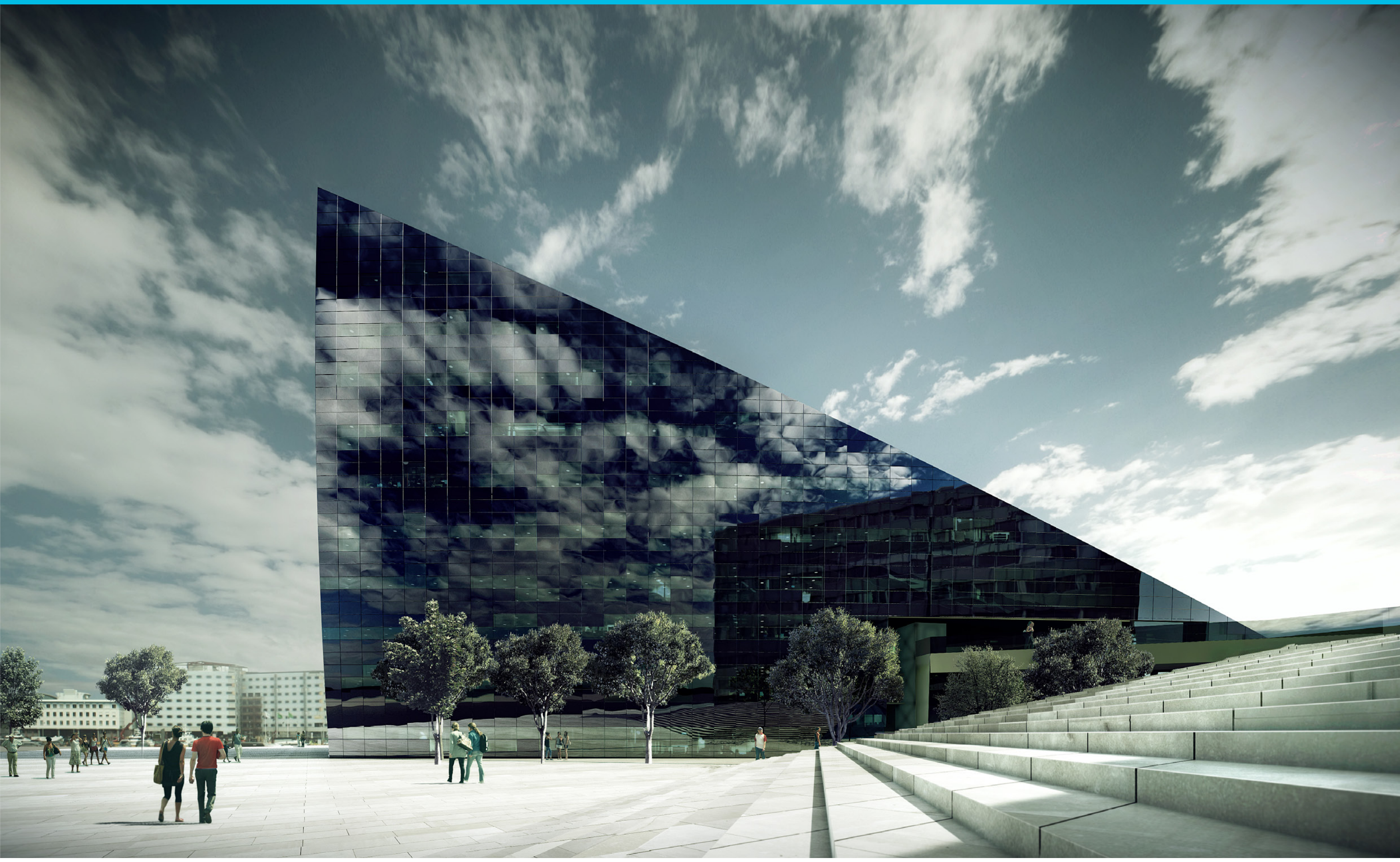
ZEB Project report 6 – 2012

Cezary Misiopecki, Arild Gustavsen and Berit Time

Cooling of PV panels by natural convection

The Research Centre on Zero Emission Buildings



A world where buildings do not contribute with greenhouse gas emissions

SINTEF Academic Press

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Keywords:
Roof, BIPV, Natural Convection, Simulations

Cover, illustrations: Snøhetta/MIR

ISSN 1893-157X (online)
ISBN 978-82-536-1290-4 (pdf)

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Preface

This work has been performed within the Research Centre on Zero Emission Buildings (www.ZEB.no), workpackage 2 *Climate-adapted low-energy envelope technologies*.

The intention of this work has been twofold;

1) To get an overview of previous research – state-of-the art – on cooling of Building Integrated Photo Voltaics (BIPVs) by natural convection
2) To investigate the need for cooling of BIPVs by natural convection by analysis of different air gap widths by numerical modelling

The work was initiated as a part of the planning process of the ZEB pilot building *Powerhouse 1* at Brattørkaia in Trondheim.

Summary

Building Integrated Photovoltaic (BIPV) is an important source of renewable energy production for Zero Emission Buildings, even in Norwegian climate. In the planned Powerhouse 1 building at Brattøra in Trondheim the idea to reach a zero emission building level is to use PVs as a roofing material covering the entire roof. Challenges and questions raised in the design process of this building have motivated the work reported here.

Photovoltaic (PV) panels directly convert solar radiation into electricity with peak efficiency in the range of 9–12%. It means that more than 80% of the solar radiation falling on PV cells is not converted to electricity, but either reflected, transmitted or absorbed. Reflected and transmitted radiation is relatively small in comparison to absorbed radiation. Part of absorbed energy is converted into electricity and the rest is change to the heat, which increases unit temperature. Higher temperature of unit has negative influence on PV panel's efficiency.

