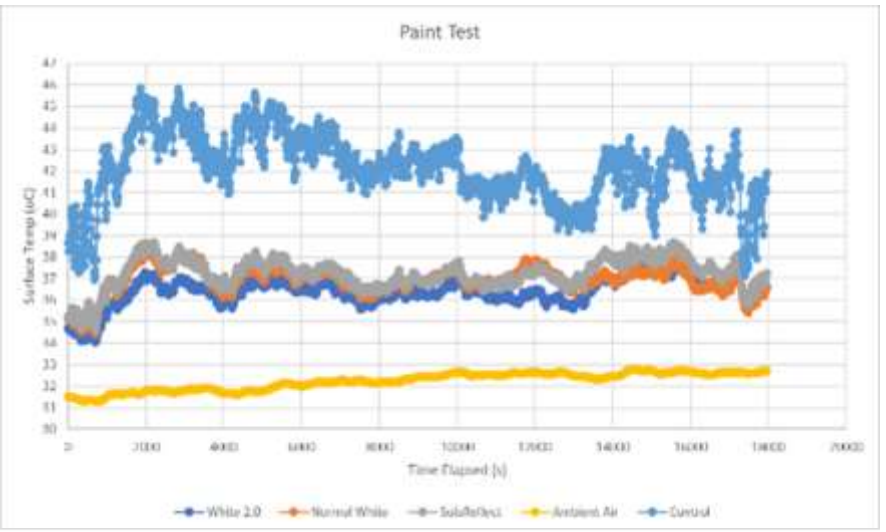

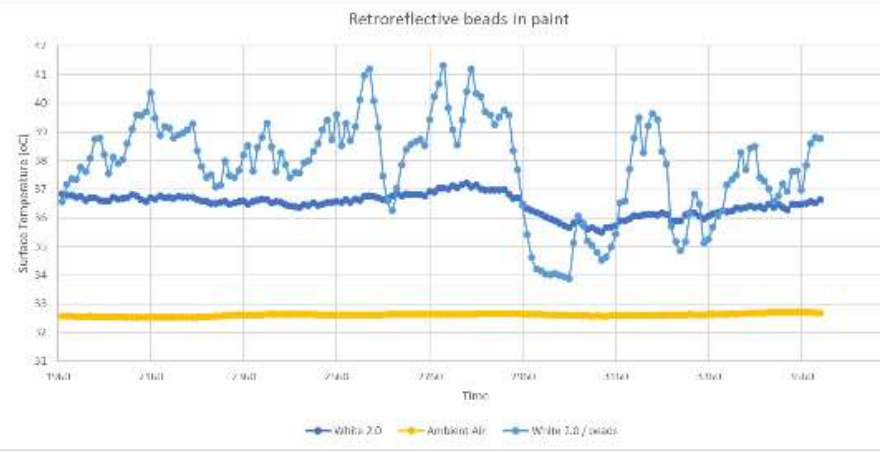

Cooling Paints

- Chosen white paints showed similar results
- White 2.0 was the best
  - 9^{o}C lower than control surface temp
  - 5^{o}C above ambient air temp
- Larger fluctuations when used with retroreflective beads
- Potential for quick cooling & close to ambient temperatures (1^{o}C)
- Passive system

