MODULATING NATURAL VENTILATION TO ENHANCE RESILIENCE THROUGH NOZZLE PROFILES

A Thesis

by

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ABSTRACT

This study aimed to develop and test an environmentally friendly, easily deployable, and affordable façade solution for socio-economically challenged populations of the world. The façade system would modulate air velocity by utilizing natural cross ventilation techniques in order to improve human comfort in buildings. Constrained by seasonal weather and interior partitions which block the ability to cross ventilate, buildings can be equipped to perform at reduced energy loads and improved internal human comfort by using a façade system composed of retractable nozzle-forms developed through this empirical research. Drawing inspiration from a simple yet innovative idea of a powerless air-cooler developed in Bangladesh, this research investigated the efficiency of velocity-moderated evaporative cooling method by using a two-step development process of physical experimentation and software simulations. A velocity increase of 4.74 m/s was achieved through modulating profiles of nozzle-forms. Natural ventilation and cross-ventilation have been used well in architectural design thus far, however, these techniques have never been harnessed to modulate the speed of incoming wind into built spaces to improve building resilience. This study is an attempt to fill this gap.

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NOMENCLATURE

ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
AM	Additive Manufacturing
HVAC	Heating, Ventilation, and Air Conditioning
OPM	Official Poverty Measure
PLA	Poly Lactic Acid
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
PVC	Poly Vinyl Chloride

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CHAPTER I

INTORDUCTION AND PROBLEM STATEMENT

Purpose of the Study

The purpose of this study was to develop and test a façade system that would modulate wind velocity utilizing natural cross ventilation techniques in order to improve human comfort and to enhance building resilience.

Background

Due to population growth, demand for infrastructure and built services has increased. An upward trend in the energy use in buildings has been observed due to rise in the time spent inside the buildings and higher expectations of comfort levels by the occupants. An estimated 50% of building energy consumption and 20% of total energy consumption in the US is contributed by HVAC system (Pérez-Lombard et al. 2008). In even the most developed nations, such as the United States, approximately about 15% of its total population is in poverty – equating to 46.5 million people as per the 2012 OPM (Official Poverty Measure) (Mitra and Brucker 2017). Whereas on a global scale, these numbers are as high as 42% (i.e. 2.6 billion people) living in poverty, as indicated by data from the World Development Indicators (Elvidge et al. 2009).

Utilizing natural ventilation not only lowers the cost of energy consumption by the building in comparison to mechanical ventilation, but it also improves the indoor air quality (Mora-Pérez et al. 2016). The envelope of a building is a significant element with respect to studies related to its energy behavior. Factors such as location of the building, its orientation, the envelope, as well as wind flow, infiltration rates, associated heat losses or gains affect the building façade's performance (Mora-Pérez et al. 2016). Therefore, the building envelope plays a crucial role in determining and analyzing its energy consumption.

Double-façades are designed for high-rise buildings: in order to reduce cooling loads, cut noise from the outdoor environment, and to allow for natural ventilation in multi-storied high-rise buildings (Pasquay 2004). However, movement in the building façades, owing to manual, mechanical, or electrical operations have certain disadvantages. Manually-operated openings and their shading devices introduce a greater level of uncertainty due to inconsistent operational behavior of its occupants (O'Brien et al. 2013). Kinetic façades usually not only have a relatively high investment cost, but also incur recurring expenditure in the form of maintenance & repair costs (Pasquay 2004; Zhou and Chen 2010).

Traditionally, design of buildings included careful selection of sustainable materials, reliance on natural ventilation, night-purge cooling techniques, consideration for cross-ventilation, etc. to lower its energy demands (Artmann et al. 2008; Xiang and Zhou 2015). However, today, in an effort to standardize, modernize, and make construction more flexible, this crucial knowledge of harvesting natural resources in a sustainable way has been taking a back seat (Solgi et al. 2016). This study is an attempt to develop a sustainable façade solution that would enhance wind speed and improve natural cross ventilation in the interior spaces.

CHAPTER II

RESEARCH OBJECTIVES & HYPOTHESIS

Research Goal and Objectives

The goal of this study was to develop a façade solution with an intention to enhance natural cross ventilation in built spaces. The primary objectives of this study were as follows:

1. To test the efficiency of actual 'coke-bottle' sections to modulate wind velocity.
2. To investigate if the profile of the bottle-shaped nozzle section affects the velocity of wind flowing through it.
3. To simulate and physically test different sectional profiles of nozzle-forms that would modulate (essentially augment) velocity of air flow through them.

Research Hypothesis

Bottleneck sections could be used as an element of a façade system that would help accelerate wind velocity, hence improving natural ventilation in built spaces. Use of plastic bottles was the start point, but since this study was an experimental and exploratory research, the research hypothesis underwent certain modifications after achieving every milestone in the development process.

CHAPTER III

LITERATURE REVIEW

ASHRAE Standards for Human Comfort

With global climate change being a reality (IPCC 2014), the construction industry is steering towards achieving maximum energy-efficiency in buildings. ASHRAE Standard-55 is the American Society of Heating, Refrigerating, and Air-Conditioning Engineers' document titled "Thermal Environment Conditions for Human Occupancy." It defines *thermal comfort* as "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (Standard 2004). Following are six factors that require consideration for Human Comfort:

1. Metabolic Rate – Energy generated from the Human body;
2. Clothing Insulation – Thermal insulation rendered by clothing;
3. Air Temperature – Consideration of Mean radiant temperature;
4. Air Velocity – Rate of air movement;
5. Relative Humidity – Percentage of water vapor in the air; and
6. Skin Wettedness.

The focus of this study is modulation of #4 - Air Velocity and #5 – Relative Humidity to improve natural ventilation, and thus enhance comfort level of occupants in built spaces.

Ole Fanger developed a method to describe thermal comfort which was later adopted as an ISO standard. It is referred to as the 'Predicted Mean Vote' (PMV), and is a mathematical model that sums up environmental and physiological factors as mentioned earlier. ASHRAE-55 acclaims -0.5 to +0.5 as a comfortable range for PMV value for interior spaces. Thermal comfort of occupants is considered to be affected by both, environmental factors and adaptability of the human body (De Dear and Brager 2002); hence the PMV scale based on occupant satisfaction is important. Another measure used to describe thermal comfort is PPD – 'Predicted Percentage Dissatisfied', a mathematical function of PMV. It denotes a percentage of occupants that would presumably be dissatisfied within a certain temperature range (Peeters et al. 2009).

Table 1 elaborates the PMV scale and relevant sensations:

Table 1: PMV scale and corresponding sensations.

PMV Value	Sensation
-3	Cold
-2	Cool
-1	Slightly cool
0	Neutral
+1	Slightly warm
+2	Warm
+3	Hot

In an attempt to validate the results of this study, the developed product could be tested against these parameters to see how effective it would be in bringing thermal comfort to the occupants.

Natural Ventilation in Buildings

According to a review of energy consumption conducted in 2007, energy use in buildings amounts to 20-40% of the total energy consumption in developed countries. The study shows an increasing trend in building energy consumption, especially due to rising dependence on HVAC systems all over the world (Pérez-Lombard et al. 2008). Thus, it is imperative to curb this rising energy demand and take effort towards a sustainable energy future. Natural ventilation can be described as passive ventilation that utilizes difference in wind and/or buoyancy pressure to freshen up air in indoor spaces with outside air (Mora-Pérez et al. 2016). Natural ventilation has been utilized in the design of shelters for a long time; borrowing these concepts and integrating them with modern-day technologies is a plausible solution (Axley 2001).

It has also been shown that the range of thermal comfort is observed to be wider in occupants of naturally-ventilated buildings, whereas occupants of air-conditioned buildings demonstrate a narrower range of temperature tolerance (Brager and de Dear 2000). Designers have been trying to incorporate features like operable windows in non-residential buildings which enable the occupants with an opportunity for adaptive comfort; and stress the importance of natural ventilation in modern-day built spaces (De Dear and Brager 2002; Nicol and Humphreys 2002). Physical and thermodynamic properties of air such as dry-bulb & wet-bulb temperatures, humidity, enthalpy, and air density are graphically represented in the form of a psychrometric chart (Givoni 1992). Figure 1 depicts the location of human comfort zone, along with the ones of passive cooling, natural ventilation, etc. on the psychrometric chart, as per the ASHRAE-55 standard. It shows the extent to which human comfort zone can be expanded by incorporating natural ventilation. Furthermore, in cases where weather events lead to power outages, including a backup system of natural ventilation enhances resilience. Fundamentals such as these establish the importance of this study.

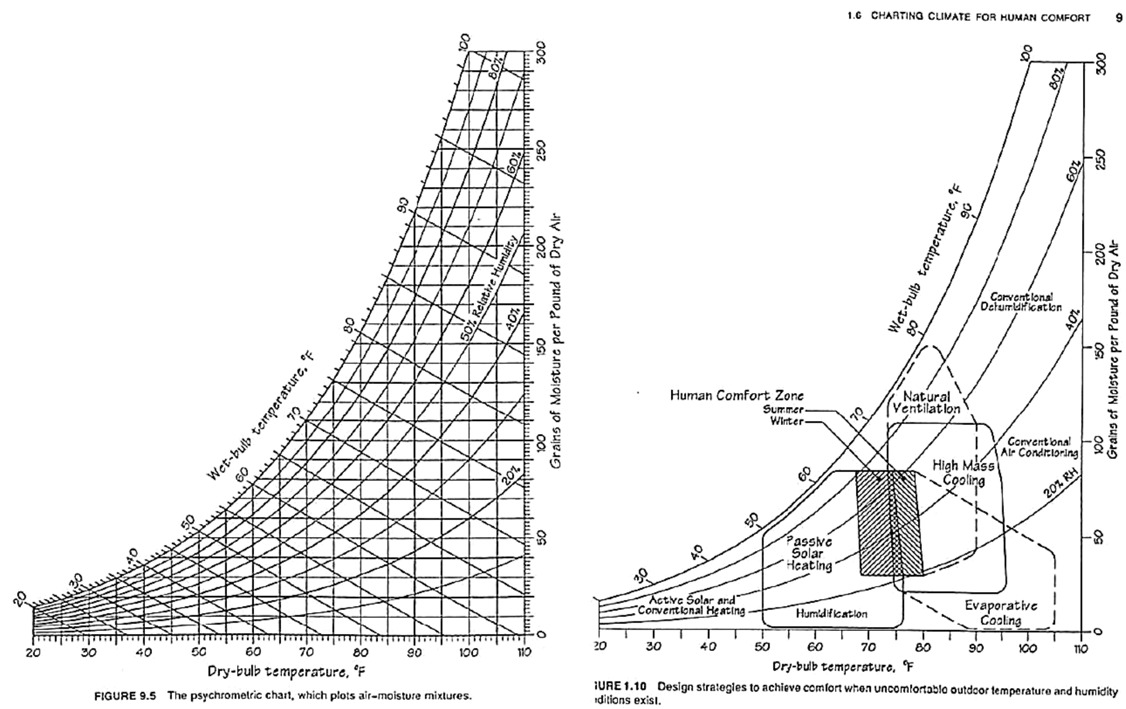


Figure 1: Psychrometric chart depicting extent of human comfort zone as mentioned by AHSRAE-55, and that achieved by natural ventilation reprinted from (TNRKITECT 2014)

Inspiration – “Eco-friendly Air-Conditioner”

The smart air-cooler that operates without electricity, and which has been developed by Bangladeshi innovator, Ashis Paul’s “DIY” (Do-It-Yourself) idea, inspired this study. It consists of a simple screen composed of a board, and uses plastic bottles to cool air. News articles and web blogs claim that this innovation has brought relief during peak summers, to the socio-economically challenged populations living in tin houses in Bangladesh. Along with Ashis’s company, the Grey Group and Grameen Intel Social Business has helped install these air coolers in more than 25,000 households (DiStasio 2016). A video film documenting the need and process of the product claims that, in Rajbari, Bangladesh where these ‘air-coolers’ were installed in tin houses, the summer temperatures rise to 45°C. These coolers, in most cases reduce the temperature by 5°C (BoF 2016).