Conducted study focuses on finding the best cooling strategy for PV panels which simultaneously perform as a roof finishing layer of large roof and test it by numerical methods. Comparison analysis of different air gap widths for natural convection cooling was done using numerical model. The results shown that 5 cm wide air gap is not sufficient to provide natural convection cooling of 70 meter-long rooftop made of PV panels. Moreover, increasing air gap width over the 25 cm seems to not giving substantial improvements of natural convection cooling.

The developed model is good starting point for further study in this area. Findings and experience gained during this study hopefully can be transferred into more precise 3D modeling of this case.

CONTENT

1 Introduction

Building Integrated Photovoltaic (BIPV) is an important source for renewable energy production for Zero Emission Buildings, even in Norwegian climate. In the planned Powerhouse 1 building at Brattøra, see Figure 1, in Trondheim the idea to reach a zero emission building level is to use PVs as a roofing material covering the whole roof. Challenges and questions raised in the design process of this building have motivated the work reported here. This study focuses on finding the best cooling strategy for PV panels which simultaneously perform as a rooftop of a relatively large roof (approximately length of 70 m).

Figure 1. Illustration of the Powerhouse 1 building with its huge sloped roof integrated with PVs. Illustration: Snøhetta

Photovoltaic (PV) panels directly convert solar radiation into electricity with peak efficiency in the range of 9–12%. It means that more than 80% of the solar radiation falling on PV cells is not converted to electricity, but either reflected, transmitted or absorbed. A reflected part has a relatively small share (up to 5%) and is dependent on glass physical properties. Transmission of solar radiation can only be observed for glass to glass PVs (kind of PV panels in which crystalline silica is placed between two layers of glass). For other panels which are "non-transparent" (the most common is glass to Tedlar®[4] panels) solar transmission does not occur and absorption of the solar radiation becomes dominant. Approximately 9% to 12% of absorbed energy is converted to the electricity and the rest is changed to the heat, which increases unit temperature. This has negative influence on photovoltaic panel's efficiency, what can be seen in the Figure 2.

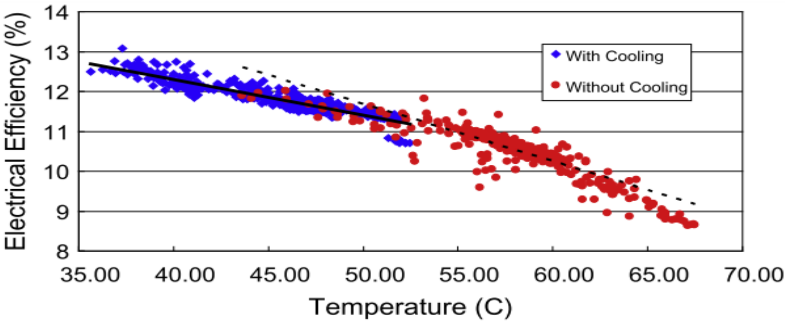

Figure 2. Electrical efficiency as a function of PV panel temperature (Teo, Lee et al. 2012).

To maintain a high electrical efficiency some strategies for PV cooling need to be implemented. In order to build a good theoretical background and find the most efficient strategy for maintaining a high efficiency and assess potential of efficiency gains a literature study was performed. After this, natural convection is evaluated as a cooling strategy for 70 meter long roof, made of PV panels.

2 COOLING STRATEGIES FOR PV SYSTEMS

In the literature the following strategies for PV panels cooling can be found: cooling by natural convection (cooling fluid: air and water), cooling by forced convection (cooling fluid: air and water) and methods of enhancing those two techniques done by PV panel surface modification or duct (the space under panel created for cooling purpose) geometry. Those strategies can be used by themselves for panel cooling only or implemented in hybrid PV/T (PV/thermal) systems. The advantage of those systems aside PV cooling is also providing space heating of hot service water for buildings.

Dubey, Sandhu et al. (2009) studied two types of PV modules, glass to glass and glass to Tedlar®. Experimental studies of PV panel performance were done with and without a duct under the panel (the dimensions of the duct were 0.605 m x 1.0 m x 0.04 m). PV panels were tilted at 30 degree and tested under latitude and climate of New Delhi, India. The systems cross-sections are shown in the Figure 3.

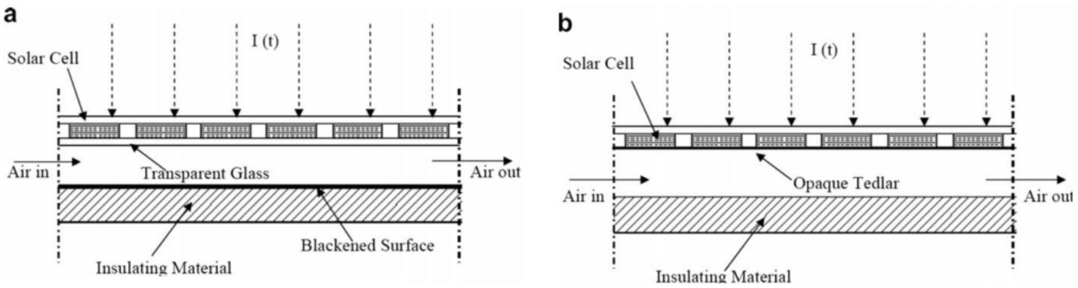

Figure 3 (a) Cross section of glass to glass PV module with duct. (b) Cross section of glass to Tedlar® PV module with duct, (Dubey, Sandhu et al. 2009).

The peak efficiency percentage difference between PV panels with and without duct was found to be 3.3% for (PV's glass to Tedlar® type) and 4.5% (glass to glass type). The conditions (temperature and solar heat flux) during conducted test can be seen in Figure 4.

