

Article

Aerodynamic Design and Laboratory Evaluation of a Variable Cross-Section Wind-Suction Channel for Capturing Small Agricultural Pests

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Abstract

Physical control technology as an alternative to chemical pesticides is of great significance for modern sustainable agriculture. However, small pests such as tea green leafhoppers and tea thrips possess sensitive aerodynamic receptors that easily perceive disturbances generated by suction airflow and initiate stress-induced escape behavior. The current bottleneck in the state of the art is that conventional straight tube capture devices generate severe airflow pulsations and turbulence near the intake which act as alarm signals causing pests to escape before entering the effective capture zone. To resolve this trade-off, this study developed and validated a variable cross-section wind-suction channel based on the principle of biological behavioral suppression. This design incorporates a three-stage functional structure consisting of a flow-stabilizing intake section a guided acceleration section and a high negative-pressure throat to achieve a synergistic balance between low disturbance induction and strong aerodynamic confinement. Numerical simulations and prototype experiments show that this design establishes a stable rectified environment at the intake with relative wind speed deviations within 5%. Under controlled laboratory conditions, the average capture rate for target pests exceeded 85% within an effective operating radius of 20 cm. Comparative biological validation further confirms that the capture efficiency of this design is improved by more than 32 percentage points compared with a conventional straight-tube benchmark device. Furthermore, the critical stress-response distance was reduced by approximately 50%, significantly enhancing the concealment of the capture process. These findings elucidate the critical role of channel geometry in resolving the conflict between suction intensity and environmental disturbance providing a theoretical foundation and technical support for the development of high efficiency and precision plant protection equipment.



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1. Introduction

Driven by global strategies for sustainable agricultural development, reducing the adverse impacts of chemical pesticides on ecosystems and food safety has become a central

concern in modern plant protection. Agricultural pest management is currently undergoing a critical transition from chemical dependency toward integrated green prevention and control, which has become a strategic priority worldwide [1]. Under the combined influence of climate warming and evolving cultivation practices, the structure of field pest communities has undergone a pronounced shift. Small piercing–sucking pests, such as leafhoppers, whiteflies, and thrips, have increasingly replaced traditional lepidopteran defoliators as the primary biological threats to crop yield and quality [2]. These insects are characterized by small body size, rapid reproduction, severe generational overlap, and a strong propensity for developing insecticide resistance. Consequently, conventional chemical control methods are exhibiting diminishing marginal returns while posing serious risks to agricultural biodiversity. To effectively manage these resilient pests, it is imperative to accelerate the development of green control technologies to resolve the conflict between pesticide residues and ecological safety [3].

In response to this challenge, physical control technologies have gained increasing attention in modern plant protection systems due to their residue-free operation, lack of resistance risk, and relative safety for non-target organisms [4]. At present, field-based physical control strategies primarily employ environmental physical factors—such as light, color, sound, and electromagnetic waves—to attract or repel pests [5]. Among these methods, yellow sticky traps based on insect color preference are widely used both for monitoring pest activity and relative abundance through trap counts and for physical trapping [6], whereas insecticidal lamps exploit phototactic behavior for pest capture [7]. However, these passive trapping techniques often perform poorly during sudden pest outbreaks and suffer from limitations including difficult waste disposal and unintended mortality of natural enemies. To address these shortcomings, wind-suction pest control technology based on aerodynamic principles has emerged as an alternative approach. This method employs specific light wavelengths to attract insects toward an inlet, where negative-pressure air-flow subsequently draws them into a collection chamber. This integrated light-lure and wind-suction model significantly improves capture efficiency for small insects and has been validated in various agricultural and forestry applications [8]. In both greenhouse and open-field environments, intelligent solar-powered wind-suction devices have demonstrated effective pest suppression while alleviating energy supply constraints in remote areas, offering new prospects for unmanned pest management [9].

Beyond direct pest control, suction-based technologies also play an important role in insect population monitoring and ecological research. Compared with traditional sweep-net sampling or visual counting methods, suction traps enable standardized and continuous insect collection. Nusser et al. demonstrated that suction devices can effectively assess arthropod diversity, thereby providing quantitative support for biodiversity conservation [10]. Similarly, Slavíková et al. analyzed two decades of suction trap data to reveal the coupling between aphid migration patterns and climate change, confirming the reliability of pneumatic suction systems for long-term ecological monitoring [11,12].

With the rapid advancement of information technology and artificial intelligence, physical pest control equipment is increasingly evolving toward higher levels of precision and intelligence. For large-scale monitoring of migratory pests, insect radar systems can now systematically track population dynamics at high altitudes [13]. At the near-ground level, intelligent traps integrating the Internet of Things and deep learning algorithms have become a major research focus. For example, neural network–guided systems are capable of distinguishing pest species from beneficial insects through real-time image recognition, thereby enabling selective capture and substantially reducing unintended mortality [14]. For public health pests such as mosquitoes, intelligent traps equipped with high-resolution cameras and real-time detection algorithms have achieved highly

accurate automated monitoring [15]. However, despite their technical sophistication, the high manufacturing costs, complex maintenance requirements, and limited adaptability of these devices to harsh field environments have constrained their large-scale application in agricultural production.

In contrast, pneumatic control technology exhibits broad potential in agricultural pest management due to its simple structure, controllable cost, and strong environmental adaptability. Hua et al. noted in their review that the use of blowing or suction airflow to directly influence pest behavior represents a highly promising yet underexplored research direction [16].

Current research highlights the effectiveness of intelligent wind-suction solar insect lamps across a broad spectrum of agricultural environments. These systems are widely deployed in vegetable production areas for both leafy and fruit vegetables, as well as in ecological industrial parks. Beyond vegetables, successful pest management has been reported in diverse crop scenarios including apple orchards, tea plantations, vineyards, and fresh corn fields. These applications focus on controlling major lepidopteran pests from the Noctuidae, Pyralididae, and Plutellidae families, specifically targeting species such as the beet armyworm, slit litura, diamondback moth, and melon borer. The use of such technology is particularly vital in organic farming systems where chemical interventions are restricted. By employing a specific light wavelength range from 320 to 680 nm, these devices achieve a high pest capture rate of approximately 85.01 percent while protecting biological diversity. This selective capture ensures that the population of natural enemies like ladybugs and parasitic wasps is preserved, with a beneficial to pest ratio of only 0.04 to 1. In these organic environments, the lamps facilitate the reduction in traditional chemical pesticides, thereby preventing soil pollution and enhancing the overall quality of agricultural products [9].

Despite these advancements, a gap remains in the existing literature regarding the bio-aerodynamic interaction between suction flow fields and the behavioral ecology of micro-insects. Conventional optimization strategies have primarily focused on macro-aerodynamic metrics—such as increasing overall intake volume or preventing macroscopic stall—treating target pests essentially as passive aerodynamic particles. For instance, while Wang et al. employed computational fluid dynamics to optimize suction cylinders, their analysis relied heavily on static flow fields and did not fully parameterize the dynamic stress-escape responses of living insects [17]. Similarly, Shi et al. demonstrated that configuring the inlet angle to 60° effectively eliminated near-wall vortices that previously expelled pests, thereby improving the mechanical collection efficiency of conventional traps [18]. While such geometric tuning is effective for optimizing legacy trap architectures, these studies overlook the microscopic fluid-dynamic cues (e.g., localized pressure pulsations and micro-turbulence) that serve as alarm signals for the highly sensitive mechanoreceptors of small pests [19,20]. Consequently, achieving high capture rates in state-of-the-art systems often necessitates a brute-force increase in fan power to overpower the insect's escape velocity. This strategy not only generates excessive turbulence that prematurely warns the insects but is also incompatible with the stringent low-power constraints of distributed agricultural equipment.

To systematically overcome this bottleneck and explicitly position the present study beyond traditional empirical optimizations, this research proposes a design approach from “power-driven aerodynamic confinement” to “stealth-based bio-aerodynamic regulation.” It was hypothesized that the structural mitigation of turbulence-induced mechanical cues at the induction boundary is equally as critical as the terminal suction intensity. Accordingly, the primary objective of this study is to design and evaluate a variable cross-section wind-suction channel intended for low-power operation in distributed pest-monitoring

systems operating on the converging nozzle principle. This specific structural approach aims to establish a highly rectified, fully attached induction flow field that systematically minimizes localized velocity fluctuations, thereby reducing the likelihood of triggering insect alertness. To ensure a rigorous validation of this mechanism, the execution of this research is structured across three interdependent phases: (1) defining the multi-stage geometric transitions of the channel; (2) conducting a CFD investigation to characterize the spatial evolution of the favorable pressure gradient and the suppression of near-wall eddy structures; and (3) empirically correlating macroscopic fluid mechanics with microscopic behavioral suppression through standardized laboratory assays utilizing both equivalent physical targets and live biological subjects.

2. Materials and Methods

The process of capturing and confining the target pests within this design relies on a continuous aerodynamic gradient that prevents backflow or escape. Once the insects are induced into the flow-stabilizing intake section, they are rapidly accelerated through the guided section toward the high negative-pressure throat. Upon reaching the throat, the insects are transported by the high velocity airflow into a collection chamber located at the rear of the device. This chamber is equipped with a fine mesh screen that allows the air to pass through while effectively trapping the biological targets. The sustained negative pressure within the channel creates a one way transport path which ensures that the pests remain confined in the collection area without the possibility of flying back against the stream. This mechanism provides a reliable method for the physical suppression of pest populations.

2.1. Wind-Suction Channel Design

To provide an overview of the system assembly and airflow path, ambient air and attracted insects enter through the lower suction inlet and move sequentially through the flow-stabilizing intake section, the guided acceleration section, and the high negative-pressure throat. The insects are then conveyed into the collection chamber downstream of the throat, where a fine mesh screen retains the biological targets while allowing the airflow to pass through and exit the device. The light source, suction channel, fan assembly, and collection chamber therefore operate as an integrated capture pathway rather than as independent components.

Figure 1a–c presents orthographic views of the wind-suction channel itself, whereas Figure 1d presents the bottom view of the assembled device rather than an additional ovoid channel component. The component labels in Figure 1 are independent of the functional-zone numbering used in Figure 2. The lower opening shown in Figure 1 is the suction inlet. Air and insects enter through this opening, pass sequentially through zones 1–3 in Figure 2, and are subsequently conveyed into the collection chamber; thus, zone 3 in Figure 2 represents the downstream high negative-pressure throat rather than the initial suction point.

