CFD Simulations to Improve Ventilation in Low-Income Housing

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Motivation

- Globally, respiratory illnesses and infections cause deaths of over 1.2 million children per year [1].
- In Dhaka, Bangladesh, the leading causes of death include chronic obstructive pulmonary diseases, tuberculosis, and lower respiratory infections [2].
- Past literature has suggested that insufficient ventilation of homes is associated with increased infection rates, and increasing the ventilation rate can reduce the infection risk [3].
- Across some of Bangladesh's most populous slums, an average of 43% of households do not have windows [4].

Objectives and Methods

Objectives

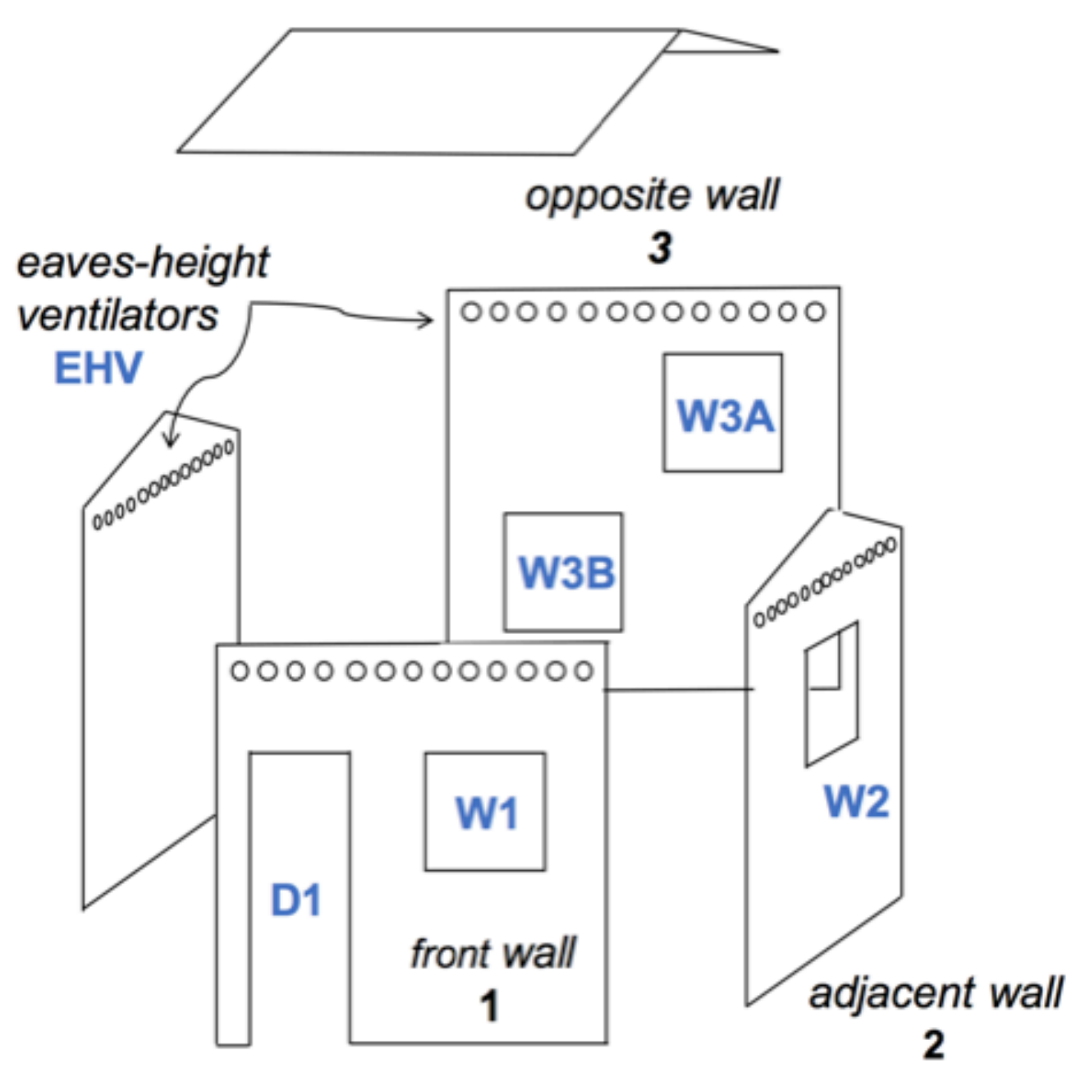
- Determine the relative effectiveness of different ventilation strategies for Dhaka homes using CFD.
- Focus on buoyancy-driven natural ventilation first.
- Compare the relative performance of the different window configurations to previous lab experiments [3].