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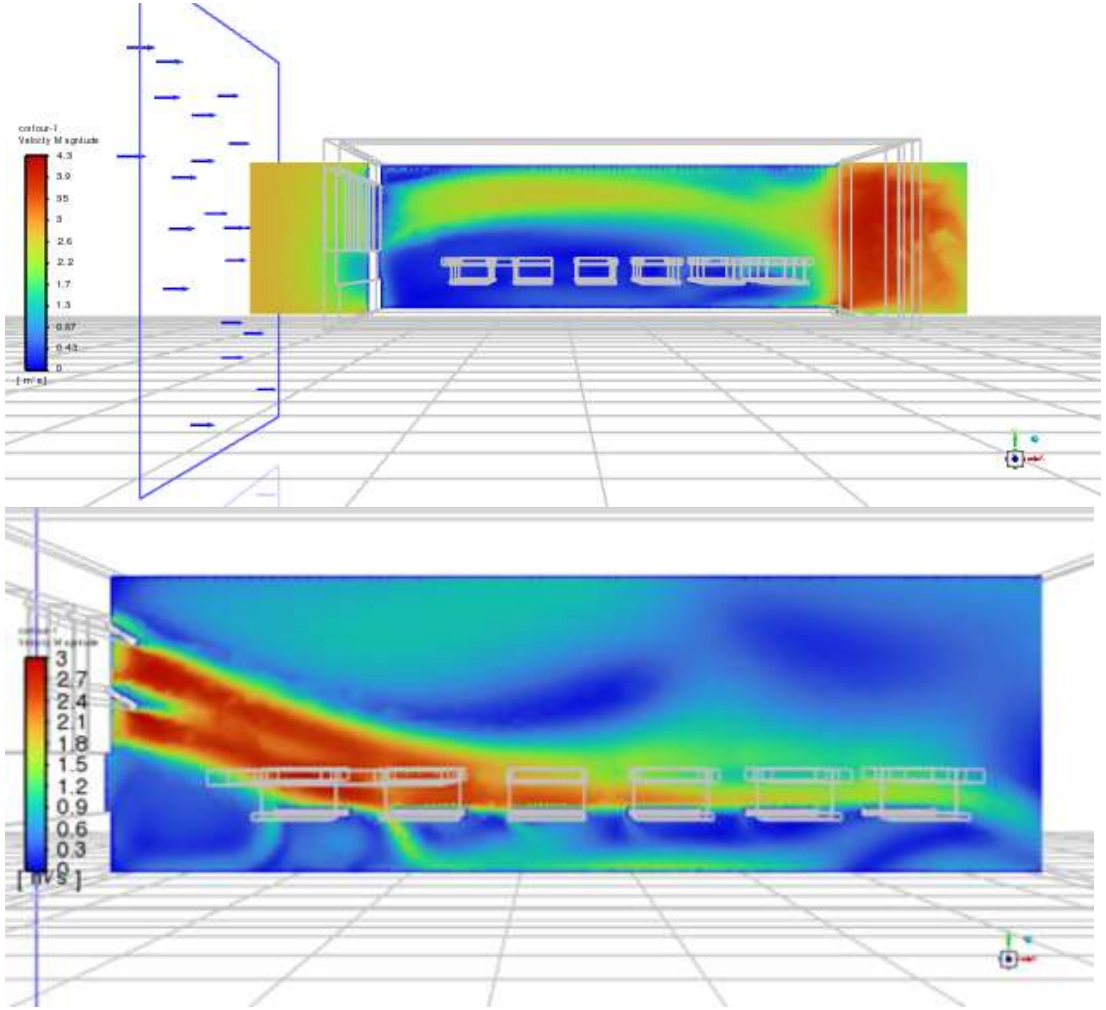
CFD – Redirecting wind

- In original set up, wind was directed towards ceiling due to the presence of parapet wall
- Wind redirected towards occupants
- Area weighted average wind velocity increased 0.56 > 0.96 m/s
- Passive system



