[DATE]

BIPV/T SOLAR COLLECTOR

BUILDING INTEGRATED PHOTOVOLTAIC-THERMAL SOLAR COLLECTOR

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Report Purpose and Context

This report is a refined and consolidated technical version of a team-based engineering capstone project, prepared for portfolio and professional presentation purposes. The original university capstone report and associated conference paper were produced under different constraints and for different audiences — one for academic evaluation and one for publication. This version integrates and refines the technical content, clarifies assumptions, and improves consistency and readability, while accurately reflecting my individual contributions and the final design outcomes.

The technical content in this report is derived from the original capstone documentation and supporting analyses, with reference to the conference paper where applicable. This document is not intended to replace the original submissions, but to present the work in a clear, professional format suitable for engineering review and discussion.

Executive Summary

This report presents a refined technical analysis of a building-integrated photovoltaic and thermal (BIPV/T) solar air collector developed as part of a team-based engineering capstone project. The primary objective of the project was to investigate and improve the thermal performance of the BIPV/T system through airflow management within the collector air channel, with particular emphasis on enhancing convective heat transfer from the photovoltaic panels.

The work focused on evaluating airflow enhancement strategies that promote turbulence and mixing without increasing system complexity or energy consumption. Multiple airflow configurations were assessed, including modifications to inlet geometry and the introduction of passive internal features such as baffles. These design concepts were analyzed using a combination of analytical heat transfer calculations and computational simulation to compare relative thermal performance, airflow behavior, and practical implementation considerations.

My contributions to the project encompassed both technical analysis and project coordination. From a technical perspective, I was responsible for the development and evaluation of airflow enhancement geometries, implementation of the airflow simulation model, and analysis of key performance indicators such as Reynolds number trends and outlet air temperature rise. Comparative assessments were conducted to support selection of the final airflow configuration. In parallel, I contributed to project management and documentation efforts, including task coordination, meeting organization, integration of team inputs, and leadership in the preparation and refinement of the final technical deliverables.

The selected airflow configuration demonstrated a measurable improvement in thermal performance, achieving an outlet air temperature increase of approximately 8.7 °C relative to baseline conditions. The results highlight the importance of airflow behavior in BIPV/T system performance and demonstrate that meaningful thermal gains can be achieved through passive design modifications guided by fundamental fluid mechanics principles. The findings demonstrate how passive airflow modifications can influence heat transfer performance in BIPV/T systems and provide a basis for future design refinement.

Contents

1. Project Summary

This project investigated strategies to enhance the thermal performance of a building-integrated photovoltaic/thermal (BIPV/T) solar collector by improving heat transfer within the air channel beneath photovoltaic (PV) panels. In conventional PV systems, only a fraction of incoming solar radiation is converted to electrical energy, with the remainder dissipated as heat. Elevated panel temperatures reduce electrical efficiency but also represent an opportunity for thermal energy recovery if that heat can be effectively extracted.

A simulation-based air channel model was developed to examine airflow patterns and heat transfer behavior within a representative BIPV/T configuration. Several passive airflow enhancement concepts were explored with the goal of increasing turbulence and convective heat transfer between the PV panel surface and the air stream. The recovered thermal energy was considered for use as preheated intake air for an air-source heat pump (ASHP), aligning with residential heating applications.

Multiple internal flow configurations were compared, including guiding walls, fin-based enhancements, and porous media concepts. A configuration combining fin baffles with a porous metal mesh produced the most consistent improvement in turbulence intensity and temperature rise along the duct. Under representative design conditions, this final configuration increased outlet air temperature by approximately 8.7 °C while maintaining average airflow velocities similar to the baseline case.

These findings indicate that relatively simple, passive airflow enhancement features can meaningfully improve the thermal effectiveness of BIPV/T systems without increasing airflow rates or adding complex control strategies. While the results are based on simulation and subject to modeling assumptions, they provide useful insight into design trends and trade-offs relevant to residential BIPV/T applications.

2. Problem Statement

2.1 Background

Residential space heating in Ontario has historically been dominated by natural gas systems due to low fuel costs and established infrastructure. Rising energy prices, carbon pricing mechanisms, and increasingly stringent climate targets are expected to increase both the cost and environmental impact of fossil-fuel-based heating. These trends motivate the development of low-carbon heating solutions that can reduce operating costs while lowering greenhouse gas emissions.

