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BIPVT SOLAR COLLECTOR

Building Integrated Photovoltaic-Thermal Solar Collector

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Contents

1. Project Summary

This project focused on improving the thermal performance of a building-integrated photovoltaic/thermal (BIPV/T) solar collector by enhancing heat transfer within the air channel located beneath photovoltaic (PV) panels. Conventional PV systems convert only a portion of incoming solar radiation into electrical energy, with the remaining energy dissipated as waste heat. Elevated panel temperatures reduce electrical efficiency while representing an opportunity for thermal energy recovery.

An air-channel simulation model was developed to analyze airflow behavior and heat transfer performance within a BIPV/T system. The project investigated multiple airflow enhancement concepts designed to increase turbulence and improve convective heat transfer between the PV panel surface and the air flowing through the channel. The recovered thermal energy was intended to preheat outdoor air for integration with an air-source heat pump (ASHP), thereby improving overall system efficiency and reducing residential heating energy demand.

Several design configurations were evaluated, including guiding walls, fin-based enhancements, and porous media concepts. A final design incorporating fin baffles coupled with a porous metal mesh demonstrated the most effective thermal performance. Simulation results showed a consistent increase in air temperature along the duct length while maintaining turbulent flow conditions throughout the system. Under design conditions, outlet air temperatures increased by approximately 8.66 °C, with significantly higher Reynolds numbers observed compared to initial configurations.

The results indicate that simple, cost-effective airflow enhancement methods can substantially improve the thermal performance of BIPV/T systems. By increasing heat extraction from PV panels, the proposed design improves both photovoltaic electrical efficiency and the usefulness of recovered thermal energy for residential and industrial heating applications.

2. Problem Statement

2.1 Background & Motivation

Residential air heating in Ontario is predominantly supplied by natural gas systems due to historically low fuel costs. However, increasing energy prices, carbon taxation, and stricter climate regulations are expected to raise the cost of residential heating and increase the environmental impact associated with fossil fuel consumption. As a result, there is a growing need for efficient, low-carbon heating solutions that reduce both operating costs and greenhouse gas emissions.

Solar photovoltaic systems are widely adopted for residential electricity generation; however, their overall efficiency remains limited. Typical PV panels convert only a small fraction of incident solar radiation into electrical energy, with the majority of the energy lost as heat. Elevated operating temperatures further reduce PV electrical efficiency, resulting in diminished electrical output during peak solar conditions. This waste heat is typically dissipated to the surrounding environment and remains underutilized.

Building-integrated photovoltaic/thermal (BIPV/T) systems address this limitation by enabling the 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 heat pump integration. However, the effectiveness of heat extraction is highly dependent on airflow behavior within the thermal duct.

The core problem addressed in this project was the limited heat transfer between the PV panel surface and airflow within the BIPV/T air channel under conventional designs. Insufficient airflow turbulence and low convective heat transfer coefficients restrict the amount of recoverable thermal energy. Without effective airflow enhancement, the potential benefits of BIPV/T systems remain constrained.

This project aimed to address this challenge by investigating practical airflow enhancement strategies that increase turbulence and improve heat transfer within the BIPV/T air channel, while remaining cost-effective and suitable for residential implementation.

2.2 Team Contribution & Project Context

This project was completed as a team-based engineering design and analysis effort as part of an academic capstone initiative?/project?. The work involved collaborative development of the BIPV/T system concept, simulation modeling, and performance evaluation. Team members contributed across system design, airflow modeling, heat transfer analysis, and interpretation of results.

The author’s contributions focused on …simulation-based analysis of airflow enhancement concepts, evaluation of thermal performance metrics, and comparison of design configurations to support final design selection. The results presented reflect a collaborative engineering effort and integrated contributions from all team members.

3. Assumptions & Constraints

The analysis and simulation of the BIPV/T air-channel system required several assumptions to simplify modeling while maintaining engineering relevance. In addition, practical constraints related to system design, operation, and implementation influenced the scope of the study. These assumptions and constraints are outlined below.

3.1 Assumptions

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Steady-State Operation
The system was analyzed under steady-state conditions. Transient effects due to **fluctuating solar irradiance**, ambient temperature variations, and startup behavior were not explicitly modeled.