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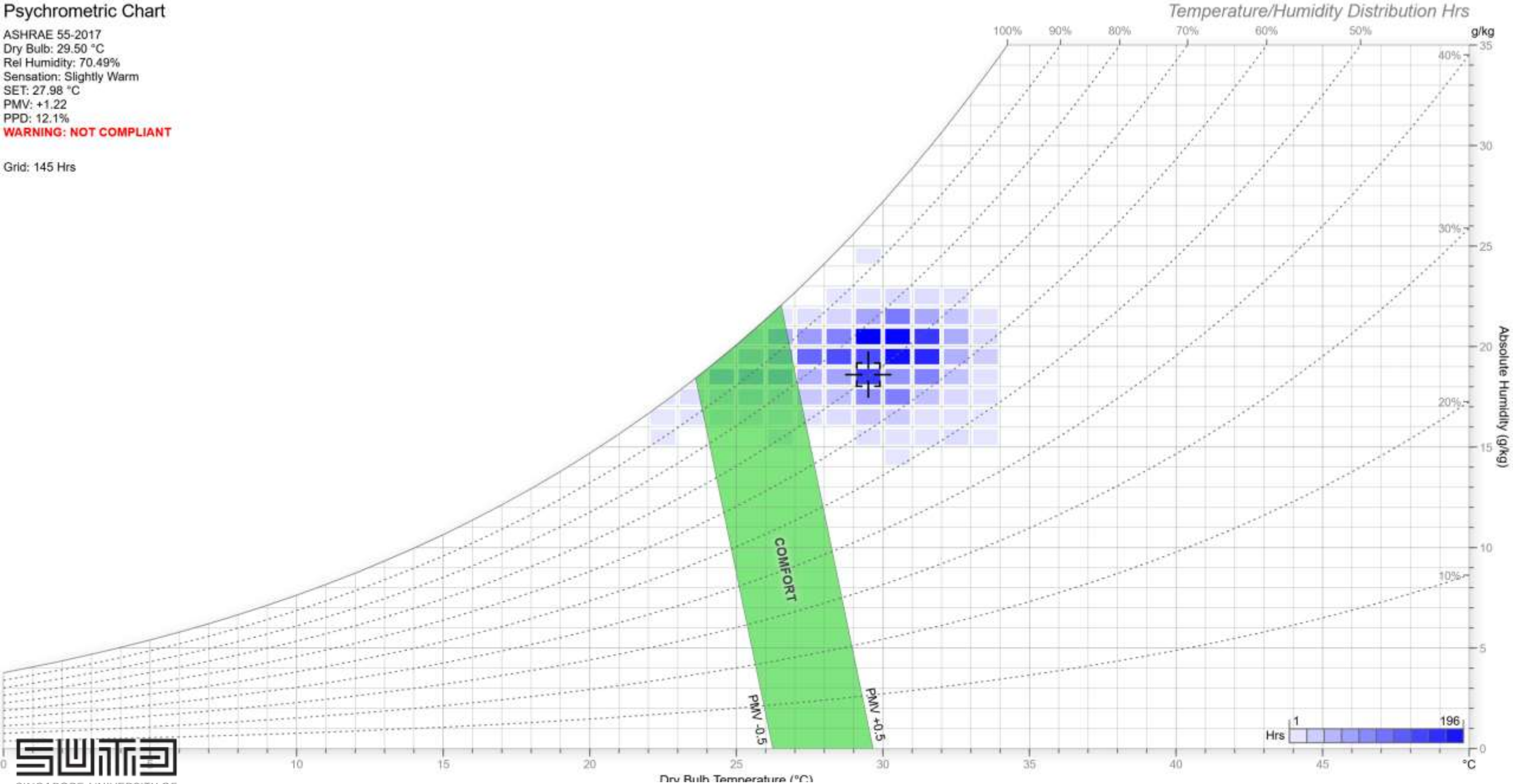
Psychrometric Chart

ASHRAE 55-2017
Dry Bulb: 29.50 °C
Rel Humidity: 70.49%
Sensation: Slightly Warm
SET: 27.98 °C
PMV: +1.22
PPD: 12.1%
WARNING: NOT COMPLIANT

