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Effective Wind-Induced Natural Ventilation in a Residential Apartment Typology

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Abstract**—**In India, cooling loads in residential sector is a major contributor to its total energy consumption. Due to the increasing cooling need, the market penetration of air-conditioners is further expected to rise. Natural Ventilation (NV), however, possesses great potential to save significant energy consumption especially for residential buildings in moderate climates. As multifamily residential apartment buildings are designed by repetitive use of prototype designs, deriving individual NV based design prototype solutions for a combination of different wind incidence angles and orientations would provide significant opportunity to address the rise in cooling loads by residential sector. This paper presents the results of NV performance of a selected prototype apartment design with a cluster of four units in Pune, India, and an attempt to improve the NV performance through design modifications. The water table apparatus, a physical modelling tool, is used to study the flow patterns and simulate wind-induced NV performance. Quantification of NV performance is done by post processing images captured from video recordings in terms of percentage of area with good and poor access to ventilation. NV performance of the existing design for eight wind incidence angles showed that of the cluster of four units, the windward units showed good access to ventilation for all rooms, and the leeward units had lower access to ventilation with the bedrooms in the leeward units having the least access. The results showed improved performance in all the units for all wind incidence angles to more than 80% good access to ventilation. Some units showed an additional improvement to more than 90% good access to ventilation. This process of design and performance evaluation improved some individual units from 0% to 100% for good access to ventilation. The results demonstrate the ease of use and the power of the water table apparatus for performance-based design to simulate wind induced NV.

Keywords**—**Prototype design, water table apparatus, NV, wind incidence angles, simulations, fluid dynamics.

I. Introduction

THE residential and commercial sectors in India, account for 30% (22% residential and 8% commercial) of total electricity use and consumption in these sectors is rising at 8% annually [1]. Ceiling fans, air conditioning and evaporative coolers constitute the majority of energy use at 45% of the total electricity consumed by the residential sector in India [2]. As a result of the expected increase in the penetration of ACs from 5% to 70% by 2040, the industry has committed to the development of super-efficient cooling systems [3]. A concurrent improvement in the effectiveness of NV in apartment designs will reduce the future installation or use of ACs.

Judicious understanding of ways of exploiting available natural resources around the building site can itself greatly help in reducing the load on energy consumption. Moreover, the residential sector shows larger potential for NV due its smaller room sizes, high envelope to floor area ratio, and occupant acceptance of mixed mode conditioning and adaptive thermal comfort control. However, the performance of NV depends on various parameters of building elements like, the orientation of the building, its form, the position of openings, size of openings, internal obstructions, etc. These have been documented in literature for specific and typical cases of single rooms. Architects rely on such documentation or their past experience to anticipate ventilation flow when they design buildings, but they often extrapolate the documented performance towards their own creative solutions. According to the study that tested the accuracy of architects' prediction of NV, their NV knowledge of typical conditions is not sufficient to anticipate ventilation performance correctly [4]. In India, a large portion of residential apartment buildings is designed by architects by arranging their prototype plans of individual units. These arrangements lead to multiple internal zones with different end conditions. Owing to the complexity of airflow in buildings as a result of interior partitions and openings, it is difficult to anticipate wind flow correctly during design. To predict wind flow in these complex conditions and the resulting performance, it is necessary to conduct computer or physical model simulations.

This paper documents how wind-induced NV can be significantly improved for a prototype apartment in Pune, India, by methodically testing modifications to the architectural elements. These design decisions were derived from the simulations using water table apparatus (WTA), a physical modelling tool for wind-induced NV. By partnering with an architectural firm, this research aims at showing possibilities of wind-induced NV by delivering effective design solutions for a cluster of prototype design of 1-bedroom unit typology that responds to predominant wind incidence angles (WIA). The design has been studied for all the WIA's, however, in this paper only 2 WIA's have been documented.

II. Literature Review

A. Survey of Current Practices for NV Design

Studies show that the architects anticipate the behaviour of natural airflow incorrectly and point out the necessity of analytical tools for design that can provide a reliable feedback to make the modifications in the design [4]. They also discuss the need felt by architects to improve existing guidelines and sample projects that show possibilities of NV [5].

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B. Analysis Techniques for NV

Three main types of analysis identified from literature review use simple empirical models, computational tools, and physical modelling tools.

With the help of simple empirical models, architects can determine ventilation performance for different building geometries and thermal conditions for one moment in time. Also, the equations obtained for one case are specific to it and cannot be used for another without modifications [6].

Out of all the computational tools, computational fluid dynamics (CFD) models [7] were most popular for predicting ventilation performance in the research community in the past year [6]. Studies reveal that CFD provides adequate data to study NV and inform design decisions; however, their disadvantages include, huge computational effort, detailed input data, knowledge of fluid mechanics, and the need for validation [7]-[9].

Physical modelling tools mainly involve measurements on two different scales; full-scale and small-scale. The full-scale models were mainly used to generate data to validate computational models [6], [7], [10], [11]. Small-scale experiments like wind tunnel experiment [12], smoke test chamber, salt bath experiment [13], water table experiment [14], [15], hydrogen bubble experiment [16], water bath modelling [17] are more economical and do not require large spaces to perform experiments [18]. These experiments use air or water as a medium to visualize airflow within the modelled enclosure. One study modified the design of the WTA, a physical modelling tool, and validated its results by comparing them with the flow pattern generated in a smoke chamber test by Boutet [14], [19]. The effectiveness of the apparatus to quantify the results of different parameters of ventilation such as the orientation of the building, opening sizes, additional openings and internal obstructions was also examined. Processed images of the video recordings of the experiment were used to analyze the wind flow. Percentage of the well-ventilated area, area of dead spots, air change rates, and mixed air temperatures have also been calculated to quantify the performance of different design options. However, the apparatus does not account for ventilation due to buoyancy effects and stack ventilation [14].

C. Design Optimization for NV

Studies carried out for NV in residential buildings include investigation of the influence of complex façade treatments with or without balcony [9], location of openings on the basis of ventilation efficiency [20] distinct façade opening configuration on indoor airflow distribution pattern [11]. These studies have either looked at a single zone, i.e. a single room of the unit or the entire unit as one zone without internal partitions. Many studies have looked at wind velocities at the façade only and not at the airflow patterns within the zones.