The success of this innovation can be credited to fundamental rules of science. According to the Bernoulli’s Equation, pressure and velocity are inversely proportional; velocity varies as liquid or gas flows through a conduit of variable cross-sections. This behavior of air blowing through the bottle-screen gives the tin house occupants relief during peak summers. For perspiring human beings, rapidly flowing air wicks away energy as the perspiration evaporates, thus cooling an overheated body. Furthermore, exploration regarding the actual working of this idea might correlate its effects to the Joule-Thomson Effect, which states that a ‘real’ gas or liquid exhibits a temperature change when forced through a valve or a porous plug, if it is insulated, and if there is no exchange of heat with its surroundings. This research is an attempt to first, validate the results of this eco-friendly air-cooler, and then, to develop an improved version of the product with a view to enhance natural ventilation in built space.

Concept of Perspiration and Thermal Relief

Relative humidity level is an important factor affecting thermal comfort of building occupants, especially if the building is ventilated naturally. (Berglund 1997) investigated several crucial factors affecting humidity levels directly and indirectly, and concluded that, increasing the air speed in humid environments can be an effective way of mitigating thermal discomfort of occupants.

As a response to thermally uncomfortable environments, occupants often resort to adaptive measures such opening up the windows, using hand-held fans, reducing/ increasing clothing, etc. This nature of ‘Adaptive Control’ can enable designers to accommodate a wider range of thermal comfort zone, and thus adopting natural ventilation techniques conducive (Nicol and Humphreys 2002; Roetzel and Tsangrassoulis 2012). Precise placement of natural ventilation directed at occupants in a built space enable them to feel a sense of relief owing to convective transfer of heat and moisture from their bodies (Axley 2001). This exchange in convection depends on the ambient air temperature and airspeed in that particular space (Givoni 1998).

Rapid Prototyping for Design Research

Currently, practitioners of architectural design and construction are reaching toward technological solutions to improve productivity within the building industry.

Traditionally, hand/ machine prototyping, physical model-making, and Building Information Modelling (BIM) have offered designers ways to realistically visualize designs, schedules, estimates, and work sequencing, before actual construction. 3D-printing is one such technology that is being used in different sectors for research and manufacturing (Guo and Leu 2013). It is a cost-efficient and speedy way to prototype, since the injection mold tools that use Additive Manufacturing (AM) are inexpensive compared to traditional machining (Berman 2012).

Significance of this Study

The success of this study will be a step closer to a sustainable and green future. Moreover, it will have an immense impact on the quality of lives of socio-economically challenged people belonging to under-developed parts of the world, where even electricity is considered a luxury.

CHAPTER IV

RESEARCH METHODOLOGY

Methodology

The study was focused on developing and testing an environmentally friendly, easily deployable, and affordable solution in the form of a façade system that would accelerate wind speed as it entered a built space. With an intent of improving natural cross ventilation to enhance resilience in buildings, following milestones were achieved as part of the development process:

1. Preliminary tests – Tests were conducted to observe and compare change in velocity when a controlled wind stream was allowed to flow through truncated plastic water bottles (straight versus bottleneck) inserted into a foam board façade. It was a physical experiment conducted indoors.
2. Flow Design™ simulations – Autodesk Flow Design™ software was used to simulate efficiency of airflow through different sectional profiles of nozzles.
3. 3D-printed nozzles – Nozzle-forms were 3D-printed and trends of air velocities flowing through different sectional forms were plotted after conducting physical tests using an anemometer and a flowmeter. Inlet and outlet sizes were kept constant for all nozzle profiles.
4. 3D-printed nozzle extensions – Outwardly-curved extensions were 3D-printed for three nozzle-forms that had exhibited a perceptible increase in air-velocity. They were physically tested using the same experimental setup as earlier, and the

resulting trend graph was compared against the velocity trend of the control nozzle for that extension.

5. Test for potential collapsible tubes – Different lengths of PVC tubes were tested using the same apparatus to observe the effect of varying lengths on air velocities.

Since this study was an experimental research, the methodology was developed as the research progressed and findings at every milestone paved the course of the study.

Delimitations

As prescribed by ASHRAE-55, there are six parameters that require consideration while assessing human comfort (Ji et al. 2006; Standard 2004). Quantifying, controlling, and modifying all six factors affecting human comfort in built spaces is potentially an extensive study; hence, scope of this research was limited to developing a façade solution that would accelerate the velocity of natural wind entering a built space, contributing to enhanced natural ventilation and improved thermal comfort for its occupants.

The study included preliminary tests conducted to observe the velocity trends of wind flowing through different sectional profiles of nozzle-forms. After optimizing form and profile of the nozzle to exhibit the most effective results (i.e. air velocity delta), the nozzle-forms were 3D-printed, and physical tests were conducted to validate the results.

Limitations

None of the tests included interaction with humans, thus limiting the subjectivity of the ‘feeling’ of relief rendered by the developed façade system.

CHAPTER V

PRELIMINARY STUDY

A pilot study was conducted to observe the trend of change in wind velocities through two different sections of plastic bottles. These readily available plastic water bottles are were cut to equal lengths (18 cm), one of them including the bottleneck, while the other one without it. Apparatus for the experiment included a small electric fan, a plastic water-cup, a piece of boxboard, a tape measure and the two plastic bottle sections cut as per decided conditions as shown in Figure 2. A VAC measuring instrument- Testo 445 Anemometer and the TSI VelociCalc Flowmeter were the instruments used to take readings of velocities at equidistant points – 10 cm apart.

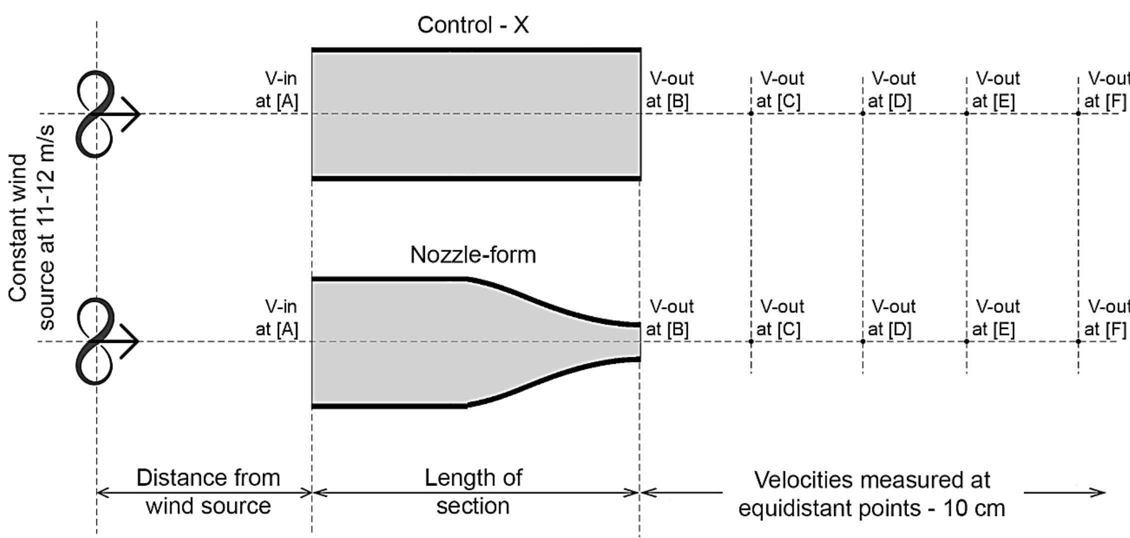


Figure 2: Arrangement of the experimental setup.

Figure 3: The actual set-up of the experiment using truncated plastic bottles.

Distance between the bottle inlet and the electric fan (20 cm) was decided by adjusting the position of the fan, such that a pressure of about 60 Pa was obtained on the surface, which simulates the average wind pressure against walls on the building envelope as described by (Gowri et al. 2009). The experiment was set-up in a closed room measuring 5.0 m x 2.8 m, with a clear height of 2.3 m at ambient temperature and with no interference of wind from the outside. After setting up the apparatus, a stretch of tape was attached to the floor, perpendicular to the electric fan box. This tape had markings to maintain the alignment of the set-up; it also served as a location guide to take readings of the velocity at pre-specified distances from the outlet of the bottle section. Eleven readings of air velocities at seven points were taken; each point marked 10 cm apart from the other on the tape, and an average of their values as shown in Table 2 (straight section) and 3 (bottleneck section) was used to plot a comparative line graph.

Table 2: Case I - Velocity readings of air stream through Straight bottle section at specified points.

CASE I - Straight Bottle Section

Wind velocity at source = 12.2 m/s (25-27 MPH) d in = 8.7 cm

Pressure on the surface = 60 Pa d out = 8.7 cm

Reading #	V in at 20 [A]	V out at 40 [B]	V out at 50 [C]	V out at 60 [D]	V out at 70 [E]	V out at 80 [F]	V out at 90 [G]	V out at 100 [H]	V out at 110 [I]
1	10.90	9.38	8.73	8.08	7.21	6.38	5.23	4.96	4.09
2	11.12	9.63	8.75	8.29	7.32	6.41	5.43	4.85	4.16
3	11.26	9.30	8.88	8.37	7.16	6.31	5.17	4.89	4.18
4	11.07	9.94	8.90	8.53	7.19	6.15	5.07	4.82	4.11
5	11.14	10.09	9.04	8.41	7.46	6.17	5.26	5.14	4.12
6	11.19	10.24	8.73	8.29	7.38	6.33	5.41	5.02	4.28
7	11.37	9.85	8.79	8.31	7.49	6.27	5.09	4.94	4.10
8	11.38	10.23	8.77	8.19	7.17	6.49	5.26	4.79	4.21
9	11.09	10.39	8.89	8.59	7.48	6.24	5.20	5.00	4.32
10	11.24	10.28	8.72	8.39	7.38	6.29	5.23	4.69	4.37
11	11.30	10.40	8.66	8.12	7.52	6.13	5.17	5.02	4.43
Average Velocity	11.19	9.98	8.81	8.32	7.34	6.29	5.23	4.92	4.22

Table 3: Case II - Velocity readings of air stream through Bottleneck section at specified points.