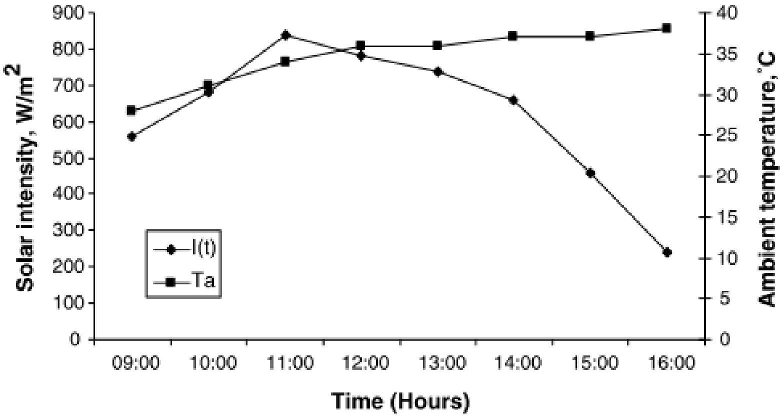

Figure 4. Hourly variation of solar intensity and temperature for the month of April, 2008, (Dubey, Sandhu et al. 2009).

Results of daily experiment measurement for different cases are presented in Figure 5.

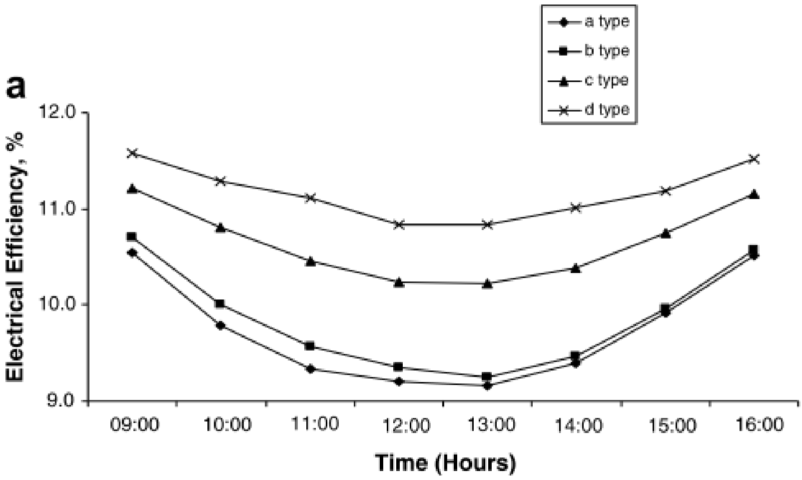

Figure 5. Hourly variation of electrical efficiency for case a (glass to glass PV module with duct), case b (glass to glass PV module without duct), case c (Glass to Tedlar PV module with duct), case d (Glass to Tedlar PV module without duct), (Dubey, Sandhu et al. 2009).

It can be observed that both glass to glass type PV and glass to Tedlar® has higher efficiency when duct under panel is applied. This is due to enchased cooling caused by air movement in the duct.

Shahsavar and Ameri (2010) in their work tested and developed a numerical model describing hybrid PV/T (air) system. The system was tested in two modes: natural convection and forced convection (using fans) at the geographic location of Kerman, Iran. Glazing cover (placed on the top of panel) influence on system performance was also determined. A theoretical model was developed and validated with data collected during experiment and a good agreement was achieved. Figure 6 shows the experimental setup of tested system and its cross-section.

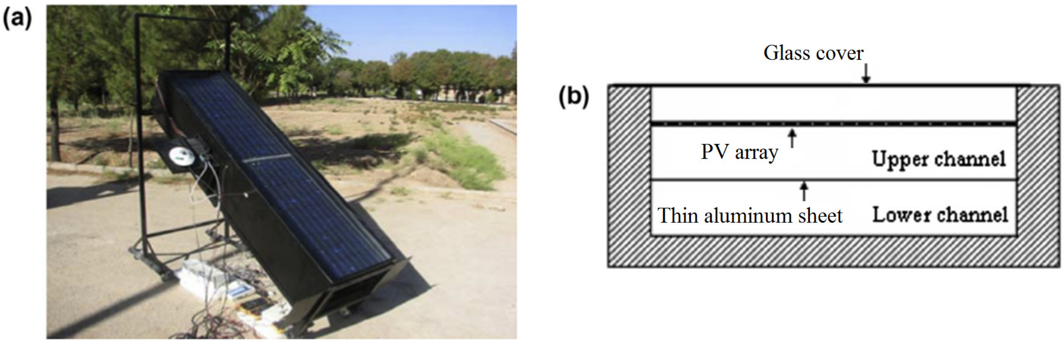

Figure 6 (a) Experimental setup of studied PV/T air collector at Shahid Bahonar university of Kerman, (b) cross-section of studied system, (Shahsavar & Ameri, 2010).

Comparison was made between electrical performance of the different mode of operations and it was concluded that there is an optimum number of fans for achieving maximum electrical efficiency, what can be observed in Figure 7.

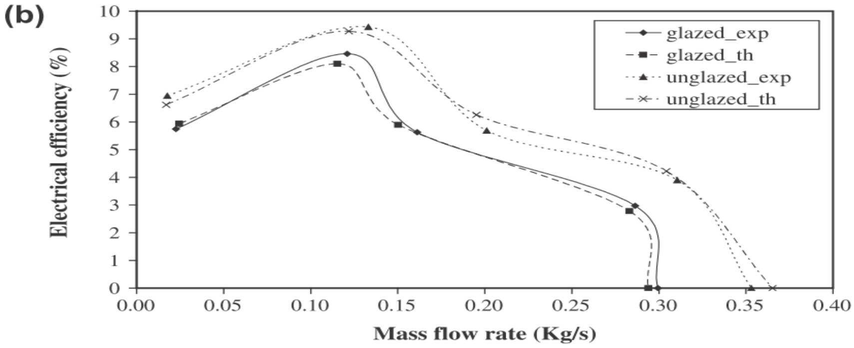

Figure 7. Effect of air mass flow rate on electrical efficiency (Shahsavar & Ameri, 2010).