Design strategies and general guidelines to design naturally ventilated buildings have been documented by the researchers after investigating the influence of the architectural elements like openings, balconies, internal partitions, wing walls, passages, etc. However, these guidelines can only be used to understand the strategies but not to test their application. In order to accurately identify the efficiency of the strategy in a particular design, simulation tools will be required to generate qualitative/quantitative results, based on which the design can be modified for its better performance [18]. It has also been noted that shading is a pre-requisite to good NV and, the studies reviewed had assumed their designs to be adequately shaded. The authors were unable to find any literature with studies of either the use of prototype design for different wind incidence angles, or a methodology to evaluate design solutions for complex structures[1] considering its physical boundaries and internal partitions.

III. Methodology

A. Residential Prototype Design

By partnering with an architectural firm in Pune, India, their prototype used in recent building design was chosen. Pune at a latitude of 18.5ºN falls in the "moderate" climatic zone in India. The city experiences a maximum temperature of 41.3 ºC, and a minimum of 5 ºC, and had 2610 cooling degree days (base 18 ºC) in the past 12 months.

Fig. 1 Site Plan

Fig. 1 shows the site plan with seven residential towers, comprised of 1, 2 and 3 BHK units. The one highlighted in red has been selected for further study.

Fig. 2 Building Floor Plan

Fig. 2 shows the floor plan of the selected building. Red outline in the figure marks the prototype cluster chosen for the study and the blue outline shows the limit of the physical model for the WTA within which the ventilation performance was evaluated. Fig. 3 shows the study area that consists of a cluster of four 1-bedroom units designed by arranging the

[1] We refer to a cluster plan of a prototype design of a unit in residential apartment as a complex structure.

prototype design so to have a common passage area and such that the adjacent units are mirror images of each other.

The internal layout of the unit is designed for minimum internal partitions Fig. 4 shows the plan of even floors, where the dining rooms of each unit open out to terrace area. On the odd floor plans, the living rooms open out to terrace area, which are indicated as alternate terrace area here.

Fig. 3 Schematic Plan of four units

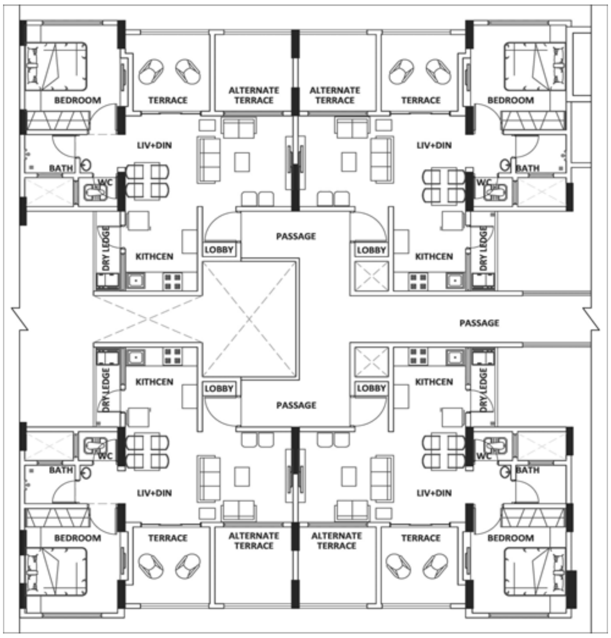


Fig. 4 Even Floor Plan

B. Identification of Base Case Condition

To analyze the performance of the existing design for NV, the bare-bones version of the design shown in Fig. 3 had to be modified to represent conditions that are most likely to prevail in a typical apartment. These are:

- Assume sliding window shutters, which are typical in India, such that 1/3rd of the total opening area is blocked due to the stacking of shutters.
- Assume bedroom doors to remain open for most of the time in 1-bedroom apartments
- Assume main entry doors to remain closed for privacy.
- Assume windows and doors of kitchen to be open.
- Assume doors of toilet and bathroom to remain closed.

C. Experimentation Method

The experimentation method has been summarized in the Fig. 5. Firstly, existing design with the base case conditions was analyzed for its ventilation performance using WTA for eight WIA's namely; 0°, 45°, 90°, 135°, 180°, 225°, 270° and, 315° and, then for its shading performance for four orientations, i.e. four cardinal directions. The WTA analysis identified four WIA's that had the worst performance for NV, and the shading analysis identified only two orientations that allowed NV[2]. Combination of these gave eight problem cases, which were then analyzed. Design strategies were proposed after considering their impact on the structural system, circulation, furniture layout and shading performance. These design strategies were tested in the WTA and the results were analyzed qualitatively and quantitatively. Design strategies that performed well for NV were then proposed in the final design solution. While the study looks at all the WIA's, results for only 2 WIA's are documented in the paper. Also, note that the shading analysis is not documented in this paper.

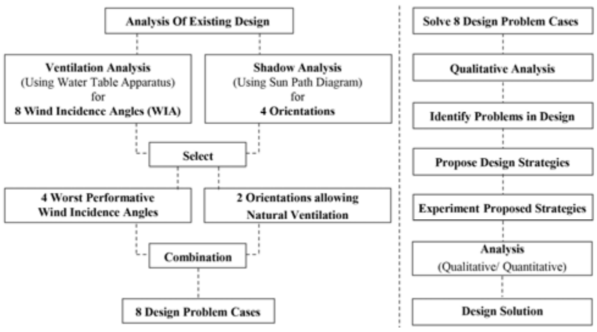


Fig. 5 Experimentation Methodology Flowchart

D. Qualitative Analysis

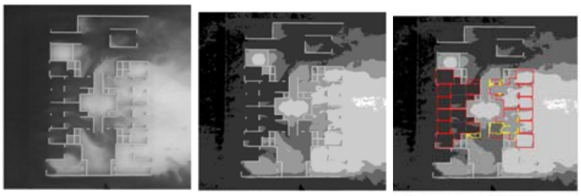
The primary focus of the qualitative analysis was to identify design features that allow or block the dyed water flow and observe areas that are poorly ventilated or have eddy formations. This was done by studying a series of images taken at an interval of every 5 seconds for the movement of the dye within the model. This enabled identification of the potential changes required in the design to improve ventilation performance.

