WindCatcher

Design and Passive Ventilation Optimization

My interest in passive cooling began in a middle school Social Studies classroom in Saudi Arabia, where I first encountered the iconic **Barjeel** of the Gulf coast. This curiosity was later reinforced through Pakistan Studies and classroom discussions on the **Manghu**—wind-scoops found across the Sindh and Balochistan regions. I became aware that from the deserts of the Hejaz to the coast of Makran, diverse cultures independently developed sophisticated architectural strategies for moving air without electricity.

I am now revisiting this shared architectural heritage through the lens of modern fluid dynamics. In this project, I examine how contemporary flow-control principles—drawn from aerospace and automotive engineering—can be used to better understand, reinterpret, and extend the underlying physical logic of the Manghu and Barjeel within a theoretical design framework focused on sustainable passive ventilation.

Project Abstract

This project investigates the design of a passive windcatcher system using first-principles fluid mechanics to improve airflow delivery without mechanical assistance. Working independently and without access to experimental or computational facilities, I developed a theoretically grounded design incorporating bell-mouth inlets, controlled geometric transitions, and flow-guiding vanes inspired by diffuser and inlet theory. The project emphasizes design reasoning, cross-disciplinary synthesis, and critical evaluation of assumptions, while explicitly acknowledging the limitations of unvalidated theoretical analysis.

About the Author

Areebah Abdul Qadir Khan is an A-Level student. This project represents an independent, pre-university theoretical study applying fluid mechanics principles to passive windcatcher design.

Reflective Statement on Independent Research Project

Windcatcher Design and Passive Ventilation Optimization

This project began with a simple question: how can a traditional windcatcher be redesigned to deliver fresh air more effectively into an indoor space without relying on electrical systems? What initially appeared to be an architectural exploration gradually evolved into a deeper investigation of airflow behavior, pressure losses, and flow conditioning.

My early work relied on commonly cited proportional rules in passive ventilation design, such as defining inlet area as a percentage of room size. While these rules were useful starting points, I soon realized that they did not explain why certain configurations performed better than others. This led me to study fundamental fluid mechanics principles, particularly continuity, pressure–velocity trade-offs, and boundary layer behavior. Applying the continuity relationship ($A_1V_1 = A_2V_2$) helped me understand how changes in cross-sectional area influence velocity and pressure, and why inlet geometry plays a critical role in determining how much air can be drawn into a space.

A major focus of the project became the role of geometric transitions in influencing airflow quality. Through the study of bell-mouth inlets and diffuser theory, I learned how smooth curvature, appropriate entry radii, and gradual area expansion can reduce energy losses and lower the likelihood of flow separation. This understanding guided my design of a bell-mouth inlet and shaft transition that prioritizes controlled expansion rather than abrupt geometric changes.

An early architectural decision to introduce a domed insert at the upper torus prompted further investigation into how incoming air would interact with this geometry. Considering the potential for stagnation and wake formation at this junction, I subsequently developed the dome into a nose-cone-like form. This refinement was intended to guide airflow more smoothly into the shaft and reduce losses associated with blunt intersections.

As the design developed, I began incorporating concepts from outside traditional architectural practice, particularly from aerospace and automotive aerodynamics. Logarithmic spiral vanes and parabolic vane-angle progression were investigated as methods for guiding airflow direction and managing changes in velocity within the inlet region. I explored micro-vortex generators as a potential boundary-layer control strategy, drawing inspiration from automotive aerodynamics. Further evaluation suggested that their placement may not align optimally with the pressure gradients present in this geometry. Investigating this limitation strengthened my understanding of when such techniques are effective, highlighting the importance of context-specific application rather than direct transfer of solutions. Although such techniques are uncommon in passive building ventilation, studying them helped me understand how similar physical principles can apply across different engineering domains.

An important lesson from the later stages of the work was using a range of values rather than relying on a single optimal value for dimensions and ratios like diffuser area ratios, vane spacing, shaft length, and the placement of flow-conditioning features. This approach helped me avoid false precision and better reflect real-world design constraints, where robustness and tolerance are often more important than theoretical optimization.