The spatial arrangement of the system components is illustrated in the engineering drawings. As shown in Figure 1d, the 420 nm phototactic light source 1 is positioned at the geometric center of the lowermost inlet plane of the flow-stabilizing intake section. The fan mounting bracket 2 is located directly above the phototactic light source at the concentric center of the intake section to support the suction fan. The collection chamber 3, which contains a fine mesh screen, is positioned directly behind the outlet of the high negative-pressure throat section to isolate the captured insects.

The wind-suction channel has a total vertical height of 220 mm. The physical configuration and engineering dimensions of the design, including the front, side, and bot-

tom views, are detailed in Figure 1. To analyze the internal airflow characteristics, a three-dimensional geometric model was constructed as shown in Figure 2, which illustrates the functional zonation of the channel into three contiguous segments from bottom to top: a flow-stabilizing intake section, a guided acceleration section, and a high negative-pressure throat section.

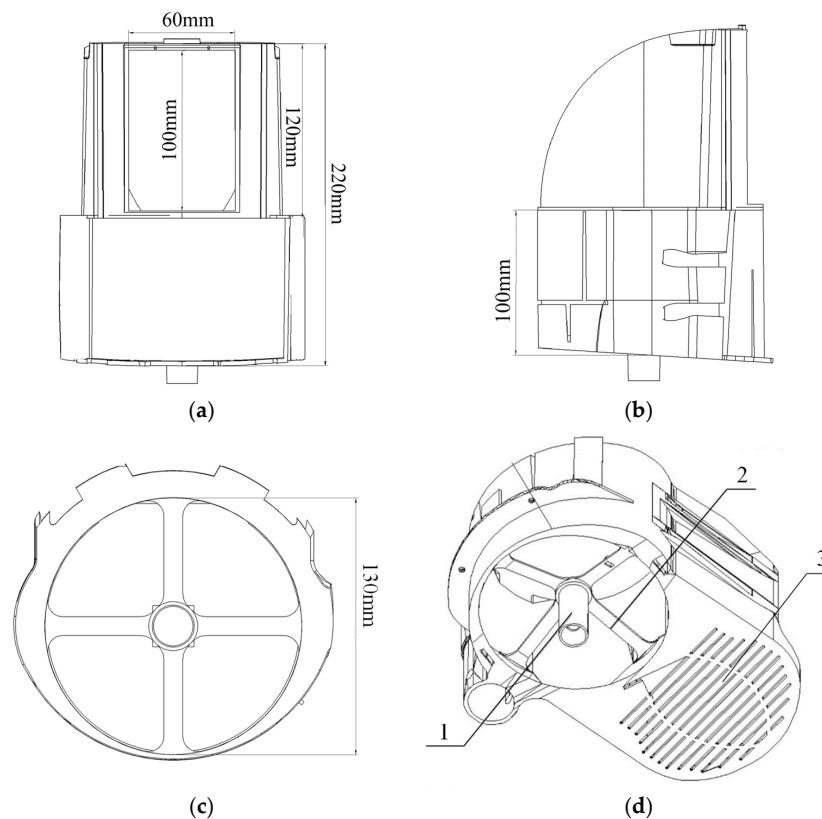


Figure 1. Engineering Drawings of the Wind Suction Channel Design. Note: (a) Front View; (b) Side View; (c) Bottom View; (d) Bottom view of the whole machine (1 light source; 2 fan mounting bracket; 3: collection chamber).

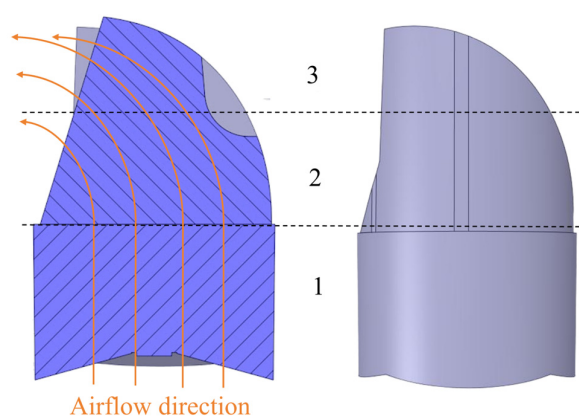


Figure 2. Three-Dimensional Geometric Model of the Air Suction Channel. Note: 1 Flow-stabilizing intake section, 2 Guided acceleration section, 3 High negative-pressure throat section.

As indicated by zone 1 in Figure 2, the flow-stabilizing intake section at the base connects to the ambient environment and features a constant-diameter cylindrical geometry with a diameter of 136 mm and a height of 100 mm. This uniform cross-section serves to buffer incoming airflow and mitigate external wind variations to provide a low-velocity and rectified induction zone [21,22].

Positioned above the intake, the guided acceleration section, labeled as zone 2, acts as a transitional segment with a continuously converging cross-section. The inner walls follow a third-order polynomial curve with a minimum curvature radius of 45 mm and transition the geometry from circular to a rounded-rectangular form. This structural convergence converts static pressure into kinetic energy to establish an accelerating velocity gradient along the axial direction [23,24].

The uppermost segment, identified as zone 3 in Figure 2, is the high negative-pressure throat section which features a constricted rectangular cross-section measuring 60 mm by 100 mm. A 12 mm fillet radius connects this section to the acceleration zone to reduce geometric discontinuities. Governed by the Venturi effect, this localized constriction minimizes static pressure and maximizes axial flow velocity [25]. This flow environment is characterized by high velocity and low static pressure, forming an effective aerodynamic barrier at the outlet. The resulting aerodynamic drag rapidly overcomes the flight resistance of small insects, transporting them into the collection chamber and effectively blocking potential upwind escape pathways [26].

The synergistic balance between the induction intensity and the flow stability is a fundamental principle that governs the performance of this design. This balance is explicitly discussed in the context of the interaction between the negative pressure gradient and the velocity uniformity within the channel. While a high suction force is necessary to overcome the biological resistance of the target pests it must be balanced with a highly rectified flow field to suppress the sensory perception of the insects. The integration of the three functional sections ensures that the mechanical energy of the airflow is effectively utilized for capture without creating turbulent fluctuations that would trigger alarm responses. This equilibrium between aerodynamic efficiency and stealthy operation provides the theoretical basis for both simulations and experiments.

2.2. Experimental Verification Scheme

To rigorously evaluate the performance of this design and verify the underlying mechanism of behavioral suppression, a comprehensive four-stage experimental framework was implemented. This framework transitions from fundamental aerodynamic characterization to practical biological application through a series of interconnected trials. The first stage involves airflow velocity measurements to validate the mean-flow magnitude at selected centreline locations. The second stage utilizes simulated targets to establish a controlled physical baseline for quantifying the effectiveness of the aerodynamic drag without biological interference. The third stage involves comparative performance trials against conventional capture equipment to demonstrate the improvement in capture efficiency under realistic conditions. Finally the fourth stage consists of behavioral response experiments using live insects to evaluate the stealthiness of the induction environment and its ability to suppress stress-induced escape.

A commercially available straight-tube suction insect-trapping device was selected as the engineering comparator because its uniform-diameter suction channel represents a commonly used straight-through configuration. The structural configuration and engineering dimensions of the straight-tube control device are shown in Figure 3. The straight tube features a uniform cylindrical geometry with an inner diameter of 155 mm and a total vertical length of 255 mm. The difference in suction-channel length reflects the respective structural configurations of the two devices. The commercial comparator retained its original 255 mm straight-tube structure, whereas the 220 mm length of the proposed channel was determined by the combined dimensions of its flow-stabilizing intake, guided acceleration, and high negative-pressure throat sections. As shown in Figure 3, the device consists of a lower rectifying grid, the cylindrical suction channel, a fan, and a collection chamber. The rectifying grid at the lower inlet conditions the incoming airflow before it en-

ters the straight channel. For comparison, the commercial device and the proposed device were equipped with the same fan model and 420 nm light source, allowing their practical trapping performance to be compared under consistent fan and light-source conditions.

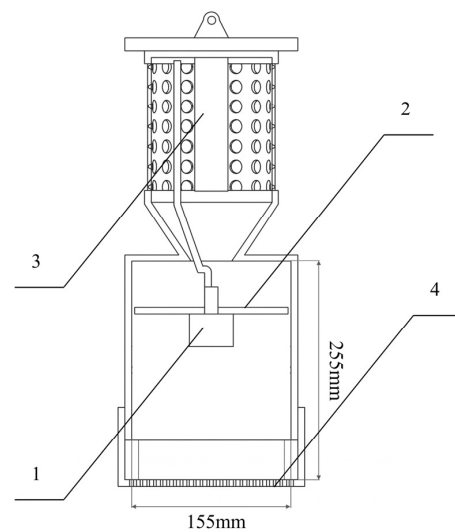


Figure 3. Structural Diagram of the Commercially Available Straight-Tube Control Device. Note: 1 light source; 2 fan mounting bracket; 3: collection chamber; 4: rectifying grid.

The electrical characteristics of the complete device were measured as follows: the suction fan operated at 24 V and 250 mA (6.00 W), the 420 nm light source at 12 V and 250 mA (3.00 W), the standby state at 12 V and 40 mA (0.48 W), and the communication state at 12 V and 70 mA (0.84 W). The fan speed was not adjustable, and all experiments were conducted at the rated operating condition. The straight-tube control used the same suction fan and 420 nm light source; therefore, the fan and light-source power were identical between the two devices, whereas the standby and communication power differed because of differences in circuit design.

The necessity of employing both simulated targets and live insects lies in the requirement to distinguish between mechanical force efficiency and biological sensory perception. While simulated targets provide repeatable data on the stability of the rectified flow, live insect experiments are indispensable for assessing how the low disturbance characteristics of this design interact with the complex sensory organs of the target pests. The schematic diagram of the experimental setup is shown in Figure 4.