E. Quantitative Analysis

Quantitative analysis is done to enable comparison amongst alternative experiments, evaluate the performance and help in making design decisions. Quantification of ventilation performance for this study is done based on the areas under good and poor access to ventilation. To do quantitative analysis, a common time frame is chosen for all the experiments at a stage of the experiment when the dyed water

[2] When the major rooms such as living, dining or bedrooms faced either east or west, any shading solution that adequately blocked the solar radiation resulted in blocking the opening areas for NV for the entire unit.

has passed through the model and around it, and the flow is in a temporary steady state. The images of this time frame are processed with the filters like, Desaturate and Posterize in Photoshop. Posterization to a level of 6 divides the entire range of pixels within the images into 6 bands[3]. These 6 bands are then classified into two categories, wherein the 3 darker bands represent the areas under good access to ventilation and 3 lighter bands represent the areas under poor access to ventilation. Outlining of these areas and area calculations are done in AutoCAD. Fig. 6 (a) shows desaturated image, Fig. 6 (b) shows posterized image and, Fig. 6 (c) shows the outlined image.



(a) Desaturation (b) Posterization (c) Area calculation

Fig. 6 Image Processing for Quantitative Analysis

F. Shading Analysis

The shading performance of the existing design was evaluated for the hours of the year when outdoor dry bulb temperature exceeded the comfort range of the ASHRAE Standard 55 -2010 adaptive thermal comfort model. If these hours were not shaded they would not allow NV since the occupants would draw curtains or blinds which would block the air flow. Thus exterior shading solutions were then proposed to shade the windows adequately for these hours.

This required analysis and solutions for 52 cases from a combination of fenestration conditions and building orientation. Horizontal shading devices were given preference since they comparatively cause minimum interference in the airflow [21].

IV. Results and Discussion

A. Analysis of Existing Design

Experiments were conducted to analyze the performance of the existing design for 8 WIA's. The overall length of the experiments is 8 to 11 minutes. The common steady state for all 8 experiments is at 4 minutes 20 seconds. Fig. 7 shows the images of the common steady state for all 8 WIA's.

1) Quantitative Analysis

Table I shows the results of experiments for different WIA's and identifies four worst performing WIA's that showed less than 75% of its total area of all units under good access to ventilation namely, 45^0, 90^0, 135^0 and 315^0. Unit 1 gets minimum access to ventilation (25%) for 90^0 WIA and (36%) for 45^0 WIA. Less than 5% of unit 2 gets good access to ventilation for 90^0 WIA and 135^0 WIA and of unit 3 for 315^0 WIA. Unit 2 gets only 15% good access for 45^0 WIA. Unit 4, however, showed best access to ventilation for all the WIA's with its minimum of 73% of its total area under good access for 225^0 WIA. The difference in the performance of units for different WIA's, despite being exactly identical to each other is because of its difference in surrounding structural conditions. Unit 4 gets an additional access to open passage area that allows accumulation of outdoor fresh air which is later drawn through its openings in the kitchen.

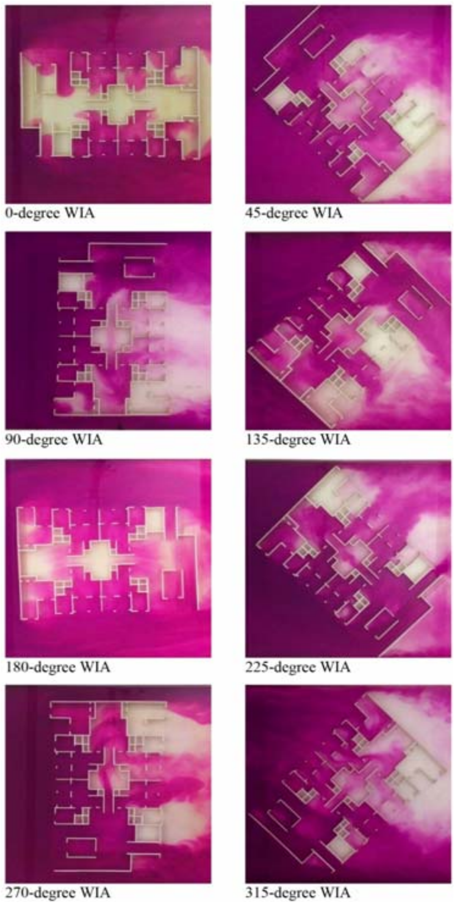


Fig. 7 Common steady state images of 8 WIA's

It is important to note that in all the units, living, kitchen and dining rooms get better access to ventilation than the bedrooms.

2) Shading Analysis

Shading analysis showed that the shading devices in the existing design do not provide shade at required hours for the following fenestration when oriented to their respective cardinal directions.

- Fenestration in kitchen facing East, West and South
- Window opening in alternate terrace facing North and West
- Door opening in terrace facing East, West and South
- Window opening in bedroom oriented in any direction

[3] Posterization at different levels revealed that 6 levels provided adequate detail and consistency to enable comparative analysis of the area calculations.

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TABLE I
GOOD ACCESS TO VENTILATION

	Unit	E1 0°	E2 45°	E3 90°	E4 135°	E5 180°	E6 225°	E7 270°	E8 315°
Area in sq. m	1	26.1	17.5	12.3	35.7	43.1	48.8	48.8	47.2
% area		53	36	25	73	88	100	100	97
Area in sq. m	2	41.6	7.2	1.0	0.0	47.9	47.7	48.8	48.8
% area		85	15	2	0	98	98	100	100
Area in sq. m	3	46.2	48.3	48.7	47.9	44.2	24.0	20.8	2.0
% area		95	99	100	98	91	49	43	4
Area in sq. m	4	45.9	48.8	48.8	48.6	47.0	35.6	37.3	46.2
% area		94	100	100	100	96	73	76	95
Total area in sq. m		159.8	121.7	110.8	132.3	182.1	156.1	155.6	144.1
Total % area		**82**	**62**	**57**	**68**	**93**	**80**	**80**	**74**

TABLE II
SHADING SOLUTIONS PROPOSED FOR FENESTRATION IN EXISTING DESIGN

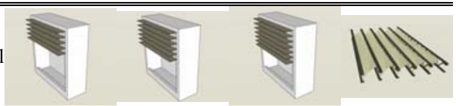
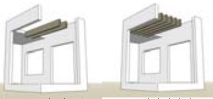
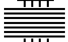
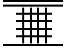
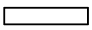
K	3D model	
	Symbol	
BR	3D model	
	Symbol	
TR	3D model	
	Symbol	
Alt. TR	3D model	
	Symbol	

TABLE III
APPLICATION OF PROPOSED SHADING SOLUTIONS PROPOSED

		East	West	North	South
Kitchen	Unit 1			NA	
	Unit 2			NA	
	Unit 3			NA	
	Unit 4			NA	
Bedroom	All units				
Terrace	All units			NA	
Alternate Terrace	All units	NA		NA	NA

Shading solutions proposed for the fenestration are such that the shading devices cause minimum interference in the ventilation performance. For this, horizontal shading devices were given preference and have been proposed for all the fenestrations except the ones in the bedroom facing north and south which required vertical triangular fins on either side of the opening. The shading analysis also showed that the solutions that can shade the required hours on windows facing East and West would result in blocking the entire window and would severely curb its ventilation performance. Thus, it was concluded that only North-South orientation i.e. the openings in the bedroom facing north and south worked for NV.