Results show that setting glass cover on photovoltaic panels causes increase in thermal efficiency and decreases electrical efficiency of the system. Further discussion includes only unglazed system since considered system in the study is oriented on electricity production. While operating fans peak efficiency of unglazed panel was increased by 37% in comparison to system with natural convection cooling. In those calculations the energy needed for fan operation was included.

Shahsavar, Salmanzadeh et al. (2011) studied integrated photovoltaic panels coupled with air thermal collectors. The system was connected with mechanical ventilation system of the building. Exhausted air from mechanical ventilation during the summer cools PV units, while during winter cold air preheated under warm panels is used for enhancing space heating system in the building. This model was tested numerically under climatic data of city Kerman, Iran. The sketch of the system is presented in the Figure 8.

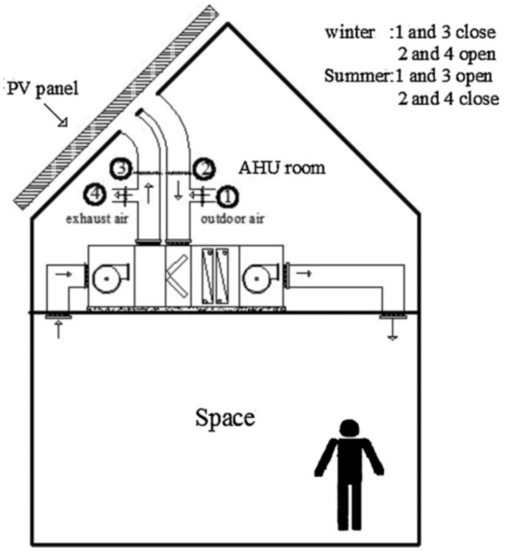

Figure 8. Schematic diagram for the studied system (Shahsavar, Salmanzadeh et al. 2011).

The authors found an optimum air mass flow rate (of ventilation/exhaust) for cooling of the PV panels (for all months) to achieve the maximum electricity production from the PV panels.

Using ventilation system for cooling PV panel, electricity production increased by 7.2 % during the year. Moreover, annually calculation for an area of $10m^2$ of PV panels shows that

3400 kWh of energy was recovered to the space heating system. For the same area it was found that 56 kWh of additional electricity was generated thanks to coupled system/PV panel cooling.

Teo, Lee et al. (2012) tested cooling of photovoltaic by forced convection. The innovative approach in this study is that in contrary to other studies air duct was designed, and optimized to achieve the most efficient panel cooling by uniform airflow distribution. The duct design can be seen in the Figure 9.

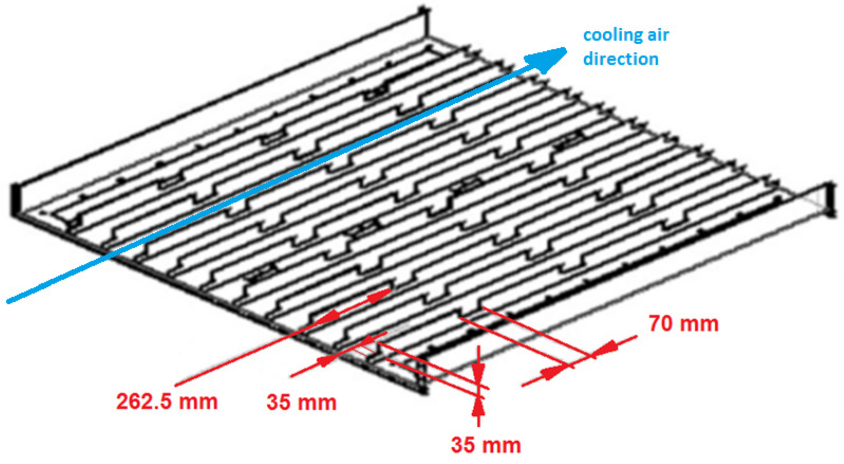

Figure 9. PV panel sketch design (Teo, Lee et al. 2012).

Velocity contours modeled for the duct using CFD software Fluent are presented in the Figure 10.

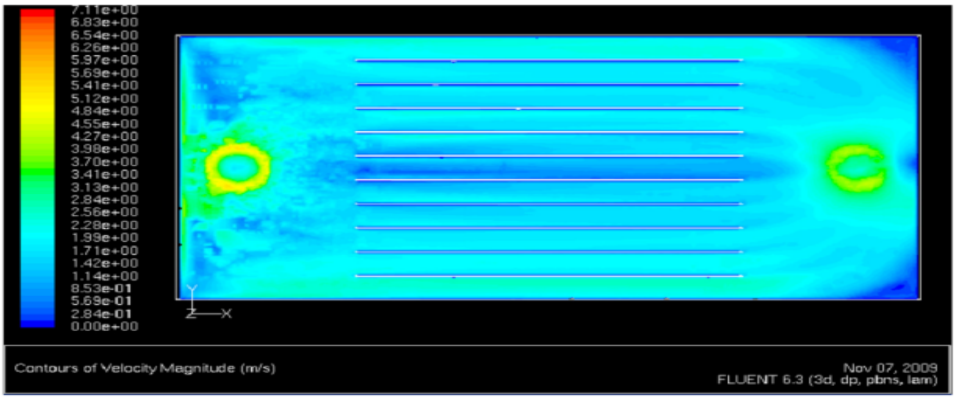

Figure 10. Top view of velocity contour of manifold design (Teo et al., 2012).

