Performance Evaluation and Optimization of a Building-Integrated Photovoltaic Thermal Air Collector

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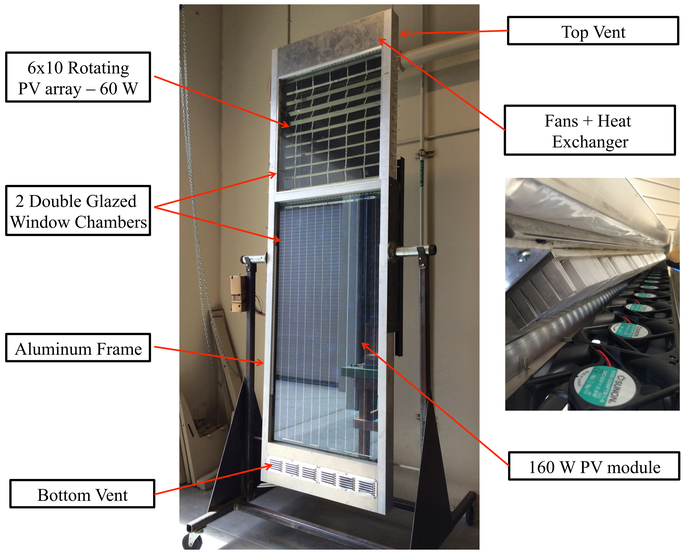
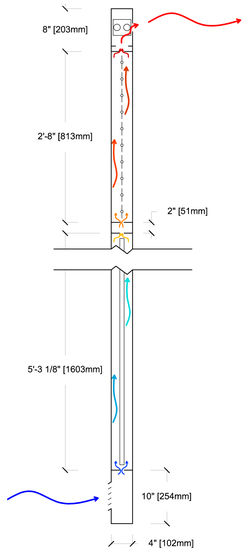
Abstract

Integrated building elements which combine their structural and architectural functions with that of energy generation are expected to become increasingly important in the future scenario of energy efficient buildings, and they could significantly contribute to the thermal behaviour of the building envelope in order to provide energy savings. A prototype of a building-integrated photovoltaic/thermal (BIPV/T) solar collector for air heating has been built by a Palo Alto start-up company, and consists on a double pane airflow window wall with photovoltaic (PV) louvers embedded in it. The unit is intended to perform the functions of both thermal and electrical generation, as well as light transmission and shading control, and its façade integration makes it more economical than installing separate collectors for the same scope. In this work, the prototype performances have been tested in different outdoor conditions and under different airflow speeds, and a maximum air temperature rise above 30 °C and average thermal efficiency of 31% have been achieved. By using inexpensive PV modules with a rated efficiency of 12.5%, an actual efficiency of 7% was recorded under the maximum operating temperatures. A two dimensional model was built in COMSOL Multiphysics to reproduce the experimental results, which has been used to optimize the glazing unit structure through the use of coatings and additional glass panels. Different configurations have been analyzed, and a 3-pane low-e coating system has been found to be the best cost-effective solution, which results in a 43°C temperature rise.

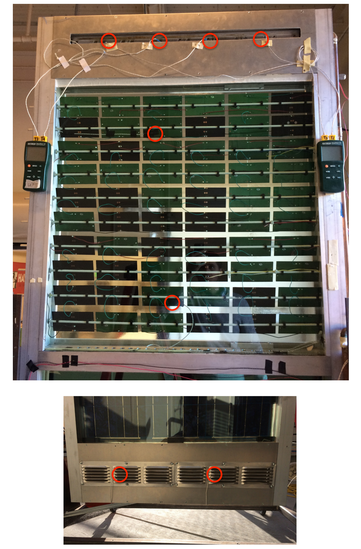
Prototype Overview



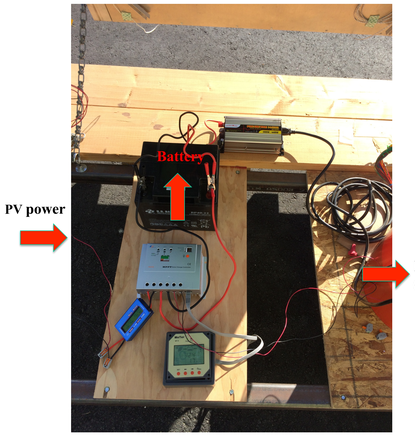
Airflow schematics



Thermocouples Placement



24VDC PV System



- MPPT solar charge controller
- 12 VDC, 40Ah battery
- 12VDC load (fans)
- Watt meter – PV output
- Meter for battery and load status

