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Development and Testing of a Tall Building Façade System to Collect Rainwater

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Joseph Pinto graduated with a BArch from Illinois Institute of Technology in 2018, having founded real estate brokerage and development companies prior to attending architecture school. He has been exploring the effect architecture, and systems within architecture, have on current, global affairs, which led him to developing the focus and proposal that won the 2018 CTBUH Student Research Competition.

Akram Maradni graduated with a BArch from Illinois Institute of Technology in 2018, with a specialization in digital design. He focused on advanced computing, specifically exploring the possible integration of computational methods in the field of architecture; such as simulations for design problem-solving and systemization, as well as digital fabrication.

John Paul graduated with a BArch from Illinois Institute of Technology in 2019 with two years in the field. He is currently an Associate Architect, passionate about design, functionality and sustainability.

Rahman Azari, PhD, is an assistant professor, former interim director of the PhD program, and founding director of Building and Urban Environmental Modeling (BUEM) Lab at Illinois Institute of Technology College of Architecture. Azari's research centers on environmental life-cycle impacts of built environments, innovative materials for energy production and carbon sequestration, and urban environmental modeling. Azari's research has been funded by the AIA, Illinois Institute of Technology, and the University of Texas. In 2019, Azari was listed as "Researchers to Know" by the Illinois Science and Technology Coalition. Azari has also sponsored student projects listed as finalists in the 2016 and 2017 COTE Top Ten competitions by the American Institute of Architects (AIA) and the Association of Collegiate Schools of Architecture (ACSA). Azari holds a PhD in Built Environment (Sustainability track) from the University of Washington in Seattle (2013).

Abstract

The key objective of this research was to devise and test a vertical rainwater harvesting system and demonstrate that the rainwater could be collected off building envelopes in sufficient quantities, and then cycled into the buildings' water systems. While tall building envelopes have traditionally been designed to prevent water infiltration, this study proposes a building envelope system to allow for "controlled water leakage", transforming into a channel to catch desired rainwater, as well as a barrier to unwanted water infiltration. Weather data were collected for six major cities around the globe experiencing a water crisis, and in which the tall building is the principal building type in the central districts, to determine the optimum building orientation based on normal and average amounts of rain per event. Next, buildings of varying heights were digitally modeled, simulating rain events for each city and the resulting rain volumes. Finally, water-droplet size, adherence, cohesion, filming and streaming of rainwater on building façade were studied, using rainwater performance simulation.

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Keywords: Façades, Rainwater Harvesting, Tall Buildings, Sustainability

Introduction

For most of history, buildings have been constructed using the exterior wall as the main structural system. Advancements in steel and reinforced concrete allowed the structural system to be independent of the façade and recede behind the envelope. The exterior walls were then allowed to be much lighter, and thus non-load-bearing. With this advancement, buildings such as the Crystal Palace, London (1851), and the Kaufhaus Tietz, Berlin (1901), used large glass façades in lieu of masonry walls. The Bauhaus movement started to incorporate the idea of a modern curtain wall, consisting of mullions and glass; the same idea predominates in much of contemporary high-rise design.

Curtain wall construction has always been concerned with water and moisture. The materials used in the system are heavily dependent on how well they withstand corrosion and water accumulation. Modern curtain walls use an array of sealants, gaskets and flashing to prevent such issues. Watertight construction is integral to the life of the façade system and the overall building.

Understanding Tall Building Pressures

Tall buildings experience an immense amount of pressure on their envelopes, as well as on the interiors. Known phenomena, such as the "stack effect," give mechanical engineers headaches in their task to balance the interior pressure loads within the building. Failure to do so results in lobby doors being difficult to open, as well as infiltration and exfiltration of moisture. In addition, wind loads on buildings increase pressure on the exterior envelope, and on the building as a whole. As wind hits the façades of buildings, its velocity is abruptly exchanged for an increase in pressure, pushing on the building façade. When an obstructing building impedes the wind, it will cause increased pressure on the face of the building. However, while the wind may stagnate on the windward side, it will most likely increase in velocity along the sides and top of the building. In these areas, the pressure will be reduced, thereby causing a suction or pull on the building façade. The diagrams in Figure 1 depict wind patterns and their pressure in cases where wind hits the building head-on and at an angle of approximately 45 degrees. Negative and positive pressures are also represented.