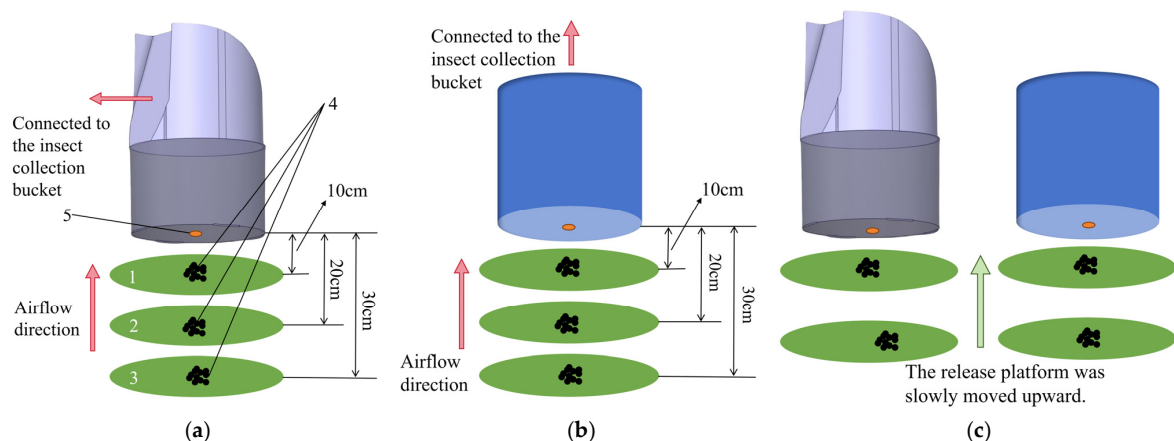


Figure 4. Schematic Diagram of the Experimental Setup. Note 1: (a) the suction-trapping experiment of this design; (b) Straight tube control group; (c) Concealment Validation Test. Note 2: 1, 2, 3 denote

release planes of varying distances, 4 Simulated targets or insects, 5 insect-attracting light source (420 nm).

2.2.1. Flow Velocity Measurement

Three characteristic monitoring locations were selected along the axial centerline of the device: the center of the flow-stabilizing intake section, the center of the guided acceleration section, and the center of the high negative-pressure throat section. At each location, the axial airflow velocity was measured directly using a calibrated anemometer after the flow reached a steady state. The airflow velocity measurements for this design were conducted using a SMART SENSOR AR886A handheld thermal anemometer. This instrument provides high precision data acquisition with a resolution of 0.01 m/s. The anemometer installation and its spatial arrangement during the experiments are shown in Figure 5.



Figure 5. Experimental Photograph of Wind Speed Installation.

2.2.2. Experimental Validation with Simulated Targets

To eliminate the biological variability associated with live insects (including flight posture, behavioral response, and stress-induced escape) and ensure experimental repeatability while complying with the single-variable control principle, physical surrogate targets were employed in place of real insects.

The simulated targets in this study represent a generalized category of small volume agricultural pests with shared physical characteristics. These targets are defined by a body length of approximately 3–5 mm and a mass of 2–5 mg. These specific values are chosen to represent the common physiological profiles of micro insects found in tea plantations and similar agricultural environments. Therefore, these spherical physical targets are designed to approximate the effective windward projected area of small-bodied pest insects, establishing an objective mechanical baseline for quantifying the aerodynamic force without biological interference. However, it is essential to explicitly recognize the inherent limitations of utilizing passive filter paper spheres as surrogates for live biological organisms possessing active flight mechanics. The passive targets are employed exclusively to quantify the terminal mechanical capture threshold—specifically, verifying that the aerodynamic drag force generated in the throat section is mathematically sufficient to overcome the physical inertia of the simulated object. Nevertheless, this terminal mechanical capture is only successful if the target physically enters the high-velocity zone. Live insects, unlike passive spheres, possess highly sensitive mechanoreceptors that trigger rapid upwind escape maneuvers. Therefore, the necessity for aerodynamic regulation lies in the pre-capture induction phase, aiming to suppress sensory alarm cues before the terminal mechanical

drag takes over. This dual-phase logic reconciles the use of passive particles for force verification with the stringent requirement for biological behavioral suppression.

Spherical particles with diameters ranging from 2 to 5 mm were fabricated from quantitative filter paper. The mass of the fabricated particles was measured at 22.7 ± 2.2 mg. While fabricating physical targets with a strict mass of 2 mg is inherently constrained by the material density of the filter paper, aerodynamic transport within this micro-scale regime under high-velocity airflow is primarily governed by the aerodynamic drag force rather than gravitational mass. Because the aerodynamic drag generated by the 20 m/s inlet velocity far exceeds the gravitational force, the mass difference becomes aerodynamically negligible. Therefore, these spherical physical targets are designed to approximate the effective windward projected area of small-bodied pest insects, establishing an objective mechanical baseline for quantifying the aerodynamic force without biological interference.

The suction tests with simulated targets were conducted in an open indoor laboratory environment without an enclosed chamber or a restricted-volume test space. The targets were released along the central vertical axis at distances of 10, 20, and 30 cm below the suction inlet, corresponding to the three release planes illustrated in Figure 4.

During the experiments, the device was operated at its rated power; after the airflow stabilized, the wind speed at each characteristic monitoring point was measured three times, and the corresponding average value was calculated. These experimentally measured velocities were then compared with the corresponding values extracted from the numerical simulation to evaluate the relative deviation between simulation and experiment:

$$\delta = \frac{V_{MAF} - V_{CFD}}{V_{EXP}} \times 100\%$$

where V_{CFD} denotes the velocity extracted from the numerical simulation, and V_{MAF} denotes the experimentally measured average flow velocity.

2.2.3. Biological Validation with Live Insects

To evaluate the capture effectiveness of the proposed wind-suction channel under controlled laboratory conditions and assess its ability to suppress stress-induced escape behavior in live insects, adult tea green leafhoppers and tea thrips were used as representative small-bodied pests. Only active and undamaged individuals were selected for the assays. Capture-rate tests were performed at release distances of 10 cm, 20 cm, and 30 cm below the suction inlet along the central vertical axis. For each test condition, a separate group of 50 insects was used, and individuals were not reused among replicates or treatments. The order of the distance tests was alternated to reduce potential sequence effects. After 60 s of operation, the number of insects captured in the collection chamber was recorded, and the average capture rate was calculated from three independent replicates.

To further evaluate the low-disturbance performance of the proposed design, the critical distance was experimentally identified at which insects initiate stress-induced escape behavior. Stress-induced escape behavior was defined as sudden take-off, vigorous wing flapping, rapid movement away from the inlet, or sustained avoidance movement. The first distance at which any of these responses was observed was recorded as the critical stress-response distance. A shorter critical distance indicates a lower degree of environmental disturbance perceived by the insects.

During the biological tests, the ambient air temperature was maintained at 25 ± 1 °C, and the relative humidity was regulated at $60\% \pm 5\%$. The background airflow velocity was kept below 0.05 m/s. The tests were conducted in darkness, utilizing the 420 nm light source as the single illumination source.

The capture efficiency is evaluated using the capture rate (η , %). The calculation is performed as the ratio of the number of captured insects to the total number of released insects. The formula is expressed as:

$$\eta = \frac{N_c}{N_t} \times 100\%$$

where N_c is the number of insects successfully drawn into the collection chamber, and N_t is the total number of insects released. The exposure time for each experimental trial was 60 s.

The selection of a straight tube channel as the control group is grounded in its widespread application in conventional pneumatic pest control equipment. Current commercial suction traps and traditional experimental devices predominantly utilize uniform straight tubes due to their manufacturing simplicity and low cost.

2.2.4. Data Statistical Analysis

All experimental protocols, including simulated target suction, live insect capture, and critical stress response distance measurements, were performed in triplicate to ensure the reliability and reproducibility of the results. Quantitative findings are expressed as the mean and standard deviation.

One-way analysis of variance was applied to evaluate the influence of release distance on capture efficiency, and Duncan's multiple range test was used for post hoc comparisons where applicable. For the comparative biological experiments between this design and the straight tube control, independent-samples *t*-tests were employed to compare capture performance at each spatial coordinate. Because the tables present summarized replicate-level values, inferential results were interpreted cautiously and in relation to the available replicate summaries.

The significance thresholds were established at $p < 0.05$ for statistically significant differences and $p < 0.01$ for highly significant differences. This systematic statistical framework ensures that the observed enhancements in aerodynamic performance and behavioral suppression are mathematically robust and representative of actual operating conditions.

2.3. Numerical Simulation Methods

2.3.1. Mesh Generation

A three-dimensional geometric model of the wind-suction channel was constructed using Dassault Systèmes SolidWorks 2024 and subsequently imported into ANSYS Mechanical 2024 R2 for mesh generation. Owing to the geometric complexity of the channel and the presence of regions with large velocity gradients, an unstructured mesh was adopted for spatial discretization.

To accurately capture viscous flow behavior near solid boundaries and the motion characteristics of small insects within critical regions, a multi-scale mesh refinement strategy was implemented. Local refinement zones were applied at key locations, including channel corners, guide-plate edges, the annular inlet region, and the high negative-pressure throat section, ensuring that the minimum mesh size was comparable to the characteristic scale of the target insects. To further enhance numerical accuracy in near-wall regions, five inflation layers were generated along the inner walls of the channel to resolve steep velocity gradients and reduce numerical errors associated with boundary layer effects.

2.3.2. Mesh Independence Study

A mesh independence study was conducted to eliminate the influence of grid density on simulation accuracy and to achieve a balance between computational efficiency and numerical precision. Six mesh schemes with progressively increasing element counts were

evaluated while maintaining identical geometric models, boundary conditions, and solver settings. Because this specific region features the minimum cross-sectional area and the maximum velocity gradient within the channel, its local flow characteristics are highly sensitive to spatial discretization. Utilizing this critical region as the primary indicator ensures that once numerical convergence is achieved under these stringent local conditions, the mesh resolution is adequate for the entire computational domain. The axial velocity predicted by CFD at the center of the high negative-pressure throat section was selected as the mesh-convergence indicator. The relative variation rate was defined as the percentage difference between the simulated throat-center velocity obtained with the current mesh scheme and that obtained with the preceding scheme. The detailed results are summarized in Table 1.

Table 1. Mesh independence verification data for the wind-suction channel.

Mesh Count (Million)	Simulated Axial Velocity at Throat Center (m/s)	Relative Variation Rate (%)
1.22	37.25	-
2.41	39.88	7.06
3.76	41.02	2.86
5.15	41.80	0.68
6.59	41.94	0.33
8.13	41.99	0.12

The relationship between the total number of mesh elements and the simulated throat-center axial velocity is illustrated by the convergence curve shown in Figure 6.

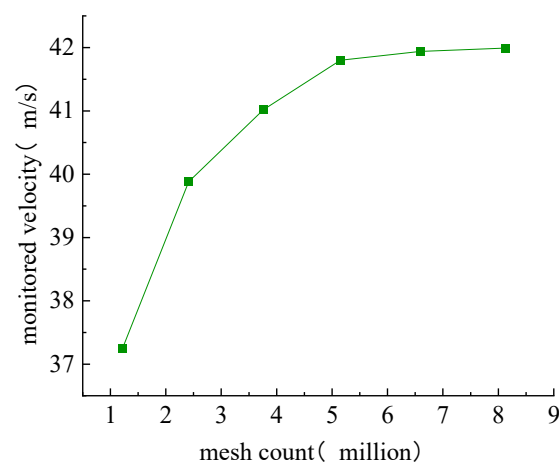


Figure 6. Convergence Characteristics of Simulated Throat-Center Velocity with Variation in Mesh Element Count.