Solar photovoltaic (PV) systems are widely deployed for residential electricity generation, but their overall efficiency remains limited. A significant portion of incident solar radiation is converted to heat rather than electricity, and elevated operating temperatures further reduce electrical output. This waste heat is typically dissipated to the surrounding environment and remains largely unutilized.

Building-integrated photovoltaic/thermal (BIPV/T) systems address this limitation by enabling simultaneous generation of electrical and thermal energy from a single roofing system. By extracting heat from the underside of PV panels and transferring it to a working fluid, BIPV/T systems can reduce panel operating temperature while providing usable thermal energy for space heating or integration with an air-source heat pump (ASHP). The effectiveness of this approach is strongly influenced by airflow behavior within the thermal duct.

The core problem addressed in this project was the limited convective heat transfer between the PV panel surface and the airflow in conventional BIPV/T air channels. Insufficient turbulence and poor mixing restrict the amount of recoverable thermal energy, thereby limiting the overall benefit of BIPV/T systems. This project focused on investigating practical, passive airflow enhancement strategies that improve turbulence and convective heat transfer while remaining cost-effective and suitable for residential applications.

2.2 Team Contribution & Project Context

This work was completed as part of a team-based engineering capstone project, with responsibilities distributed across system design, analysis, coordination, and documentation. The project involved collaborative development of the BIPV/T system concept, simulation modeling, and performance evaluation. Team contributions included system layout development, literature review, modeling support, and integration of results into the final deliverables.

My contributions focused primarily on the technical evaluation of airflow enhancement strategies within the BIPV/T air channel, as well as project coordination and technical documentation. From a technical perspective, I developed and evaluated airflow concepts through the implementation of turbulence-enhancing geometries, conducted airflow and thermal trend analysis using Reynolds number and temperature data, and performed comparative assessments of multiple design configurations to support final design selection. Supporting analytical calculations were used to assess relative thermal performance between design iterations.

In addition to technical analysis, I contributed to project coordination and documentation efforts, including organizing team tasks, coordinating meetings and site visits, compiling and refining team deliverables, and leading the preparation, editing, and finalization of the technical report.

3. Assumptions & Constraints

The analysis and simulation of the BIPV/T air channel system required several simplifying assumptions to enable tractable modeling while preserving engineering relevance. In addition, practical constraints related to system design, operation, and implementation influenced the scope of the study.

3.1 Assumptions

Steady-State Operation

The system was analyzed under steady-state conditions. Transient effects due to fluctuating solar irradiance, ambient temperature variations, and system startup behavior were not explicitly modeled. This assumption allowed direct comparison between configurations under consistent operating conditions.

Uniform Solar Heat Flux

A uniform thermal input from the photovoltaic panel surface was assumed across the length of the air channel. While this does not capture localized irradiance variations, it allowed meaningful relative comparison between airflow enhancement concepts by isolating the effect of internal flow behavior.

Constant Thermophysical Properties

Air properties, such as density, viscosity, and specific heat capacity, were assumed constant and evaluated at representative operating temperatures. Variations due to temperature gradients within the duct were neglected to simplify analysis.

Negligible Heat Losses to Surroundings

Heat losses through conduction, radiation, and leakage to the external environment were assumed small relative to convective heat transfer within the air channel. This focused the analysis on internal heat transfer trends rather than absolute system efficiency.

Fully Developed Flow Regions

Flow within the air channel was assumed fully developed over most of the duct length, enabling Reynolds number and turbulence behavior to serve as primary performance indicators.

Idealized Enhancement Geometry

Flow enhancement features, such as fins and porous metal mesh, were represented using simplified geometries that captured their functional behavior rather than detailed manufacturing-level complexity.

Stable Fan Performance
Airflow provided by the fan was assumed to remain stable, with no degradation due to pressure losses or operational variability. This allowed comparison of thermal performance independent of fan-specific effects.

3.2 Constraints

Geometric Constraints
Air channel dimensions were constrained by PV panel geometry and roofing integration requirements, limiting duct height and cross-sectional area.

Residential Applicability
Design concepts were restricted to solutions suitable for residential applications, prioritizing simplicity, low cost, and ease of installation.

Material Practicality
Enhancement devices were limited to commercially available, durable materials compatible with rooftop environments.