I am aware that this work has clear limitations. The design decisions and observations are based on theoretical reasoning, established geometric ratios, and insights from existing engineering literature, rather than experimental testing or computational simulations. I did not have access to wind tunnel facilities or CFD tools, and therefore treated this project as a design and reasoning exercise rather than a validated research study. If given the opportunity to continue this work at university, my next steps would be to define operating conditions more rigorously, examine sensitivity to wind speed and turbulence, and evaluate the design using simulation or physical models.

This project taught me that research is not about arriving at final answers, but about understanding assumptions, asking better questions, and making informed design decisions within constraints. If beginning this project again, I would establish clearer performance metrics and operating constraints at the outset, as this would have helped focus design decisions and made assumptions more explicit throughout. More importantly, it confirmed my interest in pursuing engineering and applied sciences at a deeper level. I found that I am particularly motivated by problems that sit at the intersection of mathematics, physics, and design, and I am eager to develop the analytical and experimental skills needed to turn conceptual reasoning into validated solutions.

Document Structure

This technical documentation is organized to build understanding progressively through the complete design development:

- **Inlet Design** - Area calculations and continuity principles
- **Nose Cone** - Stagnation control and flow conditioning
- **Vanes** - Logarithmic spirals and angle progression
- **MVG** - Boundary layer management and flow uniformity
- **Diffuser** - Diffuser geometry and shaft length
- **Summary** - Complete system assembly and design philosophy
- **Appendix** - Formulas, references, and theoretical foundations
- **Citations** - Academic and technical literature sources

Inlet & Bell Mouth Fundamentals

Inlet & Shaft Area Fundamentals

Room Specifications

Room Area: 4 × 5 = **20 m²**

Area Calculations

1) Inlet Area → 3% of room area

3% × 20 m² = **0.6 m²**

2) Shaft Area → 3.5% of room area

3.5% × 20 m² = **0.7 m²**

Continuity Principle

According to: $\mathbf{A_1V_1 = A_2V_2}$

The cross-sectional area does increase, causing velocity to decrease. We are trading off **velocity for static pressure**, allowing greater mass flow rate (total volume of fresh air delivered) rather than just local velocity at the entrance, as a suction effect is formed, pulling more air through the inlet.

Making internal shaft slightly larger than inlet, the necessary space is provided for the air to unfold and fill the duct without hitting the walls and creating rotational turbulence or secondary vortices.

Bell Mouth Dimensions

Ideal Bell-Mouth Dimensions

Length-to-Shaft Ratio (L / d)

The axial length (L) of the bell-mouth should be: **0.55 × diameter of exit shaft (d)**

The entry diameter (D) should be: **1.625 × diameter of exit shaft (d)**

Exit shaft diameter (d): **94 cm** (from $0.7m^2$ cross-sectional shaft area)

L = 0.55 × 94 = 51.7 cm ≈ **52 cm**

Entry Diameter (D) = 1.625 × 94 = 152.75 cm ≈ **153 cm**

Entry Corner Radius (r / D)

The most critical factor for minimizing **vena contracta** (flow narrowing) is adding an entry radius (r) that is:

0.08 × entry diameter (D) = 0.08 x 153 = 12.24cm

Performance Benefits

- This specific addition jumpstarts efficiency by around **0.5%**
- Reduces boundary layer thickness by **7 times**
- Allows the air to be closer to the aluminum and remove the heat away much faster
- The thickness provides the gradual turn air needs to stay laminar (smooth)

Discharge & Loss Coefficients

Relationship between Coefficient of Discharge (C_d) and Loss Coefficient (K_e)

Without bell mouth → K_e = 0.5

With bell mouth (first ratio set):

$C_d \geq 0.95 \rightarrow K_e < 0.1$

Formula Relating C_d to Pressure Loss

$\Delta P_t / (0.5\ \rho\ U^2_{avg}) = -2.207\ C_d + 2.193$

If C_d = 0.975 → $K_e = 0.041$

Nose Cone & Inlet Torus Design

Inlet Torus Gap

Cylindrical area of gap (where wind enters) must be **greater than entry area of bell-mouth**.