During the initial refinement stage, when the mesh count increased from 1.22 million to 3.76 million elements, the curve exhibited a steep slope, with relative variation rates exceeding 2.8%. This behavior indicates that discretization errors strongly affected the resolution of flow field characteristics at lower mesh densities. As the mesh count increased to 5.15 million elements, the incremental change in velocity decreased markedly, with the relative variation rate falling to 0.68%. Further refinement to 8.13 million elements resulted in only minor fluctuations in the simulated throat-center velocity, which remained within the range of 41.80–41.99 m/s. These variations are well below the commonly accepted engineering threshold of 1%.

To further substantiate the spatial convergence of the numerical solution and ensure that local aerodynamic gradients are adequately resolved, velocity-contour comparisons

were conducted across the critical high-velocity throat section using three representative grid resolutions: coarse (2.41 million), medium (5.15 million), and fine (8.13 million).

As shown in Figure 7, the medium and fine meshes produced similar velocity-contour patterns in the throat section, indicating that further mesh refinement did not substantially alter the resolved high-velocity region.

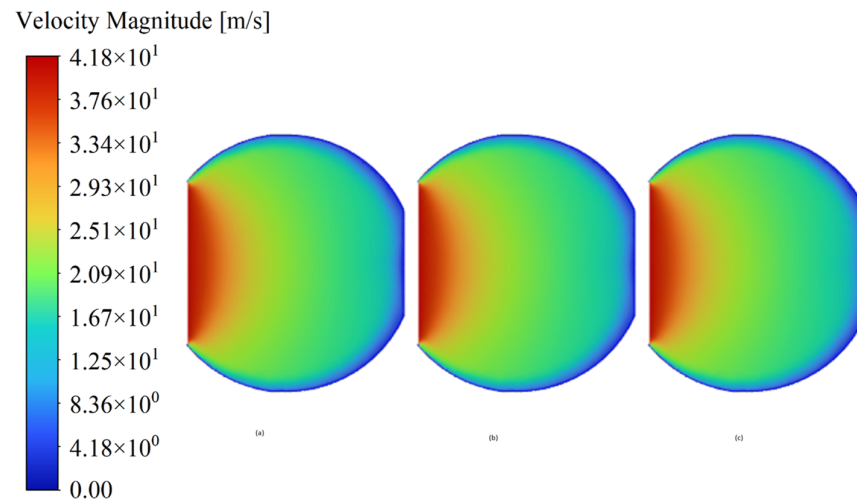


Figure 7. Local Mesh-independence Comparison Based on Velocity Contours at the Throat Section. Note: (a) coarse mesh; (b) medium mesh; (c) fine mesh.

Therefore, considering both numerical accuracy and computational cost, a mesh size of approximately 5.15 million elements was selected for all subsequent simulations.

For the selected computational grid comprising 5.15 million elements, rigorous mesh quality assessments were conducted to ensure numerical stability. The specific values are presented in Figure 8. The volume-weighted average orthogonal quality was evaluated at 0.815, with a minimum orthogonal quality of 0.202. In engineering practice, an average orthogonal quality exceeding 0.8 and a minimum value above 0.15 are generally categorized as excellent indicators for high-fidelity simulations. The metrics obtained in this study align closely with these professional standards, ensuring the reliability of the spatial discretization. Although the minimum orthogonal quality was recorded at 0.202, this localized minimum value strictly occurs at the complex 3D geometric transition boundary coupling the circular guided acceleration section with the rectangular throat. Because this minimum metric strictly exceeds the standard finite-volume solver threshold of 0.15 required to prevent numerical divergence, and is physically confined to a minimal localized volume, it does not induce unphysical numerical diffusion. Consequently, this mesh quality is computationally sufficient to ensure reliable boundary layer resolution and stable numerical convergence across all critical zones of the model. Furthermore, the maximum cell skewness was strictly controlled at 0.798.

Notably, the maximum dimensionless wall distance, y^+ , was recorded at 23.8. Because the first grid nodes are located in the viscous sublayer and buffer layer ($y^+ < 30$), standard wall functions are physically inapplicable. Consequently, the Enhanced Wall Treatment (EWT) was employed in conjunction with the $k-\varepsilon$ turbulence model. Spatial monitoring confirms that the y^+ values within all critical zones, including the near-wall domains of the constant-diameter intake section, the complex curvature of the circular-to-rectangular transition zone, and the constricted boundary of the high-velocity throat section, remain strictly below the upper validation limit of 30. Because the EWT incorporates a two-layer zonal formulation, the governing equations within the near-wall grid are resolved adaptively based on the local y^+ infrastructure. In localized areas where $y^+ < 5$, the model automati-

cally adopts a low-Reynolds-number formulation to directly resolve the viscous sublayer, whereas in critical sections where the grid cells fall within the buffer zone ($5 < y^+ < 30$), the velocity profile and wall shear stress are determined via a blended continuous interpolation function. Consequently, the entire y^+ distribution across all functional segments satisfies the mathematical requirements of the EWT framework, confirming that the spatial discretization in all critical zones is acceptable for computing boundary layer flow development without grid-induced discontinuities, which ensures accurate prediction of wall shear stress for the refined near-wall mesh.

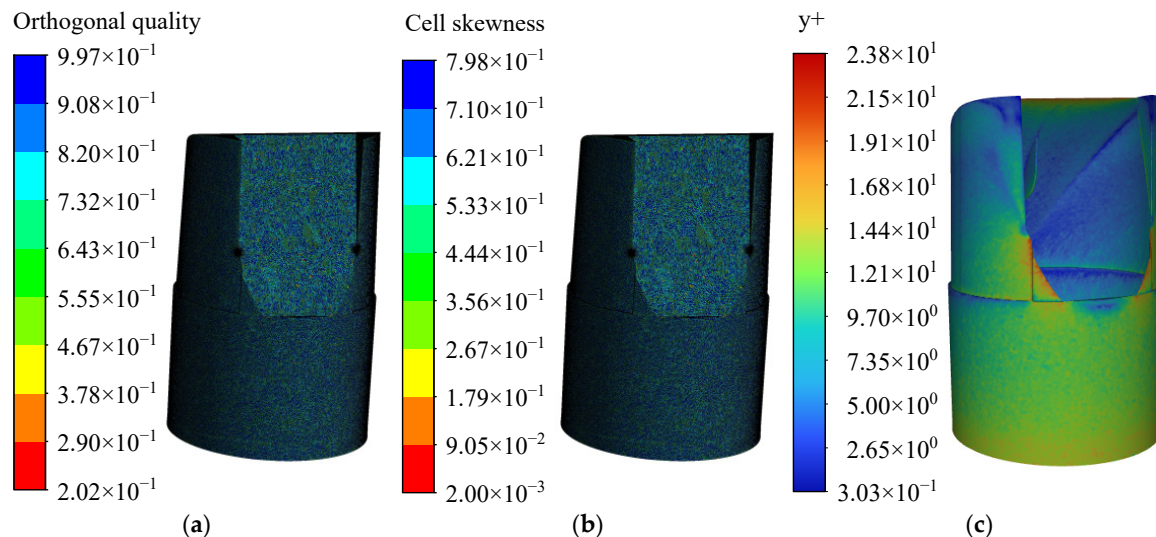


Figure 8. Schematic of Key Mesh Parameters. Note: (a) contour of mesh orthogonal quality; (b) distribution of mesh skewness; (c) wall y^+ -plus.

2.3.3. Governing Equations and Turbulence Model

Computational fluid dynamics (CFD) was employed to analyze the internal flow field characteristics of the wind-suction channel [27]. Given that the estimated Reynolds number within the channel is approximately 1.7×10^5 , the internal flow operates entirely within a turbulent regime. Therefore, the fluid dynamics were governed by the steady-state, incompressible Reynolds-Averaged Navier–Stokes (RANS) equations.

The continuity equation is expressed as:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0$$

The momentum conservation equations are expressed as:

$$\rho \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\mu \frac{\partial \bar{u}_i}{\partial x_j} - \rho \overline{u'_i u'_j} \right)$$

In these governing equations, $\bar{u}_i$ and $\bar{u}_j$ are the time-averaged velocity components, $\bar{p}$ is the time-averaged static pressure, ρ denotes the air density, and μ represents the dynamic viscosity of air. The additional term $-\rho \overline{u'_i u'_j}$ defines the Reynolds stress tensor, which accounts for the momentum transfer induced by turbulent fluctuations. To achieve closure for the RANS equations, the standard k - ϵ turbulence model was employed to evaluate the Reynolds stresses [28].

The governing equations for this design were solved using the finite volume method based on a pressure based solver. To ensure spatial accuracy, the second-order upwind scheme was selected for the discretization of convective terms while the diffusion terms

were discretized using central differencing. The coupling between the pressure and velocity fields was resolved using the SIMPLE algorithm which is a standard procedure for steady state incompressible flows. Numerical convergence was monitored through the residuals of the continuity and momentum equations with a convergence threshold of 10^{-4} while the turbulence kinetic energy and dissipation rate were required to reach 10^{-5} . These specific settings ensure that the simulated flow field accurately reflects the aerodynamic characteristics of the three functional sections of this design.

Given the relatively high Reynolds number at approximately 1.7×10^5 and the presence of turbulent features within the channel, the standard $k-\epsilon$ turbulence model was adopted for closure. This model offers robust convergence behavior and reliable accuracy in predicting turbulent kinetic energy and its dissipation rate in engineering flow simulation [29]. The variable cross-section channel proposed in this study operates aerodynamically as a converging nozzle, which inherently generates a continuous favorable pressure gradient along the streamwise direction. This favorable pressure gradient continuously supplies momentum to the boundary layer, effectively overcoming viscous drag and structurally suppressing macroscopic boundary layer separation or the formation of significant recirculation zones. Because the flow remains fully attached and continuously accelerating, the deployment of turbulence models specifically designed for severe adverse pressure gradients and flow separation (such as the $k-\omega$ SST model) is computationally unnecessary. Instead, the standard $k-\epsilon$ model provides verified numerical robustness and adequate precision for predicting the turbulent kinetic energy and induction field characteristics under these specific attached-flow conditions.