Lab experiments

- Considered 7 different combinations of openings
- Performed ventilation measurements using the decay technique:
  - Generate smoke from a match
  - Measure the decay in PM concentration over time
  - Extracted the air change rate per hour (ACH) from:

$$(1)\ V\frac{dc_t}{dt} = -Qc_t$$

$$(2)\ ACH = 3600 * \frac{ln(t_2 - t_1)}{t_2 - t_1}$$



Dhaka house model

- No clearly defined driving mechanism for the flow

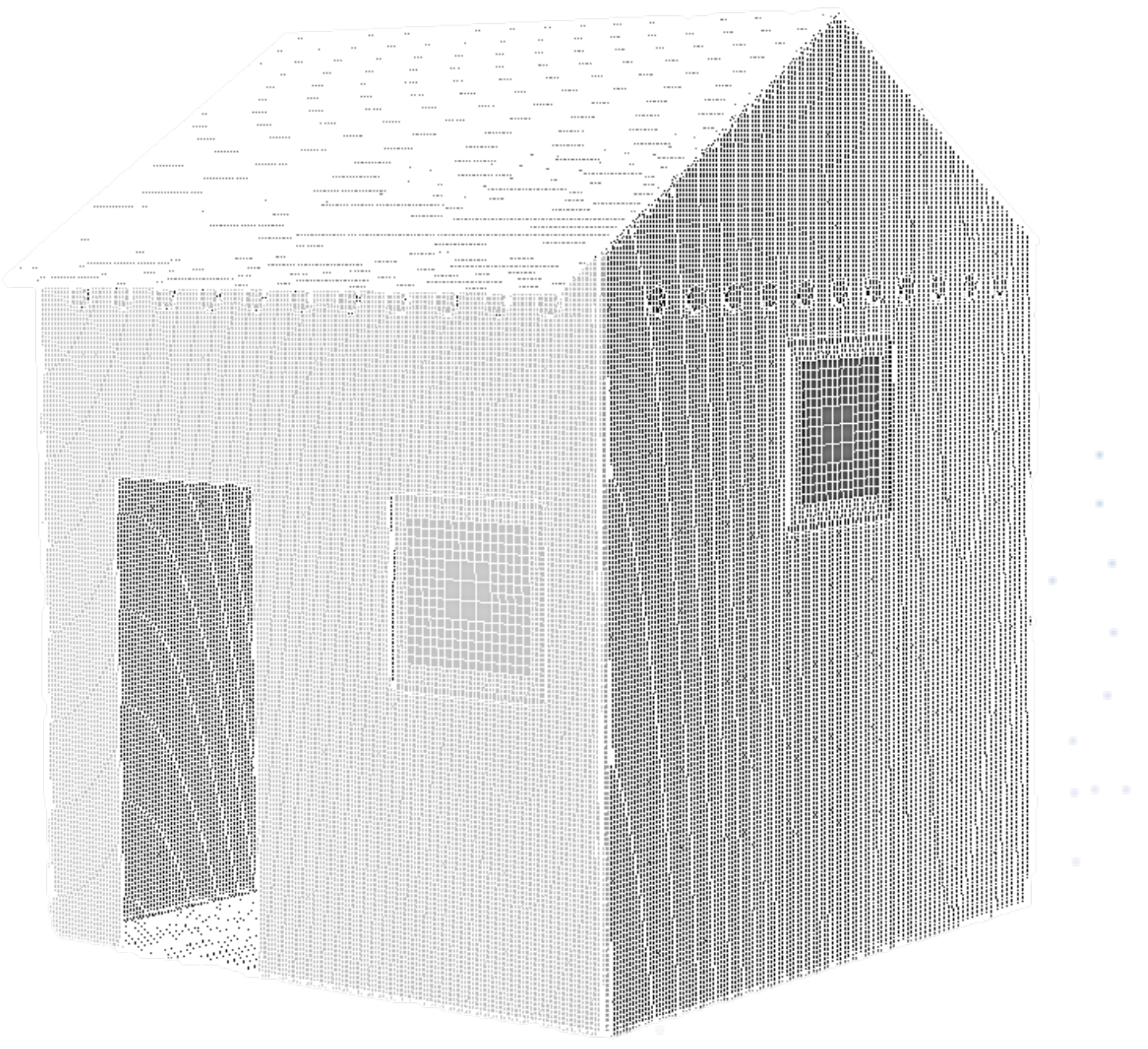
CFD simulations

- Same house and window configurations
- OpenFOAM software for meshing
- ANSYS Fluent for incompressible Reynolds-Averaged Navier-Stokes simulations with the RNG k-ε model
- Boussinesq approximation to represent the effect of buoyancy
- Natural ventilation flow driven by an initial temperature difference of 5K between the indoor and outdoor environment
- ACH from the decrease in temperature over time, following eq. (2)

CFD Simulation Set-Up

Computational Model and Mesh

- One room housing unit with various window openings, surrounding area
- Mesh: ~ 2 million cells