Area of bell-mouth entry:

$\pi D^2 / 4$ (D = entry diameter)

Area of 360° gap:

$\pi \times D \times H_{gap}$

Required condition:

$H_{gap} \geq D / 4$

Range for H_{gap}: 0.25 D to 0.31 D → 38.85 cm to 45.9 cm

Selected: 40 cm

Nose Cone Geometry

Why Should the D/4 Gap be Prioritized Over 3% Room Area Rule?

- Using 3% rule gives gap = 12.5 cm
- Using $H_{gap} \geq D/4$ gives gap = 40 cm

Using smaller gap would create a **bottleneck**, increasing K_e and energy loss.

Nose Cone

Shape: Conical or elliptical profile with a sharper apex

As angle of apex decreases (becomes pointier), drag coefficient C_d decreases.

Optimal height: 0.5 r to 1.5 r (1.5r gives **81.4% reduction in head loss**)

r = radius of shaft = 47 cm

1.5 × 47 = 70.5 cm ≈ **71 cm** (height of nose cone [conical])

Diameter of cone = shaft diameter = **94 cm**

Nose Cone Extension Logic

- Purpose of nose cone is to **eliminate stagnation point** when air hits a blunt surface.
- Acts as **curved guide rail**
- Extending cone into shaft expands flow area by **76.29%**
- Prevents **flow tipping and wake formation**
- Avoids massive turbulence at shaft center

Structural Core and Internal Vane Transition Design

1. Central Rod (Internal Flow Stabilization Core)

As the 94 cm diameter nose cone tapers to a sharp point at approximately 71 cm depth, the absence of a central structure would promote the formation of a low-pressure wake and central swirl region. To mitigate this effect, a central support rod was incorporated.

Rod Diameter: 8 cm

Rod Length: Extends from the 71 cm depth (attached to the nose cone tip) to the downstream termination of the internal vanes

Structural Role: Acts as the central hub for the internal vane assembly

Aerodynamic Function:

The rod occupies the stagnation and wake region downstream of the cone tip, preventing flow collapse toward the centerline. By doing so, it maintains the airflow in an annular configuration, reducing the tendency for central recirculation and promoting more uniform axial velocity distribution through the vane passage.

This approach stabilizes the internal flow field while simultaneously providing a mechanically robust anchoring spine for the vane system.

2. Internal Radiusing (Fillets at Structural Junctions)

Given the use of 5 mm aluminum plate for vane construction, sharp 90° junctions at vane interfaces would introduce strong local adverse pressure gradients, leading to corner vortex formation and increased drag. To reduce these effects, internal radiusing was applied at critical junctions.

Fillet Radius: 10–15 mm

Implementation Method:

- Formation of a slightly oversized, concave structural fillet weld
- Subsequent smoothing using radiused sanding tools or an epoxy-based fairing compound (e.g., Lab-Metal or JB Weld) to create a continuous curved transition

Priority Locations:

- **Vane-to-Shaft Interface (Root):** Most critical region, as boundary-layer thickening and separation are most likely to initiate here
- **Vane-to-Rod Interface (Hub):** Essential for maintaining attached flow around the central core and minimizing secondary vortices

These fillets reduce local flow separation, lower form drag, and improve overall internal flow uniformity without adding significant structural complexity.

3. Integration of Central Rod with Nose Cone

Joint Geometry:

The upstream end of the 8 cm rod is tapered or machined to mate flush with the terminal geometry of the nose cone, eliminating abrupt cross-sectional changes.

Alignment and Assembly:

The twelve internal vanes are welded to the central rod beginning at the 71 cm depth, ensuring precise axial alignment and providing a rigid structural framework for the internal vane array.

This integrated configuration ensures both aerodynamic continuity and mechanical stability throughout the internal transition region.