Table II shows 3D models of all the shading devices proposed along with their indicative illustration. Table III shows the application of the proposed solutions for their respective orientations.

B. Design Problem Cases

Based on the analysis of the existing design, combination of four WIA's i.e., 45^0, 90^0, 135^0 and, 315^0, and, two orientations i.e., openings in the bedroom facing North and South, gave eight design problem cases. Using the qualitative analysis of the experiments for these eight cases, a few common design modifications were proposed after considering them for their effect on structural systems, circulation, furniture layout, and construction cost. They are –

1. Introduction of ventilator openings in living rooms of all the units
2. Repositioning of window openings in kitchens of unit 1 and 3
3. Introduction of window openings with the wing wall in the bedrooms of leeward units.

Fig. 8 illustrates these modifications in the plan in red. Table IV provides the legend used to denote rooms in a unit. Since this was an iterative process with experimentation done with a series of modification, some modifications came about from the qualitative analysis of a previous iteration. These were: increasing the size of the ventilator opening in the living room of the leeward unit and introduction of a self-closing door in the passage. These modifications are illustrated in Fig. 8 in blue.

TABLE IV
LEGEND

L	Living room
D	Dining room
TR	Terrace
Alt. TR	Alternate terrace
BR	Bedroom
K	Kitchen
LO	Entrance lobby
P	Passage
U	Utility
T	Toilet
B	Bathroom

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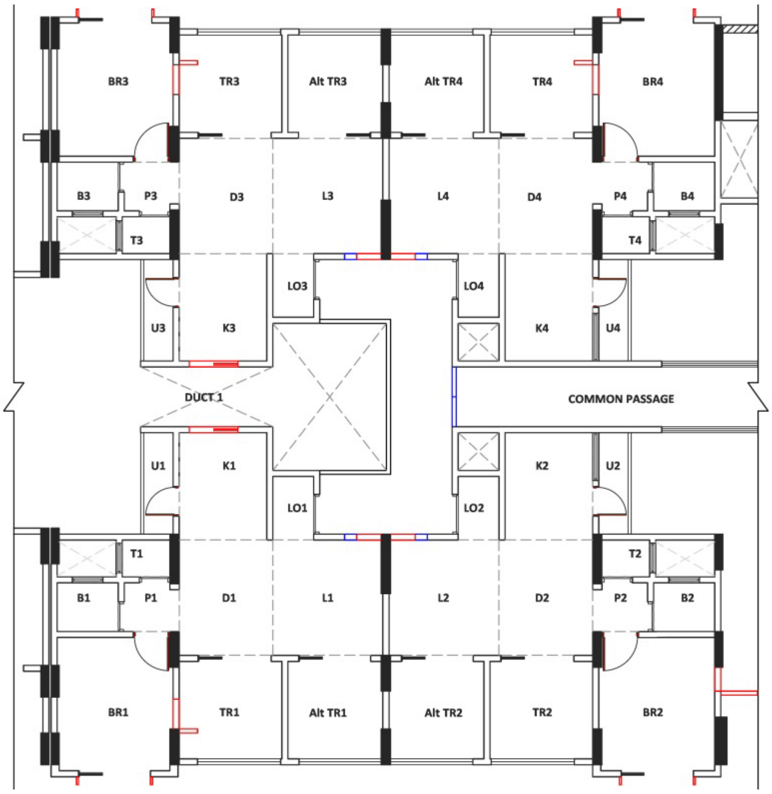

Fig. 8 Proposed common design modifications

TABLE V
EXPERIMENTS TO SOLVE 45-DEGREE WIA

Experiments	Modification	Anticipated Results
E2_1	NA (existing design)	NA (existing design)
E2_2	Introduction of proposed shading devices	Shading devices will act as wing walls and improve ventilation performance
E2_3	Introduction of ventilator openings on walls at side 1 of L1 and L2 and on walls at side 3 of L3 and L4 and stacking the shutters of the opening in L1 to side 2 along with the proposed shading devices	Direct passage of flow from living rooms of windward units to living rooms of leeward units through introduced ventilator openings.
E2_4	Introduction of a double shutter self-closing door in the common passage area along with the modifications in E2_3	Create more positive pressure by the ventilator openings in the leeward units than any other openings in the common lobby area
E2_5	Increase in width of the ventilator opening by 0.3m in the living rooms of leeward units only	Reduce eddy formation in the flow at the entrance of the leeward units and provide better flow through them.
E2_6	Introduction of window openings in BR1 and BR2 on side 2 along with their respective wing walls and proposed shading devices and with the modifications in E2_5	Improved access to ventilation to respective bedrooms through the introduced window openings.

C. Analysis of Design Problem Case 1 – 45-Degree WIA

1) Experimentation for 45-Degree WIA

Table V shows the series of experiments conducted to solve 45-degree WIA with the modifications tested for their performance and anticipated results.

2) Qualitative Analysis

Compilation of images of all experiments for all WIA's is documented in Fig. 14 in the Appendix to mark the progression of an experiment in time vertically and compare the same timeframe for different experiments side-by-side horizontally. U in the figure denotes unit and S denotes side.

a) E2_2 (With Shading Device)

The dyed water approaches the corner of the model diagonally. The walls on side 4 of BR, TR and Alt. TR of unit 3 and 4 drive the flow towards the internal areas of respective units. Thus unit 3 and 4 get good access to ventilation. Due to the absence of any obstruction in the path of the flow entering from L3 and D3 towards the outlet openings (K3 openings), the dye enters and directly exits the unit (Image 2_1 and 2_2 in Fig. 14).