CASE II - Bottle Section with constriction at the neck

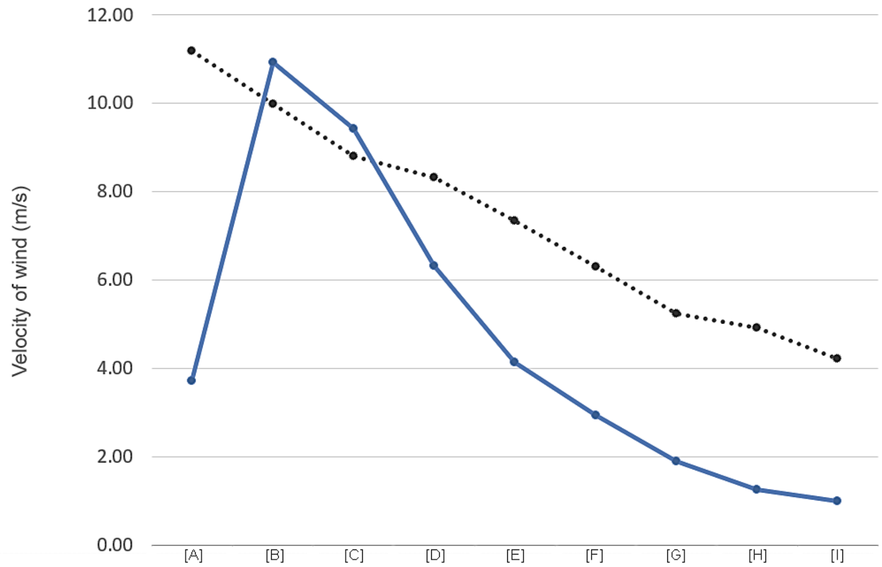
Wind velocity at source = 12.2 m/s (25-27 MPH) d in = 8.7 cm

Pressure on the surface = approximately 70 Pa d out = 2.4 cm

Reading #	V in at 20 [A]	V out at 40 [B]	V out at 50 [C]	V out at 60 [D]	V out at 70 [E]	V out at 80 [F]	V out at 90 [G]	V out at 100 [H]	V out at 110 [I]
1	3.86	10.80	9.57	6.48	4.31	3.10	2.04	1.39	1.02
2	3.64	11.12	9.53	6.18	4.15	3.05	2.09	1.39	1.18
3	3.78	10.98	9.52	6.20	4.01	3.04	2.02	1.20	0.96
4	3.61	11.05	9.53	6.34	4.20	2.72	1.86	1.27	0.83
5	3.49	11.06	9.43	6.29	4.24	2.78	1.79	1.26	1.06
6	3.51	10.91	9.36	6.41	4.18	2.80	1.75	1.28	1.08
7	3.75	10.96	9.33	6.49	4.11	2.94	1.87	1.43	1.04
8	3.78	10.71	9.34	6.46	3.90	3.09	1.95	1.23	0.93
9	3.91	10.81	9.55	6.26	4.03	3.01	1.88	1.06	0.98
10	3.85	10.99	9.26	6.16	4.07	2.92	1.86	1.20	0.85
11	3.66	10.82	9.24	6.15	4.33	2.84	1.69	1.04	0.94
Average Velocity	3.71	10.93	9.42	6.31	4.14	2.94	1.89	1.25	0.99

The following observations were made after plotting the trend of change in the wind velocities in both the cases as shown in Figure 4:

1. Maximum wind velocity (11.2 m/s) was observed at the inlet of straight bottle section, it decreased gradually as one moved away from the outlet of the bottle.
2. In case of the bottleneck section, due to the constriction at the outlet, there was an increase of approximately 10 Pa in the pressure at the inlet.
3. Wind velocity at the inlet of the bottleneck section was very less (3.71 m/s) compared to the straight section.
4. A sharp spike in wind velocity (10.93 m/s) was seen at the outlet i.e. at the bottleneck in case II; wind-velocity increased by 0.95 m/s in comparison to the outlet velocity measured in case I.
5. Some inconsistency was seen in the velocity readings at points where the perpendicular side of the box-board ended; this led to the conclusion that wind moved along the apparent ‘building surface’.



	20	40	50	60	70	80	90	100	110
Straight bottle section	11.19	9.98	8.81	8.32	7.34	6.29	5.23	4.92	4.22
Bottleneck section	3.71	10.93	9.42	6.31	4.14	2.94	1.89	1.25	0.99

Distance from wind source (cm)

Straight bottle section   Bottleneck section

Figure 4: Graph showing a comparison in the air velocity trends in Cases I & II.

After concluding that constriction at the neck of the bottle section led to a sharp spike in the wind velocity readings, next step involved exploring the effect of different sectional profiles on the velocity trends of a wind stream flowing through them.

CHAPTER VI

SOFTWARE SIMULATIONS

Autodesk Flow Design™ software was used to understand flow patterns formed by the wind stream while it blew through different sections of the nozzles. This exploration provided a direction to develop the nozzle-forms that were to be 3D-printed for the wind-velocity experiment. Figure 5 depicts four distinct profiles that were explored for the printed nozzles. Silhouettes such as a sharp conical form, extreme concave and convex curves, and a typical bottleneck form as a reference for comparison of the wind flow patterns were used in the simulations.

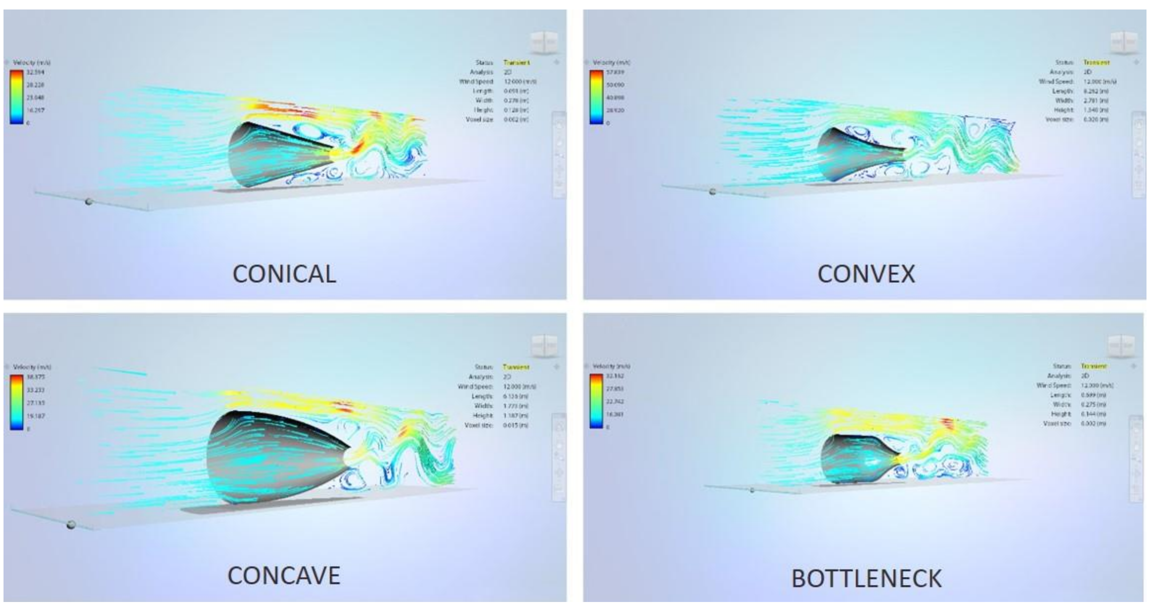


Figure 5: Autodesk Flow Design™ simulations for understanding the effect of different nozzle profile sections on the flow of air stream through them.

CHAPTER VII

RESULTS AND DISCUSSION

3D-Printed Nozzle Prototypes

Based on the explorations of sectional profiles using Flow Design™ simulations, five different nozzle-forms and a control group - X were printed as shown in Figure 6. The Ultimaker 3 printer, with Essentium Engineering grade Poly Lactic Acid (PLA) filament was used for 3D-printing them.

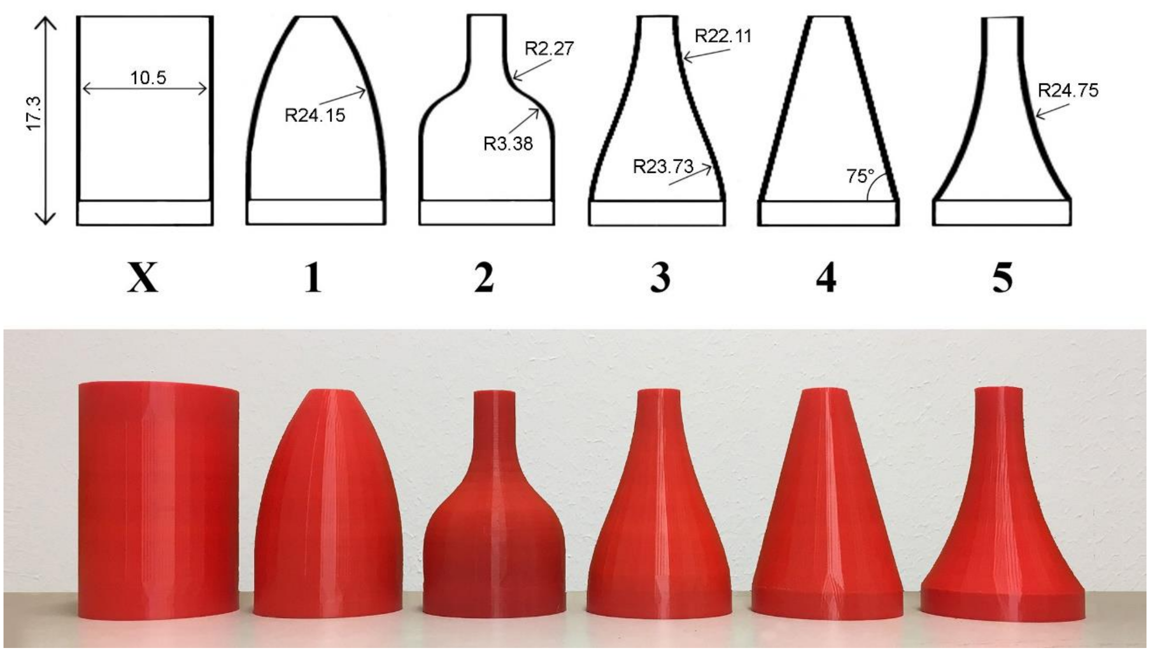


Figure 6: Sections of nozzle-forms 1-5 tested against the control group-X (above). 3D-printed nozzles developed with uniform inlet diameter = 10.8 cm & outlet diameter = 2.5 cm (below)
All radii and length measurements are in cm.

Effect of Sectional Profile on Wind Velocity

Air velocities were measured at 10 cm intervals from the outlet of each 3D-printed nozzle-form using a flowmeter. The apparatus included a small electric fan, a plastic water-cup, and a sheet of foam board held in place by 3-prong clamps on ring-stands, a tape measure, and the 3D-printed nozzle-forms. To maintain consistency, the same procedure as followed in the case of plastic bottle sections, was used to test these nozzle-forms as shown in Figure 7.