2.3.4. Boundary Conditions

The boundary conditions for the numerical simulation of this design are defined to reflect actual operating states where the negative pressure generated by the fan drives the airflow. An inlet velocity of 20 m/s is specified at the intake to represent the measured stable flow rate during experimental trials. The outlet is assigned a standard atmospheric pressure condition to simulate the discharge of air from the fan into the ambient environment. This configuration characterizes the internal pressure gradient where the static pressure drops significantly within the throat section to maintain the prescribed flow velocity. By establishing this potential difference between the atmospheric intake and the exhaust the simulation accurately captures the suction mechanism and the resulting aerodynamic environment within the channel.

The selection of the inlet flow velocity at 20 m/s is determined by a quantitative force balance analysis between aerodynamic drag and the biological resistance of the target pests. According to the drag equation $F_d = 0.5 \rho C_d A u^2$, a flow velocity of 20 m/s generates an aerodynamic force of approximately 2.25×10^{-4} N for a typical tea green leafhopper with a conservative projected area of 1 mm^2 . C_d is the dimensionless drag coefficient, which is set to 1.0 based on the irregular morphology of the tea green leafhopper. ρ denotes the air density, taken as 1.125 kg/m^3 under standard atmospheric conditions. A signifies the projected area of the insect, which is the effective windward surface and is conservatively estimated at 1 mm^2 for this study. u indicates the flow velocity at the intake. Considering that the representative mass of the pest is 2 mg, its corresponding weight is approximately 2.0×10^{-5} N. The maximum biological lift generated during flight is also estimated at 2.0×10^{-5} N; the aerodynamic force produced by this design is an order of magnitude higher than the intrinsic biological forces of the insect. This significant force disparity is sufficient to disrupt the flight stability and posture control of the pests, ensuring that they are effectively captured and prevented from escaping the suction field. This operational parameter provides a robust physical foundation for the capture mechanism.

All internal walls of the channel were treated as no-slip boundaries, where the fluid velocity at the wall surface was set to zero. The walls were assumed to be hydraulically smooth, thereby neglecting the influence of microscopic surface roughness on flow resistance.

2.3.5. Material Properties

The working fluid in the simulation was defined as air under standard atmospheric conditions. Based on the experimental ambient temperature of 25 °C, air was treated as an incompressible ideal gas. The density of air was set to 1.125 kg/m³, and the dynamic viscosity was specified as 1.7894×10^{-5} Pa·s.

The working fluid was treated as an incompressible Newtonian fluid. The mathematical justification for this incompressibility assumption is governed by the Mach number (Ma) analysis. Given that the maximum local velocity (V_{max}) within the high negative-pressure throat section is approximately 41.8 m/s, and the local speed of sound (c) in air at 25 °C is approximately 346 m/s, the peak Mach number is calculated as:

$$Ma = \frac{V_{max}}{c} = 0.12$$

Since the maximum Mach number is significantly lower than the widely accepted compressibility threshold of $Ma = 0.3$, the corresponding maximum variation in fluid density is strictly less than 5%. Therefore, the compressibility effects are negligible.

3. Results

3.1. Numerical Simulation Results and Analysis

This section evaluates whether the internal airflow generated by the proposed channel provides the two aerodynamic conditions required for suction capture: a relatively stable induction environment near the inlet and progressive transport toward the collection chamber. Accordingly, velocity, wall shear stress, pressure, turbulence intensity, and streamline fields are analyzed as complementary indicators of internal airflow regulation. The CFD domain is limited to the suction channel and does not quantify airflow decay in the external space below the inlet. The practical spatial effectiveness outside the inlet was therefore evaluated experimentally at release distances of 10, 20, and 30 cm, as reported in Section 3.2.2.

3.1.1. Velocity Field Analysis

The velocity distribution within the wind-suction channel is presented in Figure 9, including a vertical central cross-sectional view in Figure 9a and a series of transverse cross-sectional planes evaluated at key axial locations in Figure 9b. The contour colors represent the magnitude of the airflow velocity, where cooler colors correspond to low-velocity regions and warmer colors indicate high-velocity regions.

As shown in Figure 9, the overall velocity distribution exhibits a clear inverse relationship with the local cross-sectional area of the channel, which is consistent with the continuity principle. As the airflow progresses from the inlet at the bottom toward the outlet at the top, the gradual reduction in channel cross-sectional area results in a smooth and continuous increase in flow velocity, forming a well-defined velocity gradient along the axial direction.

In the flow-stabilizing intake section at the lower part of the channel, the velocity field is dominated by cool cyan tones, indicating a relatively low flow velocity of approximately 18 m/s to 20 m/s. This low-velocity region facilitates the formation of a gentle negative-pressure field during the initial stage of suction. Such a flow environment minimizes

disturbances to the surrounding air and reduces the likelihood that target insects perceive mechanical cues associated with danger, thereby allowing them to enter the channel naturally under the influence of the airflow.

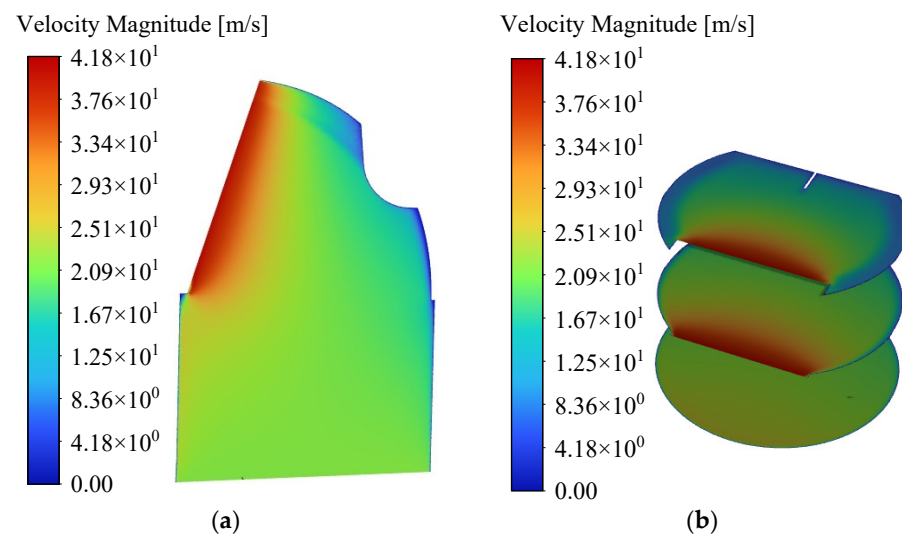


Figure 9. Airflow Velocity Cloud Map. Note: (a) central cross-sectional view; (b) velocity of transverse cross-sections at key axial locations.

As the airflow enters the guided acceleration section, the inner walls of the channel gradually converge. The fluid velocity reaches approximately 30 m/s, and correspondingly, the velocity contours transition smoothly from cyan to yellow and orange, reflecting a progressive acceleration of the flow. The absence of abrupt color changes or discontinuities indicates that the velocity increases in a stable and uniform manner. This behavior confirms that the streamlined wall geometry effectively suppresses boundary layer separation and prevents the formation of large-scale vortices, ensuring continuous and efficient transport of insects through the channel.

The maximum airflow velocity occurs within the high negative-pressure throat section at the upper outlet of the device, where the peak velocity reaches approximately 41.8 m/s. The high-speed airflow in this region generates a strong aerodynamic drag force. Once insects are conveyed through the guided acceleration section and enter the throat, this force far exceeds their flight propulsion capability, effectively preventing upwind escape and ensuring a high probability of capture.

To further resolve the internal fluid dynamics and visualize the three-dimensional evolution of the flow field, Figure 9b details the velocity profiles across three critical axial stations: the flow-stabilizing intake section, the mid-acceleration zone, and the high negative-pressure throat section. At the intake plane, the velocity contour exhibits a highly uniform, symmetric, and low-velocity distribution, rigorously demonstrating that the constant-diameter buffer successfully rectifies the incoming airflow and eliminates localized asymmetric perturbations. As the fluid progresses to the mid-acceleration zone, the cross-sectional contour captures a pronounced core-acceleration profile; the continuous contraction of the third-order polynomial inner walls forces the high-velocity fluid toward the center while restricting boundary layer growth near the edges. Finally, at the throat section plane, the velocity profile reaches its peak magnitude with exceptional uniformity across the constricted rectangular domain, providing direct aerodynamic evidence of the robust kinetic energy concentration required to securely confine target pests.

Furthermore, to numerically assess flow attachment along the channel walls, the Wall Shear Stress (WSS) distribution was computed and analyzed, as illustrated in Figure 10. In

fluid dynamics, boundary layer separation and flow reversal are strictly characterized by the WSS dropping to zero or assuming negative values. Figure 10a presents the 3D contour of the WSS, demonstrating that the shear stress remains strictly positive across the entire internal surface, with a minimum value of 3.48×10^{-3} Pa. To provide a precise quantitative assessment, Figure 10b plots the WSS distribution extracted along the streamwise profile of the channel wall. The scatter plot confirms that despite local fluctuations induced by the complex transition from a circular to a rectangular cross-section, the WSS consistently maintains a positive magnitude ($\text{WSS} > 0$) throughout the entire guided acceleration and throat sections. The converging geometry establishes a robust favorable pressure gradient ($dp/dx < 0$) that continuously supplies momentum to the boundary layer, effectively overcoming adverse viscous forces near the wall. This strictly positive WSS distribution provides numerical evidence consistent with attached flow across the guided acceleration and throat sections. Consequently, this aerodynamic configuration suppresses flow reversal and helps maintain boundary-layer attachment, thereby maximizing kinetic energy transfer to the target insects.