Computational Limitations
The number and complexity of simulations were constrained by available computational resources, requiring a balance between mesh resolution, turbulence modeling detail, and simulation runtime.

Lack of Experimental Validation
The study relied entirely on simulation-based analysis; full experimental validation was outside the project scope.

Control and Instrumentation Availability
The absence of real-time sensors and control systems limited the ability to model adaptive or feedback-based airflow control strategies.

Timeline and Site Access Constraints
The project was conducted within a single academic semester, imposing strict limits on design iteration, simulation refinement, and experimental validation. Activities were completed alongside concurrent coursework.

The BIPV/T system was located at an off-campus test site, requiring travel for site visits, data collection, and system review. Coordination among multiple team members introduced additional scheduling constraints, limiting the frequency and duration of on-site activities such as testing and measurements.

3.3 Impact of Assumptions and Constraints

The assumptions and constraints outlined above enabled comparative evaluation of multiple design configurations within a practical project scope. As a result, the findings should be interpreted as indicative of performance trends rather than precise real-world predictions. Incorporating transient analysis, detailed material modeling, and experimental validation would further improve confidence in predicted system performance.

4. Methods & Approach

The methodology for this project involved the development and evaluation of a computational air channel model for a building-integrated photovoltaic/thermal (BIPV/T) system. The primary objective was to analyze airflow behavior and convective heat transfer performance under various airflow enhancement strategies in order to identify a configuration that improves thermal energy recovery while remaining practical for residential implementation.

A comparative simulation-based approach was adopted, beginning with a baseline system and progressing through multiple enhancement concepts. Performance was evaluated using flow and thermal metrics relevant to BIPV/T operation, allowing relative improvements to be quantified across design iterations.

4.1 System Overview

The BIPV/T system consists of PV panels integrated into a roofing structure, with a sealed air channel located beneath the PV modules. Outdoor air is drawn through the channel by a fan, allowing heat generated at the PV panel surface to be transferred to the airflow through convective heat transfer. The heated air may be supplied directly for space heating or used as preheated intake air for an ASHP.

The air channel extends along the length of the PV panel assembly and is designed to promote effective heat transfer while maintaining acceptable airflow velocities and pressure losses. Inlet placement and internal flow features play a critical role in determining airflow distribution, turbulence development, and overall thermal performance.

4.2 Air-Channel Modeling Approach

A computational simulation model of the BIPV/T air channel was developed to predict airflow patterns, turbulence characteristics, and temperature distribution along the duct length. The model was used to evaluate the influence of internal geometries and airflow enhancement features on both flow behavior and thermal performance.

Key performance indicators used for comparison included:

- Reynolds number distribution along the air channel
- Airflow velocity profiles
- Air temperature rise from inlet to outlet

These metrics were selected to characterize turbulence intensity, assess convective heat transfer potential, and evaluate overall thermal effectiveness. Together, they provided a consistent basis for comparing the relative performance of each design configuration.

4.3 Benchmark Configuration

An initial benchmark configuration was established to represent a conventional BIPV/T system without airflow enhancement features. In this configuration, air entered the system through a bottom-mounted inlet and flowed along the length of the channel beneath the PV panels.

The benchmark model served as a reference case against which all subsequent enhancement concepts were evaluated. Performance metrics obtained from this configuration provided baseline values for airflow distribution, turbulence development, and temperature rise, enabling the effectiveness of each design modification to be assessed quantitatively.

4.4 Airflow Enhancement Concepts

Three airflow enhancement concepts were developed and simulated with the objective of increasing turbulence and improving convective heat transfer within the air channel:

- **Concept 1: Guiding Walls**
  Internal guiding walls were introduced to redirect airflow paths and promote mixing within the channel, with the intent of reducing flow stratification and improving heat transfer uniformity.

- **Concept 2: Fin-Based Enhancements**
  Fin structures were added to increase internal surface area and disrupt the flow field, encouraging higher turbulence levels and enhanced convective heat transfer.

- **Concept 3: Porous Media (Mesh) Enhancement**
  A porous metal mesh (porous media) was incorporated within the air channel to significantly disrupt laminar flow, promote mixing, and sustain turbulent conditions throughout the duct.

For each concept, variations in fan inlet positioning were also examined to assess the influence of inlet geometry on airflow distribution and overall system performance.