Proposed Design

This research proposes a system to collect the rainwater off the vertical surface of tall buildings. The curtain-wall sections depicted in Figure 2 include mullion-less assemblies. These types of non-protruding mullions are essential to the success of the rainwater collection system. They provide a smooth, unimpeded surface that will allow the rainwater to adhere, as well as maintain a streaming film of water on their surface.

Figures 3–5 illustrate this system as used in physical simulations. The uppermost hopper is the water delivery assembly that was designed to create rain streaming on the vertical surface. A garden hose connects to the rear of the hopper to fill it. As shown in the diagram, the film flow moves downward

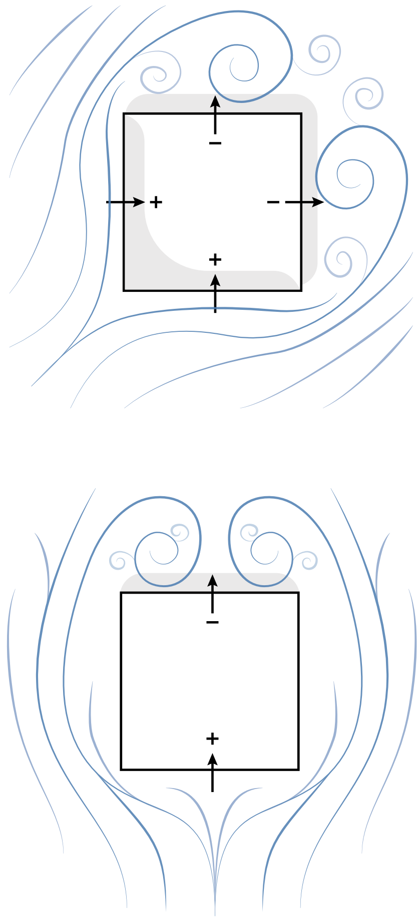

Figure 1. Illustration of wind effects on and around tall buildings when striking the façade at 45 degrees (top) and 90 degrees (bottom).

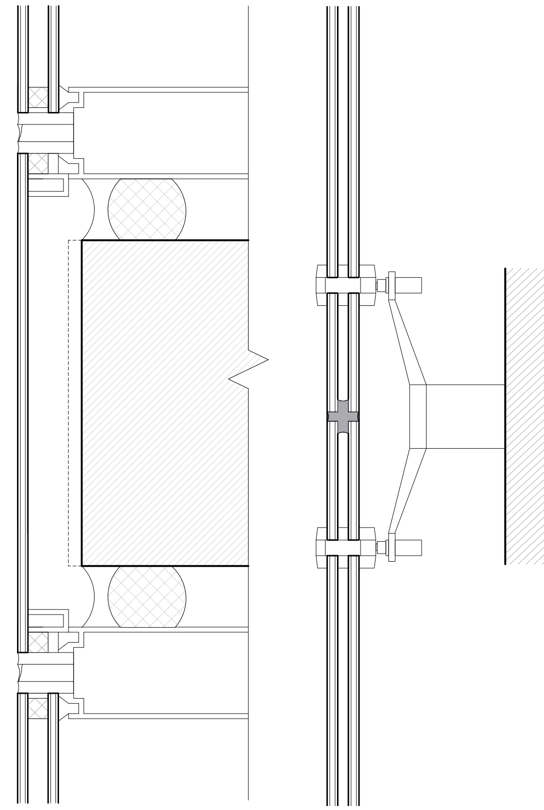

Figure 2. Mullion-less window assemblies, sectional view (left) and plan view (right), which serve as the base model for the experiments.