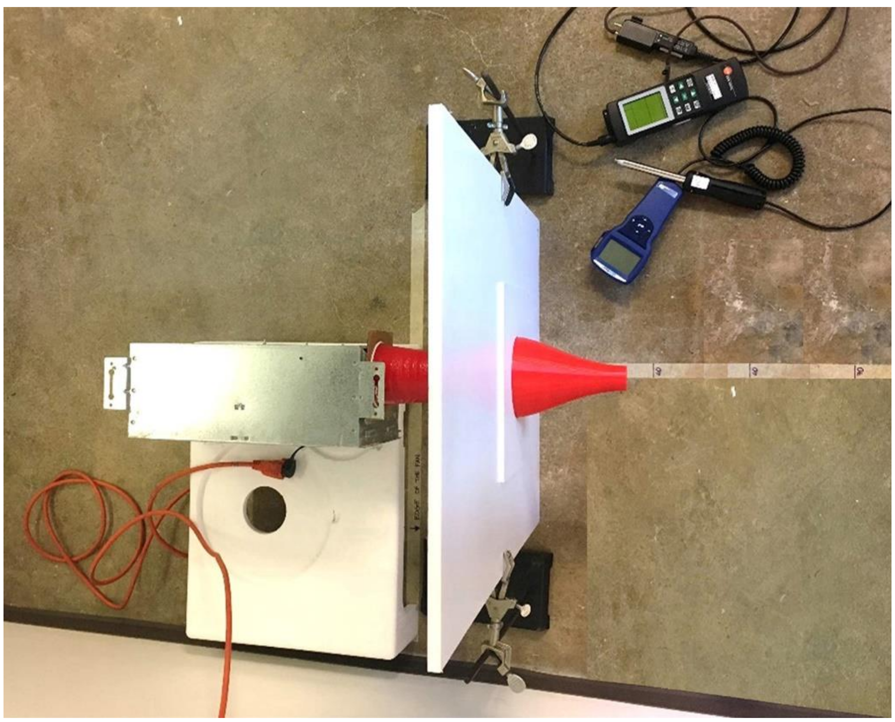


Figure 7: Experimental setup to physically test the 3D-printed nozzle-forms.

Velocity readings through nozzles 1, 2, 3, 4, 5, and the control group-X as shown in Tables 4, 5, 6, 7, 8, and 9 respectively were plotted as a comparative line graph depicted in Figure 8.

Table 4: Velocity readings of the air stream at specified points from the wind source through control-X.

Control group nozzle - X

Wind velocity at source = 11-12 m/s (25-27 mph)
Pressure on the surface = 60 Pa

d in = 10.8 cm
d out = 10.5 cm
length = 17.3 cm

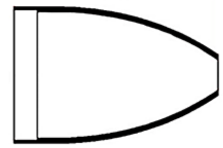
Reading #	V in at 20 [A]	Avg. of A & B	V out at 40 [B]	V out at 50 [C]	V out at 60 [D]	V out at 70 [E]	V out at 80 [F]	V out at 90 [G]	V out at 100 [H]	V out at 110 [I]
1	10.81	9.88	8.95	7.96	7.12	5.60	4.89	4.06	3.77	3.42
2	10.90	9.96	9.01	7.85	6.96	5.82	4.77	4.16	3.65	3.23
3	10.78	9.83	8.87	7.95	6.91	5.88	4.84	4.05	3.76	3.28
4	10.85	9.87	8.88	7.94	7.08	5.80	4.67	4.18	3.91	3.21
5	10.77	9.73	8.69	7.65	7.00	5.97	4.73	4.22	3.86	3.45
6	10.82	9.97	9.11	7.84	6.84	5.93	4.33	4.29	4.02	3.28
7	10.88	9.92	8.95	7.62	6.96	6.16	4.32	4.06	3.90	3.36
8	10.89	10.01	9.12	7.80	6.90	6.03	4.75	4.58	3.85	3.20
9	10.75	9.96	9.16	7.68	6.74	5.99	4.42	4.04	4.03	3.18
10	10.81	9.96	9.11	7.83	6.84	5.94	4.56	4.25	3.81	3.15
11	10.92	10.05	9.18	7.81	6.78	6.02	4.52	4.32	4.09	3.23
Average Velocity	10.83	9.92	9.00	7.81	6.92	5.92	4.62	4.20	3.88	3.27

Table 5: Velocity readings of the air stream at specified points from the wind source through Nozzle #1.

Nozzle-form #1

Wind velocity at source = 11-12 m/s (25-27 mph)
Pressure on the surface = 45 Pa

d in = 10.8 cm
d out = 2.5 cm
length = 17.3 cm



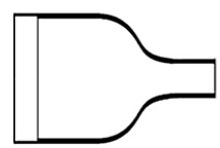
Reading #	V in at 20 [A]	Avg. of A & B	V out at 40 [B]	V out at 50 [C]	V out at 60 [D]	V out at 70 [E]	V out at 80 [F]	V out at 90 [G]	V out at 100 [H]	V out at 110 [I]
1	6.97	8.05	9.12	5.13	3.77	2.48	2.10	1.58	1.08	0.99
2	6.73	8.00	9.27	5.20	3.56	2.46	2.02	1.62	1.10	1.01
3	6.84	7.93	9.02	5.26	3.62	2.57	2.07	1.77	1.18	1.03
4	6.29	7.73	9.17	4.91	3.69	2.72	1.99	1.79	1.25	0.96
5	6.43	7.75	9.07	4.87	3.78	2.63	1.96	1.75	1.23	0.87
6	6.85	7.88	8.91	4.94	3.73	2.42	1.90	1.78	1.29	0.85
7	6.68	7.91	9.13	5.01	3.64	2.56	1.92	1.69	1.27	0.98
8	6.64	7.93	9.21	5.21	3.68	2.45	2.03	1.56	1.32	1.05
9	6.55	7.83	9.10	5.15	3.57	2.61	2.12	1.71	1.24	1.10
10	6.85	7.95	9.04	5.25	3.56	2.36	2.11	1.65	1.20	0.85
11	6.87	7.92	8.97	5.21	3.62	2.42	2.08	1.68	1.23	0.83
Average Velocity	6.70	7.90	9.09	5.10	3.66	2.52	2.03	1.69	1.22	0.96

Table 6: Velocity readings of the air stream at specified points from the wind source through Nozzle #2.

Nozzle-form #2

Wind velocity at source = 11-12 m/s (25-27 mph)
Pressure on the surface = 56 Pa

d in = 10.8 cm
d out = 2.5 cm
length = 17.3 cm



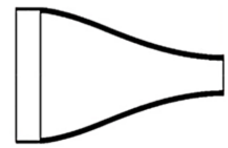
Reading #	V in at 20 [A]	Avg. of A & B	V out at 40 [B]	V out at 50 [C]	V out at 60 [D]	V out at 70 [E]	V out at 80 [F]	V out at 90 [G]	V out at 100 [H]	V out at 110 [I]
1	7.36	8.24	9.12	5.11	4.56	2.74	2.33	1.73	1.08	1.02
2	7.38	8.23	9.07	5.34	4.81	2.82	2.31	1.78	1.12	0.98
3	7.24	8.12	8.99	5.27	4.75	2.78	2.28	1.70	1.18	0.95
4	7.41	8.21	9.01	5.23	4.72	2.64	2.25	1.69	1.03	0.88
5	7.52	8.35	9.18	5.29	4.63	2.53	2.29	1.67	1.07	0.99
6	7.48	8.36	9.23	5.45	4.58	2.81	2.17	1.62	1.15	1.15
7	7.43	8.27	9.11	5.38	4.51	2.85	2.21	1.68	1.18	1.01
8	7.39	8.23	9.06	5.32	4.60	2.90	2.23	1.72	1.32	0.94
9	7.35	8.19	9.02	5.18	4.72	2.73	2.20	1.75	1.19	0.96
10	7.22	8.18	9.14	5.25	4.68	2.84	2.15	1.60	1.23	0.83
11	7.36	8.23	9.09	5.34	4.69	2.78	2.27	1.68	1.25	0.88
Average Velocity	7.38	8.23	9.09	5.29	4.66	2.77	2.24	1.69	1.16	0.96

Table 7: Velocity readings of the air stream at specified points from the wind source through Nozzle #3.

Nozzle-form #3

Wind velocity at source = 11-12 m/s (25-27 mph)
Pressure on the surface = 43 Pa

d in = 10.8 cm
d out = 2.5 cm
length = 17.3 cm



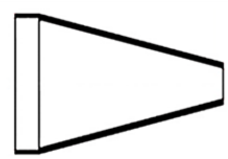
Reading #	V in at 20	Avg. of A & B	V out at 40	V out at 50	V out at 60	V out at 70	V out at 80	V out at 90	V out at 100	V out at 110
	[A]		[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]
1	7.62	8.47	9.32	7.26	5.32	3.41	2.62	2.24	1.87	1.36
2	7.58	8.47	9.36	7.34	5.12	3.45	2.58	2.27	2.01	1.45
3	7.47	8.38	9.28	7.38	5.28	3.52	2.67	2.31	1.82	1.48
4	7.64	8.45	9.26	7.29	5.43	3.26	2.80	2.38	1.86	1.24
5	7.68	8.49	9.29	7.41	5.48	3.31	2.71	2.47	1.91	1.38
6	7.72	8.54	9.35	7.45	5.67	3.42	2.54	2.42	2.00	1.30
7	7.75	8.53	9.31	7.57	5.35	3.47	2.63	2.18	1.82	1.27
8	7.78	8.63	9.47	7.24	5.40	3.40	2.62	2.25	1.97	1.35
9	7.63	8.57	9.51	7.35	5.37	3.57	2.57	2.22	1.88	1.42
10	7.54	8.43	9.32	7.38	5.29	3.35	2.76	2.22	1.83	1.18
11	7.60	8.53	9.45	7.43	5.24	3.38	2.67	2.20	1.85	1.32
Average Velocity	7.64	8.50	9.36	7.37	5.36	3.41	2.65	2.29	1.89	1.34

Table 8: Velocity readings of the air stream at specified points from the wind source through Nozzle #4.

Nozzle-form #4

Wind velocity at source = 11-12 m/s (25-27 mph)
Pressure on the surface = 54 Pa

d in = 10.8 cm
d out = 2.5 cm
length = 17.3 cm



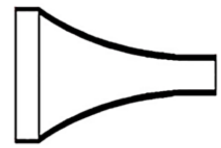
Reading #	V in at 20	Avg. of A & B	V out at 40	V out at 50	V out at 60	V out at 70	V out at 80	V out at 90	V out at 100	V out at 110
	[A]		[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]
1	7.47	8.45	9.43	7.46	4.65	3.21	2.61	1.99	1.32	1.01
2	7.53	8.47	9.41	7.43	4.67	3.23	2.47	2.10	1.35	1.12
3	7.80	8.59	9.38	7.57	4.72	3.41	2.63	2.03	1.42	0.99
4	7.65	8.55	9.44	7.62	4.63	3.27	2.65	2.09	1.37	1.03
5	7.42	8.45	9.47	7.81	4.58	3.29	2.71	1.98	1.24	1.05
6	7.72	8.65	9.57	7.59	4.65	3.12	2.62	1.99	1.28	1.24
7	7.77	8.60	9.43	7.54	4.57	3.21	2.58	2.23	1.40	1.13
8	7.67	8.69	9.71	7.45	4.55	3.20	2.42	2.08	1.38	0.97
9	7.63	8.62	9.60	7.51	4.60	3.18	2.57	2.12	1.32	1.08
10	7.65	8.58	9.51	7.50	4.61	3.15	2.63	2.15	1.27	1.10
11	7.68	8.58	9.48	7.57	4.64	3.22	2.65	2.10	1.24	1.18
Average Velocity	7.64	8.56	9.49	7.55	4.62	3.23	2.59	2.08	1.33	1.08

Table 9: Velocity readings of the air stream at specified points from the wind source through Nozzle #5.