Vane Geometry & Logarithmic Spirals

Vanes Geometry & Logarithmic Spiral

Vanes Thickness

5 mm throughout

Vane Parameters by Depth

Depth Range	Zone	Vane Angle	Width	Arc Gap
0–40 cm	Entry gap	31°	27.5 → 31.3 cm	40cm
40–71 cm	Transition	31° → 0°	31.3 → 45 cm	40 → 26.2 cm
71 cm	Cone tip	0°	45 cm	26.2cm
71–112 cm	Guidance	0°	47 cm	24.6cm
112 cm	Fin End	0°	47cm	24.6cm

Arc gap reduces: 40 cm → 26 cm → 24.6 cm

Vane width calculation = $R_{(bellmouth)}$ − $R_{(cone)}$ − clearance

Logarithmic Spiral from Upper Torus to Bell-Mouth Entrance

- Using this allows the air to see the same vane slope at all points along the spiral
- This prevents the air from stalling or creating turbulance as it accelerates

Formula: $r = a\, e^{b\theta}$

- a = 76.5 cm (starting radius)

- $b = \cot(\beta) = \cot(31°) \approx 1.66$ (The growth factor that determines how tightly the spiral winds)

Using this ensures air always sees the same vane slope and **prevents stalling**.

Vane Angle Progression

Unwinding the vanes from **31° → 0°** is done through a **parabolic progression** instead of linear.

Formula

$\beta(x) = \beta_{inlet} (1 - (x / L)^2)$

- x = current depth (0 → 52 cm)
- L = total axial length (52 cm)
- $\beta_{inlet} = 31°$

Notes for Follow-Up

Why parabolic is better than linear

- As air passes through a vane, it undergoes acceleration due to changes in flow direction, resulting in pressure gradients along the vane surface.
- A linear vane profile introduces abrupt curvature at the inlet and outlet, causing sudden pressure spikes that increase adverse pressure gradients and promote flow separation, particularly near the wall where the boundary layer is still developing.
- A parabolic vane profile imposes a smooth, continuous change in curvature, maintaining a more uniform rate of momentum change along the vane length and avoiding localized regions of high stress or turbulence.
- As air travels along the bell-mouth and vane surfaces, the boundary layer thickens due to viscous effects at the wall.

- A linear vane does not account for this boundary layer growth, often forcing the flow to turn sharply while it is still stabilizing against the surface.
- A parabolic vane initially applies gentle turning where the airflow is faster and less organized, and progressively increases turning as the flow approaches the shaft, where the boundary layer is more developed.
- This alignment between vane curvature and boundary layer growth improves flow attachment, enhances velocity uniformity, and reduces energy losses through the inlet and transition region.

Why 2 cm clearance

- Vibration Dampening (The “Chatter” Problem): Aluminum expands and vibrates under high wind speeds. If the 5mm aluminium vane were touching the cone without being welded, it would “clatter” against the cone like a drum, leading to noise and eventual metal fatigue/cracking.
- The Boundary Layer “Slip”: Air right next to a surface moves slower (the boundary layer). A 2cm gap allows a thin “film” of air to slip between the vane edge and the cone. This prevents the vane from “tripping” the air that is moving along the cone’s surface, keeping the flow attached and laminar.
- Thermal Expansion: Since you are using aluminium, it expands more than steel when it gets hot in the sun. That 2cm gives the structure “room to breathe” so it doesn’t warp or buckle the nose cone.

Why vanes should be close to cone

- Pressure Containment: If the vanes were far away from the cone (e.g., a 10 cm or 20 cm gap), the air would simply “leak” sideways from one vane section to another. This cross-flow creates large “boundary layer separation” bubbles that destroy your suction.
- The “Piston” Effect: By keeping the vanes close to the cone, you force the air to stay within its 12 designated “lanes.” This maintains the high-velocity “slug” of air that is necessary to achieve that 81.4% reduction in head loss.
- Preventing the Center-Vortex: Without vanes hugging the cone, the air would naturally start to “spin” around the cone in a chaotic way, creating a low-pressure “dead zone” right where you want the most flow.