Uniform Solar Heat Flux
A uniform thermal input from the photovoltaic panel surface was assumed across the length of the air channel. This simplification enabled consistent comparison between design configurations.

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.

Negligible Heat Losses to Surroundings
Heat losses to the external environment through conduction, radiation, and leakage were assumed to be minimal compared to convective heat transfer within the air channel.

Fully Developed Flow Regions
Flow within the air channel was assumed to be fully developed over most of the duct length, allowing Reynolds number and turbulence characteristics to be used as primary performance indicators.

Idealized Enhancement Geometry
Flow enhancement features such as fins and porous metal mesh were modeled with simplified geometries that represent their functional behavior, rather than detailed manufacturing-level complexity.

Fan Performance Stability

The airflow provided by the fan was assumed to remain stable throughout simulations, with no degradation in performance due to pressure losses or operational variability.

3.2 Constraints

Geometric Constraints

The air-channel dimensions were constrained by the physical size and geometry of the photovoltaic panels and roofing integration requirements. This limited the allowable height and cross-sectional area of the duct.

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Residential Applicability

Design concepts were restricted to solutions suitable for residential-scale applications, prioritizing simplicity, low cost, and ease of integration over complex or industrial-scale enhancements.

Material Practicality

Enhancement devices were limited to materials that are commercially available, durable, and compatible with rooftop environments. Exotic or high-cost materials were not considered.

Computational Limitations

Simulation fidelity was constrained by available computational resources. As a result, mesh resolution and turbulence modeling approaches were selected to balance accuracy with reasonable simulation time.

Lack of Experimental Validation

The study focused on simulation-based analysis. While results indicate performance improvements, full experimental validation was outside the scope of this project.

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.

Project Timeline and Scheduling Constraints

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The project was conducted within the duration of a single academic semester, which imposed strict limitations on available time for design iteration, simulation refinement, and experimental validation. Project activities were required to be completed alongside concurrent academic coursework.

Site Access and Coordination Limitations

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

3.3 Impact of Assumptions and Constraints

The assumptions and constraints outlined above were necessary to enable comparative analysis between multiple design configurations. While they introduce simplifications, they allow meaningful evaluation of airflow behavior, turbulence generation, and relative heat transfer performance. The results should therefore be interpreted as indicative of performance trends rather than exact real-world values.

Future work incorporating transient analysis, detailed material modeling, and experimental validation would further improve confidence in system performance predictions.

4. Methods / Approach

The approach taken in this project involved the development and evaluation of an air-channel simulation model for a building-integrated photovoltaic/thermal (BIPV/T) system. The methodology focused on analyzing airflow behavior and heat transfer performance under different airflow enhancement configurations to identify a design that maximizes thermal energy extraction while remaining practical for residential applications.

4.1 System Overview

The BIPV/T system consists of photovoltaic 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. The warmed air may then be supplied directly for space heating or used as preheated intake air for an air-source heat pump.

The air channel extends along the length of the PV panel assembly and is designed to promote effective convective heat transfer while maintaining acceptable airflow velocities and pressure losses. The inlet location and internal flow features play a critical role in determining airflow distribution and 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 impact of different internal geometries and enhancement features on system performance.

Key performance indicators used for comparison included:

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

These metrics were selected to quantify turbulence intensity, convective heat transfer potential, and overall thermal effectiveness.

4.3 Benchmark Configuration

An initial benchmark configuration was established to represent a baseline BIPV/T system without airflow enhancements. In this configuration, air entered the system through an inlet located at the bottom of the duct and flowed along the channel beneath the PV panels.

The benchmark model provided a reference case against which all enhancement concepts were evaluated. Performance metrics from this configuration were used to assess the relative improvement achieved through subsequent design modifications.

4.4 Airflow Enhancement Concepts

Three airflow enhancement concepts were developed and simulated to improve turbulence and heat transfer within the air channel:

- **Concept 1: Guiding Walls**
  Internal guiding walls were introduced to redirect airflow and promote mixing within the channel.
- **Concept 2: Fin-Based Enhancements**
  Fin structures were added to increase surface area and disrupt airflow, encouraging higher turbulence levels.