Nozzle-form #5

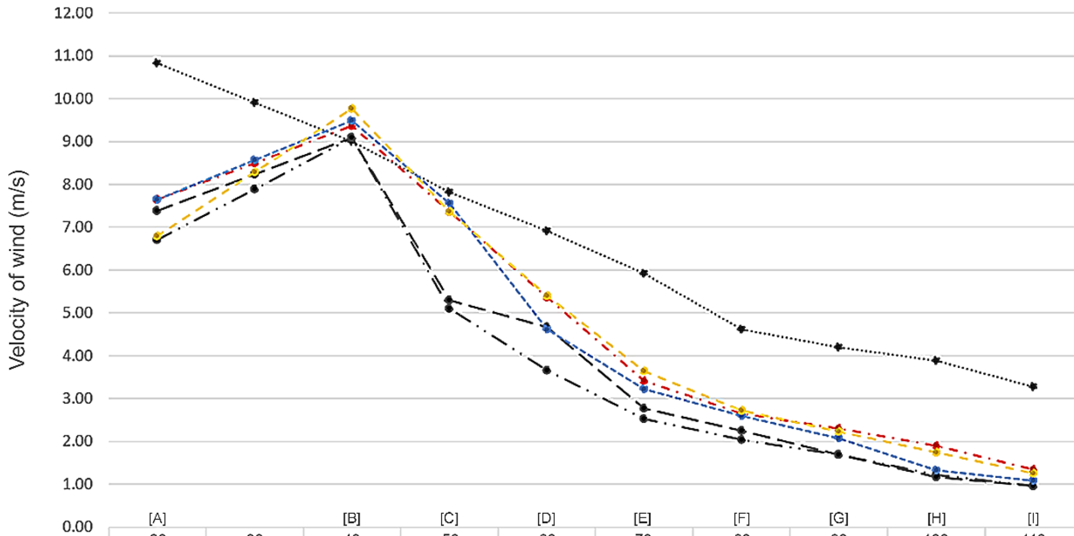
Wind velocity at source = 11-12 m/s (25-27 mph)
Pressure on the surface = 65 Pa

d in = 10.8 cm
d out = 2.5 cm
length = 17.3 cm



Reading #	V in at 20	Avg. of A & B	V out at 40	V out at 50	V out at 60	V out at 70	V out at 80	V out at 90	V out at 100	V out at 110
	[A]		[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]
1	6.89	8.34	9.78	7.36	5.29	3.84	2.69	2.23	1.71	1.24
2	6.88	8.37	9.86	7.42	5.45	3.62	2.54	2.17	1.76	1.28
3	6.73	8.29	9.84	7.46	5.70	3.63	2.79	2.19	1.67	1.12
4	6.77	8.25	9.72	7.45	5.43	3.78	2.62	2.12	1.83	1.38
5	6.82	8.29	9.75	7.33	5.40	3.57	2.59	2.20	1.87	1.35
6	6.81	8.29	9.76	7.29	5.36	3.51	2.75	2.27	2.12	1.17
7	6.78	8.29	9.80	7.22	5.49	3.77	2.83	2.36	1.50	1.25
8	6.76	8.24	9.72	7.35	5.36	3.72	2.70	2.11	1.73	1.12
9	6.61	8.12	9.62	7.37	5.22	3.73	2.73	2.28	1.61	1.34
10	6.81	8.31	9.81	7.42	5.42	3.42	2.82	2.25	1.79	1.27
11	6.78	8.28	9.78	7.39	5.22	3.45	2.75	2.30	1.59	1.32
Average Velocity	6.79	8.28	9.77	7.37	5.39	3.64	2.71	2.23	1.74	1.26

Observations from the test results suggested that nozzle-forms 3, 4, and 5 consistently showed a perceptible increase (by 0.36, 0.49, and 0.77 m/s respectively) in the outlet velocities at the point of constriction (40 cm away from the wind source), when compared to the outlet velocity of the control group – X as shown in Figure 8.



	20	30	40	50	60	70	80	90	100	110
X - control	10.83	9.92	9.00	7.81	6.92	5.92	4.62	4.20	3.88	3.27
Nozzle 1	6.70	7.90	9.09	5.10	3.66	2.52	2.03	1.69	1.22	0.96
Nozzle 2	7.38	8.24	9.09	5.29	4.66	2.77	2.24	1.69	1.16	0.96
Nozzle 3	7.64	8.50	9.36	7.37	5.36	3.41	2.65	2.29	1.89	1.34
Nozzle 4	7.64	8.57	9.49	7.55	4.62	3.23	2.59	2.08	1.33	1.08
Nozzle 5	6.79	8.28	9.77	7.37	5.39	3.64	2.71	2.23	1.74	1.26

Distance from the wind source (cm)

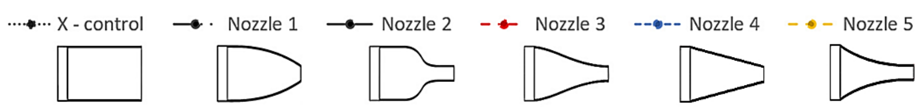


Figure 8: Trend of air velocities measured at specified distances from the wind source through nozzle-forms 1 to 5 and control group-X.

3D-Printed Nozzle Extensions

The next stage of development explored if a variation in the outlet profile of the nozzle affected the velocity of the air stream flowing through it. It led to the development of 3D-printed extensions for nozzles 3, 4, and 5 as shown in Figure 9. These were also tested using the same setup and procedure as for the mentioned earlier, and the tabulated results were depicted as line graphs comparing wind velocity trends through the nozzle-forms alone, and through straight (control) extension, 2.5 cm wide in diameter as well as an outwardly-curved extension, 4.8 cm wide in diameter. Length of the nozzle-forms was 17.3 cm, and the effective length after attaching the extension was 24.5 cm.

Figure 9: 3D-printed nozzle-forms *(L-R: 3, 4, 5)* with their extensions, control (maroon-colored) and outwardly curved (grey-colored).

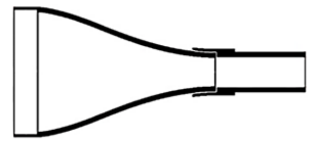
Tables 10 and 11 represent wind velocity readings of the air stream through nozzle-form #3 with the straight (control) and outwardly curved extension respectively depicted as a comparative line-graph in Figure 10.

Table 10: Velocity readings at specified points from wind source through control extension of Nozzle #3.

Nozzle #3 - extension: control

Wind velocity at source = 11-12 m/s (25-27 mph)
Pressure on the surface = 55 Pa

d in = 10.8 cm
d out = 2.5 cm
length = 24.5 cm



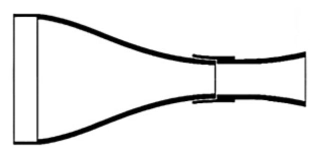
Reading #	V in at 20 [A]	Avg. of A & B	V out at 45 [B]	V out at 50 [C]	V out at 60 [D]	V out at 70 [E]	V out at 80 [F]	V out at 90 [G]	V out at 100 [H]	V out at 110 [I]
1	6.77	8.48	10.19	9.78	7.41	5.60	2.91	2.45	1.97	1.96
2	7.00	8.62	10.24	9.74	7.38	5.75	3.09	2.50	2.24	1.77
3	6.75	8.55	10.34	9.64	7.15	5.90	3.28	2.76	2.34	2.02
4	7.15	8.72	10.29	9.68	7.25	5.87	3.22	2.79	2.11	1.62
5	6.94	8.57	10.20	9.66	7.37	5.93	3.32	2.82	2.40	1.84
6	6.88	8.62	10.35	9.70	7.42	5.75	3.25	2.85	2.33	1.96
7	7.11	8.59	10.07	9.54	7.68	5.46	3.42	2.64	2.07	1.86
8	7.23	8.68	10.12	9.51	7.93	5.70	3.08	2.74	2.24	2.02
9	7.38	8.72	10.05	9.60	7.77	5.88	3.14	2.80	2.31	1.87
10	7.31	8.67	10.03	9.64	8.08	5.73	3.08	2.57	2.37	1.73
11	7.07	8.64	10.21	9.52	7.98	5.85	3.26	2.63	2.20	2.00
Average Velocity	7.05	8.62	10.19	9.64	7.58	5.77	3.19	2.69	2.23	1.88

Table 11: Velocity readings at specified points from wind source through curved extension of Nozzle #3.

Nozzle #3 - extension: curved

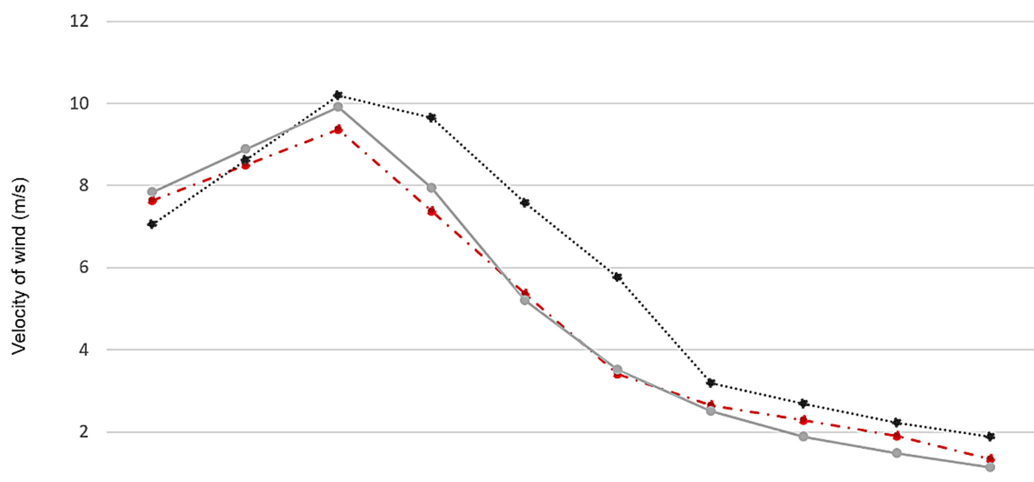
Wind velocity at source = 11-12 m/s (25-27 mph)
Pressure on the surface = 45 Pa

d in = 10.8 cm
d out = 4.8 cm
length = 24.5 cm



Reading #	V in at 20 [A]	Avg. of A & B	V out at 45 [B]	V out at 50 [C]	V out at 60 [D]	V out at 70 [E]	V out at 80 [F]	V out at 90 [G]	V out at 100 [H]	V out at 110 [I]
1	7.74	8.87	10.00	8.22	5.56	3.52	2.55	1.94	1.32	1.05
2	7.45	8.79	10.12	7.91	5.18	3.62	2.38	2.01	1.66	1.24
3	7.82	8.87	9.91	7.82	5.22	3.48	2.42	1.88	1.39	1.36
4	7.86	8.87	9.87	7.86	4.96	3.22	2.46	1.76	1.62	1.10
5	7.90	8.88	9.86	7.64	5.02	3.56	2.68	1.78	1.38	1.02
6	8.06	9.04	10.01	7.98	5.14	3.48	2.54	1.87	1.33	0.99
7	8.10	8.99	9.87	7.86	5.10	3.37	2.45	1.84	1.45	1.12
8	7.82	8.89	9.96	8.10	5.32	3.58	2.48	1.96	1.62	1.20
9	7.90	8.83	9.75	7.84	5.28	3.56	2.54	1.86	1.66	1.22
10	7.76	8.77	9.78	7.98	5.22	3.62	2.60	1.79	1.48	1.16
11	7.84	8.84	9.84	8.02	5.16	3.49	2.47	1.88	1.38	1.08
Average Velocity	7.84	8.87	9.91	7.93	5.20	3.50	2.51	1.87	1.48	1.14

Nozzle #3 with the straight (control) extension showed maximum change in velocity (3.14 m/s), when compared to nozzle #3 without any extensions (1.72 m/s) and with the outwardly curved extension (2.07 m/s). Line-graph of nozzle #3 with straight (control) extension depicted a relatively smoother curve between points 3 and 7 corresponding to a distance of 40 cm away from the outlet.