The unit was tested with and without fans. While the temperature of the module was high (68° C) the solar cells can only achieve an efficiency of 8–9% (case without fans). When the module was operated with fans, the surface temperature dropped significantly (38° C) leading to an increase in the efficiency of solar cells to the value of 12%-14%.

A particular air flow volume was found which is sufficient to absorb the maximum amount of heat from the PV module. Percentage change in the PV peak efficiency was found to be 50% however in the study the power consumed by fans has not been included in efficiency calculation, so it is impossible to evaluate the influence on the air duct design on total PV electrical efficiency. Figure 2 presents measurement results.

Artificially modified surface is currently applied to solar air heaters/collectors in order to enhance its thermal performance (see Figure 12). The surface is changed to be rougher and this enhances heat transfer. This process takes place because of increased heat transfer area and heat transfer coefficient (by increasing flow speed or introducing turbulent flow). Rough surface is applied on the surface. This creates local wall turbulence and arising recirculation flows further increasing the convective heat transfer. On the other hand energy for creating turbulence lowers the fluid speed. If the roughness is too high this can cause high flow speed losses and leads to increased use of energy by the fan. It was found that turbulence must be created in laminar sub-layer region where heat transfer takes place (Prasad and Saini 1991). In order to enhance heat transfer in boundary layer detailed calculation should be done taking into account all parameters of the flow and geometry.

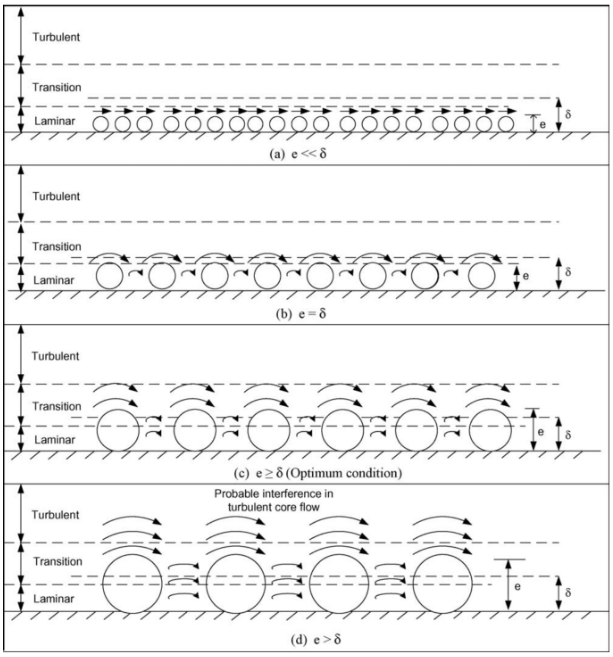

Figure 11. Effect of rib height on laminar sub layer (Hans, Saini et al. 2009).

It was concluded (Hans, Saini et al. 2009) that use of artificial roughness can give substantial improvement in the performance of the solar air panel, which can result in size reduction and maximization of heat transfer rate. This method can be applied to PV panel bottom surface in order to enhance heat transfer what would lead to better cooling.

Summary of methods used in the literature review can be found in the Table 1.

Table 1. Summary of literature review

Study	(Dubey, Sandhu et al. 2009)	(Shahsavar and Ameri 2010)	(Shahsavar, Salmanzadeh et al. 2011)	(Teo, Lee et al. 2012)	(Hans, Saini et al. 2009)
Method	Air duct (4cm), natural convention	Air duct, forced convection (fans)	Air duct, forced convection (mechanical ventilation coupling)	Designed and optimized air duct, forced convection	Artificially modified surface by increasing roughness
Efficiency percentage improvement	3.3% - 4.5% (peak)	Peak efficiency 37%	Yearly efficiency was improved by 7.2%. Additionally heat for space heating was gained	Peak efficiency increased about 50%, however fan power was not included in the efficiency calculation	No data which can give any number is available. However this modification is very likely to give additional improvements to natural and forced convection cooling
Climate	New Delhi, India	Kerman, Iran	Kerman, Iran	Singapore	-

3 NUMERICAL PROCEDURES

In this part of the report it will investigated the optimal air gap height for 70m long air channel/gap below PV panels. This was done using Ansys Workbench 13th and Ansys Fluent 13th software. Only natural convection as a cooling mechanism in the air gap was considered.

The first approach was to develop a model which includes PV panels enclosed with ambient air. The solar load model embedded in Fluent was used and configured for Trondheim location. Usage of solar load model requires 3D geometry what made calculations time consuming. Difficulties were found during validation process due to not suitable turbulence model. Finally, the idea of using the 3D model was abandoned, because of problems with finding a proper turbulence model. The next step was to develop and validate a 2D model with a more proper turbulence model and then use gained experience to develop 3D model.
However, thanks to initial 3D modeling it was proof that flow around the panel is not at steady state. It was found that flow fluctuation does not influence the panel temperature during transient calculation because of the PV panel thermal inertia. The temperature contours which show unsteady results can be seen in Figure 13.