The outgoing flow from the openings in K3 is the only source of ventilation to Unit 1 through its openings in K1. However due to the recurring obstructions like wall on side 2 of K1 and side 3 of L1 and D1 in its path, there are large eddy formations in L1 and D1 (Image 2_3 in Fig. 14). Similar flow is observed in unit 2 with large eddy formation in L2 and D2 however, the access to ventilation is better in unit 2 due to the additional source of ventilation from the opening on side 2 in the common passage (Image 2_2 in Fig. 14).

BR1 gets access to ventilation after all other areas of the unit are saturated with the flow because of the obstruction created by the toilet and bathroom blocks of unit 1 towards the windward side of BR1. Similar to this, BR2 gets no access to direct flow due to the wall on side 2 of BR2 and toilet and bathroom blocks of unit 2 on side 1 of BR2 (Image 2_3 in Fig. 14). However, despite having an additional source of ventilation to unit 2, both the units i.e. unit 1 and 2 get equal access to ventilation. This is likely because of the open areas around the staircase block through which the flow flows out.

Thus, bedrooms and living rooms of units 1 and 2 get least access to ventilation when compared to other internal areas of the units.

b) E2_3 (With L Ventilators)

With the introduction of L ventilators in living rooms of all four units, the number of outlets in unit 3 and 4 are increased. This causes the flow through them to get divided in two directions. The flow from bedroom goes out through K openings while the flow from living room goes out through its ventilator openings. No notable difference in the access to flow to units 3 and 4 is observed. Contrary to the anticipated results, the flow from L3 and L4 ventilator openings flows out into the common lobby area and does not enter L1 and L2 through their ventilator openings (Image 3_1 in Fig. 14). Later, as the flow increases, it is obstructed by the corner walls at side 1 and 4 of unit 2 and moves towards the ventilator openings in L1 and L2 (Image 3_2 in Fig. 14). This causes large eddy formations at the entrance of unit 1 and 2 (Image 3_2 in Fig. 14). The flow entering Unit 1 and 2 through L1 and L2 has been observed to escape through its openings on side 3 (Image 3_3 in Fig. 14). The access to ventilation to K2 through its openings is better than that of E2_2. This may be due to the negative pressure zone created near the openings.

Thus, compared to that of E2_2, access to ventilation in living rooms of leeward units, i.e. unit 1 and 2 is improved with the introduction of ventilator openings.

c) E2_4 (With Self-Closing Passage Doors)

Due to the obstruction by the self-closing door in common passage between unit 2 and 4, the flow from the ventilator openings in living rooms of unit 3 and 4 passes directly through the common lobby area into the living rooms of unit 1 and 2 through its ventilator openings (Image 4_1 in Fig. 14). Due to the small inlet openings in L1 and L2, large eddies are observed in common lobby area at its entrance. The flow entering through L1 and L2 escapes through its openings on the walls at side 3, and partially flows into the habitable areas (Image 4_2 in Fig. 14). The incoming flow from the openings in K2 to D2 is less than that observed in E2_3. This may be due to the decrease in pressure when the number of outlet openings in unit 4 is increased.

Thus, compared to E2_3, access to ventilation in leeward units is only slightly improved with the introduction of self-closing door in common passage area.

d) E2_5 (Increased L1 and L2 Ventilators)

The flow pattern is identical to that of E2_3, except that the flow in L2 has increased due to the increase in ventilator opening size in L2 (Compare Image 3_2 and 5_2 in Fig. 14). No notable difference is observed in other areas of unit 1 and 2.

e) E2_6 (With BR1 and BR2 Windows)

The flow in E2_6 in all units is identical to E2_5 except for BR1 and BR2. Addition of a window opening with a wing wall has caused the flow parallel to walls on side 2 of BR1 and BR2 to flow through them (Image 6_2 and 6_3 in Fig. 14). The flow from the introduced openings hits the opposite wall of the bedroom and recirculates within the habitable areas before leaving the bedroom (Image 6_3 in Fig. 14). With the proposed modifications, unit 2 now has 3 sources of ventilation; K2, L2 and BR2.

Thus, access to ventilation to units 1 and 2 has been improved in E2_6 than E2_5.

3) Quantitative Analysis

a) Quantitative Analysis of Unit 1 and 2

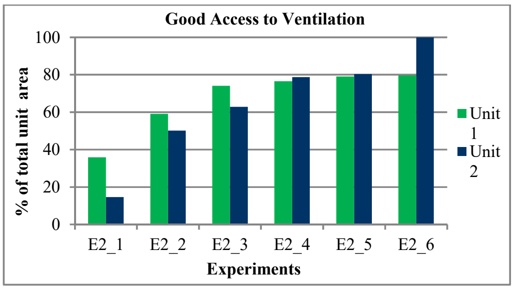

Fig. 9 Good access to ventilation to unit 1 and 2 for all experiments

Fig. 9 shows that the ventilation performance improves steadily as these modifications are successively introduced, except E2_5 which show minimal improvement over E2_4. E2_6 shows the most improved performance: unit 1 improves from 35% to 80% good access and unit 2 improves from 15% to 100%.

4) Summary of Results

Above analysis indicates, that maximum (80% and above) access to ventilation to all unit for 45-degree WIA can be achieved with the following modifications -

1. Proposed shading devices for all the fenestrations
2. Introduction of ventilator openings on walls at side 1 of L1 and L2 and on walls at side 3 of L3 and L4 and stacking the shutters of the opening in L1 to side 2.
3. Introduction of window openings in BR1 and BR2 on side 2 along with their respective wing walls and proposed shading devices.

D.Analysis of Design Problem Case 4 – 315-Degree WIA

1) Experimentation for 315-Degree WIA

Table VI shows the series of experiment conducted to solve 315-degree WIA with the modifications tested for their performance and anticipated results.