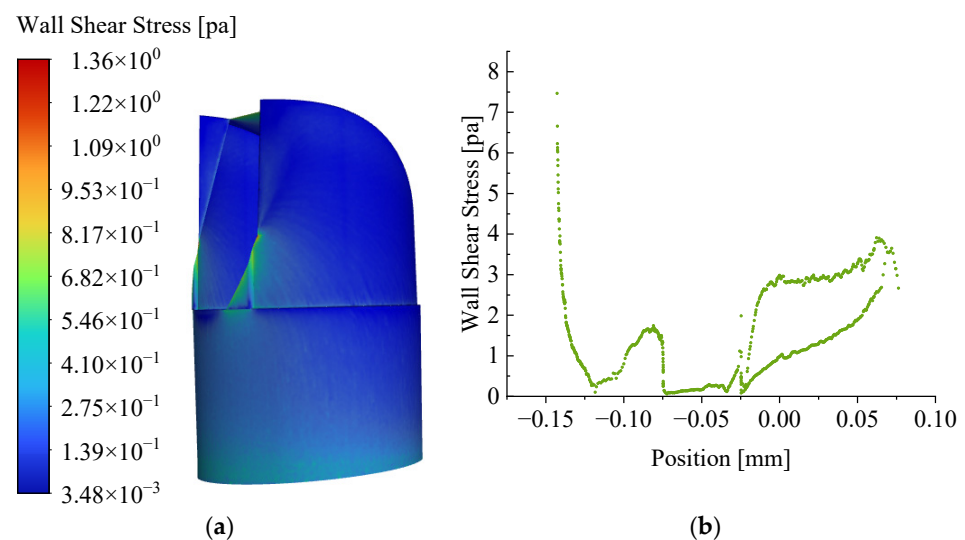


Figure 10. Wall Shear Stress (WSS) Distribution Flow Attachment. Note: (a) 3D contour of WSS on the inner walls; (b) Streamwise WSS scatter plot along the wall profile.

3.1.2. Pressure Distribution Analysis

The static pressure distribution within the wind-suction channel is illustrated in Figure 11, including a central cross-sectional view in Figure 11a and an overall view in Figure 11b. The pressure contours reveal a pronounced axial pressure gradient along the direction of airflow, which provides the driving force for continuous upward transport of air and insects.

It can be seen from Figure 11a that in the flow-stabilizing intake section, the pressure field is dominated by deep red regions, indicating relatively high static pressure with a maximum value of approximately 973 Pa. Because the airflow velocity in this section is low, a large portion of the fluid energy is stored in the form of static pressure. This elevated inlet pressure supplies the initial driving force required to overcome flow resistance throughout the channel and maintain stable suction performance.

As the airflow enters the guided acceleration section, the progressive contraction of the channel cross-section leads to a rapid increase in velocity. In accordance with Bernoulli's principle, the increase in kinetic energy is accompanied by a corresponding decrease in static pressure [30]. The static pressure decreases from 973 Pa to approximately 500 Pa. This process is reflected by the smooth transition of contour colors from red to yellow and green.

The absence of localized high-pressure stagnation zones or abrupt pressure fluctuations indicates efficient energy conversion and minimal flow loss within this region.

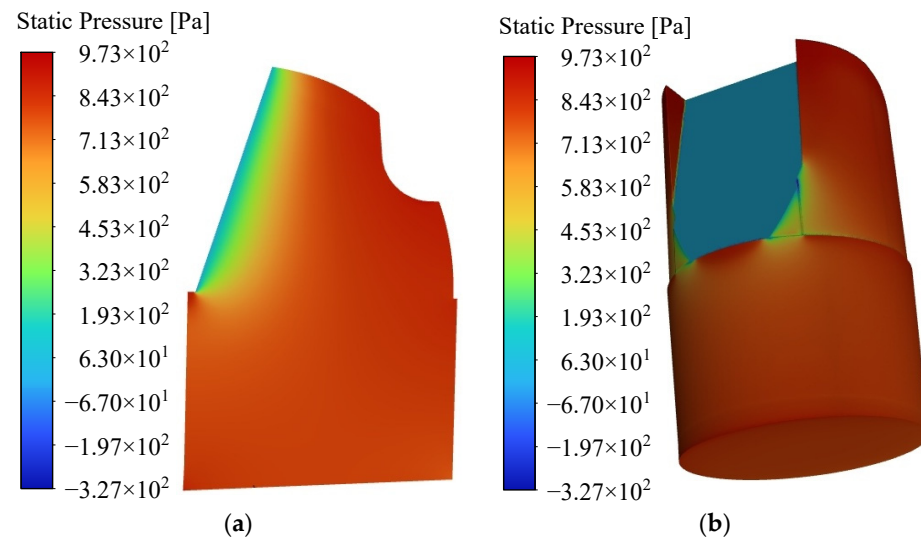


Figure 11. Contour Map of Pressure Distribution in the Channel. Note: (a) central cross-sectional view; (b) overall three-dimensional view.

At the high negative-pressure throat section, the static pressure reaches its minimum value of approximately -327 Pa. This creates a substantial pressure differential relative to the inlet section, producing a strong suction effect that rapidly transports insects toward the collection chamber. In addition, the pressure distribution across horizontal cross-sections remains highly uniform, with isobars that are nearly perpendicular to the channel axis. Such pressure field stability is beneficial for maintaining consistent suction performance and reducing unsteady flow-induced disturbances.

Figure 11b illustrates the pressure distribution at the wall which reveals a consistent and balanced gradient throughout the channel. The suction force is evenly distributed which is essential for the steady transport of insects.

3.1.3. Turbulence Intensity Analysis

The distribution of turbulent Intensity (TI) within the wind-suction channel is shown in Figure 12. TI provides a dimensionless relative metric (expressed as a percentage) that more accurately reflects the localized flow instabilities perceived by pests. In the contour plots, blue regions correspond to very low turbulence intensity, whereas red regions indicate high turbulence levels. Overall, turbulence is primarily concentrated near the throat outlet, while the majority of the channel interior remains in a relatively stable flow state.

As observed in both the central cross-sectional view (Figure 12a) and the overall view (Figure 12b), the flow-stabilizing intake section is characterized by a uniformly low turbulence intensity, approaching the minimum recorded value of 0.227% (indicated by the deep blue regions). This demonstrates that macroscopic airflow fluctuations are effectively suppressed, establishing a highly rectified induction state. Such a low-turbulence environment is biologically critical, as it prevents insects from detecting sudden flow oscillations that could trigger mechanoreceptor-induced escape responses. Within the guided acceleration section, despite the substantial increase in mean airflow velocity, the TI remains notably suppressed along the converging pathway. The absence of turbulent bursts confirms that the streamlined wall design promotes smooth acceleration while preserving flow stability. The highest TI levels peaking at approximately 626% are observed near the edges of the high negative-pressure throat section, where strong shear layers are

generated due to the high-speed flow within the confined cross-section [31]. However, these localized turbulent regions are mainly restricted to the periphery of the outlet, while the central core of the flow remains relatively stable. At this stage, insects have already been entrained by the high-velocity airflow, and the localized turbulence does not adversely affect capture efficiency.

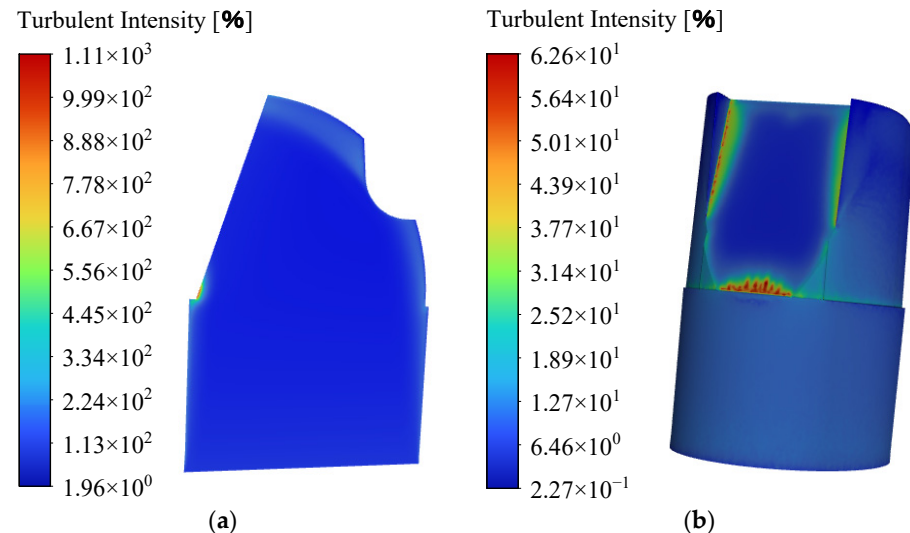


Figure 12. Contour Map of Turbulent Intensity in the Channel. Note: (a) central cross-sectional view; (b) overall three-dimensional view.

3.1.4. Streamline Topology Analysis

The mean flow structure within the wind-suction channel is characterized through streamline topology analysis, as illustrated in Figure 13, due to the excessive density of flow lines, their number in the central cross-sectional view is reduced by a factor of 200 to clearly visualize their trajectories. The streamlines are coloured by velocity magnitude to provide a physically meaningful representation of the spatial acceleration process within the channel. The spatial distribution and continuity of the streamlines provide a direct representation of the induction field's stability across the three functional stages.

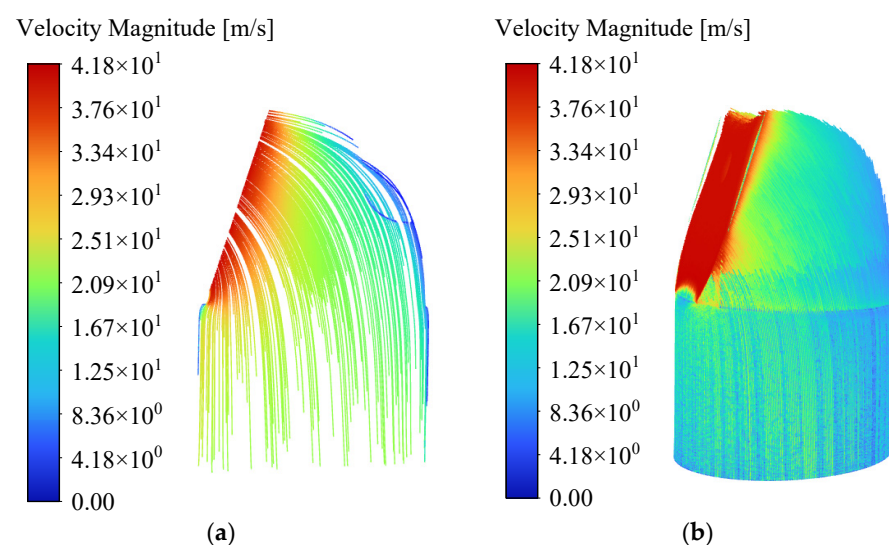


Figure 13. Simulated Streamline Distribution Coloured by Velocity Magnitude. Note: (a) central cross-sectional view; (b) overall three-dimensional view.