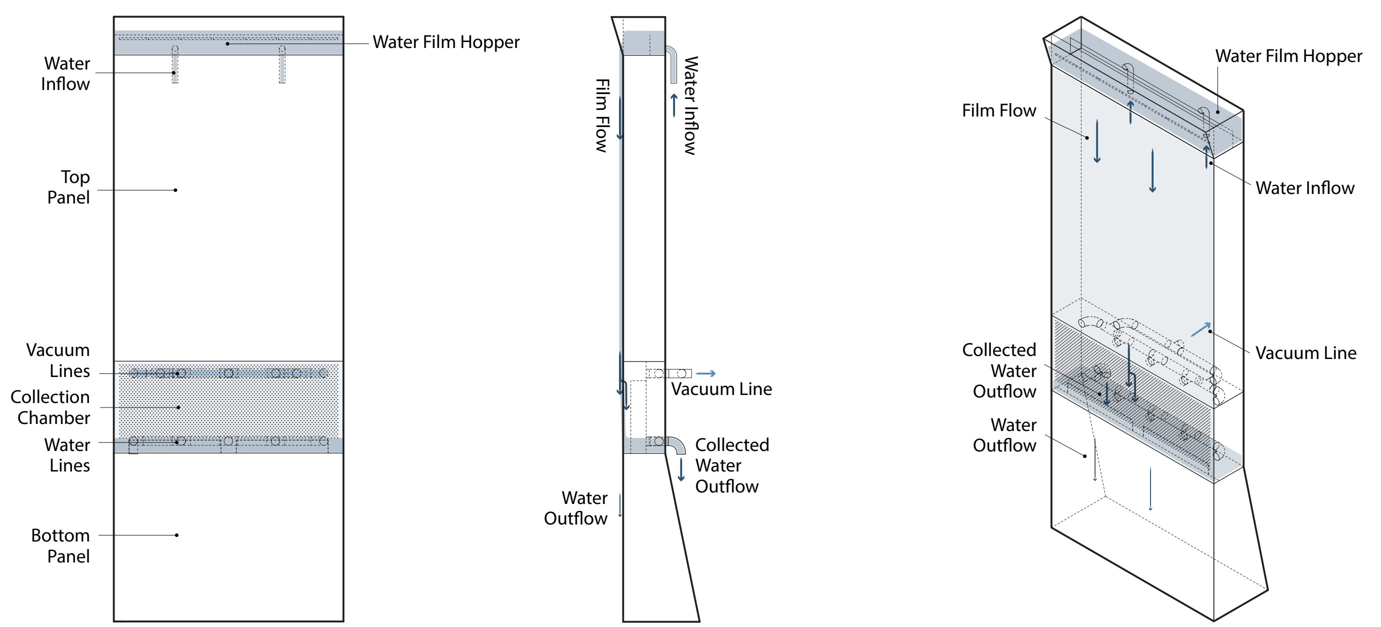

Figure 3. Elevation (left), section (middle), and axonometric (right) views, of the experimental assembly designed to siphon water accumulating on the exterior surface of the façade into a water collection system.