TABLE VI
EXPERIMENTS TO SOLVE 315-DEGREE WIA

Experiments	Modification	Anticipated Results
E8_1	NA (existing design)	NA (existing design)
E8_2	Introduction of proposed shading devices	Shading devices will act as wing walls and improve ventilation performance
E8_3	Introduction of ventilator openings on walls at side 1 of L1 and L2 and on walls at side 3 of L3 and L4 and stacking the shutters of the opening in L3 to side 2 along with the proposed shading device	Direct passage of flow from living rooms of windward units to living rooms of leeward units through introduced ventilator openings
E8_4	Increase in width of the ventilator opening by 0.3m in the living rooms of leeward units only	Reduce eddy formation in the flow at the entrance of the leeward units and provide better flow through them.
E8_5	Repositioning of window openings in K1 and K3 to side 1 and side 3 respectively along with the modifications in E8_3	Direct passage of flow from kitchen if unit 1 to kitchen of unit 3 through the introduced openings.
E8_6	Introduction of window openings in BR3 and BR4on side 2 and 4 respectively along with their respective wing walls and proposed shading devices with the modifications in E8_5	Improved access to ventilation to respective bedrooms through introduced window openings.

2) Qualitative Analysis

Compilation of images of these experiments for all WIA's is documented in the Fig. 15 in the Appendix to mark the progression of an experiment in time vertically and compare the same timeframe for different experiments side-by-side horizontally. U in the figure denotes unit and S denotes side.

a) E8_2 (With Shading Device)

The dye approaches the floor model diagonally with units 1 and 2 on the windward side. Though unit 4 in 315-degree WIA is located at the leeward side, the open areas around the staircase block gives it first access to ventilation (Image1_2 in Fig. 15). The walls on side 4 of BR, TR and Alt. TR of unit 3 and 4 drive the flow towards the internal areas of respective units. Thus units 1, 2 and 4 get good access to ventilation.

For unit 3, the only source of ventilation, i.e. the openings in K3 through the openings in K1 are located against the windward direction. Thus unit 3 gets very less access to ventilation. BR3 and BR4 gets access to ventilation only after all other areas of the unit are saturated with the flow because of the obstruction created by their respective toilet and bathroom blocks towards their windward side (Image 2_3 in Fig. 15). Thus, entire unit 3 and BR4, comparatively get least access to ventilation.

b) E8_3 (With L Ventilators)

With the introduction of L ventilators in living rooms of all four units, number of outlets in unit 1 and 2 are increased. This causes the flow through them to get divided in two directions. The flow from bedroom flows out through K openings while the flow from living room flows out through its ventilator openings. The flow from L1 and L2 ventilator openings, directly flows towards the ventilator openings of L3 and L4. Majority of the flow from L3, flows through L4 and exits through its openings on the opposite side partially circulating within L4. Thus the flow drawn from K3 recirculates more within the habitable areas of the unit than the flow from L4. Thus unit 3 gets improved access to ventilation through the introduced ventilator opening in its living room. Additional inlet opening, i.e. the ventilator opening in L4 has caused no notable difference in the flow pattern of unit 4.

c) E8_4 (Increased L3 and L4 Ventilators)

In the initial stage of experiment E8_4, a sudden jerk was in the inlet pipe of the input tank. This may be because of the fluctuations in the pressure with which the flow is supplied to the input tank by the motor. This has been observed to cause non-uniformity in the flow from the input tank to the working zone of the water table apparatus. The flow pattern in E8_4 is identical to that in E8_3. However, the increase in ventilator size in L3 and L4 has lessened the flow in unit 3. Thus comparatively, E8_3 gives better ventilation performance than E8_4.

d) E8_5 (With Repositioned Window Opening in K1 and K3)

Due to repositioning of the window opening in K1 and K3, the flow from window opening of K1 directly passes through the duct area into the window opening of K3. The flow from door opening of K1 also enters unit 3 through it door opening in K3 by passing through a larger duct area which decreases the pressure/force of the flow (Image 5_2 in Fig. 15). Thus, in unit 3, the flow from the repositioned window opening is more than the flow from it door opening.

Thus, compared to E8_3, access to ventilation to unit 3 is improved in E8_5.

e) E8_6 (With BR3 and BR4 Windows)

The flow in all the units in E8_6 is identical to E8_5 except for the flow in BR3 and BR4. Addition of a window opening with a wing wall has caused the flow parallel to walls on side 2 of BR3 and side 4 of BR4 to flow through them. The flow from the introduced openings hits the opposite wall of bedroom and recirculates within the habitable areas before leaving the bedroom. Thus comparatively, E8_6 gives improved access to ventilation to both, unit 1 and 2 than all other experiments.

3) Quantitative Analysis

a) Quantitative Analysis of Unit 3 and 4

Fig. 10 shows that compared to all the other experiments, E8_6 gives best performance. Unit 1 improves rom 5% to 85% for good access and unit 2 improves from 95% to 100%.

4) Summary of Results

Above analysis indicates, that maximum (more than 85%)

access to ventilation to all unit for 315-degree WIA can be achieved with the following modifications -

1. Proposed shading devices for all the fenestrations
2. Introduction of ventilator openings on walls at side 1 of L1 and L2 and on walls at side 3 of L3 and L4 and stacking the shutters of the opening in L3 to side 2.
3. Repositioning of the window opening in K1 and K3 on side 1 and 3.
4. Introduction of window openings in BR1 and BR2 on side 2 and 4 respectively along with their respective wing walls and proposed shading devices.

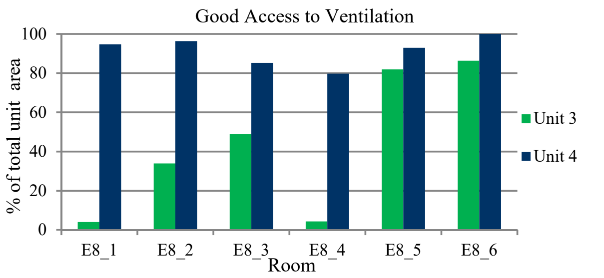

Fig. 100 Good access to ventilation to unit 3 and 4 for all experiments

E. Summary of Results for Design Problem Cases

All four design problem cases showed units in the leeward direction get least access to ventilation. Bedrooms of all leeward units had access to ventilation (less than 15% of area) except for unit 4 in 315-degree WIA. With the modifications in the existing design like, provision of opening with the shading device and wing wall, reposition of openings, etc. significant improvement in each leeward unit of all four WIA's has been achieved.