4.5 Selection of Final Design Configuration

Simulation results from the three enhancement concepts were compared against the benchmark configuration. Among the individual concepts, the porous metal mesh demonstrated the strongest improvement in airflow distribution and turbulence generation, resulting in superior heat transfer performance relative to the other designs.

Based on these findings, favorable features from both the fin-based and porous metal mesh concepts were combined to form a final design configuration. The selected design incorporated fin baffles coupled with a porous metal mesh distributed throughout the air channel. This configuration was chosen for its ability to sustain turbulent flow conditions, increase Reynolds number across the duct, and achieve a greater air temperature rise without introducing excessive increases in airflow velocity.

The final design was carried forward for detailed performance analysis and direct comparison with the benchmark BIPV/T system.

5. Calculations / Analysis

The performance of the BIPV/T air channel system was evaluated through analysis of airflow behavior and convective heat transfer along the length of the duct. The primary analytical parameters considered were Reynolds number, airflow velocity, and air temperature rise. Together, these metrics provide insight into flow regime, turbulence intensity, and the effectiveness of heat transfer from the PV panels to the air stream.

The analysis focused on comparing relative performance between the benchmark configuration, an initial enhanced design, and the final enhanced configuration, rather than predicting absolute system output.

5.1 Airflow and Reynolds Number Analysis

Reynolds number was used as the primary indicator of flow regime within the air channel and as a means of assessing the effectiveness of the airflow enhancement strategies. It was calculated along the duct length using the standard internal flow relationship:

$$\mathrm{Re} = \frac{\rho\, V\, D_h}{\mu}$$

where:

- ρ is the air density
- V is the local airflow velocity
- D_h is the hydraulic diameter of the air channel
- μ is the dynamic viscosity of air

Maintaining turbulent or transitional-to-turbulent flow was a key design objective, as higher Reynolds numbers are associated with increased convective heat transfer coefficients. Reynolds number distributions were evaluated for the benchmark configuration, the initial enhanced design, and the final enhanced configuration to quantify improvements in turbulence generation and flow mixing along the channel.

5.2 Velocity Distribution

Airflow velocity was monitored at multiple locations along the air channel to ensure that enhancement features did not introduce excessive flow restriction or undesirable pressure losses. Velocity profiles were used to verify that improvements in thermal performance were not primarily driven by increased airflow speed, which would imply higher fan power requirements.

Comparative results showed that average airflow velocities remained relatively consistent between configurations. This indicates that the observed improvements in thermal performance were achieved primarily through enhanced turbulence and mixing rather than through increases in volumetric flow rate.

5.3 Heat Transfer and Temperature Rise

The temperature rise of the air flowing through the channel was used as the primary indicator of thermal performance. Air temperature was evaluated at the channel inlet, outlet, and intermediate locations along the duct to assess the distribution of heat transfer along the flow path.

An energy balance approach was used to relate the heat transferred from the PV panel surface to the air stream:

$$Q = \dot{m}\, c_p\, \Delta T$$

where:

- Q is the rate of heat transfer
- $\dot{m}$ is the mass flow rate of air
- c_p is the specific heat capacity of air
- ΔT is the air temperature rise

Thermal input to the air channel was modeled using an effective thermal transmittance representative of combined conduction and convection heat transfer from the PV panel surface to the airflow. A value of approximately **150 W/m^2·K** was selected based on representative operating conditions and literature values. This simplified approach was considered appropriate for comparing relative performance between configurations, acknowledging that more detailed thermal modeling would be required for precise prediction of absolute heat transfer rates.

5.4 Comparative Performance Evaluation

Performance comparisons between configurations were based on the following criteria:

- Magnitude and distribution of Reynolds number along the duct
- Consistency of turbulent flow development
- Net air temperature rise from inlet to outlet

The initial enhanced configuration demonstrated measurable improvements in turbulence intensity and temperature rise relative to the benchmark system. However, the final configuration—combining fin baffles with a porous metal mesh—produced the highest Reynolds numbers across most of the duct length while achieving a comparable or slightly greater temperature increase.

This result is particularly relevant given the relationship between PV panel temperature and electrical efficiency. Typical photovoltaic modules experience an efficiency reduction of approximately **0.4% per degree Celsius** increase in operating temperature. Enhanced heat extraction from the panel surface therefore contributes not only to improved thermal recovery but also to potential gains in electrical performance.