Grid: 145 Hrs



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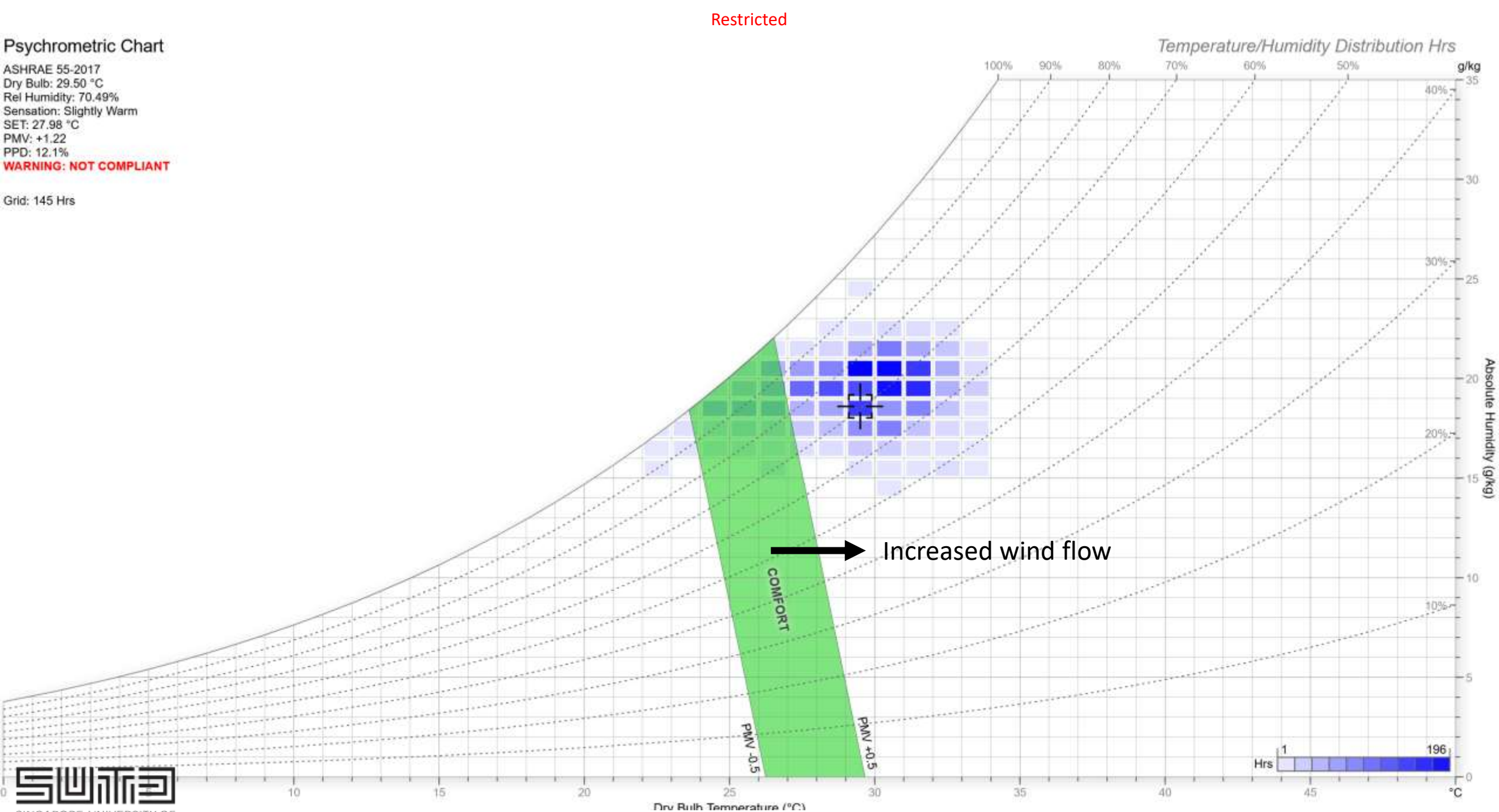