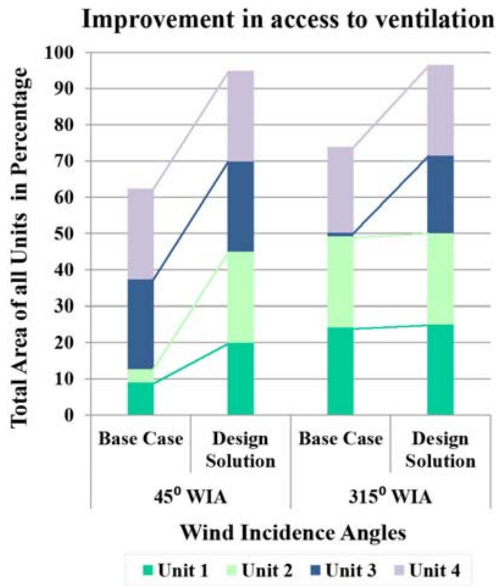

Fig. 11 Results of the Performance Improvement

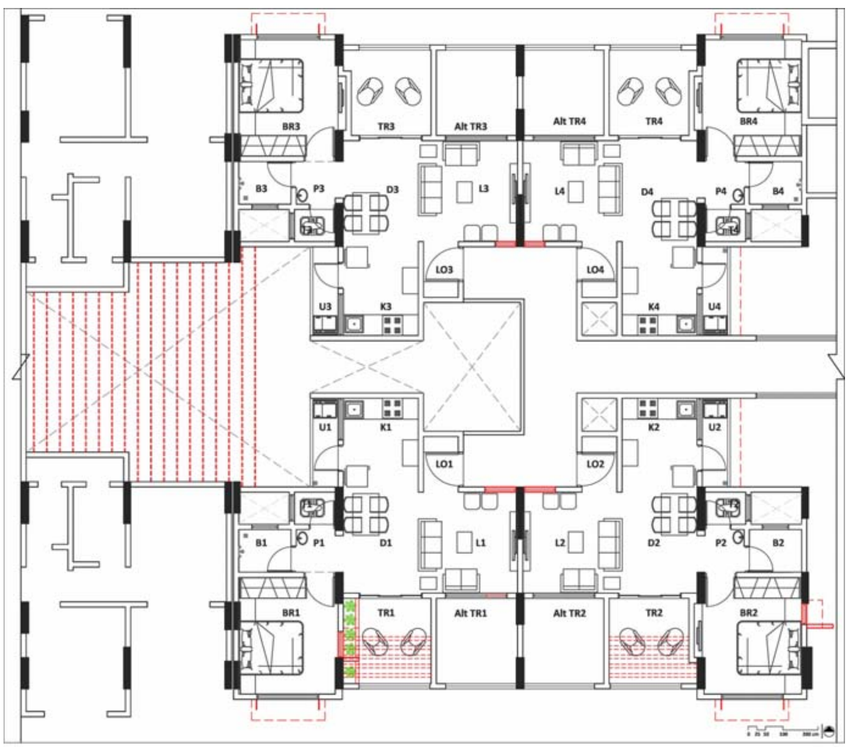

Fig. 12 Design solution proposed for 45-degree

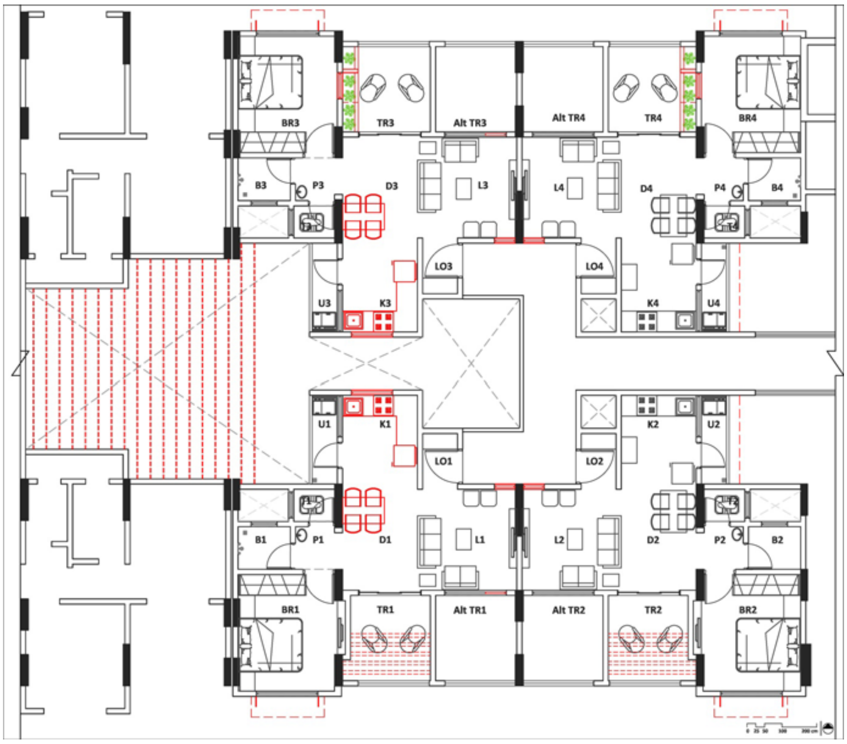

Fig. 13 Design solution proposed for 315-degree WIA

The graph plotted in Fig. 11, shows the improvement in the access to ventilation for all the units of each WIA in percentage of total unit area. The graph shows, with the modifications proposed, an improvement (100% access) was achieved for unit 2 for 45-degree WIA and for unit 4 for 315-degree WIA, and (80% and above) for the rest of the units.

See Fig. 12 for the proposed design for 45-degree WIA and Fig. 13 for the proposed design for 315-degree WIA.

V. Conclusions

The water table apparatus was used successfully to visualize air flow patterns and simulate wind-induced NV performance.

The water table experiments demonstrated that fluid flow is a complex phenomenon with multiple interactions within the system, and small changes in model configuration can produce significant changes to the flow and the resulting ventilation performance. The difference between the anticipated results of a design modification and the actual experiment results also shows that the complex phenomenon is not easy to predict for multi-zone real life cases, and that, simulations are necessary.

NV based design solutions were developed for a prototype design of 1BHK residential apartment design by an architectural firm in Pune, located in the moderate climate zone of India. When the existing design was tested in the water table for eight WIAs, it was found that the bedrooms in the leeward units had least access to ventilation. Windward units showed good access to ventilation. Based on the analysis of NV performance for eight WIAs, four WIAs that performed the worst were identified for design intervention.