- **Concept 3: Porous Media (Mesh) Enhancement**
  A porous foam or metal mesh was introduced within the air channel to significantly disrupt laminar flow and enhance mixing.

Each concept also explored variations in fan inlet positioning to assess the influence of inlet geometry on airflow distribution.

4.5 Selection of Final Design Configuration

Simulation results from the three enhancement concepts were compared against the benchmark configuration. Concept 3 demonstrated superior airflow distribution and turbulence generation, resulting in improved heat transfer performance relative to the other designs.

To further enhance performance, favorable features from the fin-based and porous media concepts were combined. The final design incorporated fin baffles coupled with a porous metal mesh arrangement distributed throughout the air channel. This configuration was selected based on its ability to maintain turbulent flow conditions, increase Reynolds number across the duct, and achieve greater temperature rise without excessive changes to airflow velocity.

The final design was carried forward for detailed performance analysis and comparison against the benchmark system.

5. Calculations / Analysis

The performance of the BIPV/T air-channel system was evaluated through analysis of airflow characteristics and heat transfer behavior along the length of the duct. Key analytical parameters included Reynolds number, airflow velocity, and air temperature rise, which together provide insight into turbulence intensity and convective heat transfer effectiveness.

5.1 Airflow and Reynolds Number Analysis

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

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

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 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.

5.2 Velocity Distribution

Airflow velocity was monitored at multiple locations along the air channel to ensure that enhancements did not introduce excessive flow restriction or undesirable pressure losses. Velocity profiles were used to verify that improvements in thermal performance were primarily attributable to increased turbulence and mixing rather than large increases in airflow speed.

Comparative analysis showed that average velocities remained relatively consistent between configurations, indicating that enhanced thermal performance was achieved through improved flow behavior rather than increased fan power requirements.

5.3 Heat Transfer and Temperature Rise

The temperature rise of the air flowing through the channel served as the primary measure of thermal performance. Temperature change was evaluated between the channel inlet and outlet and at intermediate positions along the duct.

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 temperature rise of the air

Thermal input to the air channel was modeled using an effective thermal transmittance value representative of heat transfer from the PV panel surface to the airflow. A value of approximately 150 $W/m^2 \cdot K$ was used to represent combined conduction and convection effects under operating conditions.

5.4 Comparative Performance Evaluation

Performance comparisons between configurations were based on:

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

The initial enhanced configuration demonstrated improved turbulence and temperature rise relative to the benchmark system. However, the final configuration, which combined 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 improvement is particularly significant given the relationship between PV panel temperature and electrical efficiency. Even modest reductions in panel surface temperature can result in measurable efficiency gains, with typical PV efficiency decreasing by approximately 0.4% per degree Celsius increase in operating temperature. Enhanced heat extraction therefore contributes to both improved thermal recovery and improved electrical performance.

5.5 Interpretation of Results

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

These findings support the selection of the final enhanced configuration and demonstrate the viability of using simple, passive airflow enhancement features to improve BIPV/T system performance in residential applications.

6. Results / Visuals

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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.

6.1 Benchmark Configuration Results

The benchmark configuration, which did not include airflow enhancement features, exhibited relatively uniform airflow with limited mixing within the air channel. Reynolds number values remained above the turbulent threshold; however, turbulence intensity was lower compared to enhanced configurations.

Temperature rise along the duct length was gradual, indicating limited convective heat transfer between the PV panel surface and the airflow. These results served as a baseline for evaluating the effectiveness of subsequent enhancement strategies.

(Insert Figure: Benchmark airflow and temperature distribution)

6.2 Initial Enhanced Design Results

The initial enhanced configuration, which incorporated a porous media-based airflow enhancement, showed improved airflow distribution and increased turbulence compared to the benchmark system. Reynolds number values increased along the duct length, confirming more effective disruption of laminar flow regions.

Temperature rise from inlet to outlet increased relative to the benchmark configuration, demonstrating improved heat transfer performance. The airflow remained stable, and velocity levels were comparable to the baseline case, indicating that enhancements did not significantly increase flow resistance.

(Insert Table: Reynolds number, velocity, and temperature at selected duct locations – Initial Design)

(Insert Figure: 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 significantly increased turbulence and mixing.