5.5 Interpretation of Results

The analysis indicates that turbulence intensity, as reflected by Reynolds number distribution, plays a dominant role in heat transfer performance within the BIPV/T air channel. Configurations that effectively disrupted airflow and promoted mixing achieved greater heat extraction without requiring increases in airflow velocity.

These findings support the selection of the final enhanced configuration and demonstrate the viability of using relatively simple, passive airflow enhancement features to improve BIPV/T system performance in residential applications, particularly where system complexity and energy consumption must be carefully managed.

6. Results & Visuals

Simulation results were analyzed to evaluate airflow behavior, turbulence intensity, and thermal performance for the benchmark configuration, the initial enhanced design, and the final enhanced design. Results are presented in terms of Reynolds number distribution, airflow velocity, and air temperature rise along the length of the BIPV/T air channel. Both quantitative metrics and visual outputs were used to assess the relative effectiveness of each design configuration.

6.1 Benchmark Configuration Results

The benchmark configuration, which did not include any airflow enhancement features, exhibited relatively uniform airflow along the air channel with limited mixing across the channel cross-section. Reynolds number values remained above the nominal turbulent threshold; however, turbulence intensity was comparatively low and varied minimally along the duct length.

The air temperature rise along the channel was gradual, indicating limited convective heat transfer between the PV panel surface and the airflow. These results reflect the behavior expected of a conventional BIPV/T air channel and served as a baseline for evaluating the impact of subsequent airflow enhancement strategies.

Figure 1: Benchmark airflow and temperature distribution

6.2 Initial Enhanced Design Results

The initial enhanced configuration, which incorporated a porous media-based airflow enhancement, demonstrated noticeable improvements in airflow distribution and turbulence compared to the benchmark system. Reynolds number values increased along the duct length, indicating more effective disruption of regions prone to lower turbulence intensity.

The inlet-to-outlet air temperature rise increased relative to the benchmark configuration, reflecting improved heat transfer from the PV panel surface to the airflow. Airflow remained stable throughout the channel, and velocity levels were comparable to those observed in the benchmark case. This suggests that the observed thermal performance gains were achieved without introducing significant additional flow resistance.

Table 1: Reynolds number, velocity, and temperature at selected duct locations – Initial Design

x (m)	Re	V (m/s)	T(°C)
0.63	35097.29	2.02	1.34
1.36	32240.54	1.84	2.33
2.42	33668.92	2.36	4.37
3.38	45912.16	2.73	6.01
4.49	44279.73	4.68	8.47
6.52	33566.89	1.91	8.68

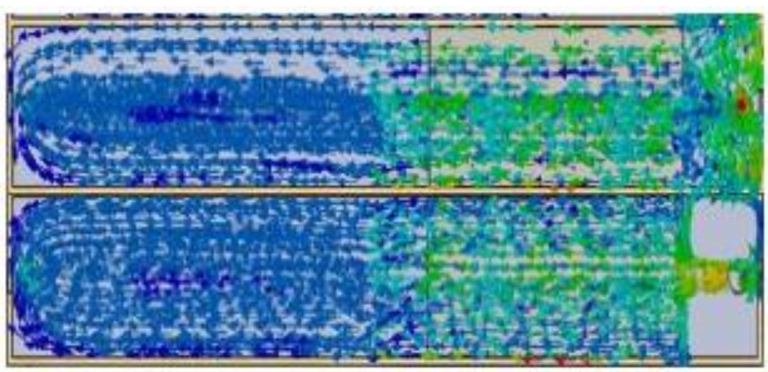

Figure 2: Initial enhanced design airflow and temperature contours

6.3 Final Enhanced Design Results

The final enhanced configuration combined fin baffles with a porous metal mesh distributed throughout the air channel. This configuration produced the highest Reynolds number values across most of the duct length, indicating a sustained increase in turbulence intensity and improved mixing relative to both the benchmark and initial enhanced designs.

Under design conditions, the inlet-to-outlet air temperature rise reached approximately **8.66 °C**, representing a modest but consistent improvement over the initial enhanced configuration. Importantly, airflow velocity remained similar to that observed in the previous configurations. This indicates that the improvement in thermal performance was primarily driven by enhanced convective heat transfer rather than increased airflow rate.