Performance Evaluation

- Thermal Output (W):

$$\dot{Q} = \Gamma \cdot c_p \cdot (T_{out} - T_{in})$$

$$\hookrightarrow \Gamma = \rho \cdot v \cdot A$$

- Thermal Efficiency: $\eta_{th} = \dfrac{\dot{Q}}{I_{gl} \cdot A_{gl}}$
- Electrical Efficiency: $\eta_{el} = \dfrac{P_{el}}{I_{gl} \cdot A_{PV}}$

Thermal Testing

Radiation on PV panels (W/m²) · Total incoming radiation (W) · Input and Output Temperatures (°C) · Temperature gradient between top and bottom · Thermal power output (W)

Date	24-Feb		South facing, vertical		Fans operated at 7.5V									
Time	I_panels	W_In	T_In_Avg	T_1	T_2	T_3	T_4	T_out_Avg	V_Avg	ρ	Γ	ΔT	Q	η
				°C										
11:00	720.00	1409.76	21.00	41.90	45.50	44.70	45.10	44.30	0.56	1.112	0.015	23.30	361.57	0.26
11:45	765.00	1497.87	21.00	48.60	51.80	52.20	50.70	50.83	0.58	1.090	0.016	29.83	471.66	0.31
12:3	770.00	1507.66	22.00	50.60	54.70	54.40	53.10	53.20	0.58	1.082	0.016	31.20	492.64	0.33
13:30	720.00	1409.76	24.00	48.30	52.30	52.50	51.20	51.08	0.58	1.089	0.016	27.08	426.47	0.30
14:15	610.00	1194.38	25.00	47.20	48.00	49.70	47.80	48.18	0.58	1.099	0.016	23.18	373.31	0.31
15:00	515.00	1008.37	21.00	42.20	42.80	43.70	42.60	42.83	0.57	1.117	0.016	21.83	351.62	0.35

Output temperature data points · Air flow properties: velocity, density and flow rate · Thermal efficiency

PV Testing

Window tilt · PV array tilt · PV array power output (W) · Incident solar radiation on PV panels (W/m²)

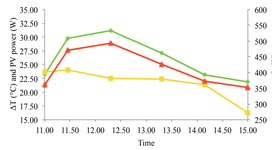
25 nov - south			PV array			Battery		DC Load				
Time			Power	V	I	V	I	V	I	I_panels	Temp-bottom	Temp-top
9:30	β1=0°	α1=0°	24	19.5	1.22	13.1	0.3	13.1	1.5	650	47	54
		α1=20°	25.2	20.7	1.2	13.2	0.6	13.2	1.6	780		
	β1=20°	α1=0°	23	18.5	1.2	13.2	0.3	13.1	1.5	775		
		α1=20°	24.9	20.8	1.22	13.2	0.5	13.1	1.6	750		
10:30	β1=0°	α1=0°	25	15.7	1.6	13.2	0.4	13.2	1.2	780	55	64
		α1=20°	32	18.4	1.76	13.4	0.2	13.4	1.8	920		
	β1=20°	α1=0°	29.5	21.5	1.23	13.4	0.5	13.4	1.2	890		
		α1=20°	30	19.9	1.4	13.3	0.6	13.3	1.7	910		
11:30	β1=0°	α1=0°	29.5	19.8	1.5	13	0.6	13	1.4	820	61	69
		α1=20°	34.8	19	1.83	13.2	0.6	13.2	1.6	985		
	β1=20°	α1=0°	35	19.3	1.83	13.3	0.6	13.3	1.6	980		
		α1=20°	34	18.5	1.82	13.3	0.5	13.3	1.6	965		

Voltage and current for PV array, Battery and Fans · Temperature (°C) on the back surface of the panels

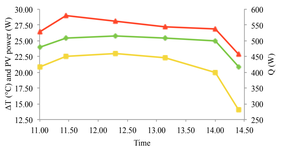
Results

- Measurements on both the thermal and electrical systems were taken in summer, fall and winter months in Salinas, CA.
- Testing conditions included different orientation, tilting and air speeds. The collector was tested in south facing and tracking conditions, in vertical (90°) and 70° tilt angle, as well as under different angles between the PV array, the window and the ground.
- Latest tests are reported below and included different air speeds, produced by varying the fans voltage (from 6V to 12V).