Temperature rise from inlet to outlet reached approximately 8.66 °C under design conditions, representing a modest but consistent improvement over the initial enhanced configuration. Importantly, airflow velocity remained similar to previous configurations, suggesting that thermal performance gains were achieved primarily through improved heat transfer rather than increased airflow rate.

(Insert Table: Reynolds number, velocity, and temperature at selected duct locations – Final Design)
(Insert Figure: 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 duct.

Although the increase in outlet air temperature between the initial and final enhanced designs was relatively small, the higher 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 extend panel lifespan.

6.5 Discussion of Visual Results

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Visual analysis of airflow and temperature contour plots revealed that enhancement features effectively disrupted airflow, eliminated stagnant regions, and promoted mixing across the channel cross-section. The porous metal mesh, in particular, contributed to uniform airflow distribution and sustained turbulence throughout the system.

These visual results support the quantitative findings and confirm that the selected enhancement strategy provides a balanced improvement in thermal performance without introducing excessive complexity or operational penalties.

7. Tools / Skills Used

This project required the application of engineering analysis, simulation, and design skills to evaluate and improve the thermal performance of a BIPV/T system. Key tools and skills utilized during the project are summarized below.

7.1 Engineering Tools

- Computational simulation software for airflow and heat transfer analysis
- Computer-aided design (CAD) tools for system geometry and configuration development
- Data analysis tools for post-processing simulation results and comparing design configurations

7.2 Technical Skills

- Fluid mechanics and internal flow analysis
- Heat transfer and thermal systems analysis
- Reynolds number and turbulence evaluation
- Energy balance and performance comparison
- System-level evaluation of photovoltaic and thermal interactions

7.3 Engineering Practices

- Concept generation and comparative design evaluation
- Application of assumptions and constraints to simplify complex systems
- Interpretation of simulation data to support design decisions
- Technical documentation and professional reporting

8. Lessons Learned / Reflections

This project provided valuable insight into the design, analysis, and evaluation of building-integrated photovoltaic/thermal (BIPV/T) systems. Through the development and comparison of multiple airflow enhancement configurations, several key technical and professional lessons were identified.

One of the primary technical lessons was the significant influence of airflow behavior on heat transfer performance. Increasing airflow velocity alone did not result in substantial thermal gains; rather, promoting turbulence and effective mixing within the air channel was critical to improving convective heat transfer. The use of passive enhancement features, such as fin baffles and porous media, demonstrated that meaningful performance improvements can be achieved without increasing system complexity or energy consumption.

The project also highlighted the importance of using appropriate performance metrics when evaluating thermal systems. Reynolds number proved to be a useful indicator of turbulence intensity and a reliable basis for comparing design configurations. However, it became clear that improvements in turbulence must be considered alongside practical constraints such as pressure losses, manufacturability, and residential applicability.

From a modeling perspective, the project reinforced the value of simulation as a design tool for early-stage system evaluation. Simulation allowed multiple concepts to be explored efficiently and provided insight into flow patterns and thermal behavior that would be difficult to obtain experimentally within limited time and resource constraints. At the same time, the work emphasized the limitations of simulation-based analysis and the need for experimental validation 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 project objectives. These considerations mirror challenges commonly encountered in professional engineering projects.

If additional time and resources were available, future work would include experimental validation of the final design, refinement of enhancement geometry, and investigation of adaptive airflow control strategies. Despite these limitations, the project successfully demonstrated that simple, cost-effective airflow enhancements can improve BIPV/T system performance and provided a strong foundation for further development.

9. Links / References

9.1 Project Documentation and Resources

- Conference Paper: *BIPV/T Airflow Analysis for Improved Heat Transfer*
- Final Project Report (PDF)
- Simulation models and supporting analysis files *(to be added)*
- Portfolio project page *(to be added)*
- GitHub Repository: [Insert URL]
- Portfolio Project Card: [Insert URL]

9.2 References

[1] Hansen, S., "Making Roofs More Functional with BIPV-T Systems," *SourceAble*, July 2, 2014.
Available: https://sourceable.net/making-roofs-functional-bipv-t-systems/

[2] EnergySage, "How Hot Do Solar Panels Get? Effect of Temperature on Solar Performance," *EnergySage*.
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