	[A] 20		[B] 45	[C] 50	[D] 60	[E] 70	[F] 80	[G] 90	[H] 100	[I] 110
Nozzle 3	7.64	8.50	9.36	7.37	5.36	3.41	2.65	2.29	1.89	1.34
ext.: Control	7.05	8.62	10.19	9.64	7.58	5.77	3.19	2.69	2.23	1.88
ext.: Curved	7.84	8.88	9.91	7.93	5.20	3.50	2.51	1.87	1.48	1.14

Distance from wind source (cm)

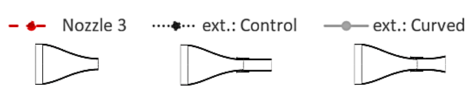


Figure 10: Trend of air velocities measured at specified distances from the wind source through nozzle #3 and its extensions.

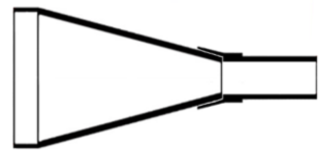
Tables 12 and 13 represent wind velocity data through nozzle #4 with the straight (control) and outwardly curved extension respectively.

Table 12: Velocity readings at specified points from wind source through control extension of Nozzle #4.

Nozzle #4 - extension: control

Wind velocity at source = 11-12 m/s (25-27 mph)
Pressure on the surface = 45 Pa

d in = 10.8 cm
d out = 2.5 cm
length = 24.5 cm



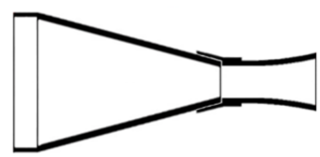
Reading #	V in at 20 [A]	Avg. of A & B	V out at 45 [B]	V out at 50 [C]	V out at 60 [D]	V out at 70 [E]	V out at 80 [F]	V out at 90 [G]	V out at 100 [H]	V out at 110 [I]
1	7.63	9.30	10.96	10.04	7.02	5.24	3.85	2.75	2.03	1.84
2	7.57	9.36	11.15	9.98	7.19	5.35	3.78	2.68	2.11	1.95
3	7.72	9.42	11.12	9.80	7.22	5.28	3.95	2.85	2.27	1.76
4	7.45	9.33	11.21	10.02	7.27	5.46	3.93	2.97	2.17	1.88
5	7.73	9.37	11.01	9.96	7.18	5.42	3.88	2.93	2.00	1.83
6	7.67	9.39	11.10	9.95	7.36	5.41	3.76	2.82	2.15	1.77
7	7.64	9.31	10.98	9.87	7.24	5.27	3.98	2.75	1.92	1.68
8	7.56	9.22	10.88	10.12	7.16	5.16	3.95	2.69	2.08	1.85
9	7.62	9.29	10.96	9.88	7.12	5.23	3.87	2.71	1.98	1.82
10	7.77	9.42	11.07	9.76	7.04	5.36	3.85	2.76	1.87	1.77
11	7.70	9.45	11.20	9.84	7.22	5.58	3.93	2.83	2.05	1.69
Average Velocity	7.64	9.35	11.06	9.93	7.18	5.34	3.88	2.79	2.06	1.80

Table 13: Velocity readings at specified points from wind source through curved extension of Nozzle #4.

Nozzle #4 - extension: curved

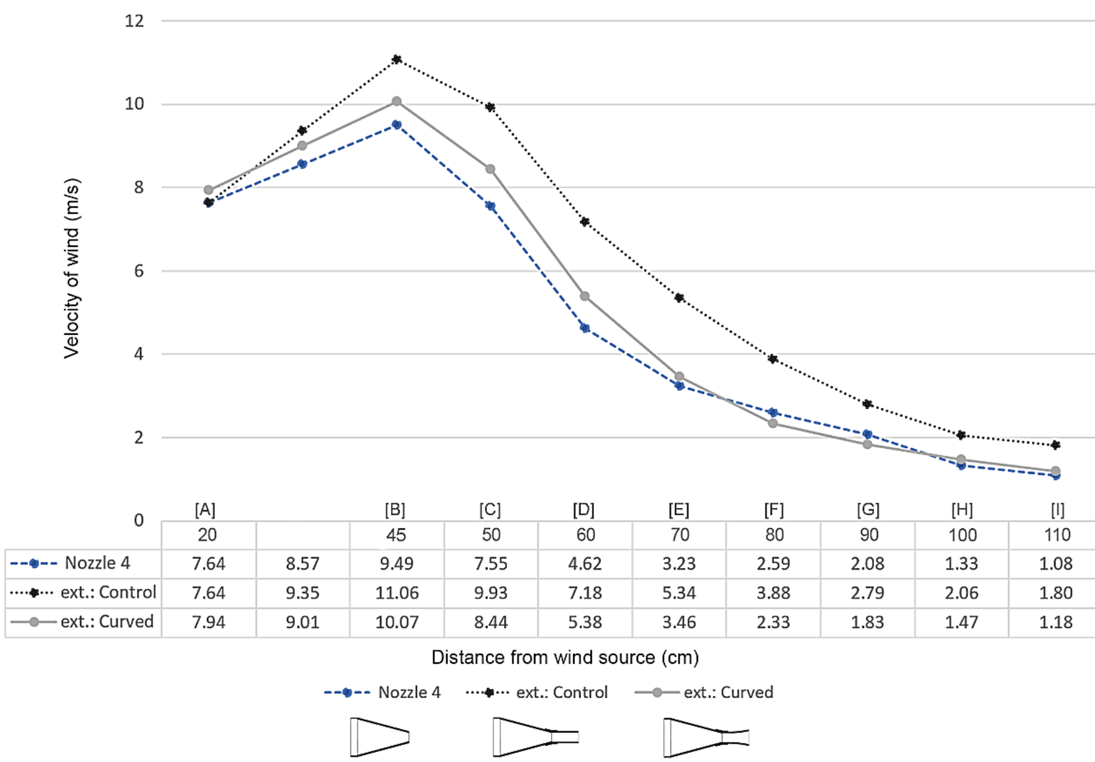
Wind velocity at source = 11-12 m/s (25-27 mph)
Pressure on the surface = 25 Pa

d in = 10.8 cm
d out = 4.8 cm
length = 24.5 cm



Reading #	V in at 20 [A]	Avg. of A & B	V out at 45 [B]	V out at 50 [C]	V out at 60 [D]	V out at 70 [E]	V out at 80 [F]	V out at 90 [G]	V out at 100 [H]	V out at 110 [I]
1	7.91	9.03	10.14	8.65	5.57	3.34	2.18	1.93	1.41	1.16
2	7.97	9.05	10.12	7.95	5.50	3.44	2.26	1.77	1.47	1.16
3	7.88	8.96	10.04	8.48	5.42	3.47	2.15	1.86	1.56	1.23
4	8.01	9.06	10.10	8.21	5.36	3.52	2.36	1.78	1.52	1.08
5	8.13	9.19	10.24	8.34	4.98	3.58	2.42	1.96	1.39	1.12
6	7.96	9.00	10.03	8.59	5.62	3.29	2.39	1.99	1.36	1.20
7	7.85	8.95	10.05	8.47	5.38	3.47	2.22	1.68	1.50	1.31
8	7.87	8.93	9.99	8.68	5.27	3.52	2.16	1.87	1.37	1.27
9	7.92	9.01	10.10	8.36	5.22	3.58	2.58	1.70	1.57	1.25
10	7.97	8.97	9.96	8.58	5.49	3.51	2.47	1.78	1.54	1.10
11	7.86	8.94	10.02	8.55	5.38	3.38	2.42	1.76	1.43	1.08
Average Velocity	7.94	9.01	10.07	8.44	5.38	3.46	2.33	1.83	1.47	1.18

Similarly, in case of nozzle-form #4, the straight (control) extension (3.42 m/s) exhibited the greatest change in velocity, when compared to trend graph of nozzle #4 without extensions (1.85 m/s) and with the outwardly-curved extension (2.13 m/s) as shown in Figure 11.



	[A] 20		[B] 45	[C] 50	[D] 60	[E] 70	[F] 80	[G] 90	[H] 100	[I] 110
Nozzle 4	7.64	8.57	9.49	7.55	4.62	3.23	2.59	2.08	1.33	1.08
ext.: Control	7.64	9.35	11.06	9.93	7.18	5.34	3.88	2.79	2.06	1.80
ext.: Curved	7.94	9.01	10.07	8.44	5.38	3.46	2.33	1.83	1.47	1.18

Figure 11: Trend of air velocities measured at specified distances from the wind source through nozzle #4 and its extensions.

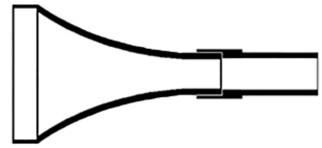
Wind velocity data of nozzle #5 with the straight (control) and outwardly-curved extension respectively is represented in Tables 14 and 15.

Table 14: Velocity readings at specified points from wind source through control extension of Nozzle #5.

Nozzle #5 - extension: control

Wind velocity at source = 11-12 m/s (25-27 mph)
Pressure on the surface = 62 Pa

d in = 10.8 cm
d out = 2.5 cm
length = 24.5 cm



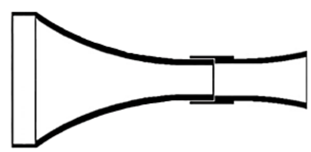
Reading #	V in at 20 [A]	Avg. of A & B	V out at 45 [B]	V out at 50 [C]	V out at 60 [D]	V out at 70 [E]	V out at 80 [F]	V out at 90 [G]	V out at 100 [H]	V out at 110 [I]
1	5.42	7.74	10.05	9.12	5.95	4.44	3.65	2.58	2.20	2.04
2	5.18	7.69	10.19	9.21	6.17	4.45	3.64	2.75	2.30	1.80
3	5.20	7.58	9.96	9.07	6.23	4.50	3.67	2.57	2.24	1.76
4	5.30	7.69	10.07	9.08	6.45	4.32	3.60	2.74	2.29	1.68
5	5.44	7.79	10.14	8.97	6.17	4.44	3.32	2.58	2.43	1.95
6	5.38	7.70	10.01	9.00	6.25	4.68	3.67	2.43	2.35	1.79
7	5.23	7.61	9.98	9.20	6.19	4.32	3.54	2.47	2.39	1.64
8	5.17	7.56	9.95	9.12	6.48	4.60	3.65	2.63	2.27	1.80
9	5.24	7.70	10.15	9.16	6.11	4.48	3.79	2.60	2.31	1.94
10	5.50	7.72	9.94	9.22	6.60	4.53	3.62	2.75	2.34	1.82
11	5.42	7.81	10.20	9.07	6.34	4.51	3.64	2.87	2.32	2.03
Average Velocity	5.32	7.69	10.06	9.11	6.27	4.48	3.62	2.63	2.31	1.84

Table 15: Velocity readings at specified points from wind source through curved extension of Nozzle #5.