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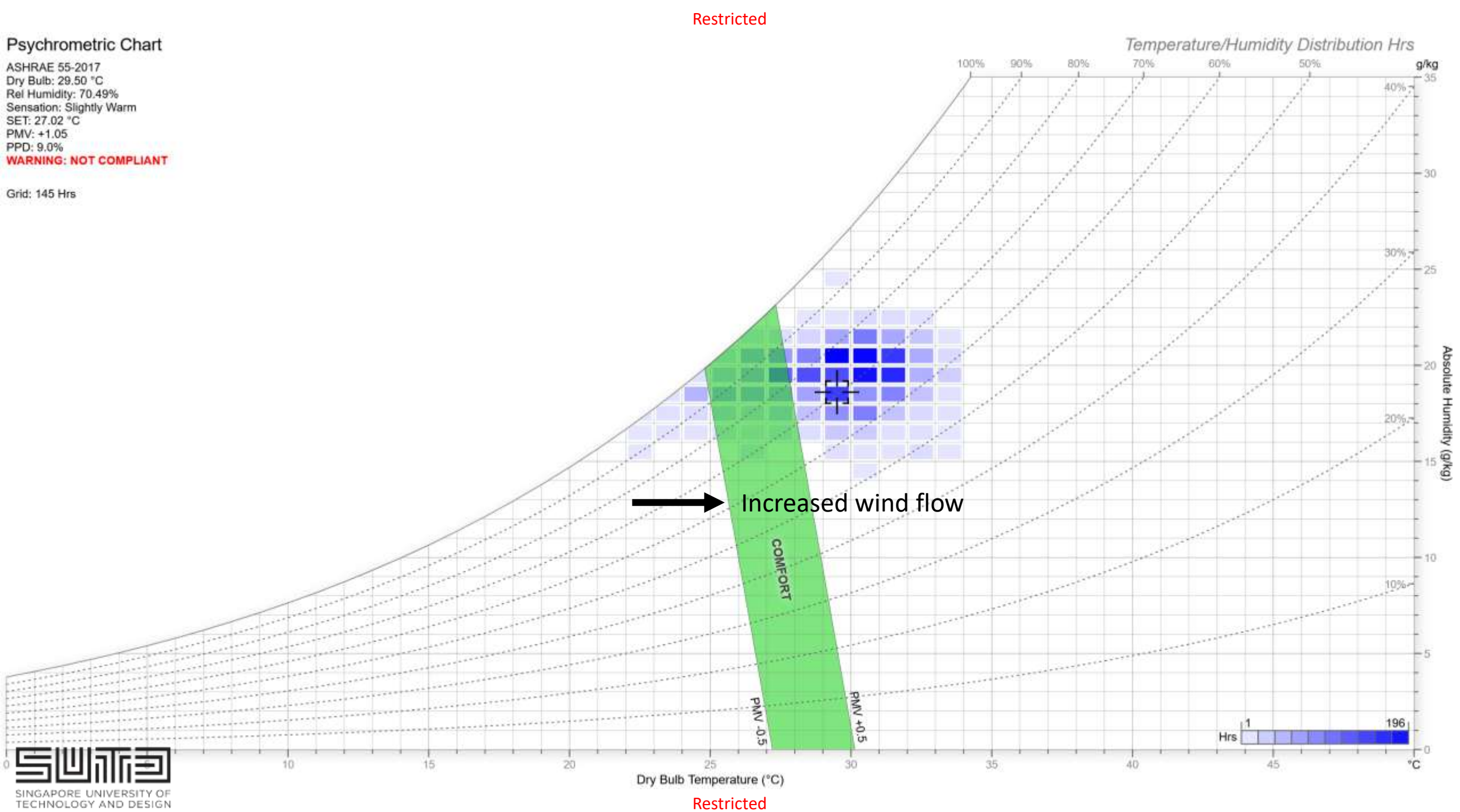