In the flow-stabilizing intake section, the streamlines originate from the ambient environment and enter the cylindrical domain in a predominantly axial direction. The streamlines exhibit a high degree of parallelism and uniform spacing, which indicates the absence of large-scale inlet vortices or non-uniform velocity distributions. This rectified flow pattern is a direct consequence of the constant-cross-section geometry, which serves as a buffer to mitigate the influence of external aerodynamic perturbations. From a biological perspective, this stable and uniform flow structure minimizes the rate of change in local pressure gradients, thereby reducing the probability of triggering the mechanoreceptors of target insects during the initial entry phase.

As the fluid progresses into the guided acceleration section, the streamline bundles converge in strict accordance with the contraction profile of the inner walls. The absence of streamline crossing or detachment from the boundaries confirms that the curvature is sufficient to suppress boundary layer separation under the current Reynolds number. The flow exhibits a continuous and monotonic acceleration, concentrating the kinetic energy toward the channel's center line.

In the high negative-pressure throat section, the streamlines are compressed into a compact configuration. Despite the severe geometric transition, the streamlines remain continuous and ordered. The filleted junction prevents the formation of corner vortices, ensuring that the maximum suction intensity is maintained without significant energy dissipation through recirculating flow. This stable streamline topology ensures that entrained targets are confined within a one-way transport path, moving from the low-velocity induction zone to the high-velocity collection zone without encountering stagnation regions.

The three-dimensional visualization in Figure 13b further demonstrates the interaction between the flow field and the internal wall surfaces. The velocity-coloured streamlines indicate the progressive acceleration of the flow from the induction region toward the high-velocity throat. The spatial distribution of the streamlines confirms that the rectified induction field maintains an orderly, predominantly axial flow topology without generating large-scale vortices, ensuring a smooth and efficient aerodynamic passage for the capture process.

Taken together, the CFD results characterize the internal aerodynamic conditions associated with the suction-capture mechanism rather than constituting an independent agronomic outcome. The relatively stable intake flow provides a mechanistic basis for interpreting the reduced stress-response distances subsequently observed in tea green leafhoppers and tea thrips. Meanwhile, the progressive acceleration, pressure decrease, attached flow, and continuous streamline pathway are consistent with the transport of entrained insects toward the collection chamber. The practical pest-control relevance of these aerodynamic characteristics was therefore evaluated under controlled laboratory conditions using capture rate and stress-response distance as biological performance indicators.

3.2. Experimental Verification Results and Analysis

Experimental validation was organized into three complementary levels. First, measured centerline velocities were compared with the CFD predictions to assess the consistency of the numerical model. Second, simulated-target tests quantified the distance-dependent suction performance of the proposed device. Third, live-insect tests directly compared the proposed device with the commercially available straight-tube device at the same release distances, using capture rate and critical stress-response distance as performance indicators. This framework distinguishes numerical-model validation, distance-dependent suction performance, and comparative biological performance.

3.2.1. Comparison of Simulated and Measured Flow Velocities

The comparison of simulated and measured flow velocities is summarized in Table 2.

Table 2. Comparison of simulated and measured average flow velocities at sections of the air suction channel.

Monitoring Point	V_{CFD} (m/s)	V_{MAF} (m/s)	δ (%)
Entrance Section Center	20.00	19.42 ± 1.78	−2.90
Acceleration Section Center	31.50	30.21 ± 1.63	−4.29
Throat Section Center	41.80	39.92 ± 0.82	−4.49

At the throat-section center, the experimentally measured average velocity was 39.92 ± 0.82 m/s, compared with the simulated value of 41.80 m/s, corresponding to a relative difference of 4.49%. The experimental results indicate that the measured airflow velocities are slightly lower than the simulated values at all monitoring locations. This discrepancy is primarily attributed to local energy losses caused by manufacturing tolerances, assembly imperfections, and wall friction effects that were neglected in the numerical model. Furthermore, it must be acknowledged that the insertion of the anemometer probe inherently introduces a physical obstruction within the channel. This instrumentation creates a localized blockage ratio, generating a downstream wake and slight geometric interference not accounted for in the idealized numerical model. Consequently, this aerodynamic blockage physically contributes to the observed discrepancy between the simulated and measured velocities. Nevertheless, the overall trends of the experimental data are highly consistent with the simulation results. The maximum relative error was within 5.0%, demonstrating that the established numerical model provides an accurate representation of the actual flow field characteristics of the device.

3.2.2. Experimental Results of Simulated Target Capture Efficiency

One-way analysis of variance indicated that the release distance significantly affected the capture rate, with $F = 44.36$ and $p < 0.01$. The specific data are displayed in Table 3.

Table 3. The experimental results of suction and capture efficiency for simulated targets.

Release Distance (cm)	Capture Rate (%)				Significance
	Group 1	Group 2	Group 3	Average	
10	94.00	92.00	94.00	93.33 ± 3.06	a
20	86.00	84.00	88.00	86.00 ± 3.46	b
30	68.00	66.00	66.00	66.67 ± 4.16	c

The capture rates at 10 cm and 20 cm reached $93.33 \pm 3.06\%$ and $86.00 \pm 3.46\%$ respectively. The low standard deviations suggest a stable aerodynamic environment established by the intake section, which provides consistent flow guidance.

Furthermore, Duncan multiple range test identified significant differences among all three distances, denoted by significance letters a, b, and c in Table 3. The high capture rate sustained within the 20 cm range demonstrates that the aerodynamic drag generated by this design is sufficient to overcome target inertia. A significant decline to $66.67 \pm 4.16\%$ was observed at 30 cm. This reduction corresponds to the spatial attenuation of the suction flow field. These statistical results define the effective operational radius of this design at approximately 20 cm, providing a quantitative basis for subsequent biological validations.

The capture rates reported in Table 3 were determined experimentally and were not directly predicted by the present CFD model. The numerical model resolves the

continuous airflow within the suction channel but does not include the external release space, Lagrangian particle tracking, target-specific drag parameters, interactions with device surfaces, or a numerical capture criterion. Therefore, the CFD results provide a mechanistic interpretation of airflow acceleration and target transport after entry into the channel, whereas the distance-dependent probability of entering the inlet and reaching the collection chamber was quantified experimentally. A coupled external-flow and discrete-particle model would be required to predict the capture rates numerically.

3.2.3. Comparative Results and Analysis of Biological Experiments Between This Design and the Straight Tube Design

Independent samples *t* tests revealed that this design achieved highly significantly greater capture rates than the straight tube control across all tested distances and insect species, with $p < 0.01$ for all comparisons. As detailed in Table 4.

Table 4. Comparison of capture efficiency between the variable cross-section design and straight-tube control at different distances.

Insect Types	Release Distance (cm)	Average Capture Rates (%)	
		This Design	Straight-Tube
Tea Green Leafhoppers	10	90.67 ± 6.11	74.67 ± 3.06
	20	85.33 ± 3.06	52.67 ± 7.02
	30	62.67 ± 4.16	42.00 ± 3.46
Tea Thrips	10	91.33 ± 5.03	72.67 ± 6.43
	20	86.00 ± 2.00	54.00 ± 2.00
	30	62.67 ± 4.62	40.67 ± 4.62

Within the 20 cm operational radius, the capture rates of this design for tea green leafhoppers and tea thrips remained robust at 85.33 ± 3.06% and 86.00 ± 2.00% respectively. In comparison, the straight tube device exhibited a severe performance drop, capturing only 52.67 ± 7.02% of leafhoppers and 54.00 ± 2.00% of thrips at the same distance. The substantial 32 percentage point improvement statistically validates the biological effectiveness of the flow field control mechanisms.

Live insects possess sensitive aerodynamic receptors and strong upwind flight capabilities. The straight tube configuration fails to regulate intake airflow, thereby generating turbulent cues that trigger early escape responses. Although the initial inlet geometries of both the proposed design and the straight-tube control group are fundamentally identical, their downstream aerodynamic developments diverge significantly due to the distinct magnitudes of their streamwise pressure gradients and subsequent flow acceleration profiles. In the uniform-diameter straight tube, the internal pressure gradient predominantly serves to balance viscous wall friction, resulting in a constant mean core velocity without spatial acceleration. Under this condition, the boundary layer continuously thickens along the streamwise direction. Consequently, minor aerodynamic disturbances or initial boundary layer separations generated at the inlet edge lack a robust hydrodynamic stabilizing mechanism; they propagate downstream and amplify into macroscopic turbulent vortices. In contrast, the variable cross-section channel functions as a converging nozzle, structurally establishing a significant favorable pressure gradient that actively drives spatial flow acceleration. This dynamic acceleration mechanism continuously converts pressure energy into kinetic momentum for the near-wall boundary layer, which restricts boundary layer growth, actively suppresses initial flow separation, and effectively dampens inlet-induced disturbances. Therefore, the converging geometry strictly maintains a highly stabilized, fully attached induction field.

This design establishes a flow-stabilizing intake section that attenuates mechanical disturbance signals. Consequently, the test insects are drawn into the high negative-pressure throat before initiating evasive maneuvers. The significantly higher capture rates and low standard deviations confirm that this design provides a viable physical control method for small bodied agricultural pests.

The average critical stress-response distances measured for each insect species are summarized in Table 5.

Table 5. Comparison of concealment performance statistics between the present design and the straight-tube design under laboratory conditions.

Insect Types	This Design (cm)	Straight-Tube (cm)	Disturbance Delay Percentage (%)
Tea Green Leafhoppers	11.2 ± 1.59	21.8 ± 1.47	48.62
Tea Thrips	7.5 ± 0.84	15.4 ± 1.32	51.39

The results show that the proposed wind-suction channel design significantly reduces the distance at which insects initiate stress responses. For the highly disturbance-sensitive tea thrips, the average critical distance decreased to 7.5 ± 0.84 cm, representing a 51.39% reduction compared with the 15.4 ± 1.32 cm observed for the straight-tube control. For tea green leafhoppers, the critical distance was reduced to 11.2 ± 1.59 cm, also indicating a substantial improvement relative to the control device.

Direct behavioral observations revealed that the straight-tube configuration generated pressure pulsations and aerodynamic noise near the inlet due to poor flow field regulation. These disturbances caused insects to perceive danger and escape before entering the effective suction zone. In contrast, the proposed design employs a flow-stabilizing intake section that establishes a highly stable and low-disturbance flow environment at the inlet. This allows insects to approach without initiating early evasive flight while being attracted by the light source.

Relative to the commercially available straight-tube comparator, the proposed device increased the capture rates at 20 cm by 32.66 percentage points for tea green leafhoppers and 32.00 percentage points for tea thrips. The corresponding critical stress-response distances were reduced by 48.62% and 51.39%, respectively.