Nozzle #5 - extension: curved

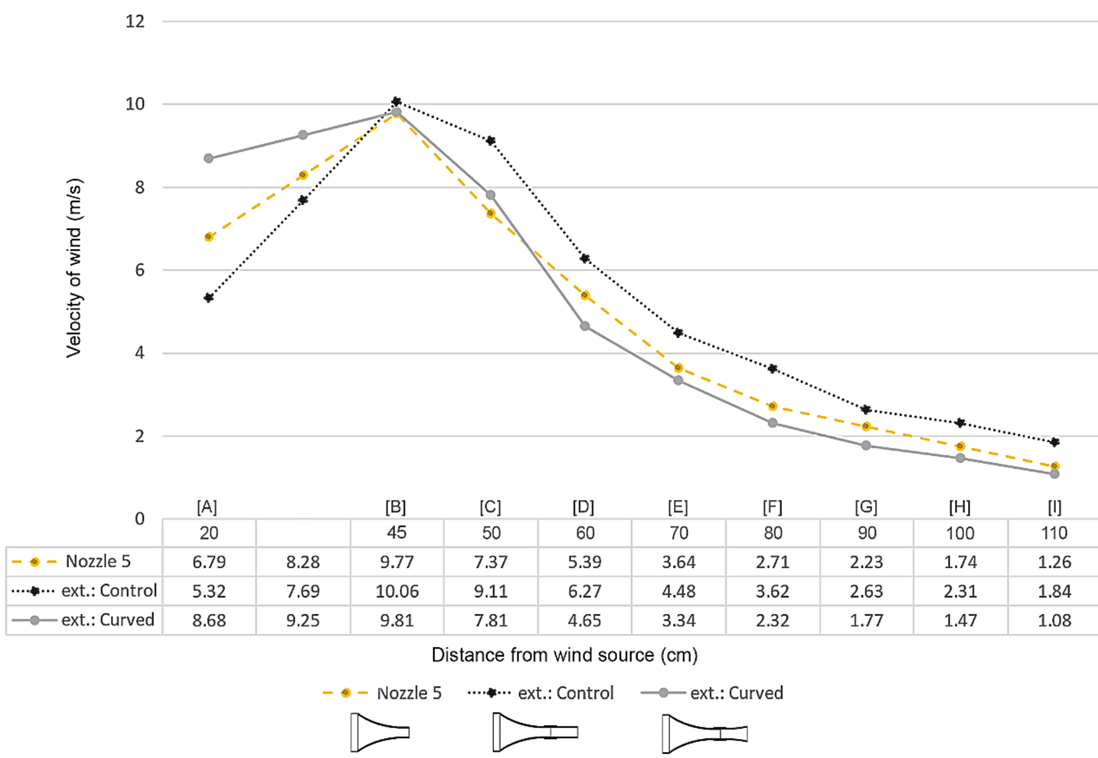
Wind velocity at source = 11-12 m/s (25-27 mph)
Pressure on the surface = 65 Pa

d in = 10.8 cm
d out = 4.8 cm
length = 24.5 cm



Reading #	V in at 20 [A]	Avg. of A & B	V out at 45 [B]	V out at 50 [C]	V out at 60 [D]	V out at 70 [E]	V out at 80 [F]	V out at 90 [G]	V out at 100 [H]	V out at 110 [I]
1	8.36	9.17	9.98	7.82	4.67	3.43	2.16	1.62	1.55	1.12
2	8.62	9.22	9.82	7.67	4.70	3.32	2.23	1.73	1.52	1.07
3	8.76	9.32	9.87	7.49	4.72	3.20	2.30	1.92	1.63	1.04
4	8.87	9.28	9.69	7.92	4.42	3.27	2.42	1.67	1.42	1.20
5	8.85	9.29	9.73	7.89	4.58	3.29	2.38	1.78	1.44	1.10
6	8.68	9.27	9.86	7.85	4.64	3.45	2.58	1.76	1.38	1.14
7	8.72	9.27	9.82	7.87	4.68	3.41	2.44	1.92	1.54	1.08
8	8.76	9.32	9.88	7.79	4.69	3.38	2.18	1.87	1.33	0.99
9	8.54	9.15	9.75	7.82	4.75	3.42	2.22	1.80	1.44	1.01
10	8.55	9.12	9.69	7.84	4.69	3.27	2.28	1.77	1.58	1.04
11	8.78	9.28	9.78	7.96	4.64	3.25	2.36	1.68	1.36	1.12
Average Velocity	8.68	9.24	9.81	7.81	4.65	3.34	2.32	1.77	1.47	1.08

Comparing wind-velocity trends of nozzle #5, with both extension attachments, nozzle #5 with the straight (control) extension exhibited the maximum change in velocity (4.74 m/s) in comparison to its output without any extensions (2.98 m/s) and with the outwardly-curved extension (1.13 m/s) as shown in Figure 12.



	[A] 20		[B] 45	[C] 50	[D] 60	[E] 70	[F] 80	[G] 90	[H] 100	[I] 110
Nozzle 5	6.79	8.28	9.77	7.37	5.39	3.64	2.71	2.23	1.74	1.26
ext.: Control	5.32	7.69	10.06	9.11	6.27	4.48	3.62	2.63	2.31	1.84
ext.: Curved	8.68	9.25	9.81	7.81	4.65	3.34	2.32	1.77	1.47	1.08

Figure 12: Trend of air velocities measured at specified distances from the wind source through nozzle #5 and its extensions.

Although the change in velocity in nozzle-form #5 was the greatest, the value of output velocity at the nozzle outlet was seen to be the maximum in nozzle-form #4 with the straight (control) extension (11.06 m/s), in comparison to nozzle #3 (10.19 m/s) and nozzle #5 (10.06 m/s). Velocity change in the case of nozzle #4 as indicated in Figure 13 was highest, when compared to the other two nozzle-forms as shown in Table 16. The velocity curve from nozzle #4 was also more streamlined than that of nozzles #3 and #5.

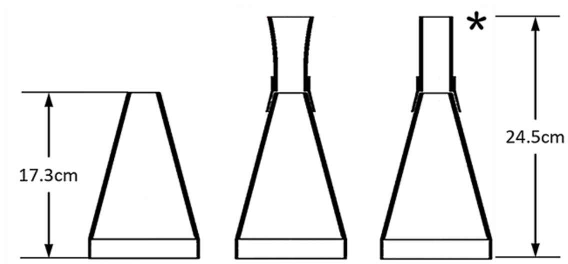


Figure 13: Nozzle #4 – The most effective sectional profile. *Nozzle #4 with the straight extension performed the best among all others.

Table 16: Change in wind velocities through nozzle-forms #3, #4, #5, and their straight (control) and outwardly-curved extensions.

	V in	*V out*	Velocity Change
	V at 20cm	*V* at 40cm	*V out - V in*
	(m/s)	(m/s)	(m/s)
Nozzle 3	7.64	9.36	1.72
Nozzle 3: ext. Control	7.05	10.19	3.14
Nozzle 3: ext. Curved	7.84	9.91	2.07
Nozzle 4	7.64	9.49	1.85
* Nozzle 4: ext. Control	7.64	11.06	3.42
Nozzle 4: ext. Curved	7.94	10.07	2.13
Nozzle 5	6.79	9.77	2.98
Nozzle 5: ext. Control	5.32	10.06	4.74
Nozzle 5: ext. Curved	8.68	9.81	1.13

Even though nozzle #4 with the straight extension performed the best among all the permutations that were tested, the comparative line-graphs indicated that the control (i.e. straight nozzle extensions in all three cases) exhibited the greatest outlet velocity reading; it was observed that the outwardly-curved outlet profile did not show any perceptible increase in the wind-velocity flowing through it. This led to the next stage of development in the research.

Impact of Tube lengths on Wind Velocity Output

Comparison of wind-velocity trends indicates the extension control (in all three cases) exhibited the greatest outlet velocity reading as shown in Table 16. The next stage in the research involved investigating the effect of change in lengths on velocity readings at specific distances from the wind source. This exploration was conducted using PVC tubes as shown in Figure 14 in the same experimental setup as before.

Figure 14: Apparatus used to investigate impact of tube lengths on wind-velocity output.

Wind-velocity trends in three scenarios were measured and recorded at four points – Inlet velocity at 20cm, and Outlet velocities at 50cm, 65cm, and 125cm away from the source:

1. Without any PVC tubes,
2. Through a PVC tube with control nozzle-X, and
3. Through a PVC tube with nozzle #4.

The wind velocity readings in each of three scenarios were tabulated as shown in Table 17, and a comparative line-graph of these velocities was plotted in Figure 16.

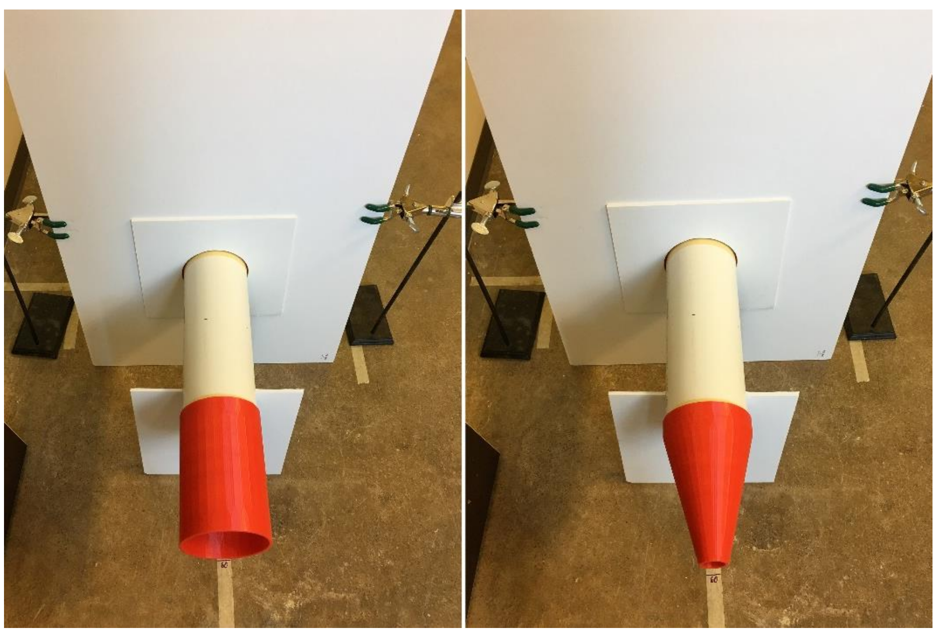


Figure 15: Tests conducted using control-X and nozzle #4 with PVC tube to investigate impact of varying lengths on wind-velocity trends through them.