Table 2: Reynolds number, velocity, and temperature at selected duct locations – Final Design

x (m)	Re	V (m/s)	T(°C)
0.63	54278.37	2.66	1.67
1.36	37545.94	1.84	2.30
2.42	47748.65	2.34	4.31
3.38	55298.64	2.71	5.93
4.49	95497.29	4.68	8.44
6.52	38974.32	1.91	8.66

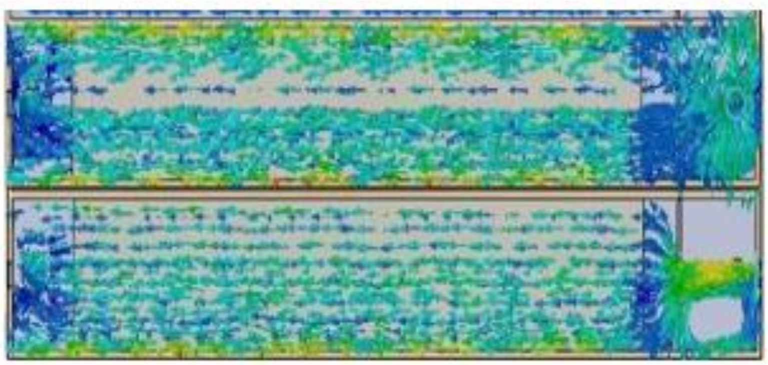

Figure 3: Final enhanced design airflow and temperature contours

6.4 Comparative Performance Summary

A comparison of all configurations highlights the effectiveness of airflow enhancement strategies in improving BIPV/T system performance. While both enhanced designs demonstrated improved thermal behavior relative to the benchmark system, the final enhanced configuration consistently produced higher Reynolds numbers and slightly greater temperature rise along the air channel.

Although the increase in outlet air temperature between the initial and final enhanced designs was relatively small, the higher and more uniformly distributed turbulence levels achieved in the final design are significant from a system performance perspective.

Enhanced heat extraction reduces PV panel operating temperature, which can improve electrical efficiency and potentially extend panel lifespan.

6.5 Interpretation of Simulation Visual Results

Visual inspection of airflow and temperature contour plots revealed that the enhancement features effectively disrupted flow patterns, reduced stagnant regions, and promoted mixing across the channel cross-section. In particular, the porous metal mesh contributed to more uniform airflow distribution and sustained turbulence throughout the length of the air channel.

These visual observations are consistent with the quantitative results and provide qualitative confirmation that the selected enhancement strategy offers a balanced improvement in thermal performance without introducing excessive system complexity or operational penalties.

7. Tools & Skills Used

This project required the application of engineering analysis, simulation, and design principles to evaluate and improve the thermal performance of a BIPV/T system. A combination of computational tools, technical knowledge, and standard engineering practices was applied throughout the design and evaluation process, enabling both quantitative assessment and professional reporting of results.

7.1 Engineering Tools

The following tools were used to support modeling, analysis, and design development:

- **Computational simulation software** for modeling airflow behavior, turbulence characteristics, and heat transfer within the BIPV/T air channel
- **Computer-aided design (CAD) tools** for developing system geometry, configuring airflow enhancement features, and preparing models for simulation
- **Data analysis and post-processing tools** for extracting simulation results, comparing performance metrics, and evaluating trends across design configurations

7.1.1 Microsoft Excel

Microsoft Excel was used as the primary data manipulation and post-processing tool. Simulation outputs from SolidWorks were imported into Excel to organize results, evaluate trends, and generate comparative plots. Excel was also used to perform supporting analytical calculations, including Reynolds number evaluation to determine flow regime (laminar, transitional, or turbulent) across design configurations.

Cell-based equations enabled efficient recalculation as design parameters were varied, and graphical outputs were used to clearly visualize airflow and temperature trends along the BIPV/T channel. This approach facilitated rapid comparative analysis between design iterations and supported quantitative decision-making.

7.1.2 SolidWorks

SolidWorks was used for three-dimensional modeling of BIPV/T airflow channel components and assemblies, as well as for computational fluid dynamics (CFD) simulations. The CAD environment supported the creation of simplified yet representative geometries to visualize airflow paths and communicate design concepts through drawings and assemblies.