Overall, the biological validation results confirm that the proposed wind-suction channel design achieves a balance between low-disturbance induction and strong aerodynamic confinement. By effectively delaying stress-response triggering and suppressing escape behavior, the device demonstrates potential for practical application in small-bodied pest control.

4. Discussion

The present study demonstrates that the improved capture efficiency of the proposed variable cross-section wind-suction channel originates not only from suction intensity but more importantly from the regulation of the internal flow field and its interaction with insect behavioral responses. By introducing a three-stage aerodynamic structure consisting of a flow-stabilizing intake section, a guided acceleration section, and a high negative-pressure throat, the design establishes a coordinated mechanism that simultaneously reduces environmental disturbance at the inlet while enhancing aerodynamic confinement at the outlet. The prototype configuration, fabricated device, and trapping result are shown in Figure 14.

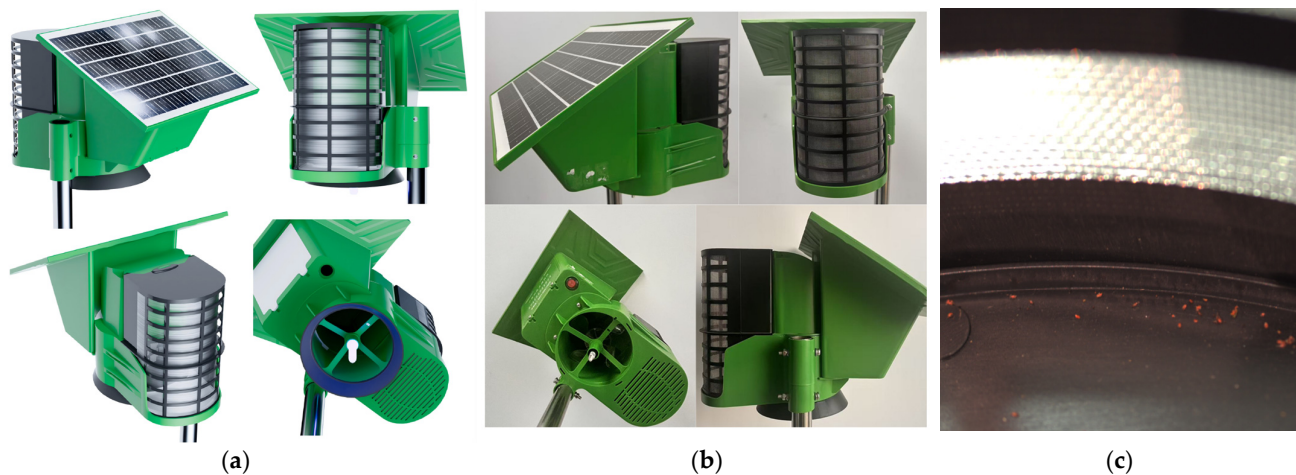


Figure 14. Prototype Configuration, Fabricated Device, and Trapping Result. Note: (a) computer-generated 3D model of the prototype; (b) photograph of the fabricated device; (c) captured tea thrips.

In the present study, the CFD analysis was used as an engineering tool to characterize the airflow conditions that directly influence suction performance, rather than as an independent agronomic endpoint. The simulated flow field provides a mechanistic basis for interpreting the subsequent suction tests with artificial targets and live insects, while the agronomic relevance of the device is evaluated mainly through its pest-suction performance under controlled experimental conditions.

The numerical simulations demonstrate that the proposed geometric configuration of the channel successfully provides the required aerodynamic conditions, specifically effectively regulating three critical indicators: velocity gradient, turbulence intensity, and pressure distribution. In the flow-stabilizing intake section, the relatively large inlet diameter maintains a moderate airflow velocity of approximately 18–20 m/s and produces a highly rectified flow field with low turbulence intensity. Such a stable aerodynamic environment is essential because many small insects possess highly sensitive mechanoreceptors that detect airflow fluctuations and pressure disturbances. Previous studies have shown that turbulent airflow can significantly impair insect flight stability or trigger rapid escape behavior before suction becomes effective. The biological experiments conducted in this study support this mechanism: the critical stress-response distances of tea thrips and tea green leafhoppers were reduced by approximately 50% compared with those observed in the straight-tube configuration. This indicates that the stabilized inlet flow effectively masks mechanical disturbance signals and allows insects to approach the suction inlet without initiating evasive flight.

The improved capture efficiency of the variable cross-section channel is fundamentally driven by a targeted bio-aerodynamic mechanism rather than a mere increase in mechanical suction power. At the micro-scale, pests such as tea green leafhoppers and tea thrips rely on highly sensitive mechanoreceptors to detect localized pressure fluctuations and initiate stress-induced escape. The computational results indicate that the flow-stabilizing intake establishes a highly rectified induction zone, maintaining a turbulence intensity as low as 0.227%. Biologically, this exceptionally stable flow environment actively remains sub-threshold for the insect's mechanoreceptors. This mechanism is supported by the behavioral observations, where the critical stress-response distance was reduced by approximately 50% compared to conventional straight-tube designs. Furthermore, within the guided acceleration section, the continuous convergence of streamlines and strictly positive wall shear stress ($WSS > 0$) prevent macroscopic flow separation. This specific fluid-dynamic topology denies the entrained micro-insects any aerodynamic stagnation zones or localized

counter-currents to recover their flight posture, ensuring irreversible transport into the high-velocity (41.8 m/s) throat.

Compared with existing suction-based insect capture devices reported in the literature, the proposed design demonstrates clear advantages in terms of flow field regulation and behavioral compatibility. Conventional suction traps typically employ straight tubes or simple bell-mouth inlets because of their structural simplicity. However, coordinating a high inductive airflow velocity with localized flow stability in these traditional structures remains a primary aerodynamic challenge. For example, the constant-diameter flexible suction cylinders investigated by Wang et al. [17] inherently induce localized velocity counter-currents and non-negative pressure zones at structural curvatures, and their internal fluid profiles exhibit severe turbulent fluctuations when operating at high inlet velocities up to 20 m/s. While such high-efficiency legacy systems demonstrate excellent performance when targeting macro-insects or operating under conditions where higher aerodynamic power inputs and physical interception meshes are standard, they are not directly comparable to the present work due to distinct operational constraints. The variable cross-section channel of the present design addresses the specific engineering challenge of capturing highly sensitive micro-insects such as tea green leafhoppers and tea thrips strictly under the low-power limitations typically required for distributed IoT monitoring nodes. By transitioning the fluid pathway into a straight converging nozzle profile, this geometry establishes a continuous favorable pressure gradient that thins the boundary layer and effectively dampens inlet-induced disturbances. Consequently, the fully attached, structurally stabilized acceleration field successfully mitigates the mechanoreceptor-triggered escape maneuvers of micro-pests. The capture rates observed in this study within a 20 cm operational radius exceeded 85%, demonstrating that equivalent or superior trapping performance can be maintained even when scaling down power consumption and removing physical mechanical barriers.

Furthermore, the present results extend previous research on pneumatic pest control systems by explicitly integrating insect behavioral responses into the aerodynamic design process. While earlier studies have mainly focused on increasing suction power or optimizing fan performance, the current work demonstrates that regulating turbulence intensity and velocity gradients at the inlet can be equally important for improving trapping efficiency. This design strategy provides a new perspective for the development of next-generation physical pest control equipment that combines aerodynamic optimization with biological behavior regulation.

To explicitly define the boundaries of this research, both the operational scope and inherent limitations of the proposed device must be clearly delineated. Regarding the operational scope, the aerodynamic mechanisms and enhanced capture efficiencies validated herein are strictly applicable to micro-scale piercing-sucking pests such as tea green leafhoppers and tea thrips within a highly localized 20 cm effective radius. This design is specifically tailored to exploit the extreme mechanoreceptor sensitivities and low flight mass of such micro-insects; it is not designed to aerodynamically suppress macro-insects (such as large Lepidoptera) that possess substantially higher flight propulsion capacities, nor is it intended for long-range spatial suction where the pressure gradient naturally dissipates. Regarding the functional scope, the present device was developed and evaluated primarily as a physical pest-capture system. In the controlled experiments, captured insects were retrieved from the collection chamber and manually counted to calculate capture efficiency; however, the current prototype does not incorporate automated species identification or real-time insect-counting functions. Future integration of optical sensing or image-based recognition may extend the device from pest capture to pest-population monitoring and provide more direct decision support for farm management. An additional limitation is

that the comparison with the straight-tube control was not performed under matched volumetric flow rate, pressure difference, or measured electrical power, and the two devices also differed in inlet diameter, total height, and collection-chamber position. Consequently, the observed improvement in capture efficiency cannot be attributed exclusively to the variable cross-section geometry. Rather, the results demonstrate the system-level performance of the integrated variable cross-section channel configuration under the tested laboratory conditions. Future work should employ geometrically matched controls and comparisons under equivalent volumetric flow rate, pressure difference, and electrical power to further isolate the contribution of channel geometry. However, the present aerodynamic and biological evaluations were conducted under controlled indoor conditions, and the performance of the device under real field conditions remains to be validated. In the field, crosswinds may disturb the rectified induction zone, while crop-canopy structure and local microclimatic flow may alter the assumed streamline pattern. In addition, scaling the device to extend the operating radius may change the turbulence profile, wall shear stress, and energy consumption in a nonlinear manner. Field trials and coupled multiphysics modeling are therefore needed to assess these effects and determine the device's practical operating range.

5. Conclusions

This study proposed and validated a three-stage variable cross-section wind-suction channel designed to improve the capture efficiency of small-bodied agricultural pests. By integrating a flow-stabilizing intake section, a guided acceleration section, and a high negative-pressure throat section, the proposed design establishes a coordinated aerodynamic environment that minimizes airflow disturbance near the inlet while generating strong aerodynamic confinement at the outlet.

Numerical simulations showed that the channel geometry produces a stable velocity gradient and suppresses turbulence in the intake region. Experimental measurements confirmed the reliability of the numerical model, with the deviation between simulated and measured airflow velocities remaining below 5%. Biological experiments further demonstrated that the capture efficiency for representative pests such as tea green leafhoppers and tea thrips exceeded 85% within a 20 cm operational radius, representing an improvement of more than 30 percentage points compared with a conventional straight-tube device.

These results indicate that regulating airflow structure and turbulence characteristics is critical for improving the performance of suction-based pest control systems. The proposed design has potential applications in solar-powered suction traps, intelligent pest monitoring systems, and unmanned plant protection equipment. Future work should focus on field validation and geometric parameter optimization to further enhance capture efficiency and adaptability under real agricultural conditions.

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