Micro-Scale Vortex Generators (MVGs)

Purpose

Micro-vortex generators were explored as a conceptual boundary-layer control strategy to mitigate flow separation under adverse pressure gradients in diffuser-type geometries. Their inclusion is based on established aerodynamic literature and is treated as **exploratory** rather than optimized for this specific passive ventilation system.

MVG Sizing (Height)

Literature-supported range:

$$h / \delta \approx 0.2 \text{ to } 0.4$$

Where:

- h = MVG height
- δ = local boundary-layer thickness

Design choice for this study:

$$h \approx 0.3\delta$$

Rationale:

- Heights below ~0.2δ generate weak vortices
- Heights above ~0.5δ introduce excessive parasitic drag
- A mid-range value balances vortex strength and drag, consistent with diffuser studies

Airfoil-shaped MVGs were considered based on literature reporting improved vortex coherence and reduced form drag relative to rectangular geometries. Reported drag reductions in controlled studies are noted as contextual references, not as predicted outcomes for this design.

MVG Length

$$l / h \approx 4 \text{ to } 6$$

This ratio supports:

- Stable vortex formation
- Delayed vortex breakdown downstream

MVG Spacing

Literature-supported range:

$$\lambda / h \approx 8 \text{ to } 15$$

Design choice for this study:

$$\lambda \approx 10h$$

Rationale:

- Prevents vortex interaction and cancellation
- Maintains uniform boundary-layer energization
- Avoids unnecessary drag from excessive MVG density

Placement Within the Conical Diffuser

MVGs are most effective when placed just upstream of the region where adverse pressure gradients begin to dominate, rather than at the diffuser entrance or exit.

Placement guideline from literature:

$$x / L \approx 0.05 \text{ to } 0.15$$

Where:

- x = distance from start of diffuser
- L = total diffuser length

For this geometry:

- L = 153 cm
- x = 7.5 to 23 cm

Design placement:

$$x \approx 15 \text{ cm}$$

This position corresponds to the early diffuser expansion zone, where boundary-layer separation risk begins to increase.

MVG Orientation and Offset

Yaw Angle

$$\alpha \approx 15° \text{ to } 25°$$

Design choice:

$$\alpha \approx 15°$$

Lower yaw angles reduce drag penalties while maintaining vortex strength in low-speed flows.

Circumferential Arrangement

- MVGs are offset from vane centerlines to avoid wake interaction
- Circumferential spacing follows the selected $\lambda \approx 10h$ guideline
- Placement avoids direct alignment with vane trailing edges

This configuration allows MVGs to interact with undisturbed, high-energy flow regions, maximizing boundary-layer re-energization potential.

Limitations

The effectiveness of MVGs depends strongly on:

- Boundary-layer thickness
- Reynolds number
- Pressure-gradient distribution

Because these parameters vary in passive ventilation systems, MVG implementation in this project is **conceptual and exploratory**, intended to examine flow-control principles rather than to assert performance gains.

Diffuser Design

Diffuser Geometry and Shaft Length

Diffuser

Follows **2.6 : 1 area ratio**

Bell-mouth style with same ratios

- **Top diameter:** 94 cm
- **Bottom diameter:** 153 cm
- **Axial length:** 52 cm

Entry Corner Radius

Radius = 0.08 × 153 = **12.2 cm**

Shaft Length

Shaft length = 150 cm

Constraint: 0.40d < shaft length < 4.0d

Selected: 1.6d

System Summary

The complete WindCatcher design integrates multiple aerodynamic principles into a cohesive passive ventilation system:

Key Components

- **Inlet Torus** with 40 cm gap for optimal mass flow
- **Bell-mouth entry** with 12.24 cm corner radius (0.5% efficiency gain, 7× boundary layer reduction)
- **Nose cone** at 71 cm height (81.4% head loss reduction)
- **Logarithmic spiral vanes** transitioning from 31° to 0°
- **Micro-vortex generators** for boundary layer control
- **Diffuser** with 2.6:1 area ratio for gradual expansion

Design Philosophy

Rather than pursuing single "optimal" values, this design uses **bounded ranges** and **design envelopes** to ensure robustness across varying conditions. Each geometric transition is carefully considered to minimize energy loss, prevent flow separation, and maintain laminar characteristics through the system.