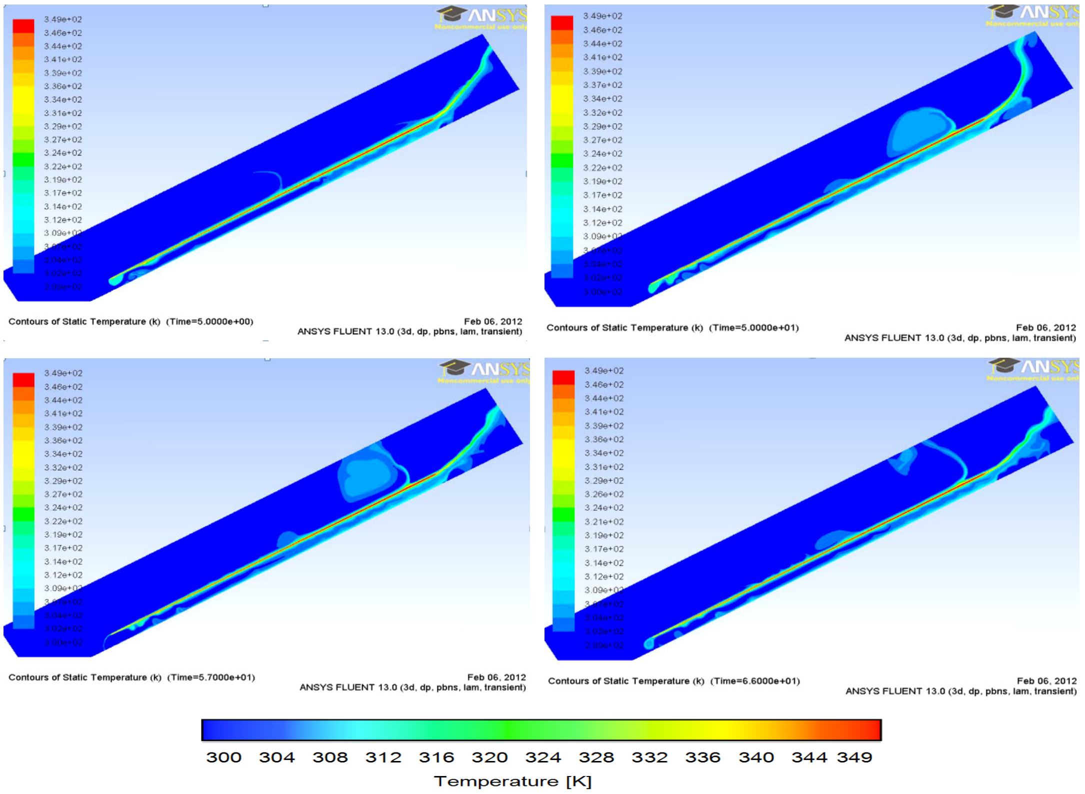

Figure 12. Temperature contours of 3D model in 5 second intervals – the not steady state of natural convection mechanism can be observed above and under the panel.

In the next step a 2D model was developed and validated with experimental results from literature (Sandberg and Moshfegh 1996). In that paper experimental study of the heat transfer and flow pattern created between two vertical parallel walls heated from one side are reported. The experimental set-up is the mock-up of a facade with integrated PV panels. The physical model was built and tested. Surface and air temperatures were recorded during the test. In the Figure 14 the sketch of experimental set-up can be seen, together with a picture of the test wall.

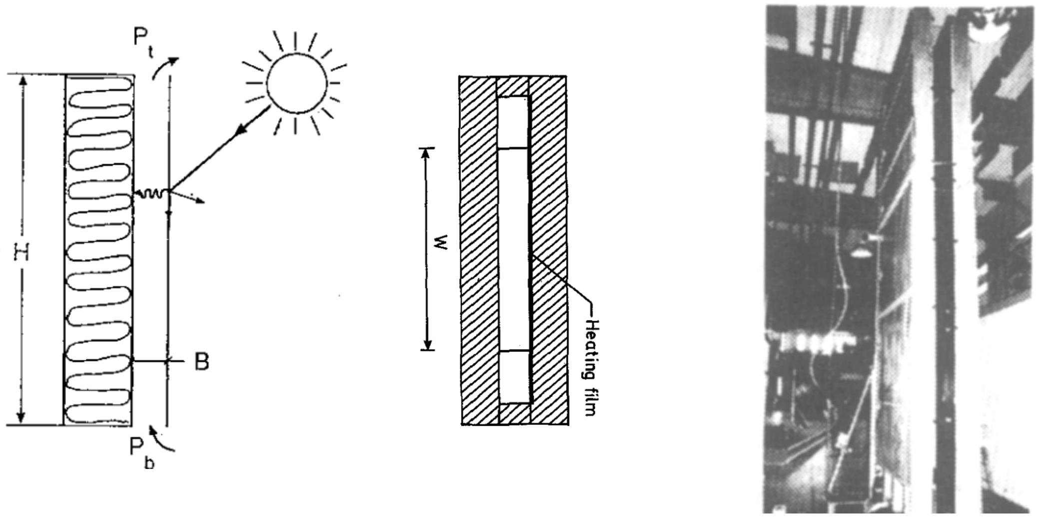

Figure 13. Sketch of PV façade, intersection of mock-up and photo of laboratory assembly. (Sandberg and Moshfegh 1996)

The numerical model was successfully validated. Good agreement was achieved using k-e turbulence model (RNG, with enhanced wall treatment and full buoyancy effect). The experimental data include measurement for different power of heating foil (50-300 W/m^2). Mean velocity was calculated for heat flux of 200 W/m^2 and 300 W/m^2, respectively differences of 2% and 1.25% between modeling and experiment were found.

The agreement between temperatures along mock-up walls was not as good as for mean velocity. This was due to the lack of detailed material properties in the paper. In this case, having achieved good agreement of mean velocity, from heat exchange point of view the next factor which determines wall temperatures is radiation. Emissivity for each wall was assumed to be 0.84 and this can cause the discrepancies shown in the Figure 15, however the shape of the curves matches quite well.

