High-efficiency ventilation and heating systems by means of solar air collectors for industry building refurbishment

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Abstract

For the purpose of energy conservation, modern buildings are becoming more and more air-tight and generally rely on a mechanical ventilation system. According to the literature, solar air heating systems can contribute in a cost-effective way to the heating and ventilation of utility buildings. Especially cost-efficient, unglazed, façade-integrated solar air collectors seem to be an attractive new market for façade renovation. To demonstrate the technical feasibility of generating heating energy on facades, a demonstration plant based on an unglazed solar air collector was installed in 2013 in the façade of a demonstration building and was intensively studied using energy metering.

Keywords: solar air collector; ventilation system; energy efficiency; industry buildings; refurbishment

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1 INTRODUCTION

In Switzerland, factory construction represents nowadays around 50% of the total construction activity. The total façade area of factory buildings amounts to around 3 Mio m². Numerous factory buildings are allegedly nearing the end of their lifetime and need to be refurbished. Refurbishment represents around 30% of total factory construction activity in the Swiss Confederation (Swiss professional association for ventilated façades, personal communication). Cost-efficient, façade-integrated ‘transpired’ solar collectors could become an attractive new market segment for façade manufacturers [1, 2]. However, there is a lack of technical know-how on the connection with the ventilation system. Therefore, the Lucerne School of Engineering and Architecture, a center of excellence for ventilation, was asked to assist in the design and the testing of a generic solar air heating system for non-domestic buildings.

A benchmark analysis was performed on the basis of building and system simulations before launching a demonstration project to investigate the competition mechanism with other renewable energy sources such as photovoltaics. The main results were presented in earlier papers [3, 4]. According to the computation results, the market prospect, especially for non-domestic buildings, is very good and it was decided to build a full-scale demonstration plant at the university campus in Lucerne, Switzerland (Fig. 1).

2 METHODS

2.1 Demonstration plant

The demonstration of solar air heating ventilation system has been tested on an existing test building. The dimensions of the test building correspond to average sized factory halls in Switzerland. The factory hall has got a useful floor area of 300 m² and a height of 8.2 m. The factory hall is a typical, steel constructed industrial building. It is equipped with large entrance gates that allow trucks to enter into the hall. The roof and the walls are thermally insulated according to Minergie Standards. The wall is constructed with liner trays, which are covered by a metal sheet cladding on the outside. A perforated metal wall is installed in the top section of the south-facing side of a building, creating approximately a 9 cm confined gap between it and the building’s structural wall. The colored wall acts as a large solar collector that converts solar radiation to heat. It will receive the maximum exposure to direct sunlight during the fall, winter and spring. Fans mounted at the top of the wall pull outside air through the transpired collector’s perforations, and the thermal energy collected by the wall is transferred to the air passing through the holes. The fans then distribute the heated air into the building through ducts mounted near the ceiling. By preheating ventilation air with solar energy, the technology removes a substantial load from a building’s conventional heating system, thus saving energy and money.
As shown in Fig. 2, the perforated collector system also contains a bypass damper located directly in front of the fan inlet duct. During the summer months when ventilation air requires no heating, this damper opens, circumventing the air-heating system. The bypass damper automatically opens when the air outside reaches a predetermined temperature, usually \( \approx 20^\circ C \).

The orientation and size of the test collector were determined by the remaining available area of the south façade of the test building. Based on the manufacturer’s recommendation, the collector area was set at \( 13.1 \times 2.2 \text{ m} \) (width \( \times \) height) with a unique point of air intake (suction point) (more details can be found in [5]). Since no special thermal comfort requirements are set, the hall is exclusively heated via hot air (primary heating: solar collector, auxiliary heating: hot-air blowers). The solar air heating system is controlled according to collector outlet temperature by means of an on/off controller with a hysteresis band of 2 K that switches the fan off to prevent the make up air from falling below \( 19^\circ C \).

### 2.2 Energy monitoring system

The measurement at the demonstration facility aims at gaining knowledge about the energy performance of the overall system and to develop energy-efficient operation strategies. The following aspects are of scientific relevance:

- pressure losses in collectors at different air flow rates,
- temperature rise characteristics depending upon irradiation and air flow rate,
- collector efficiency line,
- optimal air flow rate through the collector,
- COP/EER of the system.