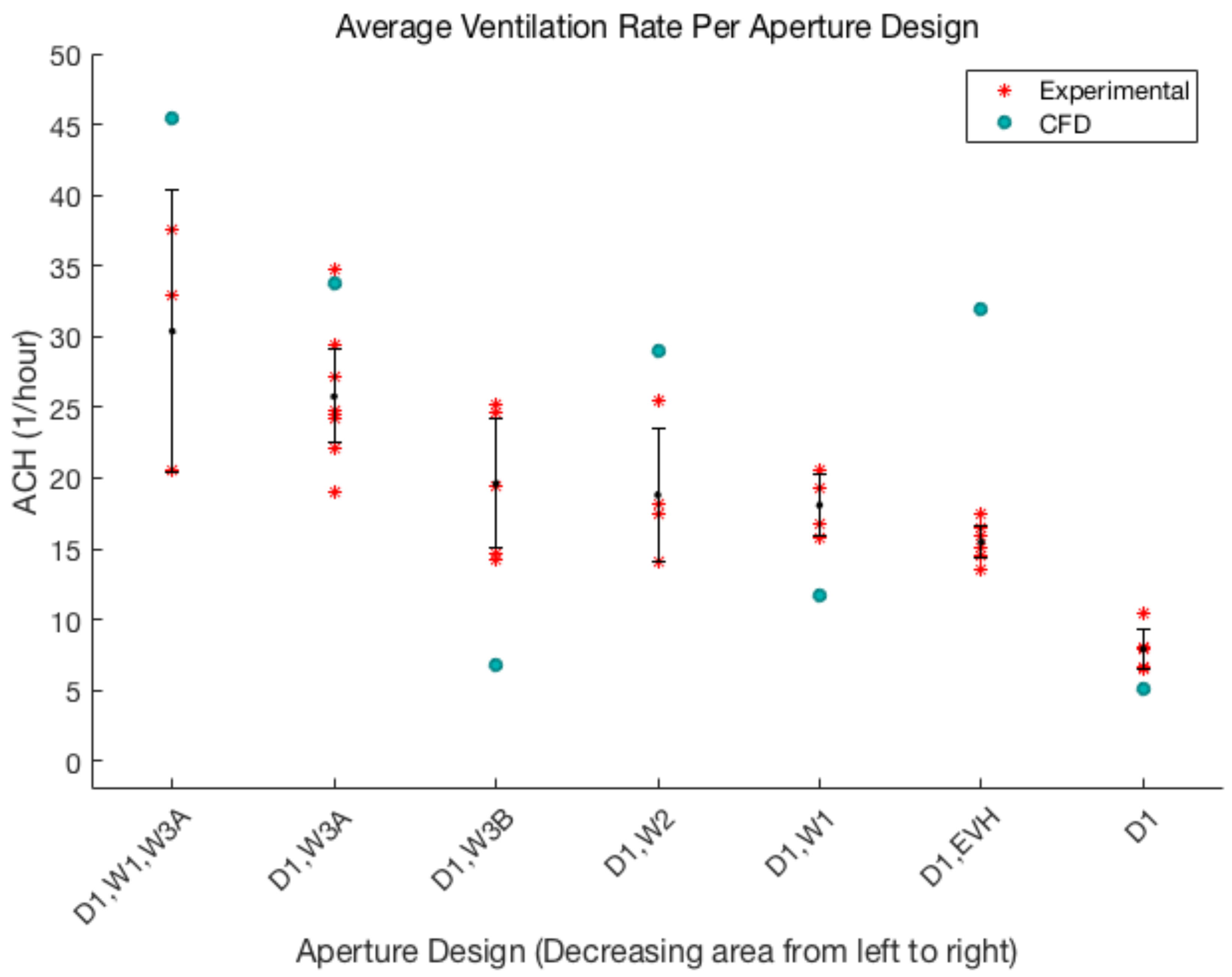
Boundary and Initial Conditions

- Exterior area initialized at 296.15 K
- Interior of house initialized at 301.15 K
- Walls: no-slip, adiabatic
- Far field: constant pressure

Solution Methods

- Pressure-Velocity Coupling: PISO
- Momentum: 2nd order upwind
- Pressure: 2nd order upwind