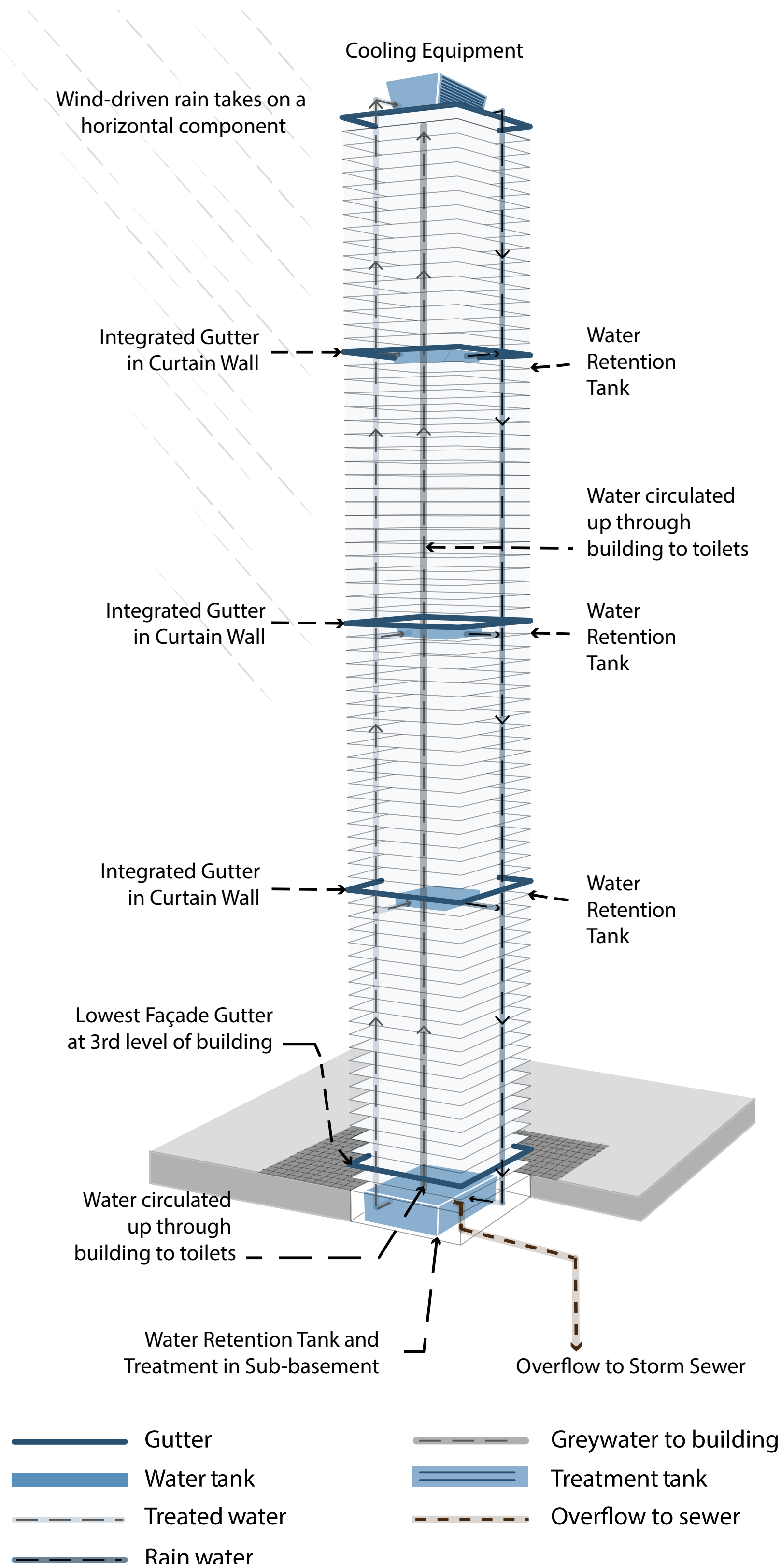

Figure 4. Example of a tall building using the proposed rainwater collection system, showing routing and storage methods.