A metering plan has been developed in line with these factors (Fig. 3 and Table 1). Owing to budget constraints, only the most relevant parameters are recorded.

### 3 RESULTS AND DISCUSSION

#### 3.1 Heat distribution in the collector

As the diameter of micro-perforations is the same on the whole width of the collector, pressure loss increases, respectively, to the distance to the suction point: that may influence air velocity and therefore the capture and transport of solar heat. Heat distribution in the collector was qualitatively analyzed using infrared pictures of the façade on sunny days in September. Figure 4...
shows the central region of the collector around the air intake of the ventilation system (i.e. collector outlet). The temperature drop is distributed concentrically to the intake, suggesting absence of flow dead zones. The relatively homogeneous temperature band at the edge of the collector proves that any leaks in the edge region have no significant impact on the operation of the collector. Thus, we can conclude that the collector frame is tight.

At the edge of the collector, the isotherms are symmetric to the center of the collector (Fig. 5), which indicates a quasi-regular distribution of the air mass flow. On the right side of the collector, the IR absorption indicates a minor leak between two sheet metal elements (Fig. 6).

### 3.2 Determination of collector performance factors
An attempt was made to determine a collector-specific characteristic line, respectively, a performance factor, which best describes the collector operation and its thermal behavior. For this purpose, the temperature rise in the collector was plotted as a function of the normal global solar radiation. The resulting slope gradient
serves as a collector performance factor \( k \) (K m\(^2\)/W). This index can also be used to determine the collector thermal efficiency.

\[
k = \frac{\text{collector temperature rise}}{\text{vertical irradiation}} \tag{1}
\]

Figure 7 shows a sunny winter day with a high daily irradiation of around 5.1 kWh/m\(^2\) day. Outside temperature on that day ranged between 5 and 10\(^\circ\)C. The air volume flow was set to 50 m\(^3\)/ (m\(^2\) h). There was no wind on that day. The sluggish thermal behavior of the collector can be clearly observed. The data points have an offset under the rising sun, respectively, under the setting sun, due to the thermal mass of the sheet metal panels. As a result, when the sun rises, the collector is always colder than the temperature the collector should have under steady conditions at the considered solar radiation level. Adversely, when the sun sets, the collector is warmer than under steady conditions. Therefore, a best fitting straight has been drawn between the two data point sets and serves as a characteristic collector line.

Exemplary evaluations on the test unit in Lucerne from 23 February 2014 show that on that day, the \( k \) ratio approximately equals 0.042 K m\(^2\)/W (Fig. 8). The resulting thermal collector efficiency equals 62%, a value that correlates well with the literature [6].

3.3 Long-term monitoring

As part of a long-term measurement campaign, particular days of operation were selected and examined. We selected sunny winter days with the air collector in operation (controller set point was 19\(^\circ\)C outlet air temperature with hysteresis of 2 K). This analysis aimed to give insights about typical performance of the ventilation system and whether simple correlations with external parameters exist.

To facilitate comparability with other heating systems, a coefficient of performance called ‘COP heating’ was defined, similar to the conventional heat pump’s COP, as the ratio between useful solar heat and power consumption (power for the fan and controller) [Equation (2)]. In this project, this ratio is meant as a ‘plant COP’, i.e. referring to the total fan power consumption to overcome the pressure drop of the whole ventilation system (including measuring devices, air distribution ducts, etc.).

\[
\text{COP}_{\text{heating}} = \frac{\text{useful solar heat}}{\text{electrical power consumption}} \tag{2}
\]

Figure 9 illustrates the solar heat output and day-COP for the considered winter days.

On all the measurement days, the plant produced more heat than needed to preheat the ambient air. Similar to a convector, the excess heat was used to remove a substantial load from the building’s conventional heating system (in this case, hot-air blowers), saving energy and money. In the measurement period, the average daily COP was at least 16. There were days marked by high COP, but low amounts of generated heat. On those days, irradiance was very intense but only for a short time (i.e. brief...
sunny intervals). Accordingly, the operating time was short, but the efficiency particularly high.