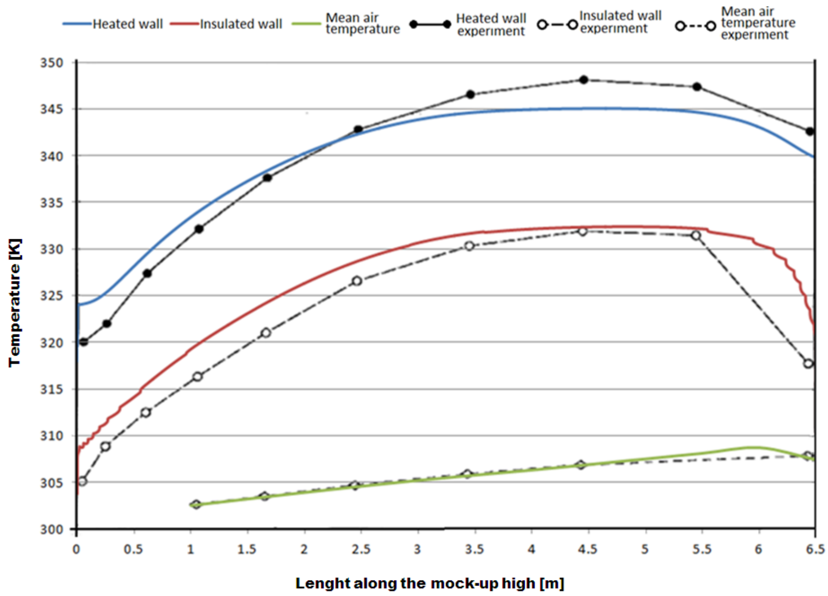

Figure 14. Temperature comparison between experimental data and simulation. Black lines indicate experimental temperatures (Sandberg and Moshfegh 1996) while color lines temperatures calculated using developed model.

The geometry was built and mesh was generated for a 70-meter long PV panel. Geometry was located in the way that angle between walls surfaces and earth surface was 30 degrees. The model is focused on the air channel below the PV panel. Ambient air above the panel and heat exchange above the panel was not modeled. Regions marked with red and blue color (see Figure 16) were set to be respectively pressure inlet and pressure outlet. Ambient air temperature was set to be 20 C. Figure 16 shows the geometry/mesh. Half-circles were created at the ends of the panel in order improve calculation accuracy (boundary conditions placed too closed to the inlet or outlet can cause velocity fluctuation in those regions).

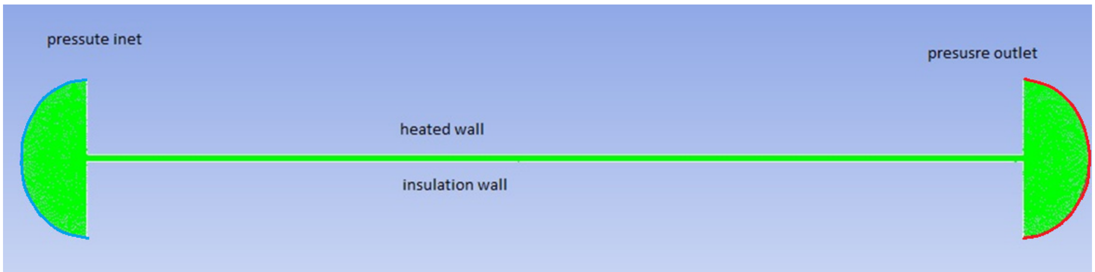

Figure 15. Geometry and mesh created for 2D model.

The following assumptions/simplifications were done in order to perform the calculations:

1. Effective heat flux value was assumed on the heated wall. Heat exchange in the real situation works in the following way. Sun emits energy by short wave radiation. A certain amount of this radiation reaches the surface of the PV panel. The theoretical solar heat flux in Trondheim equals to 730 W/m^2 according to the solar load model embedded in Ansys Fluent. Relatively small part of radiation is reflected and majority of radiation is absorbed by PV panel (assumption of glass-Tedlar panel – no sun radiation is transmitted). Roughly 9–12% of absorbed energy is converted to electricity and the rest of the energy increases temperature of PV panels. Warmer PV panel (than ambient air) releases/exchange heat from the upper and bottom panel surface by radiation and convection. Initially it was assumed that roughly half of the heat is released to the bottom. Taking into account this assumption the effective heat flux which is used for boundary conditions in 2D model was set to be 300 W/m^2 along bottom surface of panel. Later that assumption has been verified by modeling 3 m long PV panel enclosed in the air using 3D model. Solar load model was configured for Trondheim location and proper turbulence model was used. Results shown that heat flux along the bottom part of the panel varies from 250 to 300 W/m^2, while weighted average equals to 267 W/m^2.

2. Constant effective heat flux along the PV panel surface was set. In real live situation this heat flux is not constant because conditions which determine heat exchange are changing. It can be observed that temperature of upper surface of PV panel is increasing with distance from air inlet due to warming of cooling air under the duct. Higher temperature of upper surface drives heat exchange from upper PV panel to the ambient air, while slowing down heat exchange with air under the panel. When heat exchange between panel and outer air equals to the energy gain from solar radiations then temperature stays constant on the panel surface. That hypothesis was proofed by creating additional 3D model of 3 m long PV panel. Results shown that heat flux (from upper surface to bottom surface) is decreasing along the length of bottom wall of the panel. The effect of this assumption will be discussed further in the results.

4 RESULTS

Figure 17 presents temperature patterns of the bottom surface of the modeled PV panel for the cases with air gap height varied from 5 cm to 30 cm. In the graph it can be observed that temperatures of the PV panel are much higher than usually reported in the literature. This is due to assumption no 2. Effective heat flux should be decreasing with length along the panel because of more intense heat exchange over the panel (higher temperature difference between ambient air and panel surface drives heat exchange). Finally temperature values should be stabilized (at “equilibrium” temperature) when the heat exchange from upper wall equals to solar heat flux.