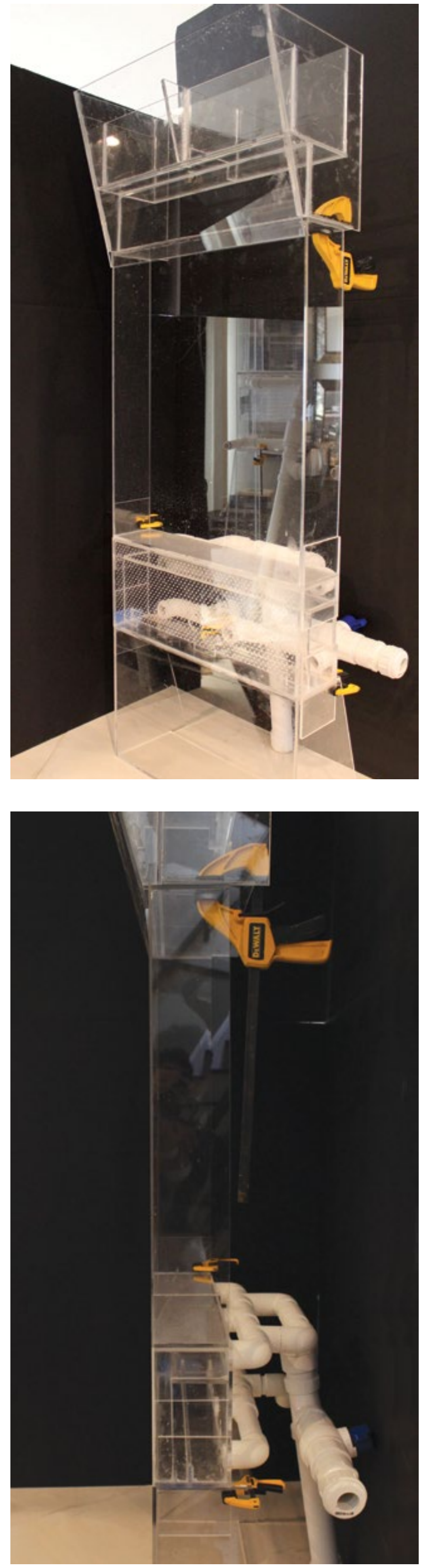

Figure 5. The physical model of the rainwater-collecting façade, as constructed.

on the face of the glass, passing over the water collection assembly that would be located where the spandrel panel would normally be. The collection assembly has two sets of pipes connected to its interior side. The upper pipes are the vacuum lines that create negative pressure on the assembly. The lower pipes are for collected water, directing it to discharge first into branch piping, and then into a cistern tank within the building. Any water not captured by that assembly would continue to flow down over the next panel of curtain wall, still adhering to the glass, to pass over the next collection assembly at the floor below.

To determine the optimum collection of the rainwater off the vertical surface, several iterations of hole sizes and configurations were designed, tested, and simulated. Iteration 3 produced the best performance, by collecting 70 percent of the water film. The holes are sized at 1/16" (1.6 millimeters), offset at 3/32" (2.4 millimeters), and vertically spaced at 1/16" (1.6 millimeters) (see Figure 6).

Testing and Simulation

Physical Model

The digital model of the first iteration was developed and simulated water collection behavior. This informed the hypothesis that using negative pressure (i.e., a vacuum) to create siphoning action on the water film streaming would work with the circular 1.6-millimeter openings. Further studies may show this to be achieved passively by the building that creates the pressure organically in a wind-driven rain event. To create that pressure condition in this physical model, ports connected to a manifold on the back of the assembly were attached to a vacuum. Additionally, there is a similar port configuration at the lowest portion of the back of the panel, to direct the collected water to a pipe for delivery to a storage tank. Panel iterations cover the attempts at finding the most advantageous hole size and pattern for the best panel's performance.

The initial model was connected to a Shop-Vac (large commercial vacuum capable of holding water) and had no volume adjustment, other than a ball valve on the vacuum line. The performance exceeded expectations. About 90 percent of the water streaming past the collection panel was collected. The system performed well anecdotally; however; there was no data to confirm it. A gauge was installed to measure the interior pressure of the collection assembly. The gauge gave no reading, as the pressure was less than 1 pound per square inch (PSI) (6.9 kPa). The average pressure of the stack effect phenomena of a building is measured in pascals. Therefore, another method was needed to quantify the pressure within the assembly. In a later attempt, a voltage fan controller was used to dial down the vacuum's capacity, since almost all the water streaming on the panel was being captured. Next, digital barometers were installed inside and outside the chamber to measure the difference in pressures.