- Time discretization: 2nd order
- Time step size: 0.8 seconds, 2000 time steps

Comparison of Air Changes per Hour



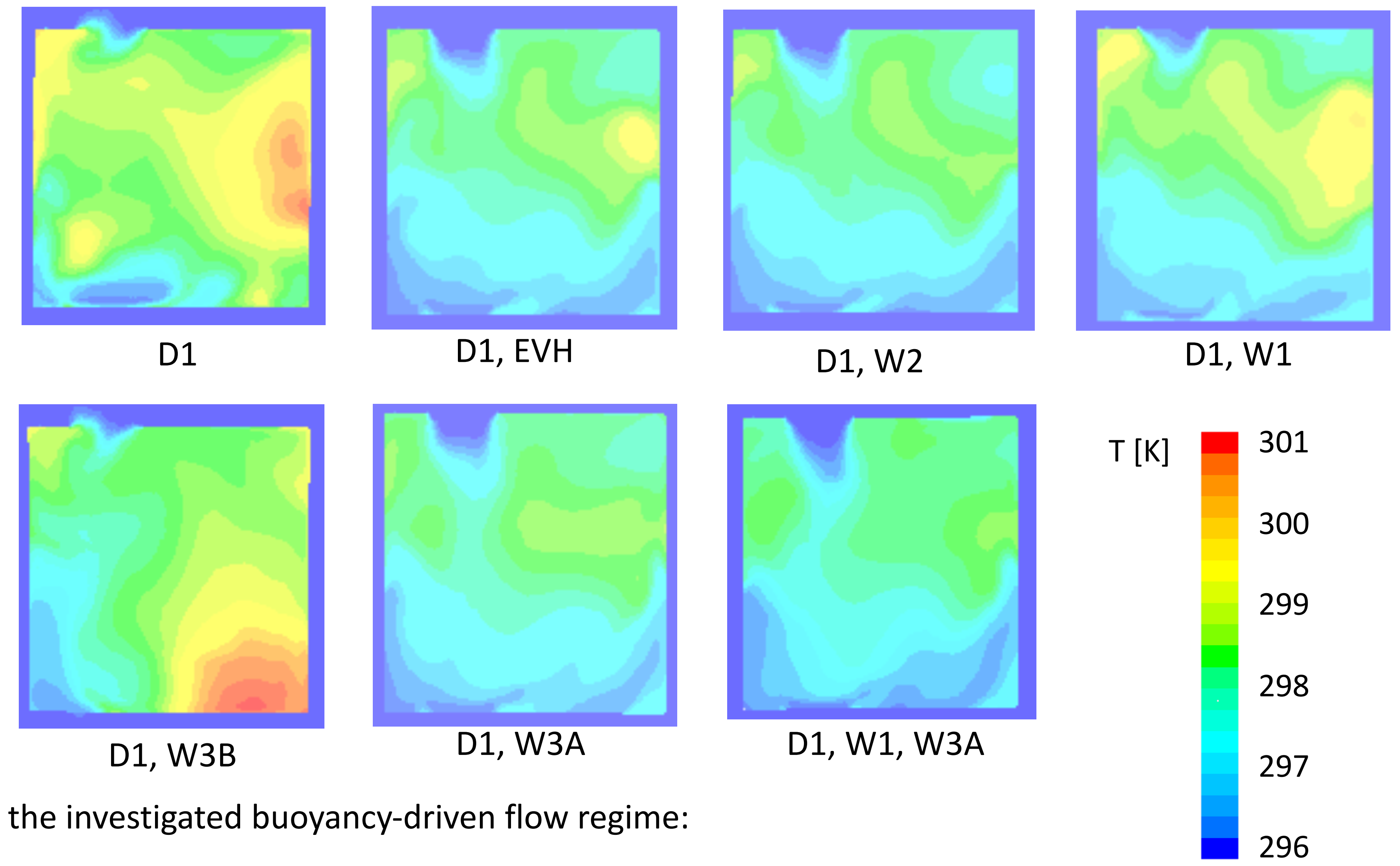
- Air changes per hour (ACH) calculated using data from 1 - 75 seconds, when buoyancy effects are strongest
- In buoyancy-driven flow, aperture area is no longer the dominant factor for ACH