Table 17: Wind-velocity readings taken at specified points from the wind source in the absence of PVC tube, and through specific tube lengths attached with control-X and nozzle #4 at points corresponding to the readings without a tube.

Without PVC tube

Wind velocity at source = 11-12 m/s (25-27 mph) d in = 10.5cm
Pressure on the surface = 60 Pa

Reading #	V in at 20	V out at 50	V out at 65	V out at 125
1	10.75	3.57	3.03	2.12
2	10.72	3.48	2.87	2.01
3	10.73	3.45	2.99	1.96
4	10.68	3.52	2.96	1.87
5	10.77	3.76	2.41	2.01
6	10.75	3.58	2.59	2.07
7	10.73	3.42	3.04	1.64
8	10.70	3.30	3.12	1.79
9	10.75	3.48	2.97	1.98
10	10.73	3.53	3.08	1.64
11	10.78	3.34	3.12	1.72
Average Velocity	10.74	3.49	2.93	1.89

Control-X with PVC tube

Wind velocity at inlet is about 11-12 m/s (25-27 mph) d in = d out = 10.5cm
Pressure on the surface = 60 Pa

Reading #	V in at 20	V out at 50	V out at 65	V out at 125
1	10.68	6.99	6.23	6.61
2	10.71	7.07	6.60	6.42
3	10.64	6.98	6.42	6.20
4	10.55	7.11	6.34	6.13
5	10.58	7.01	6.21	6.25
6	10.42	7.06	6.37	6.61
7	10.63	7.18	6.42	6.47
8	10.12	6.90	6.28	6.23
9	10.37	6.81	6.51	6.42
10	10.48	6.57	6.46	6.50
11	10.67	6.84	6.72	6.49
Average Velocity	10.53	6.96	6.41	6.39

Nozzle #4 with PVC tube

Wind velocity at inlet is about 11-12 m/s (25-27 mph) d in = d out = 10.5cm
Pressure on the surface = 55 Pa

Reading #	V in at 20	V out at 50	V out at 65	V out at 125
1	6.63	9.75	9.46	9.62
2	6.48	9.35	9.68	9.70
3	6.54	9.42	9.63	9.44
4	6.68	9.63	9.72	9.72
5	6.71	9.52	9.75	9.78
6	6.42	9.68	9.46	9.63
7	6.53	9.72	9.51	9.78
8	6.55	9.93	9.48	10.01
9	6.48	9.89	9.62	9.71
10	6.51	9.82	9.71	9.43
11	6.48	9.78	9.54	9.51
Average Velocity	6.55	9.68	9.60	9.67

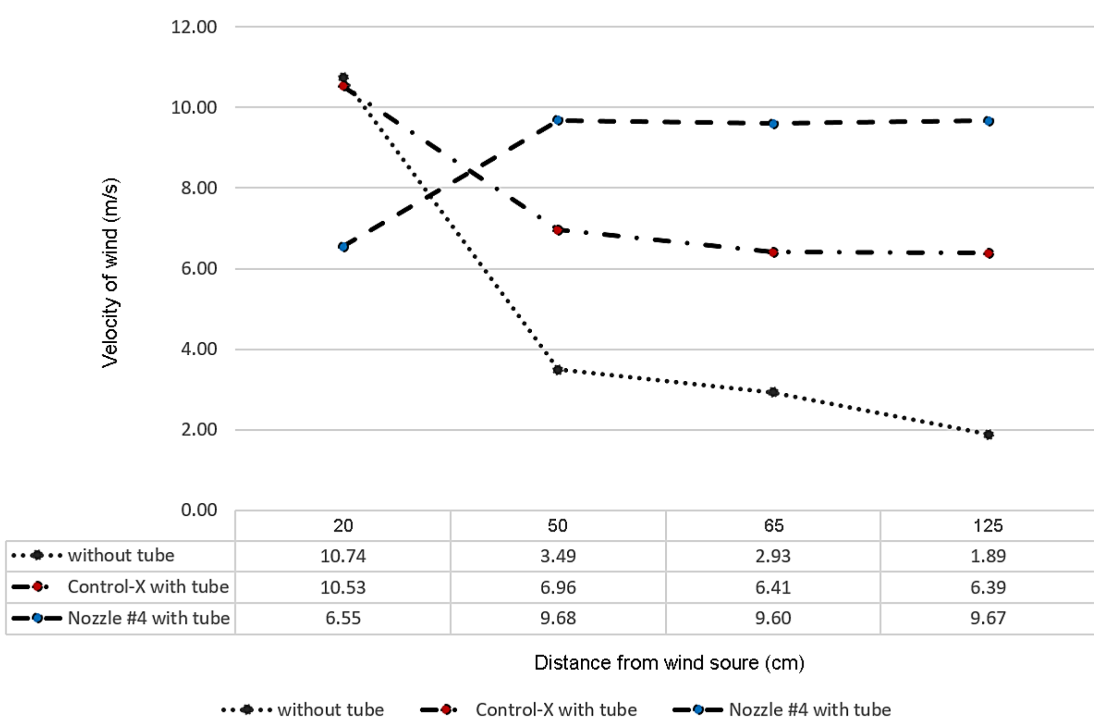


Figure 16: Trend of wind velocities measured at specified distances from the wind source in the absence of PVC tube and through PVC tube attached with control-X and nozzle #4.

It was observed that scenario 3: PVC tube with nozzle #4 performed the best, thus confirming that varied lengths had a positive effect on enhancing wind-velocity output. It not only exhibited a perceptible increase in velocity by an average of 3.13 m/s, but also showed a stable curve of increased outlet-velocities at different distances from the wind source. The "length" parameter was tested in order to understand the potential of a proposed collapsible tube system for as an alternative to enhance natural ventilation in built spaces. One potential application of extending a collapsible tube was to be enable increased air delivery at the point of an occupant's face.

CHAPTER VIII

DISCUSSION

Analysis of the outlet wind velocity trends through all nozzle-forms, and their modifications in the form of combinations with different nozzle extensions as well as varying tube lengths, led to the conclusion that nozzle-form #4 with the straight (control) extension performed the best. It resulted in a perceptible increase in the velocity (4.74 m/s), with the outlet velocity also being the greatest (11.06 m/s) when compared to all other nozzle profiles and their respective extensions.

Since positive results in the wind-velocity readings were seen with respect to the varying lengths of tubes as well, a collapsible tube-system with nozzle #4 would enhance natural ventilation in buildings and help increase sustainability and resilience, especially during natural calamities when mechanical building systems fail. Recently, Payette—a leading interdisciplinary architectural firm in Boston, MA—published a blog in August 2016 reiterating the inclusion of natural ventilation, especially in the healthcare setting to not just improve connection of the patients to a natural environment, but more importantly to be able to reduce operating costs and enhance resiliency planning during a natural disaster.

In addition to building resilience, the system is designed to provide cooling in developing countries that cannot easily afford mechanical ventilation. A collapsible tube system could work on a similar principle as the telescopic cover of an umbrella as shown in Figure 17; this would help enhance not only the velocity of natural wind entering the building, but also help provide direction to where cooling is needed most, such as towards an occupant's face (Figure 18).

Figure 17: Automatic umbrella with a telescopic cover - Conceptual inspiration for the collapsible tube system for natural ventilation. Photo Source: (eBay 2016)

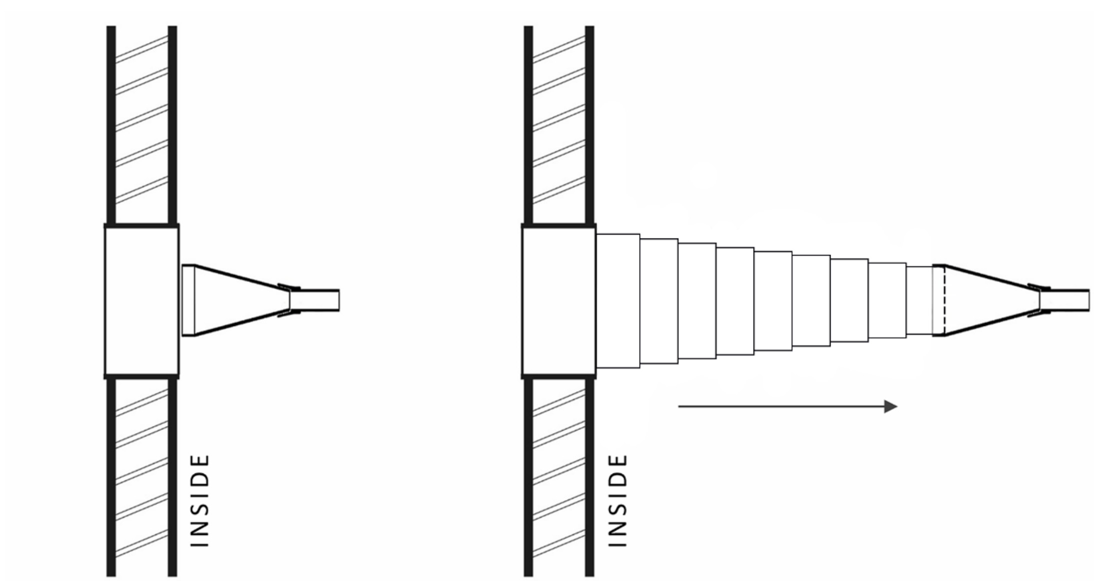


Figure 18: A collapsible tube system of Nozzle #4 with straight (control) extension could enhance natural ventilation and improve comfort of building occupants.

Autodesk Flow Design^{TM} simulations had provided insight regarding the effect of nozzle profiles on the wind-velocity output trend through them. After conducting physical experiments to investigate the impact of various factors on the output velocity trend, it was observed that the best performing nozzle #4, in fact, coincided with the software simulation result that showed greatest velocity output (depicted by warmer colors at the constriction in Figure 5 – Conical). This supports the need to extend this research to include advanced wind-flow software to simulate a wider range of nozzle modifications, and even test the most effective prototypes against the remaining five parameters affecting human comfort in buildings as mentioned in the ASHRAE-55 Standard.

CHAPTER IX

CONCLUSION AND FUTURE WORK

Measurement of wind-velocity and analysis of the readings through different nozzle profiles, while maintaining consistent experimental setup and environment enabled the study to reach significant conclusions such as:

1. Profiles of nozzle-forms 3, 4, and 5 exhibited a perceptible wind velocity increase of 0.36, 0.49, and 0.77 m/s respectively.
2. Straight extensions enhanced the wind-velocity outputs of the nozzles significantly, with nozzle #4 showing maximum velocity output (11.06 m/s) leading to a 4.74 m/s increase in velocity.
3. PVC tube with nozzle #4 exhibited a perceptible increase in wind velocity of 3.13 m/s, and also showed a stable curve of increased outlet-velocities at different distances from the wind source.

This study focused on change in wind-velocity to increase natural cross-ventilation in buildings. As this research has established a baseline for development of nozzle profiles, it is recommended that in a future study different permutations and combinations using more advanced wind-flow software be tested. Additionally, future work can focus on optimizing wind velocity through a flexible hose delivery system that would enable adjustability in directing air flow to desired targets in built spaces.

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