Wind-Driven Rain Deposit Calculation

The wind-driven rain deposition rate at different heights can be calculated based on the equation (Straube 2010) (1) that determines rain deposition in urban environments, based on the micro-wind changes at the façade of a building. The equation (2) determines windspeed at different heights.

$$(1) \quad r_{vb} = RDF \times DRF \times V(z) \times \cos(\theta) \times r_h$$

Where r_{vb} is the rain deposition rate that falls on a vertical building surface (l/m^2/h), RDF denotes the Rain Deposition Factor, the ratio of rain in the free wind to rain deposition on a building, and DRF is the Driving Rain Factor accounting for interaction of the wind and rain in the undisturbed wind (Straube 2010). This research will be dependent on the digital simulation methods for determining the DRF for each building type. The symbol θ is the angle between the normal to the wall and the wind direction, and V(z) is the windspeed in m/s at z meters above grade (Straube 2010).

$$(2) \quad V(z) = V_{10} \times \left(\frac{z}{10}\right)^{\alpha}$$

Where V_{10} is the standard wind speed at 33 feet (10 meters) above grade normally

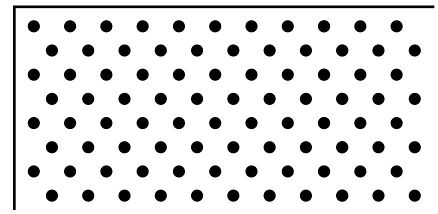

Figure 6. The selected iteration of the collection panels to be installed in the spandrel position between vision glass lites used 1.6-mm holes, offset at 2.4 mm and vertically spaced at 1.6 mm.

reported by weather stations in m/s, z is the height above grade (in meters) and α is the exposure exponent, which for the urban environment is 0.36.

Data Analysis in OpenFOAM

This project relied on weather data provided by the Meteoblue history+ dataset for each of six cities which have high drought risk and a substantial number of tall buildings in their central business districts, from 2008 to 2018 (Meteoblue 2019). The cities were: Beijing, London, Los Angeles, Melbourne, Mexico City, and Tokyo. The data is logged with year, month, day, and hour of data collection, as well as precipitation, windspeed, and temperature. From that dataset, two more data columns are created to represent the date column and wind direction by compass directions, using the following formula:

=CHOOSE(1+ROUND(H2/22.5,0),"N","NNE","NE", "ENE","E","ESE","SE","SSE","S","SW","SW","WSW","W", WNW","NW","NNW","N")

The data was later brought into Tableau software for analysis, and an "incident variable" calculated field was created by multiplying the precipitation (mm) by the wind speed (m/s) the researchers had extracted before, as a variable (In) from the numerical equation for wind-driven rain deposition on a façade of a building using Straube (2010). From these data, four data visualizations were created: total wind-driven rain (WDR) per direction, directional WDR incidents aggregated, total incident variable yearly, and a dashboard.

- The total wind-driven rain per direction visualization was created with a horizontal bar visualizing the SUM (incident variable) as a measure by the wind direction per compass, while marking the wind speed as a color variant and averaged by year.

- The directional WDR incidents aggregated visualization was created with the same parameters as a total WDR per direction, but with total precipitation (bin) as a filter; the bin was created by increments as desired.

- Total incident variable yearly visualization was created with the box and whisker plots visualization, using wind direction compass as a dimension and incident variable as a measure averaged by year.

OpenFOAM DRF

The digital simulation was dependent on the wind-driven rain solver by Pettersson et al. (2016), developed for the Open Source Field Operation and Manipulation (OpenFOAM).

From the weather data statistics, the average rain incident was used from every direction, where the variable (bin) provides the precipitation per hour, coupled with the average windspeed of the incidents from that direction, with that particular rain intensity. Then, the windspeed and the precipitation were plugged into OpenFOAM files, using models generated with Gmsh, a three-dimensional finite element mesh generator, where the building is rotated in each iteration to be oriented according to the wind direction from the inlet in the simulation model. This method allows the use of any building shape and type, against which the deposition map can be calculated later.

The results were then averaged for use in the rain deposition maps per each direction of DRF, using the yearly average rainfall statistics to calculate the statistical average expected rain deposition on a given façade using equation (1), implemented in a façade cell pulled from the simulation, where each cell has a deposition factor and is multiplied by the area that each cell represents.