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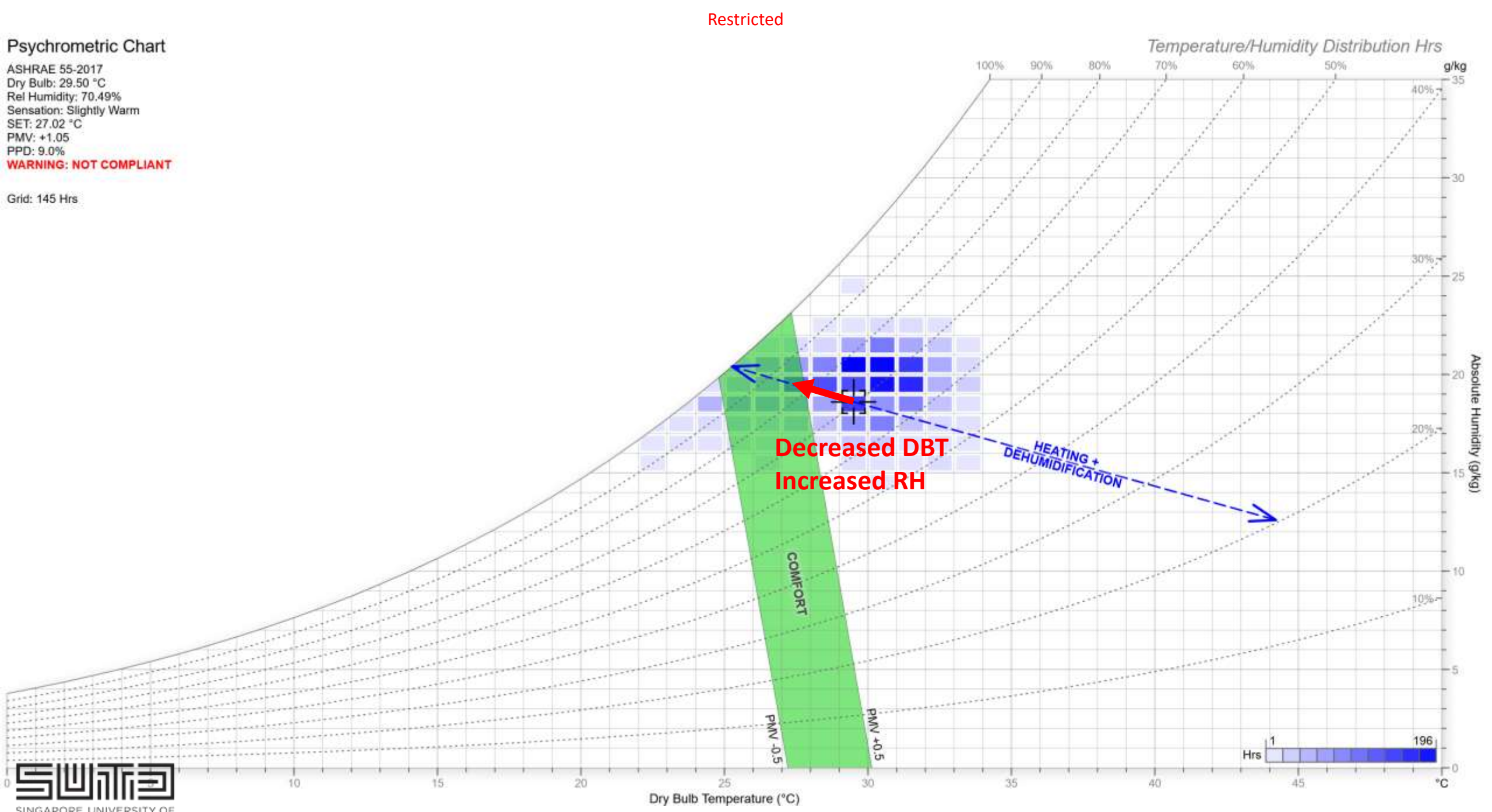

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Thank you

For further questions:

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References

- Belarbi, R., Ghiaus, C., Ghiaus, C., & Allard, F. (2006). Modeling of water spray evaporation: Application to passive cooling of buildings. Solar Energy. https://doi.org/10.1016/j.solener.2006.01.004
- Cuce, P. M., & Riffat, S. (2016). A state of the art review of evaporative cooling systems for building applications. Renewable & Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2015.10.066
- Desert, A., Naboni, E., Naboni, E., Naboni, E., & Garcia, D. (2020). The spatial comfort and thermal delight of outdoor misting installations in hot and humid extreme environments. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2020.110202
- Dombrovsky, L. A., Solovjov, V. P., & Webb, B. W. (2011). Attenuation of solar radiation by a water mist from the ultraviolet to the infrared range. Journal of Quantitative Spectroscopy & Radiative Transfer. https://doi.org/10.1016/j.jqsrt.2010.08.018
- Farnham, C., Emura, K., & Mizuno, T. (2015). Evaluation of cooling effects: outdoor water mist fan. Building Research and Information. https://doi.org/10.1080/09613218.2015.1004844
- Giuseppe, E. Di, Ulpiani, G., Cancellieri, C., Perna, C. Di, D'Orazio, M., & Zinzi, M. (2020). Numerical modelling and experimental validation of the microclimatic impacts of water mist cooling in urban areas. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2020.110638
- Montazeri, H. H., Blocken, B. B., & Hensen, J. J. (2015). CFD analysis of the impact of physical parameters on evaporative cooling by a mist spray system. Applied Thermal Engineering. https://doi.org/10.1016/j.applthermaleng.2014.09.078
- Naticchia, B., D'Orazio, M., Carbonari, A., & Persico, I. (2010). Energy performance evaluation of a novel evaporative cooling technique. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2010.05.029

References

- Oh, W., Ooka, R., Nakano, J., Kikumoto, H., & Ogawa, O. (2020). Evaluation of mist-spraying environment on thermal sensations, thermal environment, and skin temperature under different operation modes. Building and Environment. https://doi.org/10.1016/j.buildenv.2019.106484
- Oropeza-Perez, I., & Østergaard, P. A. (2018). Active and passive cooling methods for dwellings: A review. Renewable & Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2017.09.059
- Salas, C. S., Sotelo-Salas, C., Pozo, C. E., & Esparza-López, C. J. (2021). Thermal assessment of spray evaporative cooling in opaque double skin facade for cooling load reduction in hot arid climate. Journal of Building Engineering. https://doi.org/10.1016/j.jobe.2021.102156
- Sudprasert, S. (2020). Utilization of an evaporative air cooler to achieve thermal comfort in Thailand. Building Research and Information. https://doi.org/10.1080/09613218.2020.1743962
- Ulpiani, G. (2019). Water mist spray for outdoor cooling: A systematic review of technologies, methods and impacts. Applied Energy. https://doi.org/10.1016/j.apenergy.2019.113647
- Vanos, J. K., Wright, M. K., Kaiser, A., Middel, A., Ambrose, H., & Hondula, D. M. (2020). Evaporative misters for urban cooling and comfort: effectiveness and motivations for use. International Journal of Biometeorology. https://doi.org/10.1007/s00484-020-02056-y
- Yang, W., Wong, N. H., & Jusuf, S. K. (2013). Thermal comfort in outdoor urban spaces in Singapore. Building and Environment. https://doi.org/10.1016/j.buildenv.2012.09.008
- Zhang, M., Xu, C., Meng, L., & Meng, X. (2021). Outdoor comfort level improvement in the traffic waiting areas by using a mist spray system: An experiment and questionnaire study. Sustainable Cities and Society. https://doi.org/10.1016/j.scs.2021.102973
- Zheng, K., Yuan, C., Wong, N. H., & Cen, C. (2019). Dry mist systems and its impact on thermal comfort for the tropics. Sustainable Cities and Society. https://doi.org/10.1016/j.scs.2019.101727