Shading performance of the building is a prerequisite for NV so that the windows to remain open without curtains being drawn. The shading analysis revealed that, for the building to be shaded for maximum required hours, it needed to be oriented such that the units either face North or South. Shading solution were developed for a total of 52 cases for fenestration in different orientations.

The analysis of the NV performance for the base case of four WIA's with the proposed shading devices for the orientation that have units 1 and 2 to either face North or South, enable identification of common problem areas in the design. To address these, a common set of design modifications that are applicable for all WIA's were identified. From the set of common design modifications, those that correspond to each WIA in improving its NV performance were identified. The results showed that the proposed modifications to the existing design improved the performance of all the units to more than 80% good access to ventilation of all WIA's. Some units showed an additional improvement to more than 90% good access to ventilation.

This study has taken a cluster of prototype 1-bedroom units and significantly improved their access to ventilation and proposed a set of practical modifications for individual cases of WIA's.

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APPENDIX

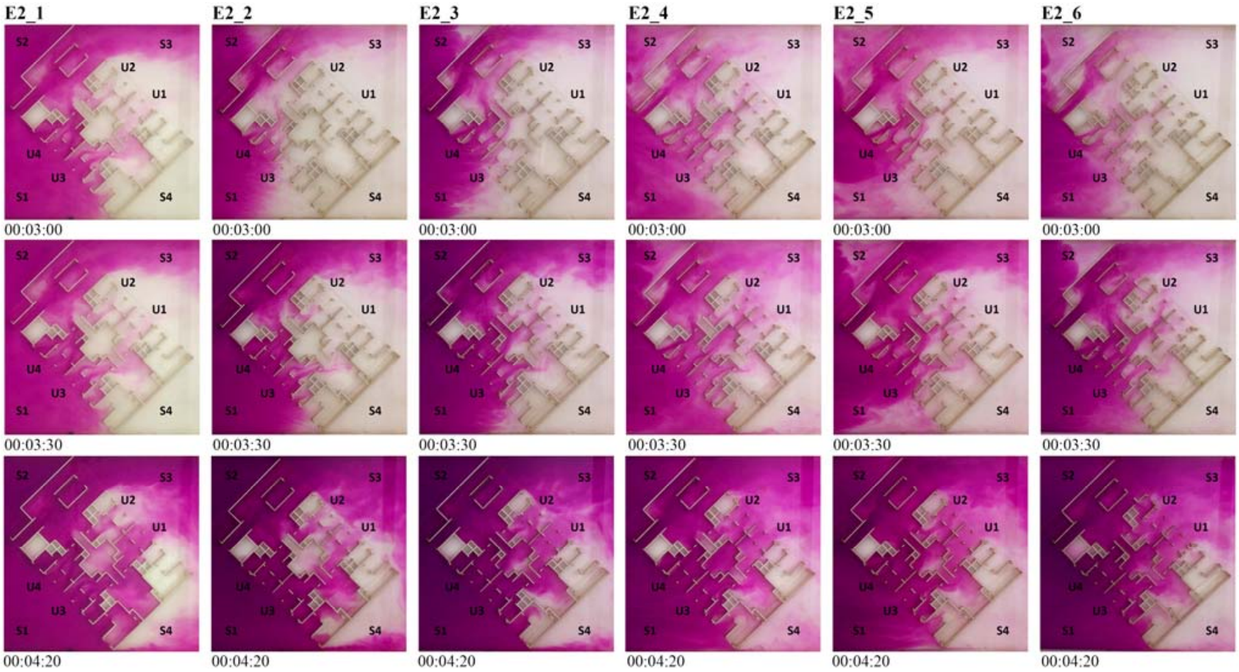

Fig. 14 Documentation of images for 45-degree WIA experiments

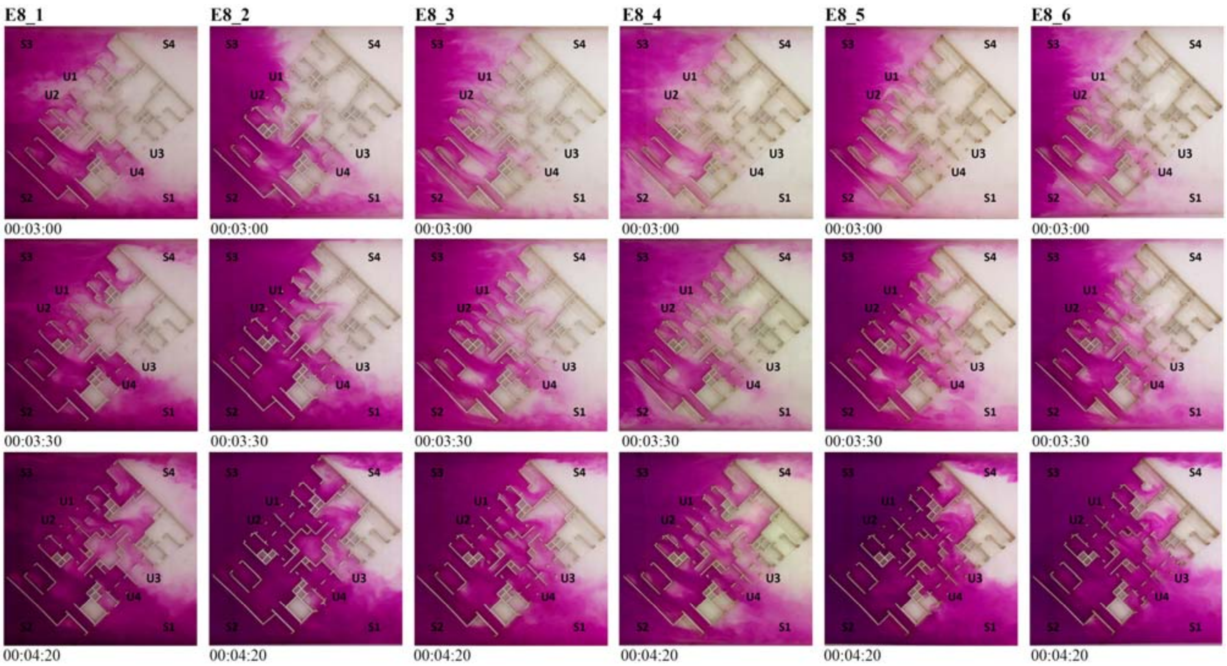

Fig. 15 Documentation of images for 315-degree WIA experiments

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