Water Film Simulation

For the local fluid simulation of the water film running on a façade, FLIP Fluids software was used, with viscosity and cohesion added through Houdini 3D animation software. In Houdini, two POP forcefields were added, one representing air drag force (popdrag); the other (popvop) is a gradient attraction forcefield around the façade collision geometry, to simulate the effects of adhesion and magnetic attraction that the film experiences while running on the façade. The geometry is imported into Houdini as Stereolithography CAD. An inlet is created at the top of the area of study. The water running on the façade is determined based on the Equation (3) (Carmeliet & Blocken 2004, Blocken & Carmeliet 2004, Kubilay et al. 2013, 2014, 2015):

$$(3)\quad \frac{\partial h}{\partial t} + \frac{\rho \cdot g}{3\mu} \cdot \frac{\partial h3}{\partial z} - \frac{qR}{\rho} + \frac{qabc}{\rho} = 0$$

where h is the thickness of the film, ρ is the liquid water density, μ is the dynamic water viscosity, q_R is the driving rain intensity, and q_abc is the water flux into the material by capillary absorption (Carmeliet & Blocken 2004). The flow output is placed below the simulation boundary. These solvers are adjusted to match the behavior of the water film on the physical model (see Figure 7).

Wind Tunnel Simulation

The researchers conducted a wind tunnel simulation to both demonstrate the wind-flow pattern of the building, and to get the pressure difference on two opposite sides of the building of the wind flow, so it can be used to calculate the flow that can be generated passively. The wind pressure generated on a building's side could be calculated using:

$q = ½\ rhV^2$ (Dalgliesh & Schriever, 1962)

where rh is the mass density and V the velocity of the air (Dalgliesh & Schriever 1962). This is called the "stagnation pressure," and refers to the maximum positive increase over ambient pressure imposed on a building surface by wind of a certain speed. This approach allows including the effect of the surroundings and the context of a given building case study with the pressures of the case-study building.

Model Studies

The physical model has two components for testing the water performance. One consists of two water collection trays; one from the façade, and the other from the collection water pipes, that would allow the researchers to measure the amount of water that is or is not carried by the system in each timed run. The second component consists of barometers inside and outside the panel face, to check the pressure difference. This component is necessary for evaluating the performance of the trays. The barometers are linked to an Arduino single-board microcontroller kit that plots its readings to a computer as the vacuum is turned on and off, to account for errors or differences between the two barometers.

The proposed test model system uses a vacuum with a known rate (volume/time) of air flow that distributes the flow at its terminal point at the face of the system, and would be divided by the active area of that face to arrive at a the amount of air flow per orifice. The air flow on the building, generated over the vacuum pipe bridging the two pressure zones at the two opposite sides of the building, could be calculated using the Hagen–Poiseuille equation (Pisano 2017) where ΔP is the pressure difference between the two points, L is the length of pipe, μ is the dynamic viscosity, Q is the volumetric flow rate, and R is the pipe radius (Pisano 2017). As ΔP is known from the above for a building and L corresponds to a building width, the flow rate can be matched to correspond to the ratio of Q over the active area by sizing the pipe, assuming that the dynamic viscosity of the air would be the same.

Results and Conclusions

Tests and simulations showed that a system using low pressure gradients would in fact collect water off the façade. The water streaming down the façade past the assembly consistently ranged from a 75 to 90 percent collection rate. Further study is needed to integrate this system with other building systems, and thus into a real-world curtain system. Moving forward, future studies may