Results

Air Change Rate per Configuration

Configuration	Full-Scale Area	Max Window Height	Experimental	CFD
D1, W1, W3A	0.434 m^2	1.83 m	34.84 h^{-1}	45.41 h^{-1}
D1, W3A	0.341 m^2	1.83 m	28.44 h^{-1}	33.71 h^{-1}
D1, W3B	0.341 m^2	0.61 m	20.95h^{-1}	6.78 h^{-1}
D1, W2	0.341 m^2	1.79 m	20.83 h^{-1}	28.99 h^{-1}
D1, W1	0.341 m^2	1.32 m	19.13 h^{-1}	11.72 h^{-1}
D1, EVH	0.298 m^2	2.25 m	17.59 h^{-1}	31.90 h^{-1}
D1	0.248 m^2	---	28.16 h^{-1}	5.15 h^{-1}

Temperature field at 1 m high, t = 60 s



In the investigated buoyancy-driven flow regime:

- Stack height becomes the dominant factor determining ACH
- Local ventilation can vary significantly and depends strongly on window position
- Positioning windows on opposing walls does not necessarily generate the highest ventilation rates
- Solution with eaves-height ventilators is very efficient, and provides an answer to residents' privacy and safety concerns

Conclusion and Future Research

Conclusions

- In the buoyancy-driven flow regime, stack height is a dominant factor determining ACH, while in the experiment ACH correlated well with aperture area
- D1, W1, W3A yields the highest ACH, in both the experiment and the CFD
- D1, EVH provides an attractive solution in the case of buoyancy driven flow, since it mitigates privacy and safety concerns

Future Research

- Collaborate with the field measurement team in Bangladesh to identify the driving mechanism for the natural ventilation flow in real houses
- Analyze a variety of wind-driven and buoyancy-driven conditions, including those with continuous heat sources due to occupancy.
- Extensive uncertainty quantification studies to investigate effects of variability in layout of homes and neighborhoods, and in local wind and temperature conditions

References and Acknowledgement

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