The cross-disciplinary synthesis of aerospace, automotive, and HVAC principles demonstrates that fundamental fluid mechanics can be applied effectively across domains when underlying physics is properly understood.

Operating Conditions

Design assumptions include moderate urban wind conditions (approximately 3–5 m/s), standard atmospheric pressure, and a target ventilation rate appropriate for a 20 m^2 occupied space. A complete design would require sensitivity analysis across a wider range of wind speeds, turbulence intensities, and thermal conditions.

Further Work

This project represents a theoretical design exercise that would benefit from validation and extension through:

- CFD simulation to examine pressure loss and flow separation under varying wind speeds
- Parametric sensitivity analysis of vane spacing and curvature
- Wind tunnel testing of scaled physical models
- Investigation of thermal buoyancy coupling under mixed-mode ventilation
- Structural vibration analysis under gust loading

Appendix

Key Formulas

Continuity Equation

$A_1V_1 = A_2V_2$

Where A = cross-sectional area, V = velocity

Bell-Mouth Ratios

- Axial length: $L = 0.55d$
- Entry diameter: $D = 1.625d$
- Corner radius: $r = 0.08D$

Pressure Loss Relationship

$\Delta P_t / (0.5\ \rho\ U^2_{avg}) = -2.207\ C_d + 2.193$

Torus Gap Requirement

$H_{gap} \geq D / 4$

Ensures cylindrical gap area exceeds bell-mouth entry area

Nose Cone Height

Optimal: 1.5r (where r = shaft radius)

Provides 81.4% reduction in head loss

Logarithmic Spiral Vane

$r = a\ e^{b\theta}$

- a = starting radius (76.5 cm)
- $b = \cot(\beta)$ where β = vane angle (31°)

Parabolic Vane Angle Progression

$\beta(x) = \beta_{inlet} (1 - (x / L)^2)$

- x = current depth
- L = total axial length
- β_{inlet} = initial angle (31°)

MVG Sizing Ratios

- Height: $0.8 < h/\delta < 1.0$ (δ = boundary layer thickness)
- Length: $L = 2.5h$
- Spacing: $s/h = 5$
- Placement: x/L = 0.05 to 0.10

Design Parameters Summary

Parameter	Value	Benefit
Room Area	20 m^2	Base specification
Inlet Area	0.6 m^2 (3%)	Mass flow optimization
Shaft Area	0.7 m^2 (3.5%)	Velocity-pressure trade-off
Shaft Diameter	94 cm	—
Entry Diameter	153 cm	Smooth expansion
Bell-Mouth Length	52 cm	Gradual transition
Corner Radius	12.24 cm	7× boundary layer reduction
Torus Gap	40 cm	Avoids bottleneck
Nose Cone Height	71 cm	81.4% head loss reduction
Vane Angle Range	31° → 0°	Prevents stalling
Shaft Length	150 cm (1.6d)	Within design envelope
Diffuser Area Ratio	2.6 : 1	Controlled expansion

Coefficient Definitions

- **C_d** - Coefficient of Discharge (dimensionless efficiency metric)
- **K_e** - Loss Coefficient (energy loss metric)
- **δ** - Boundary Layer Thickness
- **β** - Vane Angle
- **ρ** - Air Density

- **ΔP** - Pressure Differential

Design Envelope Constraints

- Shaft length: $0.40d < L < 4.0d$
- Torus gap: $0.25D < H_{gap} < 0.31D$
- Nose cone height: $0.5r < h < 1.5r$
- MVG placement: $0.05L < x < 0.10L$
- MVG spacing: $3h < s < 5h$
- Height limit: ≤ 3 storeys

Project Methodology

This design was developed through theoretical analysis and literature review rather than experimental validation. Future work could include:

- CFD simulation to validate flow patterns
- Wind tunnel testing at scale
- Sensitivity analysis for varying wind conditions
- Physical prototype construction and measurement
- Thermal comfort and air quality assessment

Cross-Disciplinary Sources

Design principles were synthesized from multiple engineering domains:

- **Aerospace:** Nose cone geometry, logarithmic spirals
- **Automotive:** Diffuser ratios, vortex generators
- **HVAC:** Bell-mouth inlets, ventilation rates
- **Fluid Mechanics:** Continuity, boundary layer theory

Key References

This design was informed by established engineering principles and ratios documented in the following sources:

- **ASHRAE Handbook - Fundamentals** - Bell-mouth inlet geometry and ventilation design principles
- **White, F.M., Fluid Mechanics** - Continuity equations, pressure-velocity relationships, and boundary layer theory
- **Idelchik, I.E., Handbook of Hydraulic Resistance** - Loss coefficients and discharge coefficients for inlet geometries
- **SAE Technical Papers** - Automotive diffuser design and vortex generator placement
- **NASA Technical Reports** - Inlet and nose cone geometry for aerodynamic applications

Note: All design decisions and performance implications are theoretical and based on established geometric ratios and fluid mechanics principles rather than experimental validation specific to this configuration. For complete citations, see the Citations page.

Citations & References

This project draws upon established engineering principles documented in academic literature, technical handbooks, and industry sources. The following sources informed the theoretical framework and design ratios used throughout this work.

Primary Engineering References

Fluid Mechanics & Flow Theory

- **White, F.M.** *Fluid Mechanics* — Continuity equations, pressure-velocity relationships, and boundary layer theory
- **ASHRAE Handbook - Fundamentals** — Bell-mouth inlet geometry and ventilation design principles
- **Idelchik, I.E.** *Handbook of Hydraulic Resistance* — Loss coefficients and discharge coefficients for inlet geometries
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- **Chen, C., Yang, Y., & Yan, Y.** (2025). Computational Analysis of Tandem Micro-Vortex Generators for Supersonic Boundary Layer Flow Control. *Computation*
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- **Xue, S., Johnson, B., Chao, D., Sareen, A., & Westergaard, C.H.** (2010). Advanced Aerodynamic Modeling of Vortex Generators for Wind Turbine Applications. *European Wind Energy Conference*

Diffuser Design & Flow Optimization

- **Ruiz, C.A., Kalkman, I., & Blocken, B.** Aerodynamic Design Optimization of Ducted Openings Through High-Rise Buildings for Wind Energy Harvesting
- **Najjar, Y.S.H., & Akeel, S.A.M.S.** (2002). Effect of Prewhirl on the Performance of Centrifugal Compressors. *International Journal of Rotating Machinery*

Industry & Technical Sources

- **NASA Technical Reports (NTRS)** — Inlet geometry, diffuser design, and nose cone aerodynamics
- **SAE Technical Papers** — Automotive diffuser design and vortex generator placement
- **Blair, G.P., & Cahoon, W.M.** (2006). I Have Been Known to Dangerously Pontificate About Intake Bellmouths. *Race Engine Technology*
- **Markiewicz, T., Kaczmarczyk, Ł., & Fabiś, P.** (2017). Influence of Intake System Modification on the Formula Student Engine Power. *Scientific Journal of Silesian University of Technology*

Note on Sources and Analytical Approach

The sources listed above provided the theoretical foundations, established geometric ratios, and design principles relevant to passive ventilation systems. This work represents an independent synthesis and application of these principles to wind-catcher–based passive ventilation design.

Artificial intelligence tools were used as a supportive analytical aid to assist in technical reasoning, exploration of design logic, and verification of calculations based on established engineering relationships. All AI-assisted outputs were critically reviewed, cross-checked against referenced literature, and integrated through independent author judgment. The final interpretations, design decisions, and conclusions reflect the author's understanding and responsibility.

All performance assessments presented are theoretical in nature and derived from published engineering relationships rather than experimental validation of this specific configuration.

Sources were accessed through academic databases, engineering handbooks, and publicly available technical literature.