Considering these examples, we can conclude solar collectors not only serve to preheat outside air, but they also provide a substantial heat amount to cover the heating load of the building.

3.4 Energy benchmark
In Switzerland, PV is viewed as the renewable energy source par excellence. In order to benchmark the energy performance of the air collector, a set of thin film amorphous PV solar laminate rolls were mounted on the south façade below the air collector.
Irradiance and wind effects were assumed to be the same on the whole façade.

The benchmark analysis is based on the period between 24 January 2014 and 28 January. The course of incoming radiation (radiation intensity) is shown in Fig. 10. The 5-day test period had varying weather conditions, with a mix of sunny days and cloudy days. The irradiation values refer to the vertical plane—thus normal to the collectors. According to measurements, the total vertical irradiation for the observation period amounts to 10.6 kWh/m².

The energy yields of the photovoltaic system were compared with the heat output of the air collector in Fig. 11. The representation is expressed in terms of primary energy, with a primary energy factor of 2 for electricity (according to the Swiss grid electricity mix) and of 1 for heat.

On 24 January 2014, the plenum of the air collector was not able to reach 21°C, thus rendering the air collector inoperable on that day. On the contrary, the PV was able to produce a small amount of electricity. The daily amount of irradiation on 25 January and on 28 January was comparably high, with vertical radiation on 28 January 10% higher in absolute terms. Resulting yields for PV and air collector were almost similar on both days. The test conditions may be considered as ‘reproducible’.

On 27 January 2014, the solar radiation was very high, but continuously interrupted by passing clouds (unsettled weather). In addition, the wind came mainly from the west, parallel to the collector surface. As a result, heat output of the air collector was rather moderate and compared with PV output, proportionally lower than on 25 January, respectively, 28 January.

Comparing the performance of thin-film PV system with the air collector during 5 days, the measured average efficiency for the thin-film PV plant achieved 4.6%, thus landing in the expected range according to the manufacturer’s data [7]. In the same period of time, the average system efficiency of air collectors reaches 57%.

This example shows that air collectors, thanks to their high efficiency at a low temperature level, display good energy potential for heating applications in non-domestic buildings. In a future project, the long-term monitoring will be continued and the annual solar yield for both technologies will be measured over one heating period. More technical insight is expected and this benchmark analysis shall be complemented.

4 CONCLUSIONS

To demonstrate the technical feasibility of generating heating energy on façades, a demonstration plant based on an unglazed solar air collector was installed in 2013 in the south façade of a demonstration building and was intensively studied using energy metering during a 3-month period.

The measurements show that the collector thermal efficiency primarily depends on parameters such as irradiance, outside temperature, air volume flow, wind speed and direction. The most disturbing factors for the energy measurement are the wind speed and direction, because they are difficult to measure precisely. Therefore, an absolute quantitative statement about
performance is not possible using a demonstration plant subject to aleatory meteorological changes, but an attempt was made to determine a characteristic line for the temperature rise in the collector. Results are in good accordance with literature data.

Furthermore, a benchmark analysis was performed in order to compare energy output of air collectors with those of PV cells. A 5-day test period with variable weather conditions was selected and the energy yields were compared in terms of primary energy. Basically, the air collector produces more primary energy than the PV due to its high efficiency at low temperature level. But since the temperature delivered by the air collector is relatively low (typically 30°C), uncovered air collectors are only suitable for low temperature heating applications such as room heating. Therefore, combining air collectors and PV-cell in the same wall panel seems to be a good approach in order to achieve a low-cost heat + electricity cogeneration plant.

Further work is planned at the demonstration plant in Lucerne. The focus is primarily set on seasonal performance and energy efficiency of the solar air heating system. Secondly, microbiological analysis will be carried out in the plenum of the collector in order to determine any biological contamination risk resulting from humidity condensation at night in the collector. Thirdly, acoustic measurements are to be performed in order to determine the sound level of the collector, especially when operated on rainy days when rain drops may partially obstruct perforation of solar absorber and so increase air velocity through the holes.

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