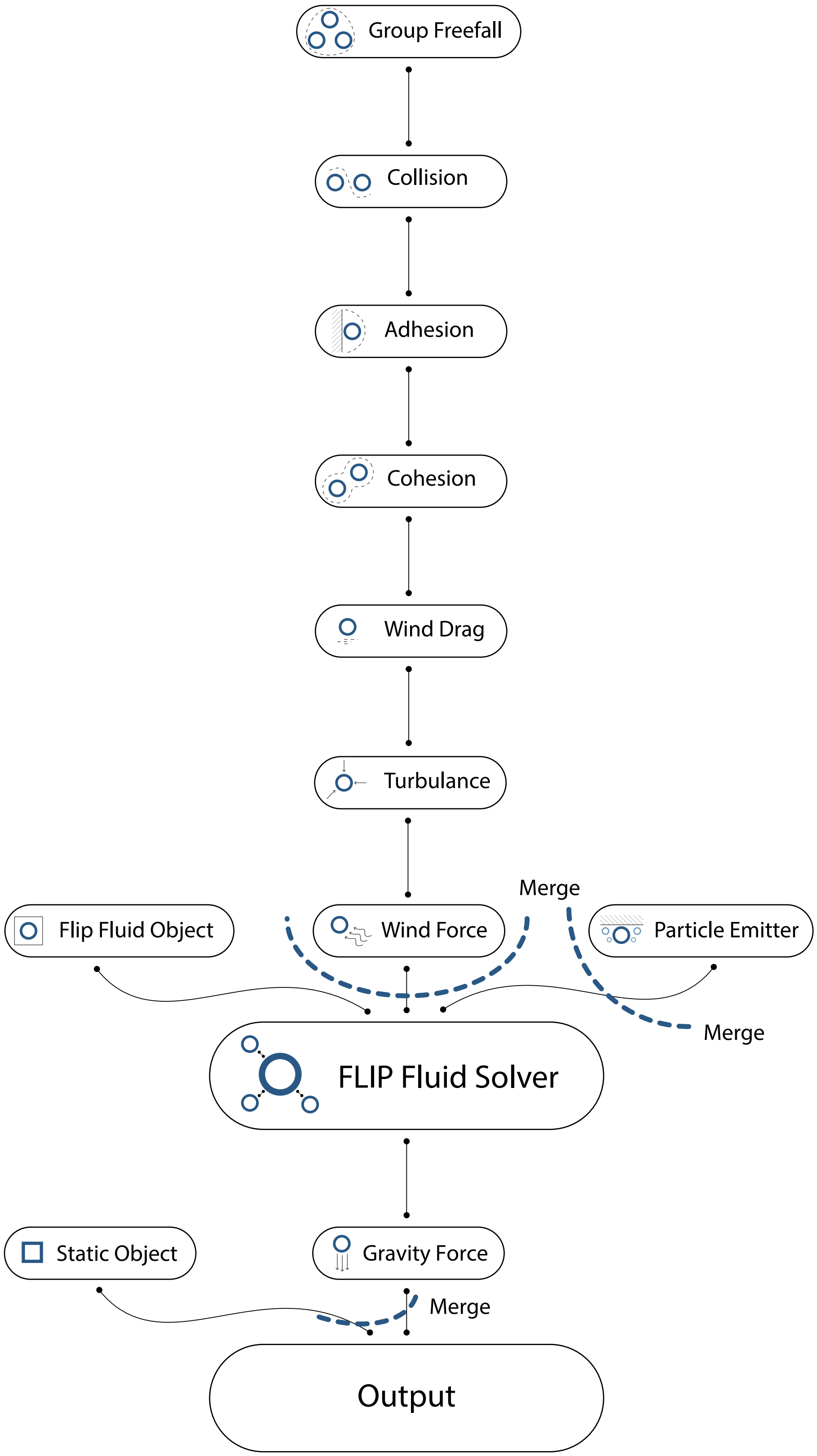

Figure 7. Workflow diagram of the fluid simulation of water film running on a building façade. Computational fluid software testing was used in parallel with the physical model tests.

reveal existing or new systems within a building that can support the proposed collection assembly.

There are several limitations associated with this research. The focus of this study was on rainwater collection from building façades alone. Larger support systems to transport, store and filter rainwater should be addressed by future studies. In addition, factors such as building adjacencies and their heights were not included in calculations; simulations r elated to these factors should be considered in future studies.

Unless otherwise noted, all image credits in this paper are to the authors.

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