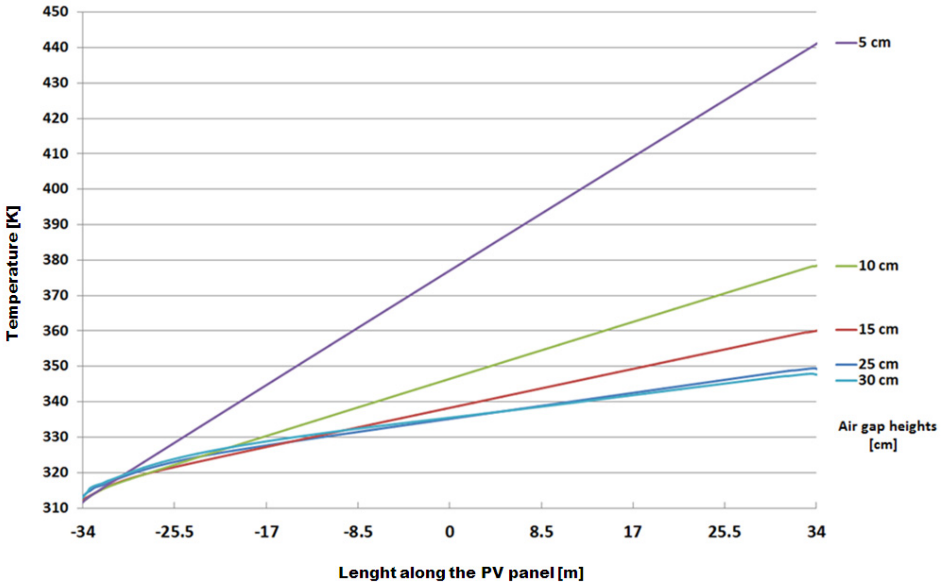

Figure 16. Heated wall temperatures (bottom surface of PV panel) for different air gap heights (5, 10, 15, 25, 30 cm) derived from the model.

Predicted behavior of the temperature curves for each case if assumption of the equilibrium temperature is made (77° C) is shown in Figure 18.

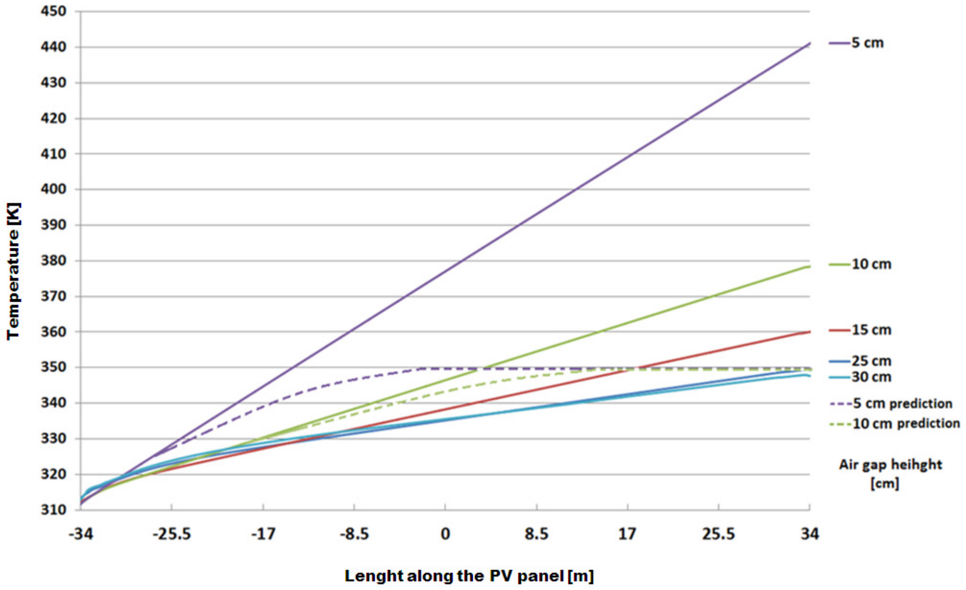

Figure 17. Predicted behavior of temperature profiles for equilibrium temp of 77° C.

5 CONCLUSIONS

The developed model can be used for comparison analysis of different air gap widths rather than predicting exact temperatures of PV panels for fixed conditions.

The following results can be drawn from the study:

It seems to be that 5 cm wide air gap is not sufficient to provide natural convection cooling of 70 meter-long roof made of PV panels.
Increasing air gap width over the 25 cm seems not to giving substantial improvements of natural convection cooling. It is important information for designers since designing optimal height of air gap will provide better conditions for PV panels operation and consequently higher electricity generation. Too small air gap would cause higher temperature of PV's what has negative influence on conversion efficiency. Designing too large air gap would require stronger supports for panels (since larger air volume can cause stronger force which can destroy large surface of panels) moreover larger gap would make roof more exposed for wind driven rains.

The developed model is a good starting point for further study in this area. Findings and experience gained during this study hopefully can be transferred into 3D modeling of this case.

6 FUTURE WORK

- 3D model should be developed and validated including experience gained during 2D modeling. A 3D model will address both assumptions/simplifications 1 and 2. Three dimensions model hopefully will give more realistic results and give opportunity to study different configurations of PV panels (e.g. gaps between panels etc.).
- A mathematical model can be developed in order to predict increased energy production due to natural convection cooling system configuration.
- The solutions like different configurations of PV panels or modification to the bottom wall surface and other methods of enhancing cooling by natural convection can be tested numerically in the next stage of the study.
- Experimental works which would validate calculation results are under consideration.

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The Research Centre on Zero emission Buildings (ZEB)

The main objective of ZEB is to develop competitive products and solutions for existing and new buildings that will lead to market penetration of buildings that have zero emissions of greenhouse gases related to their production, operation and demolition. The Centre will encompass both residential and commercial buildings, as well as public buildings.

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