7.5 V – 0.58 m/s



12 V – 0. 8 m/s

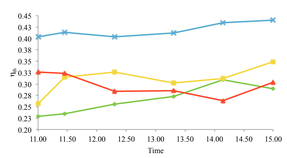


ΔT · Pv power (W) · Q

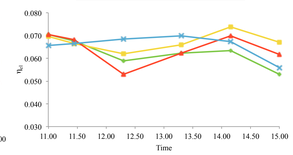
Average parameters under different voltage configurations: Air speed, temperature difference, electrical and thermal powers, input and output temperatures and power consumed by the fans

Input voltage of the fans (V)	Average air speed at the outlet (m/s)	ΔT (°C)	P_el (W)	Q (W)	T_in (°C)	T_out (°C)	Fans power consumption (W)
6	0.5	25.5	19.6	340	27.4	52.9	5
7.5	0.58	26	21.7	413	22.3	48.4	8.25
9	0.64	22.4	20.7	400	20	42.3	10.5
12	0.8	24.4	20.4	535	22.8	47.2	19.5

Thermal Efficiency



Electrical Efficiency

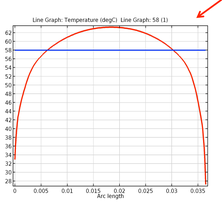


6 V · 7.5 V · 9 V · 12 V

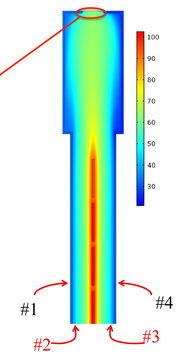
Thermal Modeling and Optimization

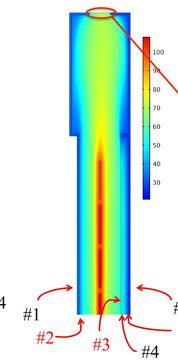
- 2D modeling and thermo-fluid dynamic simulation in COMSOL
- Reproduction of experimental results
- Optimization of the glazing system by additional pane of glass and use of low-emissivity coatings applied to the inside surfaces of the panels

Low-e on surfaces # 2, 3

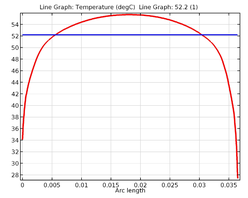


Temperature profile at top vent

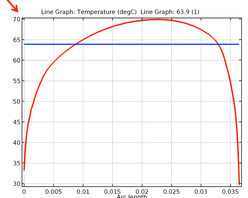


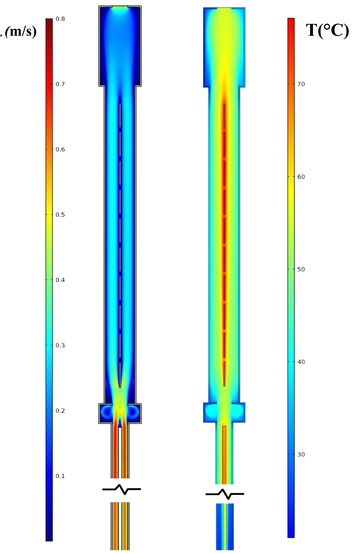


Current prototype



3 Panes system, Low-e on surfaces # 2, 3, 5





Conclusions

The thermal and electrical performances of a prototype of an airflow window, with solar modules inside a double-glazing, have been tested. The results showed that the window performed better during the winter, when the solar elevation is smaller, and the measured output temperature reached a maximum of 52.2°C under the optimal air speed of 0.58 m/s, with an average of 48.4°C, corresponding to a temperature rise of around 26°C on average and 31°C maximum. The thermal efficiency ranges between 30 and 40%, while the electrical one remains quite constant to around 6-7%, with a generation of 20-25W for the top PV array. Simulations on a 2D model have shown a lot of improvements through the use of low emittance coatings, and have established an optimal configuration of the glazing system, consisting of three glass panes with low-e coatings to # 2, 3 and 5 surfaces, which represents the best cost-effective solution. This set up provided an air temperature of 64°C and a rise of 43°C, with respect to the experimental conditions that yielded 52.2°C.

Acknowledgments

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