CFD simulations were performed to evaluate relative airflow behavior and thermal trends under controlled boundary conditions approximating the experimental test setup. Multiple inlet configurations and internal turbulence-enhancing features were tested to assess their influence on heat transfer performance.

Due to the computational cost and complexity associated with variable boundary conditions (e.g., wind effects and solar orientation), highly detailed simulations were reserved for the final design configuration. Earlier concepts were evaluated using simplified assumptions to enable efficient relative comparison between designs.

7.1.3 AutoCAD

AutoCAD was used to develop control and instrumentation schematics for the proposed experimental and idealized sensor and control system layouts. These drawings illustrated sensor placement, measurement points, and control logic to support future implementation once instrumentation became available.

The schematics informed the development of sensor requirements and supported system-level planning for experimental validation, providing a clear framework for potential experimental deployment.

7.2 Technical Skills

Key technical concepts and skills applied during the project included:

- **Fluid mechanics**, with emphasis on internal flow behavior and turbulence characterization

- **Heat transfer analysis:** Analyzed convective heat transfer and performed energy balance calculations
- **Reynolds number evaluation:** Assessed flow regime and turbulence intensity using Reynolds number.
- **Thermal performance assessment:** Performed thermal performance assessment based on air temperature rise and comparative analysis across configurations
- **System-level understanding of photovoltaic–thermal interactions**: Developed system-level understanding of photovoltaic–thermal interactions, including the impact of heat extraction on PV operating temperature

7.3 Engineering Practices

Standard engineering practices were applied to guide the design and evaluation process:

- **Concept generation and comparative design evaluation** to assess multiple airflow enhancement strategies
- **Use of simplifying assumptions and constraints** to make the problem tractable within the scope of a capstone project
- **Interpretation of simulation results** to support design decisions rather than relying solely on raw numerical outputs
- **Technical documentation and professional reporting** to clearly communicate methodology, results, and limitations

7.4 Tools & Skills Summary

The combination of computational tools, technical knowledge, and engineering practices provided the framework to evaluate airflow enhancement strategies, quantify thermal performance, and communicate findings effectively. This integrated approach enabled informed decision-making while maintaining engineering precision and clarity in presentation.

8. Lessons Learned & Reflections

This project provided valuable insight into the design, analysis, and evaluation of building-integrated photovoltaic/thermal (BIPV/T) systems. A key technical takeaway was the significant influence of airflow behavior on convective heat transfer: simply increasing airflow velocity alone did not yield substantial thermal gains. Rather, promoting turbulence and effective mixing within the air channel, achieved through passive enhancement features such as fin baffles and porous metal mesh, was critical to improving heat extraction while maintaining practicality for residential applications.

The project also highlighted the importance of selecting appropriate performance metrics. Reynolds number proved to be a useful indicator of turbulence intensity and a reliable basis for comparing design configurations. However, improvements in turbulence must be balanced against practical constraints such as pressure losses, manufacturability, and simplicity of implementation.

From a modeling perspective, the work reinforced the value of simulation as an early-stage design tool. Computational models allowed multiple airflow enhancement concepts to be explored efficiently, revealing trends in flow behavior and thermal performance that would have been difficult to measure experimentally within the constraints of a single semester. At the same time, the project emphasized the inherent limitations of simulation-based analysis, including reliance on steady-state assumptions, simplified material representations, and qualitative evaluation of pressure losses. Experimental validation remains important to confirm predicted performance.

On a project execution level, the team-based nature of the work underscored the importance of communication, coordination, and task allocation. Balancing technical depth with schedule constraints required prioritization of design efforts and clear definition of objectives, reflecting challenges commonly encountered in professional engineering projects.

Future work could focus on experimental validation of the final design, refinement of enhancement geometry, and exploration of adaptive airflow control strategies under transient solar conditions. Despite these limitations, the project successfully demonstrated that simple, cost-effective airflow enhancements can measurably improve BIPV/T system performance, providing a strong foundation for both practical design and further research.

9. Links / References

- Conference Paper: *BIPV/T Airflow Analysis for Ideal Heat Transfer*
- Portfolio Project Page: *Building-Integrated Photovoltaic/Thermal (BIPV/T) System*
- GitHub Repository: *BIPV/T Solar Collector Design Enhancement*